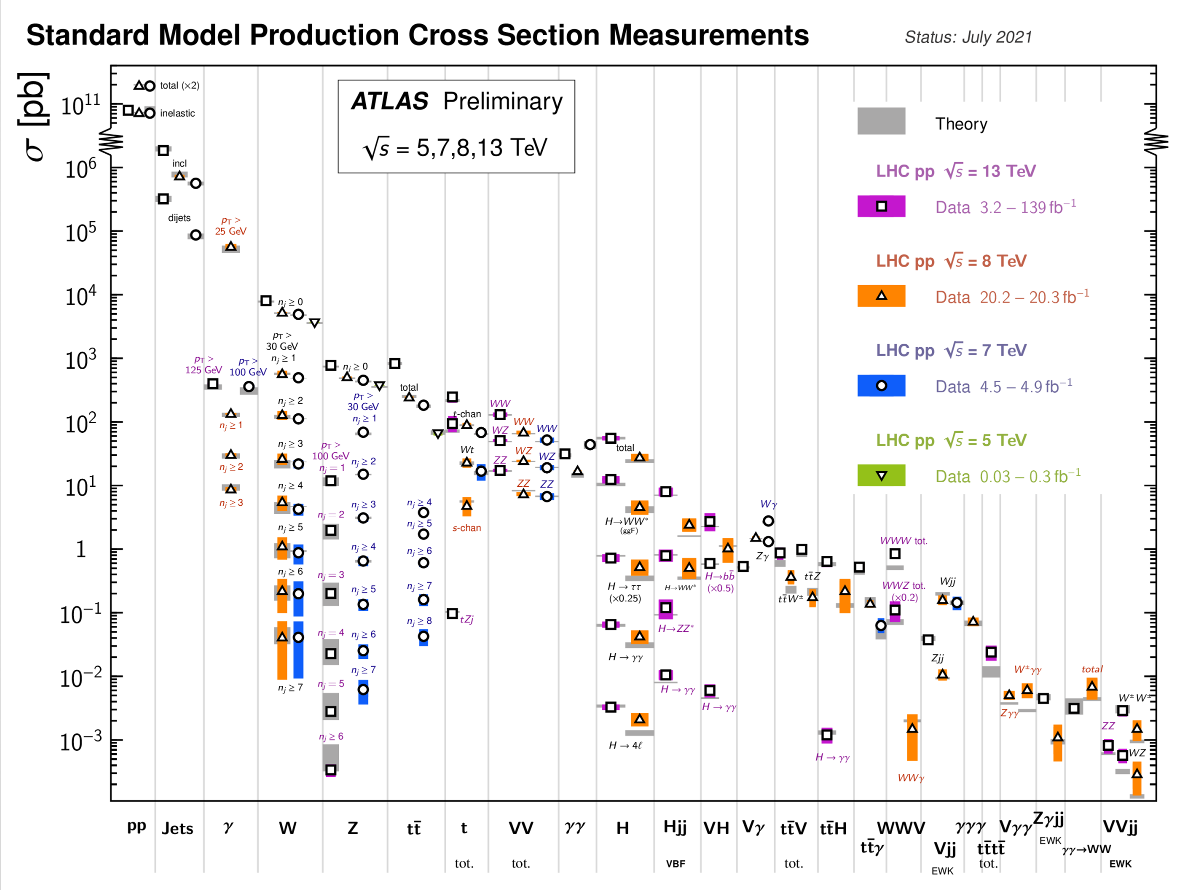
Standard Model Measurements at the LHC

Paolo Azzurri – INFN Pisa

Particle Physics Seminar

Outline

LHC explores process rates over **~9** orders of magnitude



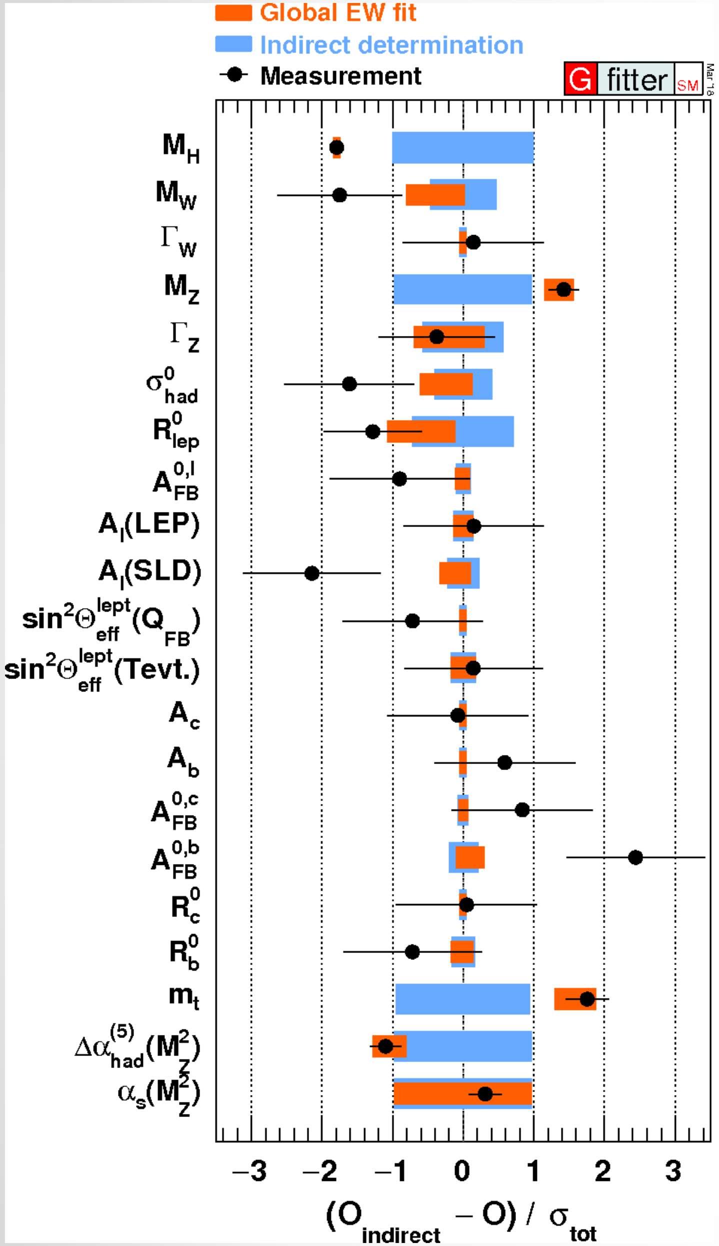
- The challenge of **high precision** with inclusive productions
- Test **models and higher order QCD and EW** calculations
- Examine differential distributions in **search for new physics effects**, with EFT formalism
- The thrill of **exploring and observing** new and most rare expected processes

Personal selection of most relevant results released in the **last year**

High precision

The challenge to improve on LEP / Tevatron

- the W boson mass
- the W boson branching fractions
- invisible Z boson decays

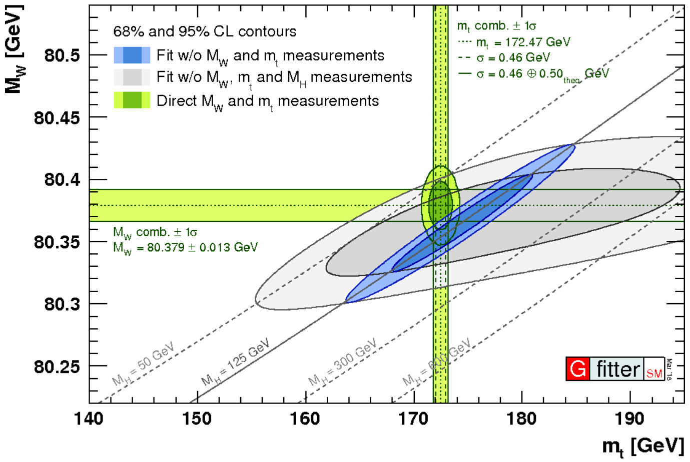


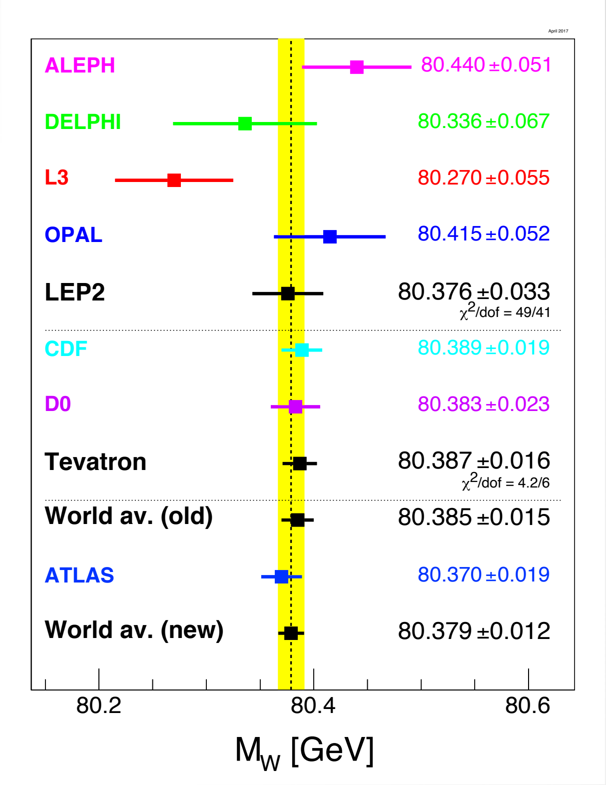
Global EW fit

looking forward to improve the direct determination of parameters with large *Measurement* error bars

- m_W, Γ_W
- Z pole asymmetrties
- Z pole (HF) decay rates

arXiv:1803.01853





PDG

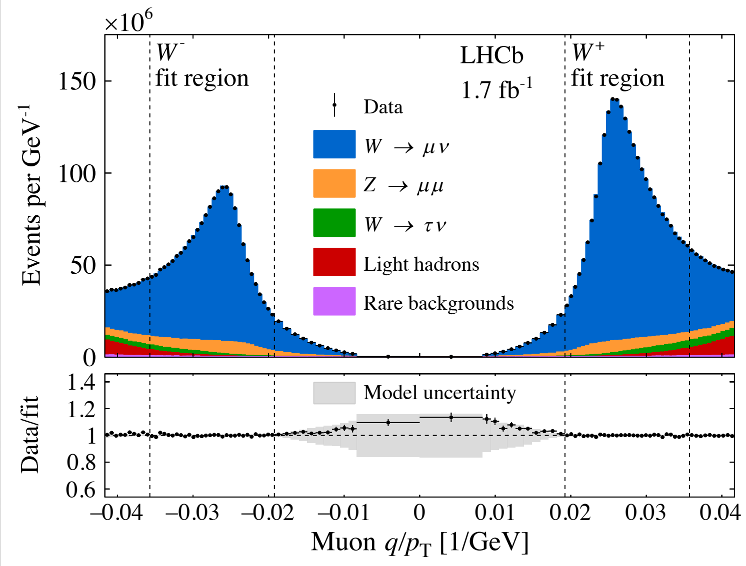
can LHC improve the W mass from (LEP) / Tevatron ?

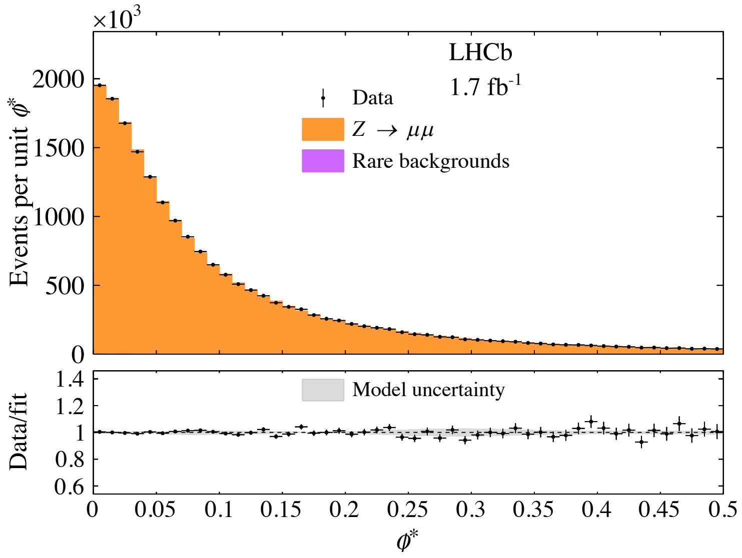
W boson mass

Fit of muon q/p_T with 2016 dataset (1.7 fb^{-1})

~2.4M muons with $28 < pT < 52$ GeV $2.2 < \eta < 4.4$

~200k Z events fitted simultaneously in φ^* : proxy for $p_T(Z)$





Muon momentum exp calibration and modelling based on fit of Z, ϒ(1S) and J/Ψ data and simulation.

Powheg+Pythia tuning of α_s and intrinsic kT
Uncertainty based on envelope of 5 models.

Angular coefficients α_S^2 predictions from DYTurbo. Uncorrelated (31 point) scale variation, A_3 floated.

NNPDF31, CT18, MSHT20 PDFs : results averaged, no constraints on uncertainties

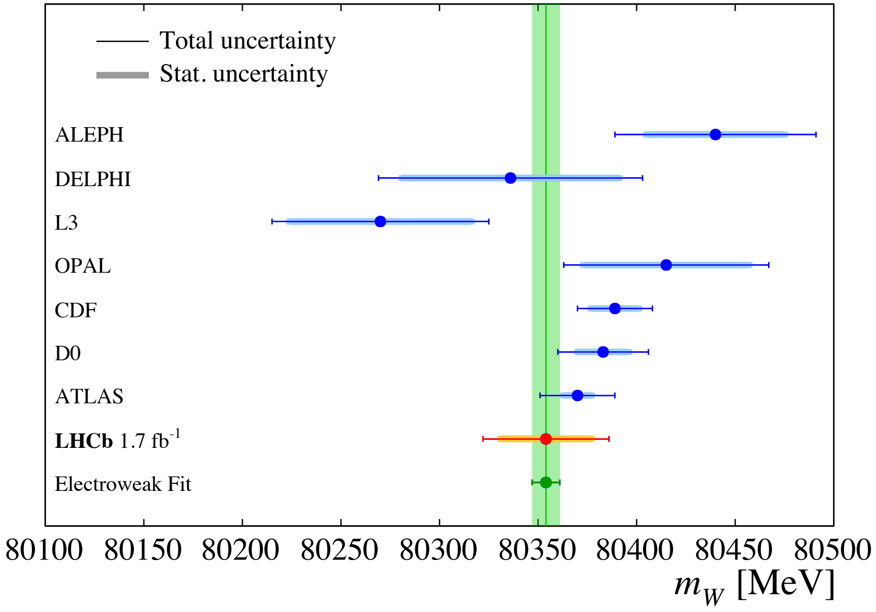
Pythia, Photos and Herwig FSR : results averaged, uncertainty is based on envelope

W boson mass

arXiv:2109.01113

$$m_W = 80364 \pm 23_{\mathrm{stat}} \pm 11_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}$$

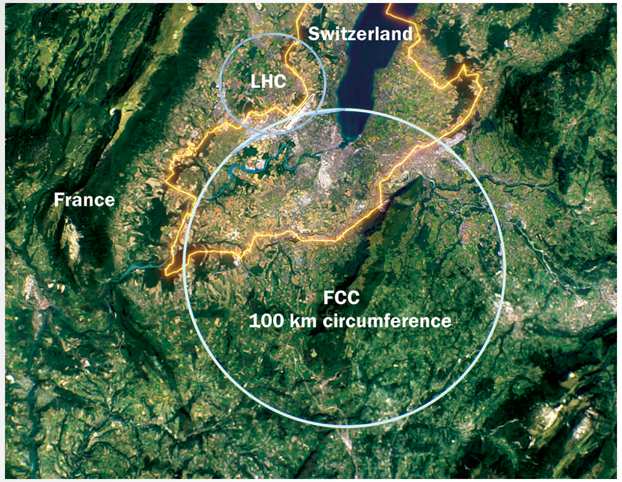
Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	**17.4**	
Transverse momentum model	12.0	Envelope from five different models
Angular coefficients	9.0	“Uncorrelated” 31 point scale variation
QED FSR model	7.2	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5.0	Test with POWHEGew
Experimental total	**10.6**	
Momentum scale and resolution modelling	7.5	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6.0	
Isolation efficiency	3.9	
QCD background	2.3	
Statistical	**22.7**	
Total	**31.7**	

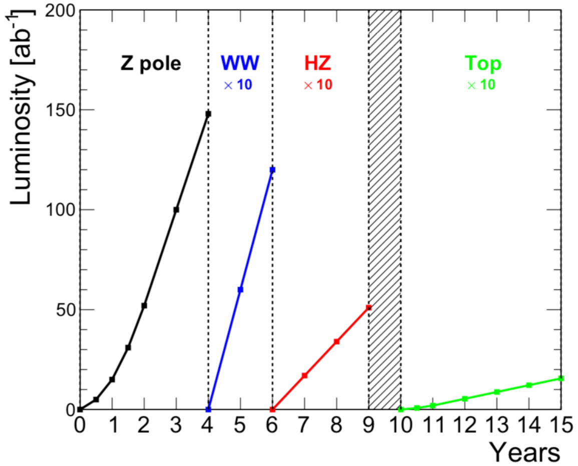


A total uncertainty of $\lesssim$ 20 MeV looks achievable with existing LHCb data : unique & complementary rapidity coverage !

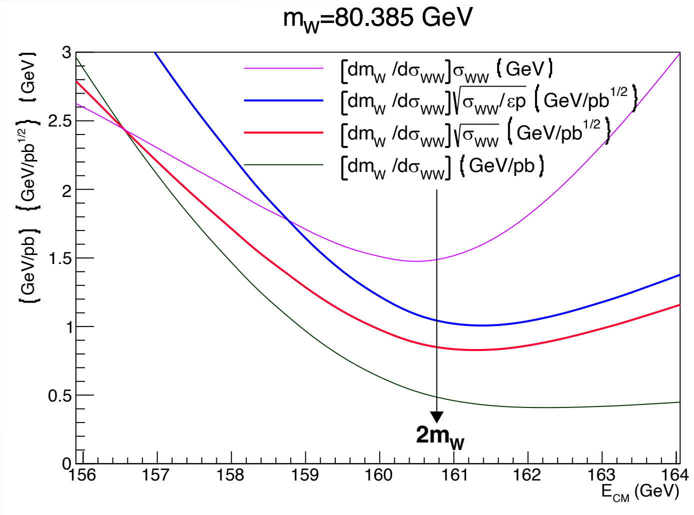
W boson mass: future

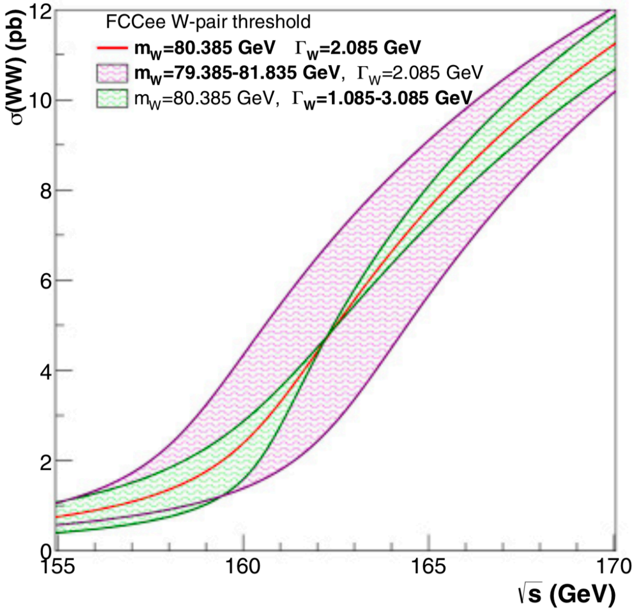
arXiv:1703.01626
arXiv:1909.12245
Eur.Phys.J.C 80 (2020) 1
arXiv:2107.04444 *Eur.Phys.J.Plus* (2021) 136

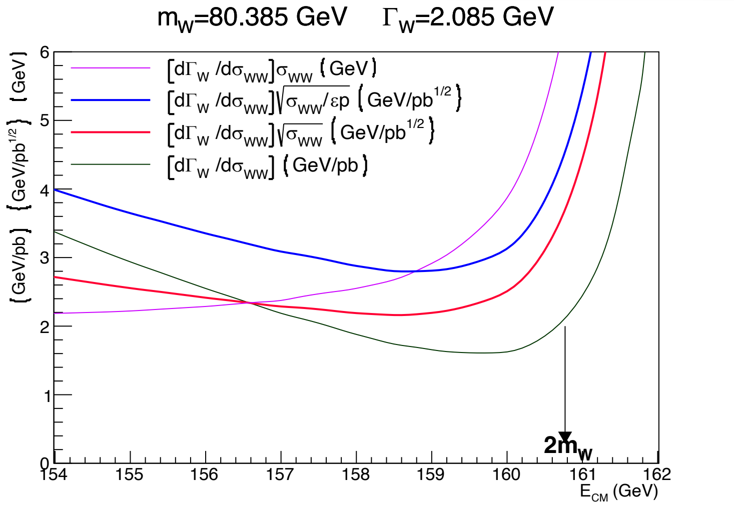




Scan of W-pair production threshold cross section at future e+e- collider
Precise determination of m_W and Γ_W

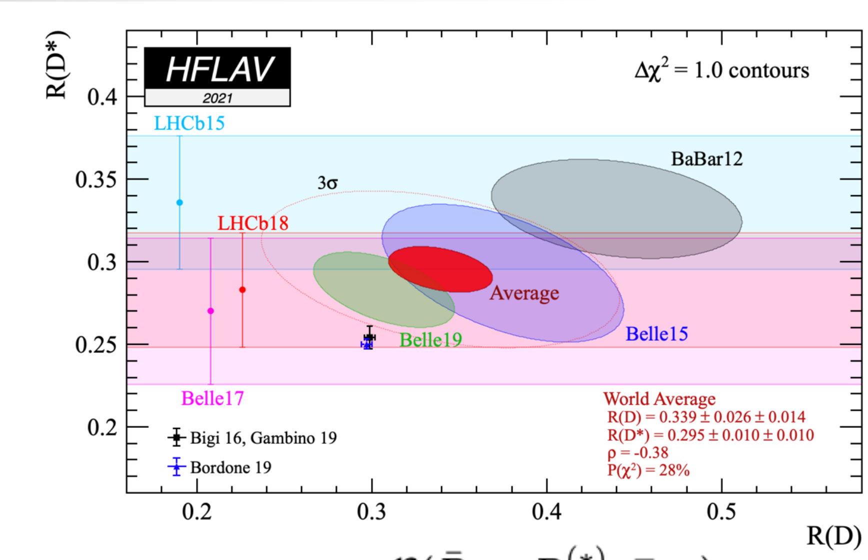






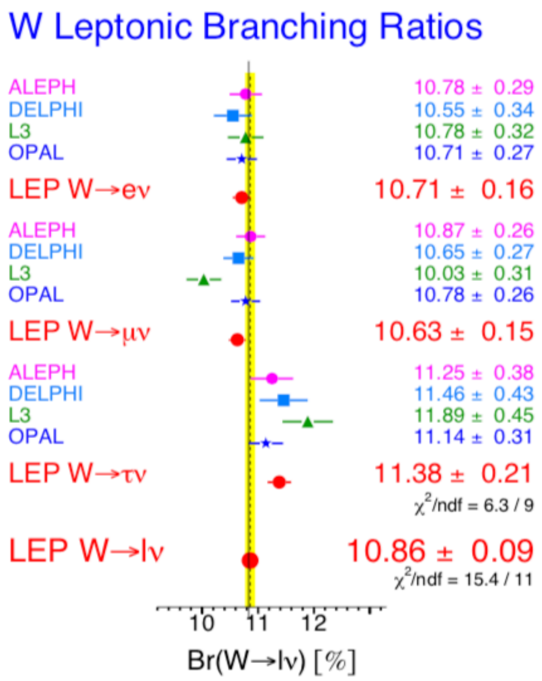
5/ab@**157.3** GeV+7/ab@**162.6** GeV
Δm_W=0.5 MeV **$\Delta\Gamma_W$=1.2 MeV**

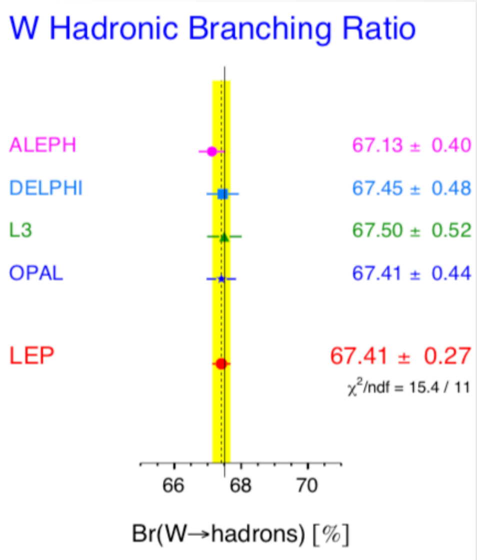
LFU & W boson branching fractions



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

The LEP results



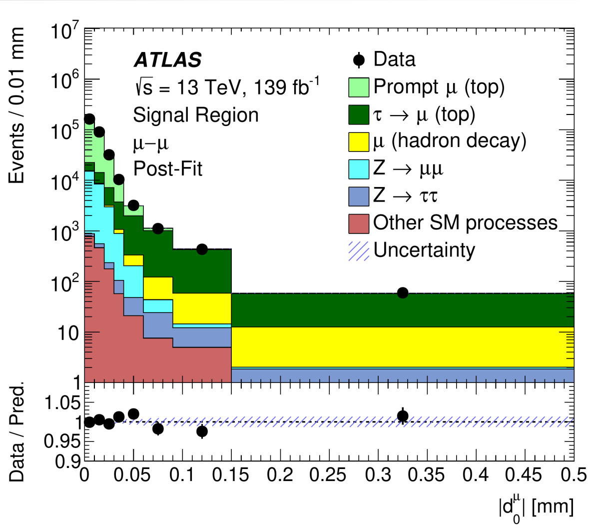


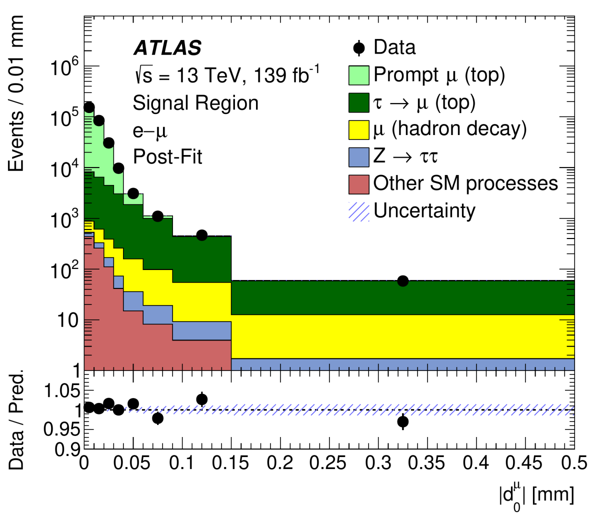
Lepton universality test at 2% level

$\boldsymbol{\tau}$ BR ~2.6 σ larger than e/$\boldsymbol{\mu}$

W boson branching fractions

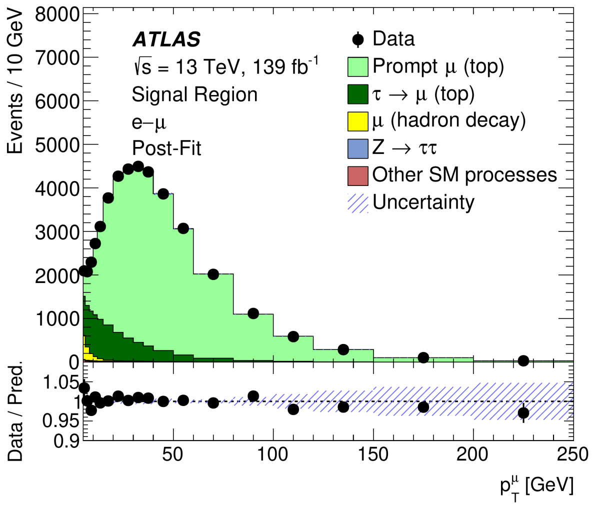
arXiv:2007.14040





Selection of di-leptonic $t\bar{t}$ events ($e\mu$ / $\mu\mu$) + b-jets

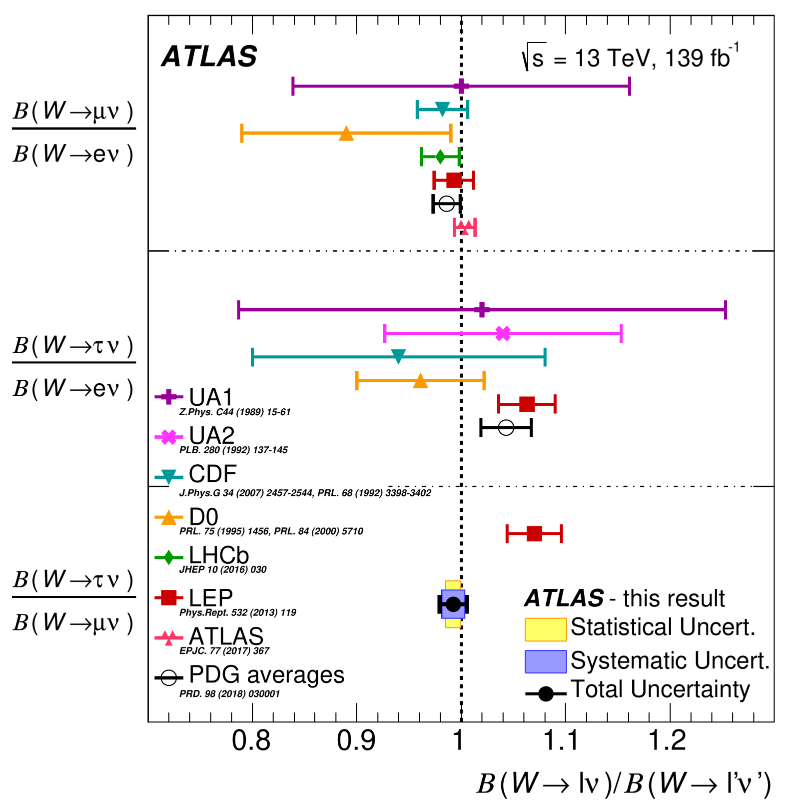
tag e/μ for event trigger : *probe* muons have no bias



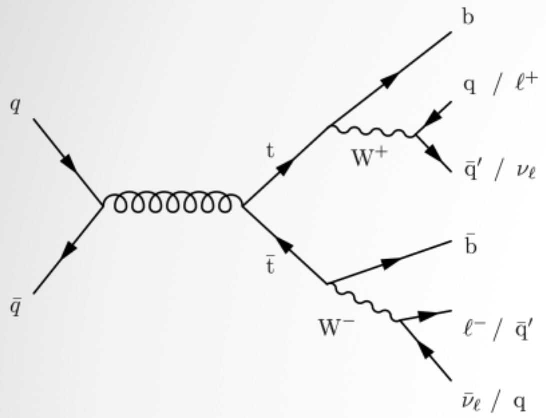
two dimensional likelihood fit in $|d_0(\mu)|$ and $p_T(\mu)$

$R(\tau/\mu) = 0.992 \pm 0.013$ [± 0.007 (stat) ± 0.011 (syst)]

uncertainty **half** of LEP results.



W boson branching fractions



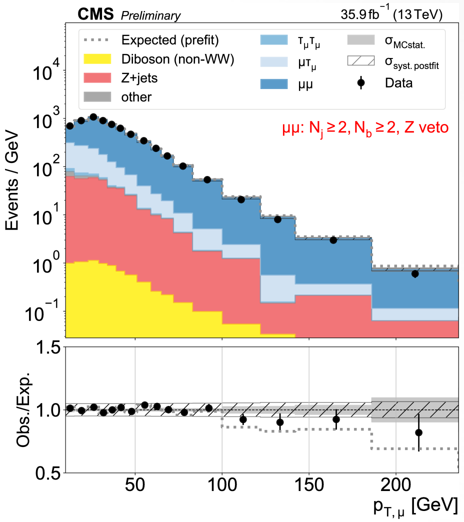
tag e/μ for event trigger
probe **all decays of the other W**
e, $\boldsymbol{\mu}$, hadronic $\boldsymbol{\tau}$, hadronic jets

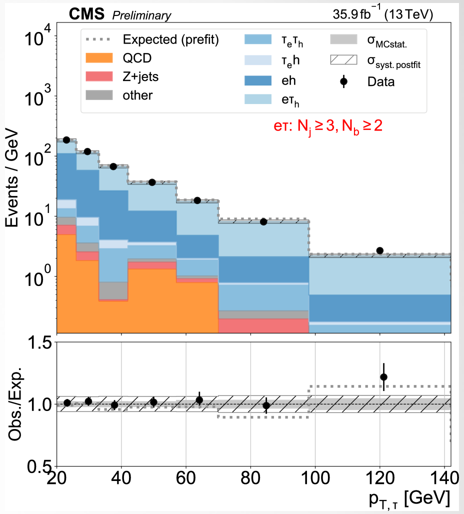
Max likelihood fit of all W BR with histogram templates of leptons p_T (IP not used in this analysis)

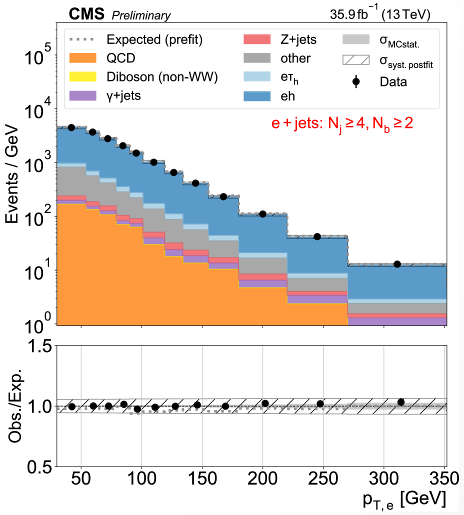
	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$		
			$ee, \mu\mu, e\mu$		
$N_b = 1$		$e\tau, \mu\tau, e\mu$	$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					eh, μh
$N_b \geq 2$			$e\tau, \mu\tau$	$e\tau, \mu\tau$	
			$ee, \mu\mu, e\mu$		
					eh, μh

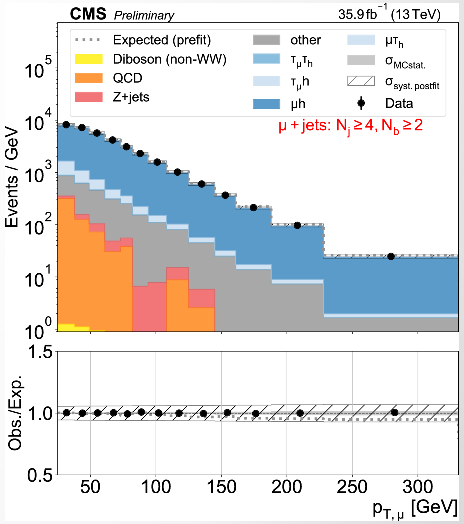
Results obtained both for LU W hadronic BR and for individual W leptonic BR

Uncertainties dominated by different syst for each BR
- theory (QCD scales, ISR, PS, ..
- exp (lepton-id efficiencies, JES, b-tagging, ..)



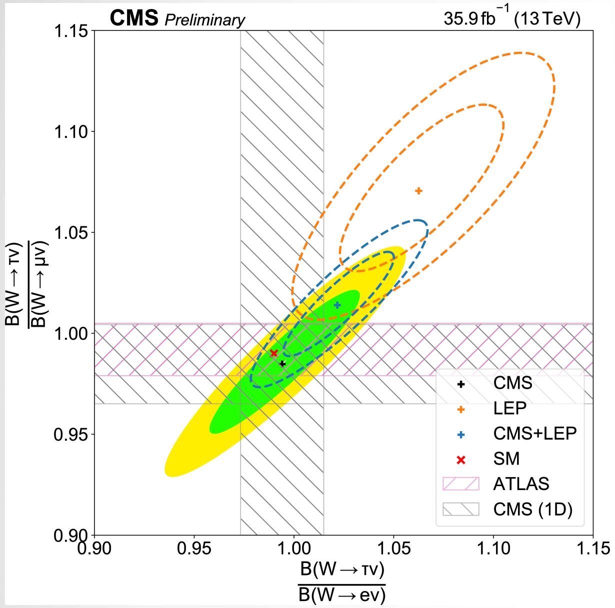


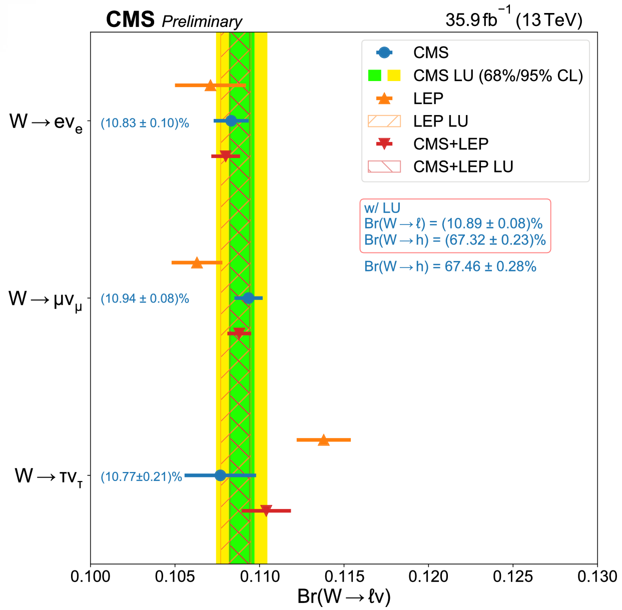




CMS-PAS-SMP-18-011

W boson branching fractions





	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

Hadronic branching fraction interpretations

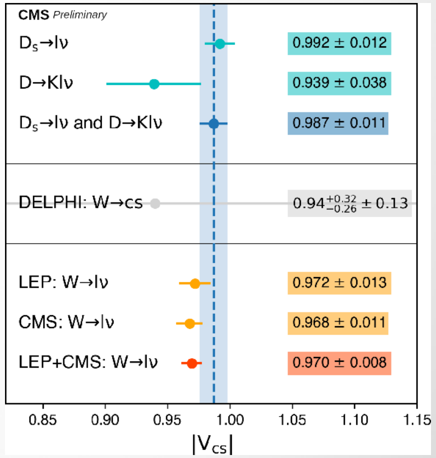
$$\frac{\mathcal{B}(W \to h)}{1 - \mathcal{B}(W \to h)} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{\substack{i=(u,c),\\ j=(d,s,b)}} |V_{ij}{}^2| = 2.060 \pm 0.021$$

	CMS	LEP	ATLAS
$R_{\mu/e} = \mathcal{B}(W \to \mu\overline{\nu}_\mu)/\mathcal{B}(W \to e\overline{\nu}_e)$	1.009 ± 0.009	0.993 ± 0.019	–
$R_{\tau/e} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to e\overline{\nu}_e)$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–

$$\alpha_S(m_W^2) = 0.094 \pm 0.033$$

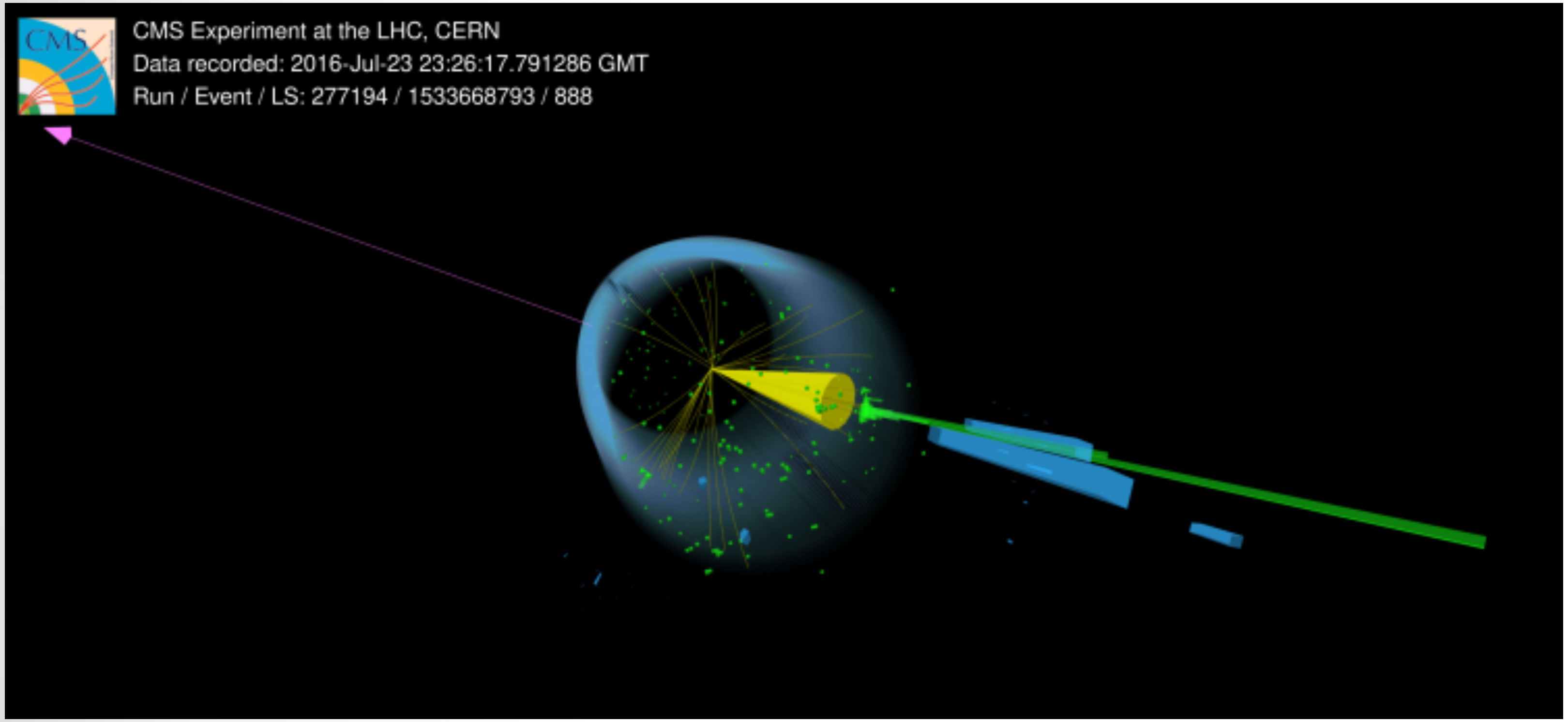
$$\Sigma_{ij}|V_{ij}|^2 = 1.989 \pm 0.021$$

$$|V_{cs}| = 0.969 \pm 0.011$$



CMS-PAS-SMP-18-014

Invisible Z width



Data regions with

Missing transverse momentum + jets
(**invisible** Z boson decays)

Single leptons (e/μ/τ) + jets
(W boson decays)

Double electrons and **muons + jets**
(dilepton Z boson decays)

Events selected in the p_T(miss)>200 GeV region
(leptons from W / Z decays excluded in the CRs)

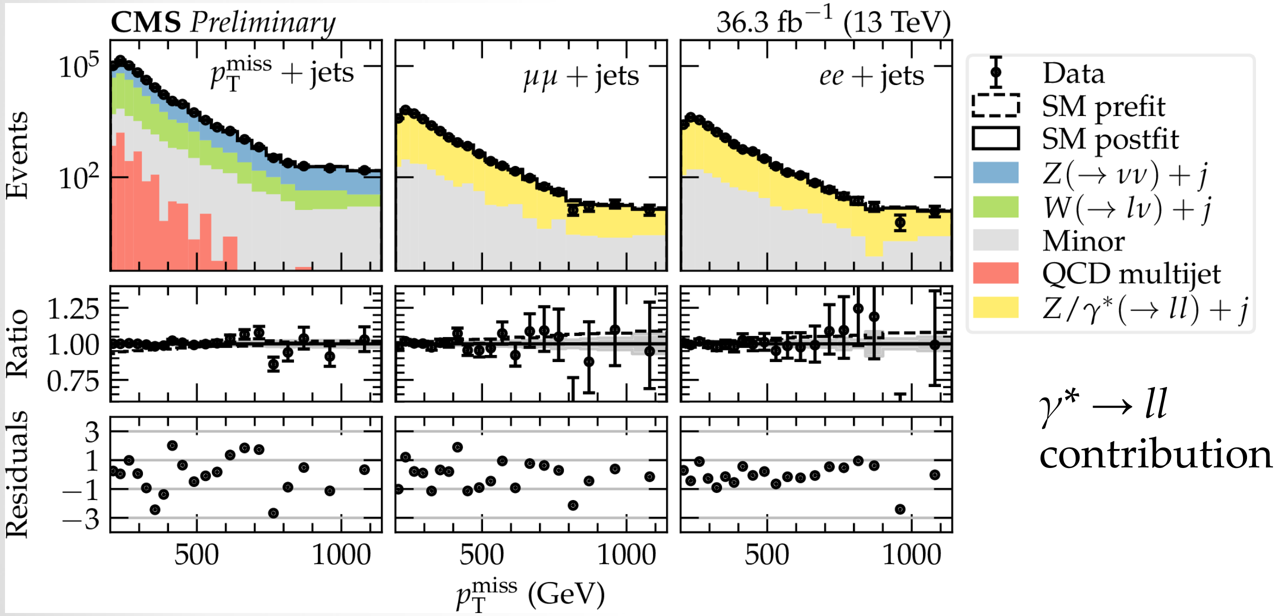
Invisible Z width

CMS-PAS-SMP-18-014

Simultaneous fit of p_T(miss) in the **invisible** region together with single and double **electrons/muons** regions

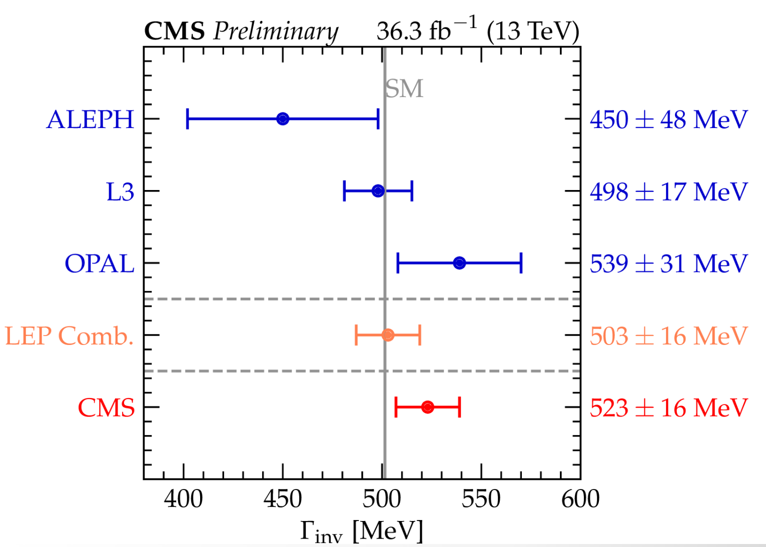
Measuring $\frac{\sigma(Z+jets)B(Z\to\nu\nu)}{\sigma(Z+jets)B(Z\to\ell\ell)} = \frac{\Gamma(Z\to\nu\nu)}{\Gamma(Z\to\ell\ell)}$

and converting to Γ_{inv}



Γ_{inv} =523±3(stat)±16(syst) MeV

$\gamma^* \to ll$ contribution subtracted



QCD backgrounds estimated with dedicated control regions

Major uncertainties from lepton efficiencies and jet energy scale

[CMS-PAS-SMP-21-002](CMS-PAS-SMP-21-002)

NEW

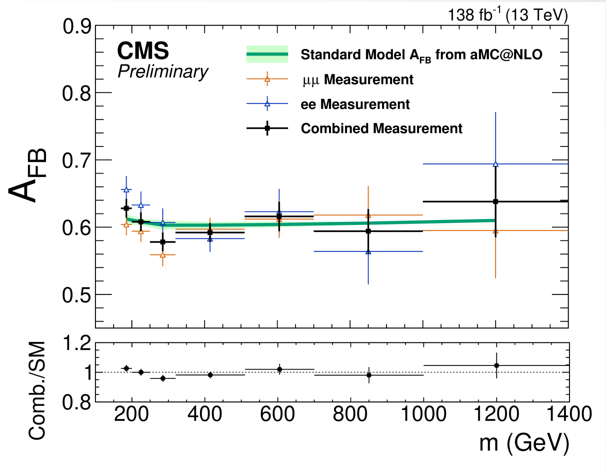
High mass DY A_{FB}

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

two OS leptons (electrons or muons) $m(\ell\ell) > 170$ GeV

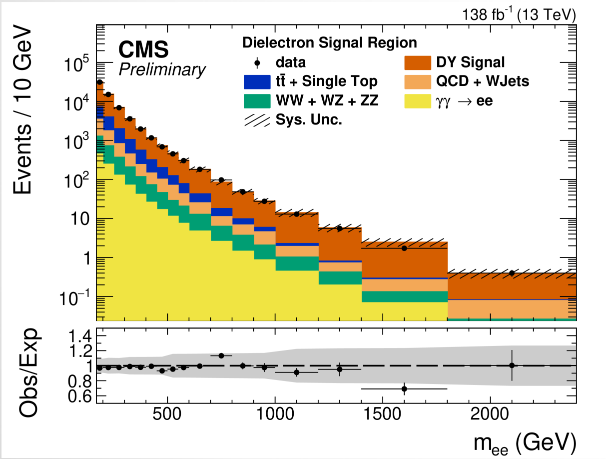
$$\frac{d\sigma}{dc_*}(m^2) \propto \frac{3}{8}\left\{1 + c_*^2 + \frac{A_0}{2}\left(1 - 3c_*^2\right) + A_4 c_*\right\}$$

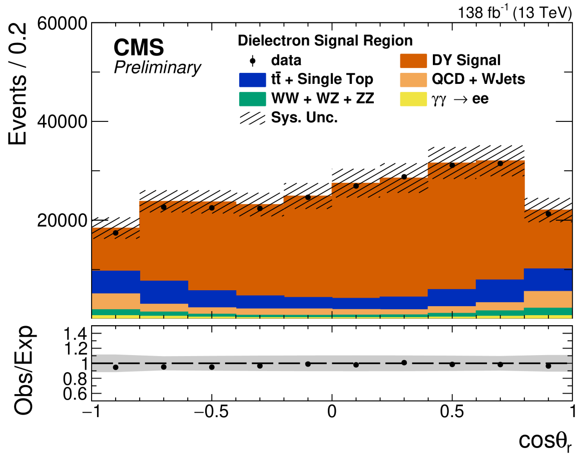
$$\frac{3}{8}A_4 = A_{FB}$$

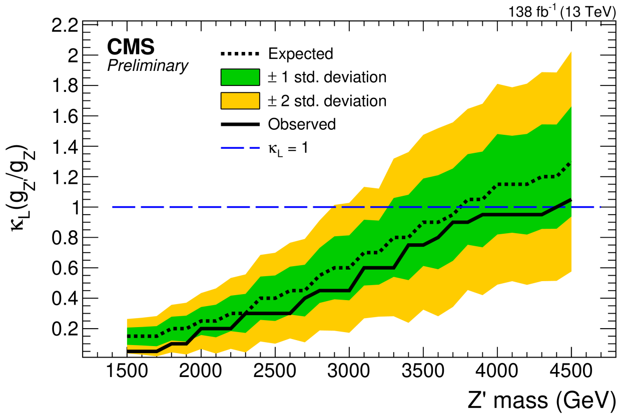


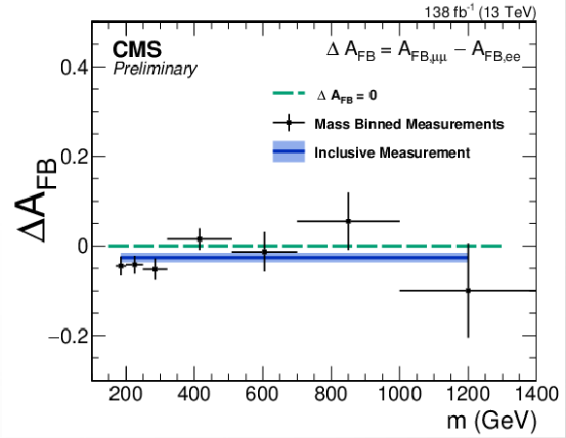
instead of initial quark → p_z of the lepton pair : $\cos\theta^* \to \cos\theta_r$ (asymmetry dilution)

electron-muon tension $2.4\boldsymbol{\sigma}$









e$\boldsymbol{\mu}$ CR for top and diboson backgrouns

limits on SSM Z'

Differential tests of QCD predictions

The "NLO" revolution

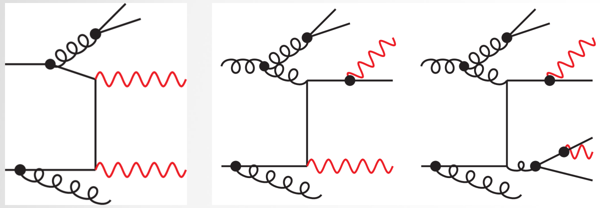
- inclusive jets & multi jets
- Vector bosons plus jets

Les Houches 2017 Theme : I am the QCD

photon pairs

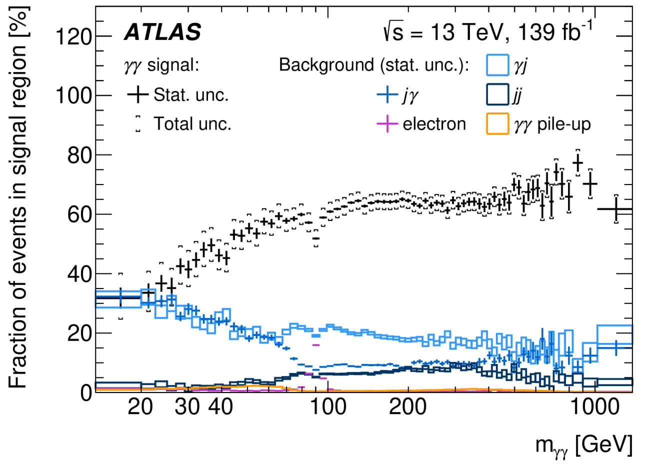
arXiv:2107.09330

Selection	Detector level	Particle level
Photon kinematics	$p_{T,\gamma 1(2)} > 40\ (30)$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$	
Photon identification	tight	stable, not from hadron decay
Photon isolation	$E_{T,\gamma}^{iso,0.2} < 0.05 \cdot p_{T,\gamma}$	$E_{T,\gamma}^{iso,0.2} < 0.09 \cdot p_{T,\gamma}$
Diphoton topology	$N_\gamma \geq 2$, $\Delta R_{\gamma\gamma} > 0.4$	

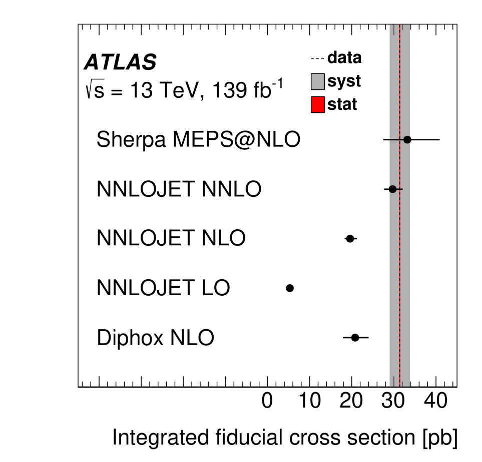


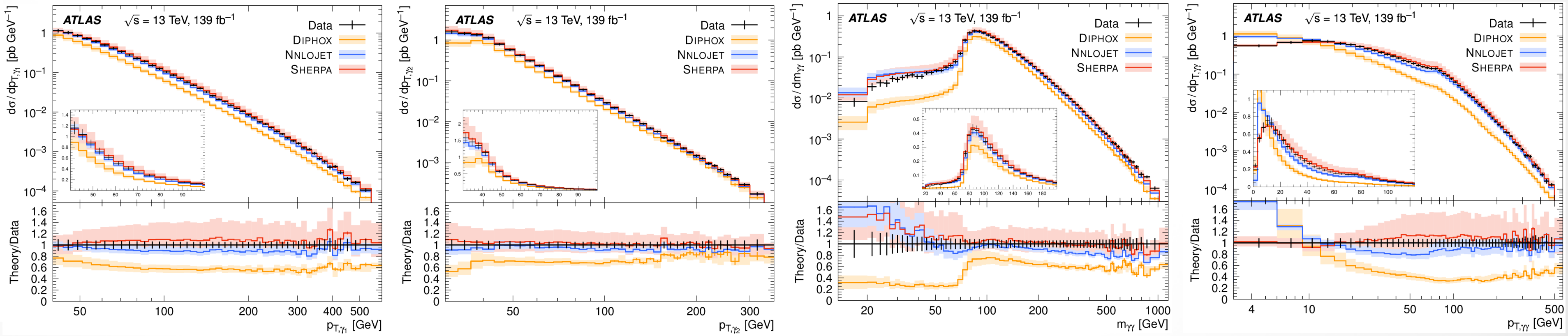
direct and fragmentation prompt γs

main challenge and uncertainty from non-prompt γs estimated with data-driven methods



average signal purity 60%





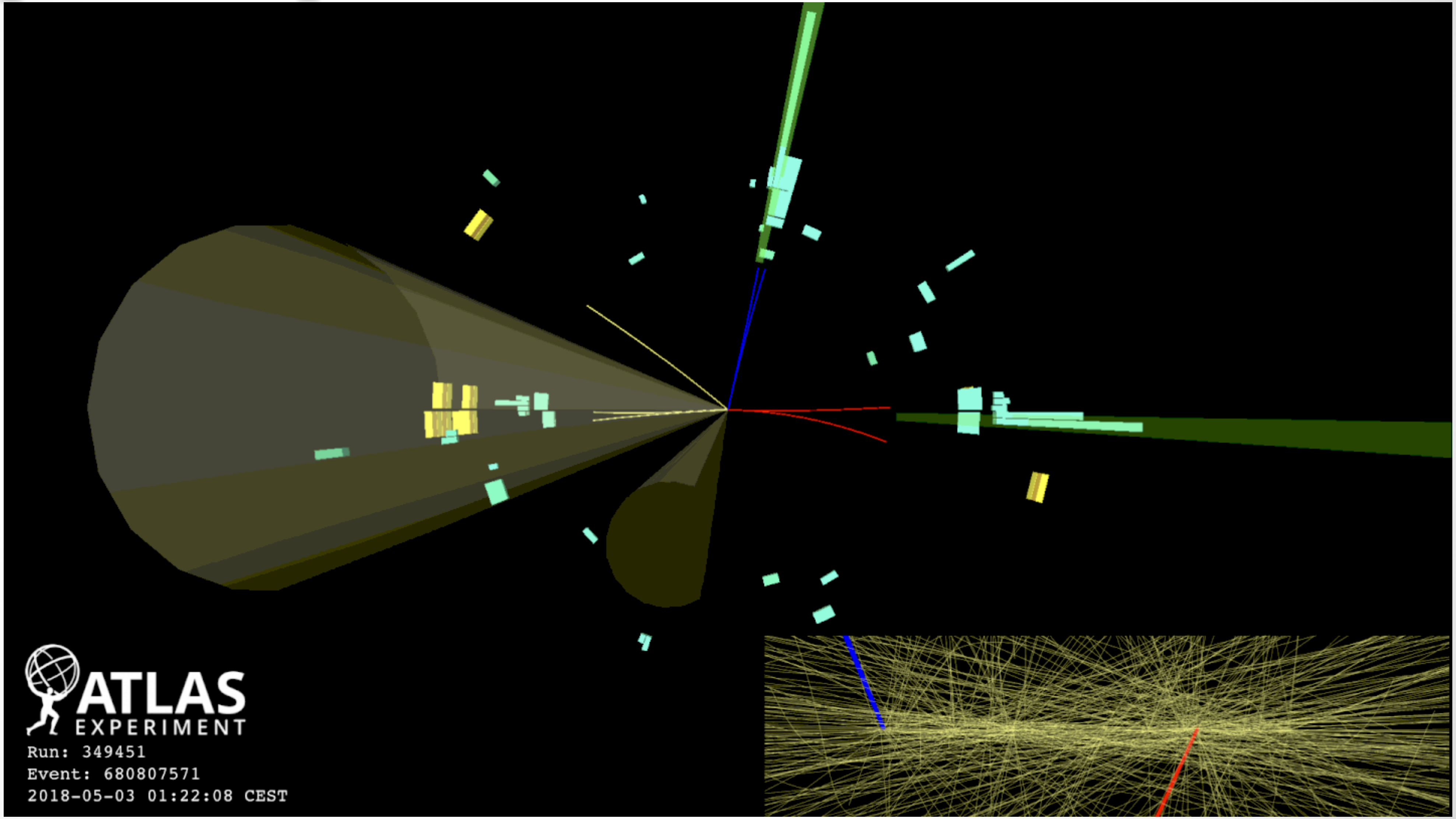
$\sigma_{\gamma\gamma} = 31.4 \pm 0.1\ (\text{stat.}) \pm 2.4\ (\text{syst.})$ pb

Differential distributions in reasonable agreement with Sherpa ME+PS and FO NNLO

photon pairs

arXiv:2107.09330

Event with two photon candidates (green cones) where both candidates have tracks in the inner detector (blue and red lines) that are compatible with photons undergoing electron–positron conversion



Pileup background !

[CMS-PAS-SMP-21-009](CMS-PAS-SMP-21-009)

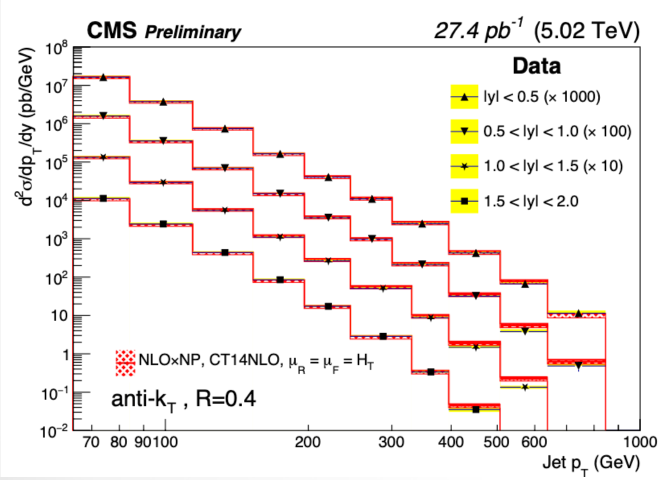
arXiv:2111.10431

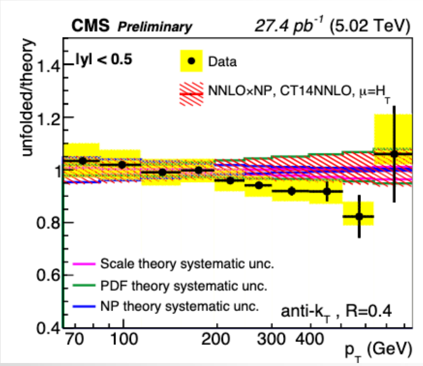
Inclusive & multi-jets

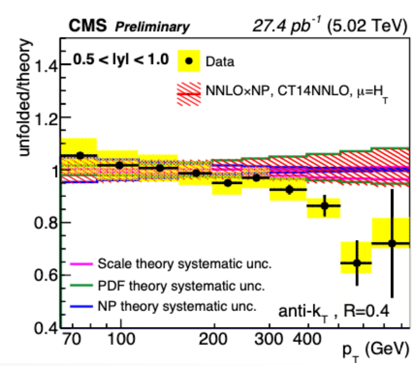
With 27.4 pb^{-1} at **5 TeV** and 33.5-36.3 fb^{-1} at **13 TeV**

Single-jet (prescaled) triggers.
Anti-k_T jets with R=0.4 (and R=0.7 @13 TeV).

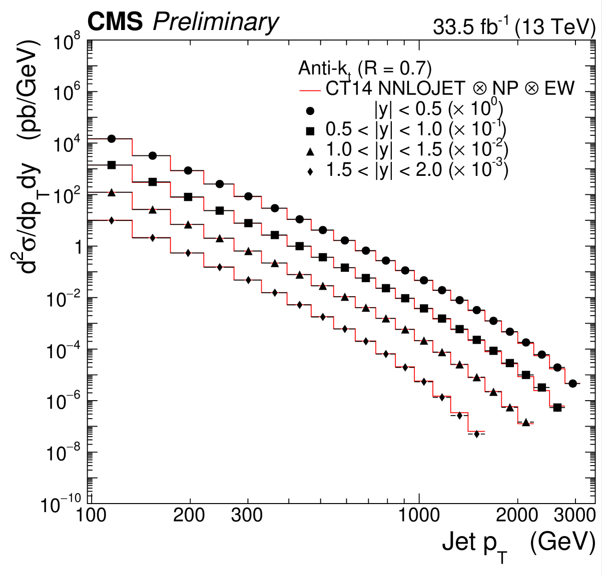
5 TeV



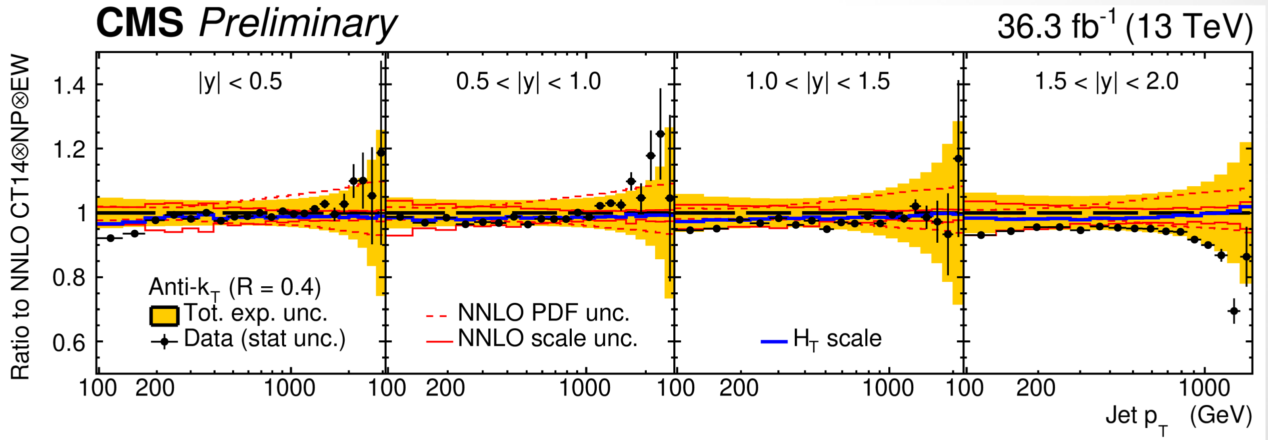




13 TeV



Results unfolded to particle level jets |y|<2
p_T>64 GeV (5 TeV) & 97 GeV (13 TeV)



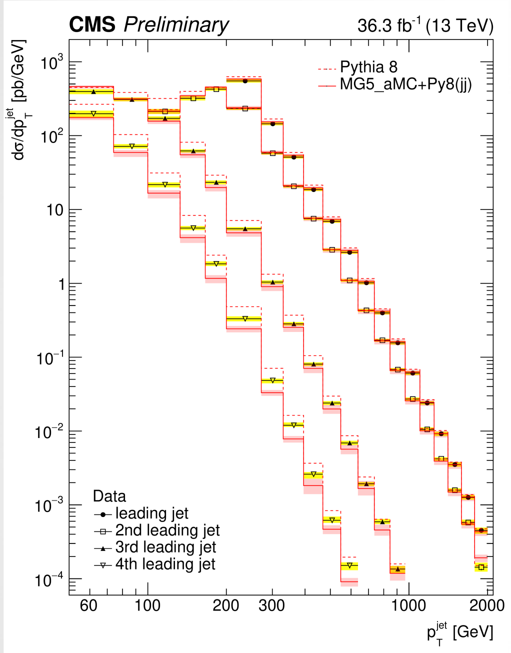
Results compared to NLO & NNLO QCD predictions $\mu = p_T \,/\, H_T$

CMS-PAS-SMP-21-006

arXiv:2111.10431

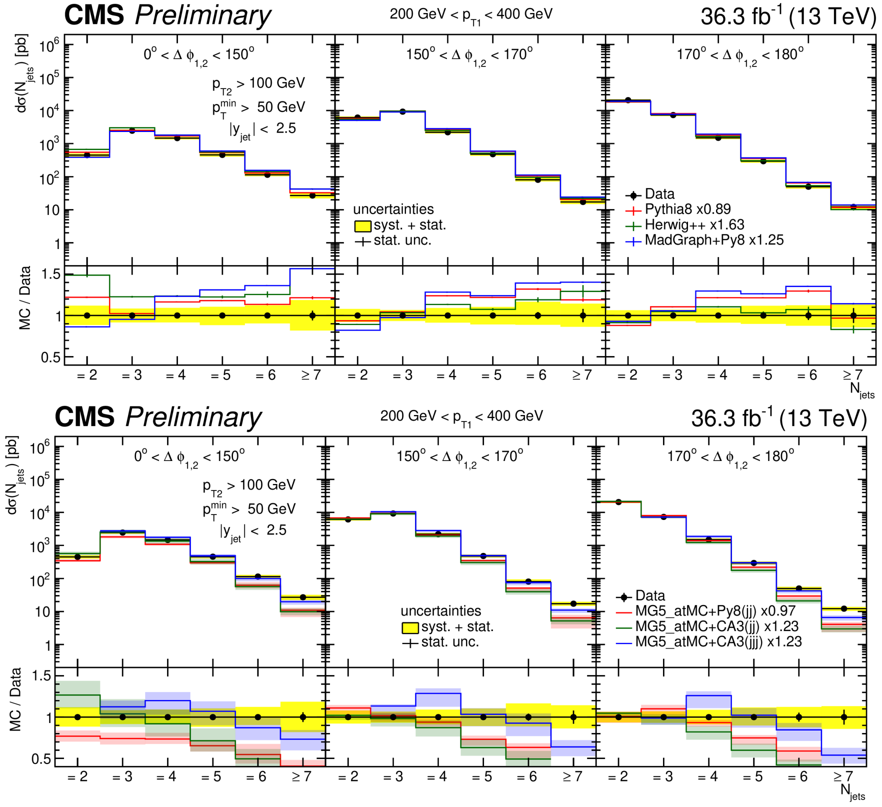
Inclusive & multi-jets

Multijet events with p_T>200, 100, 50, 50, … GeV |y|<2.5



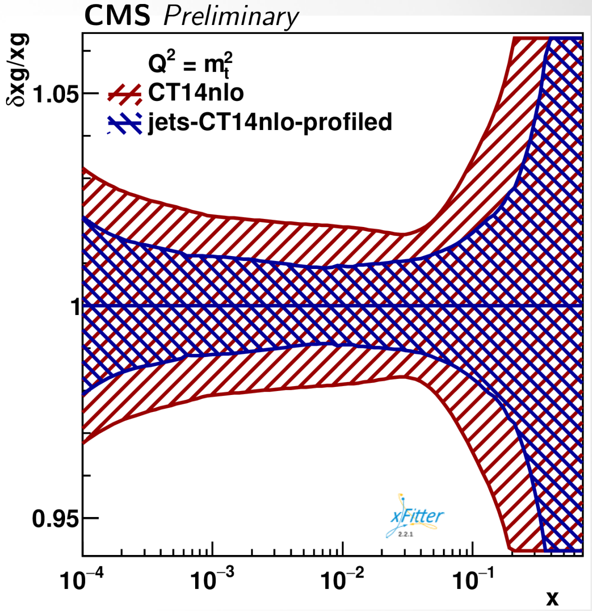
Benchmark for multijet calculations, and simulations including PS showers for higher jet multiplicity.

Up to 7 measured jets



Comparisons with PB-TMDs parton densities and TMD PS

QCD (PDF) analysis



Remarkable constraints on gluon PDF

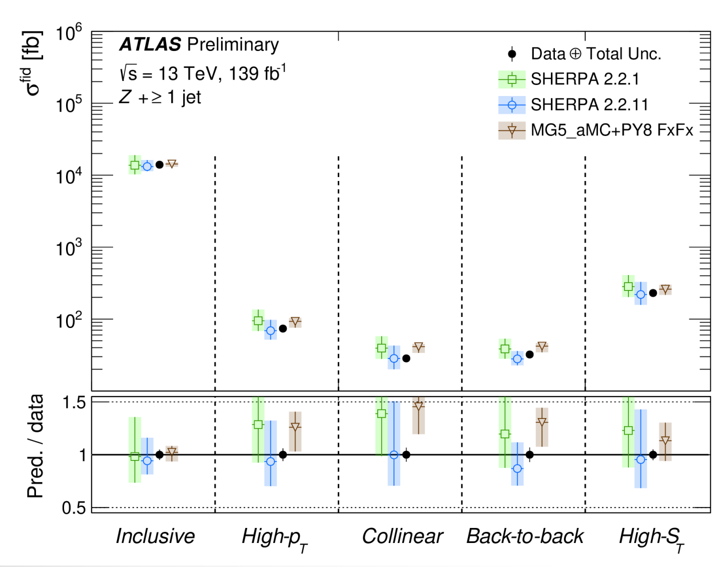
$\alpha_S(m_Z) = 0.1177 \pm 0.0014(\text{fit}) \pm 0.0022(\text{mod/par})$
$m_t(\text{pole}) = 170.2 \pm 0.6(\text{fit}) \pm 0.1(\text{mod/par})$ GeV.

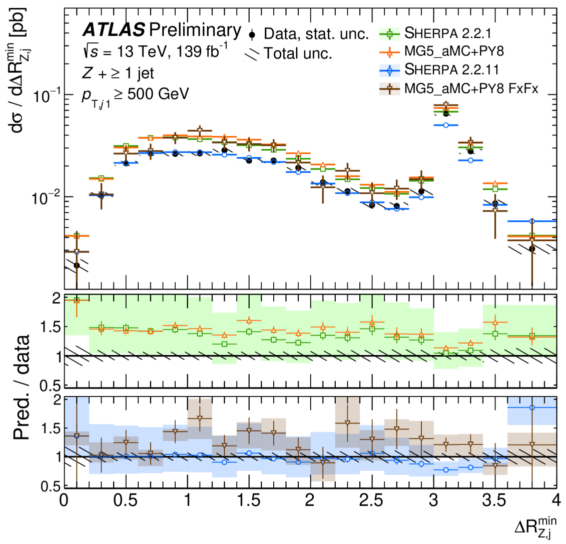
➔ Derived 68%CL on EFT CI models WC consistent with zero

Z + high p_T jets

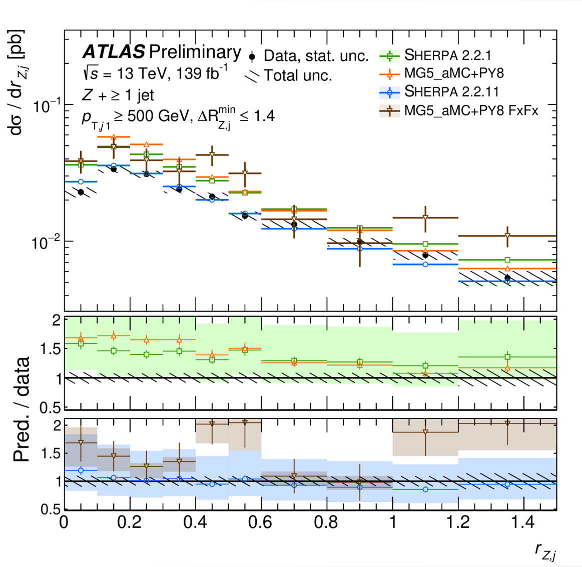
Full 13 TeV data (139 fb^{-1}), ee and $\mu\mu$ channels combined
Jet p_T > 100 GeV and |y| < 2.5 (*inclusive*) , S_T>600 GeV (*High- S_T*)
Jet p_T > 500 GeV (*High-p_T = collinear + back-to-back*)

several differential measurements in all regions





high-pT



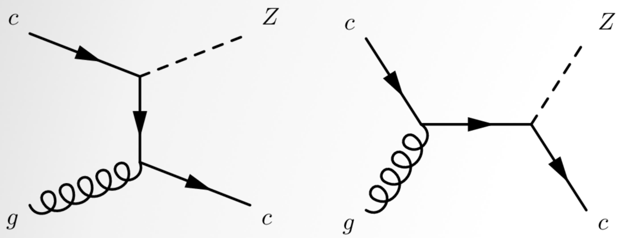
collinear

total σs : larger unc on predictions

some overestimates of large p_T σ from MG5 @LO and Sherpa v.2.2.1
good agreement with Sherpa v.2.2.11 (up to 5j ME, NLO EW, improved matching)

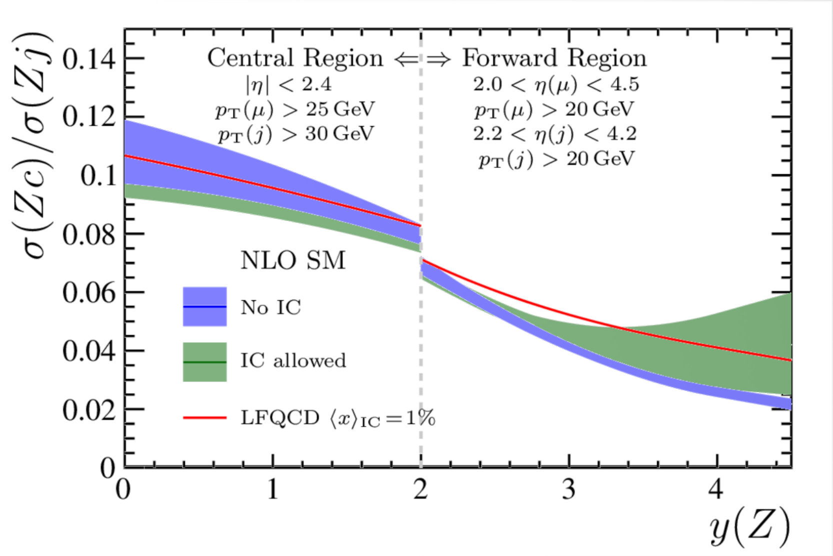
Z + charm

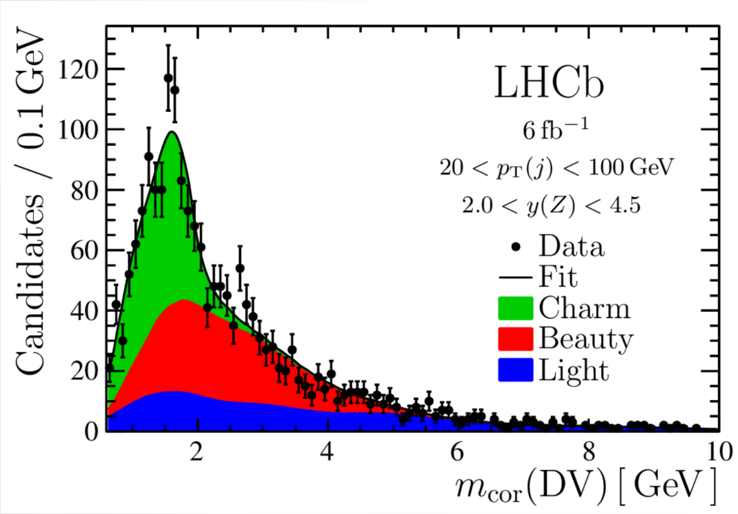
arXiv:2109.08084

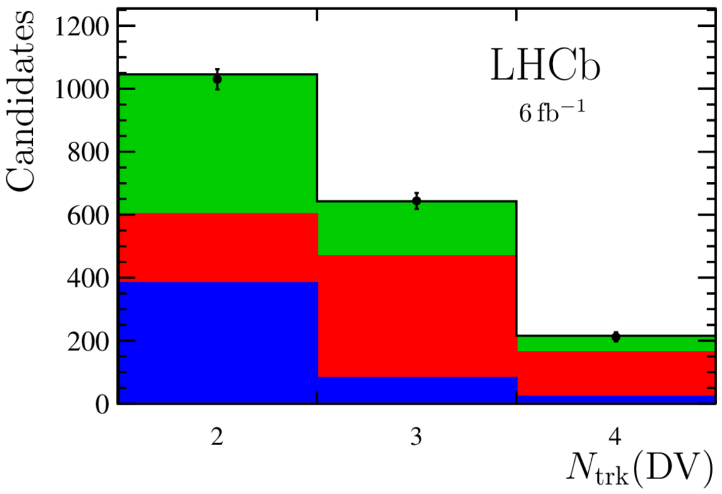


Z+c-jet production in the forward region is sensitive to the high-x intrinsic charm component

proton intrinsic charm content is possible at the % level







$\mu\mu$ + jets with Displaced Vertex

Fit m(DV) & N(DV) to flavour components
Templates are from calibration samples
(heavy flavour enriched dijets)

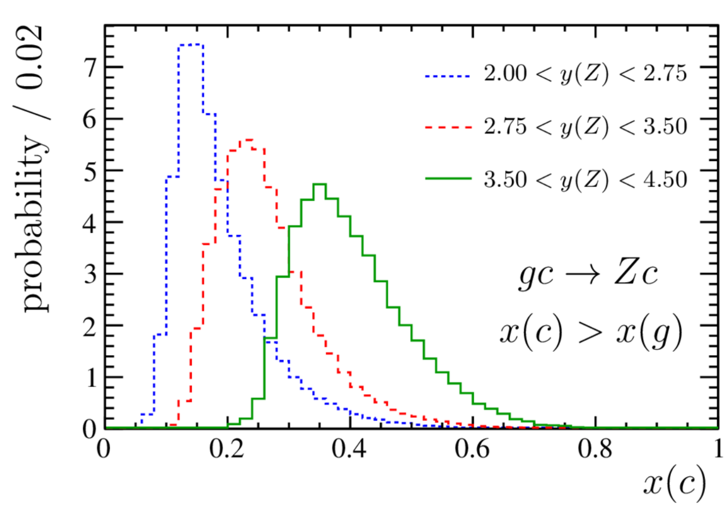
Z + charm

arXiv:2109.08084

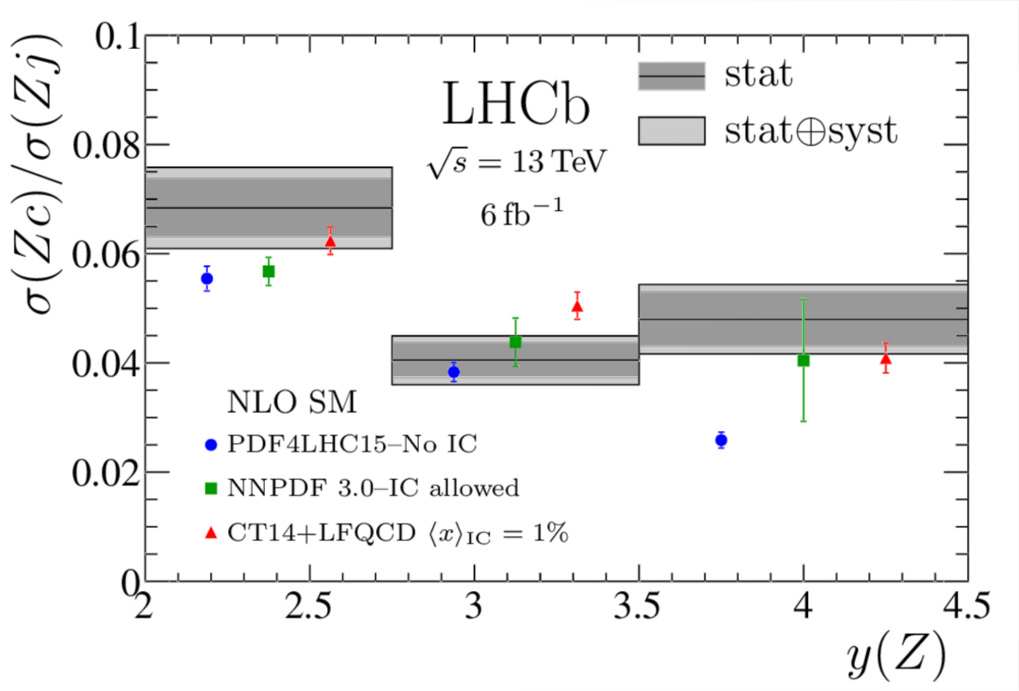
Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_T scale & resolution	1%
Total	8%

$y(Z)$	$\mathcal{R}_j^c$ (%)
2.00–2.75	$6.84 \pm 0.54 \pm 0.51$
2.75–3.50	$4.05 \pm 0.32 \pm 0.31$
3.50–4.50	$4.80 \pm 0.50 \pm 0.39$
2.00–4.50	$4.98 \pm 0.25 \pm 0.35$

Unc dominated by c-tagging efficiency (from calibration samples)



$\mu\mu$ + jets with Displaced Vertex



Hint of intrinsic charm at high rapidity

More data is needed!

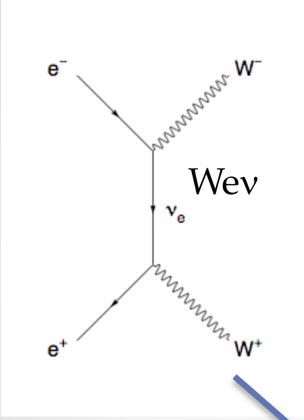
SM tests and searches for new physics

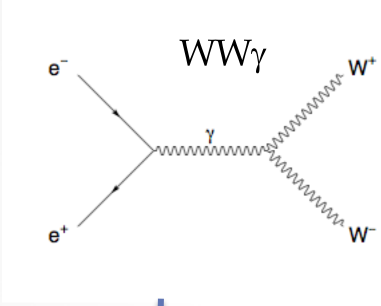
gauge, top and Higgs couplings with EFT
using high mass, pT and angular observables

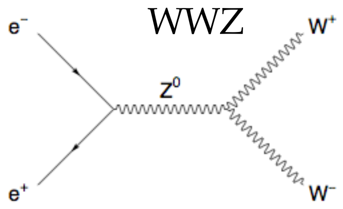
- dibosons, and VBF
- top quarks, and associated bosons

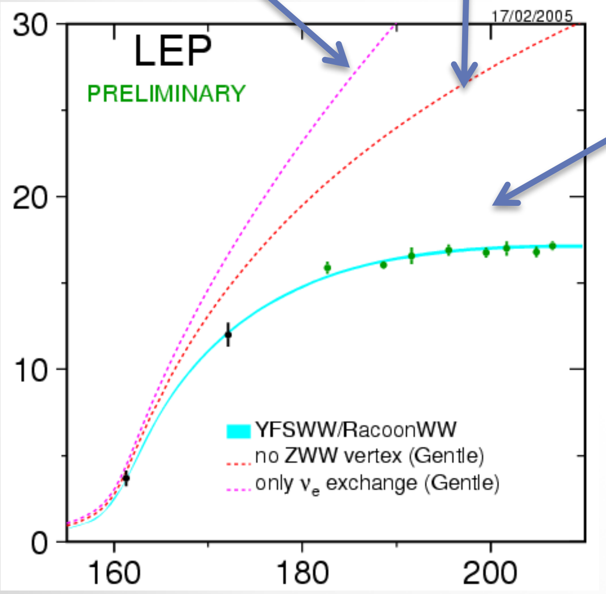
multi-boson interactions

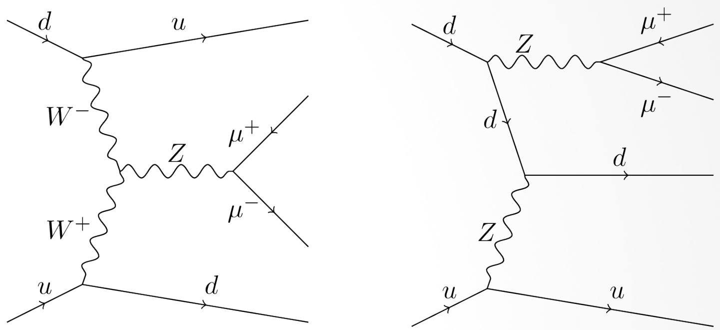
SU(2)⊗U(1) Gauge Cancellations in diboson production & Vector Boson Fusion



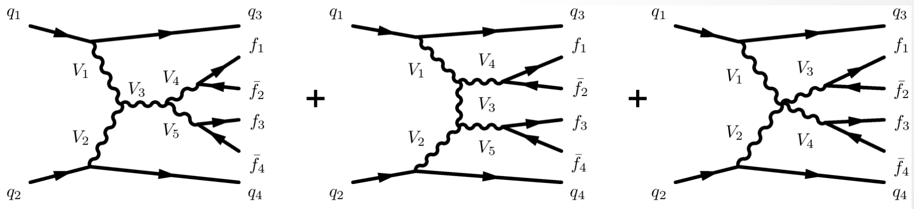




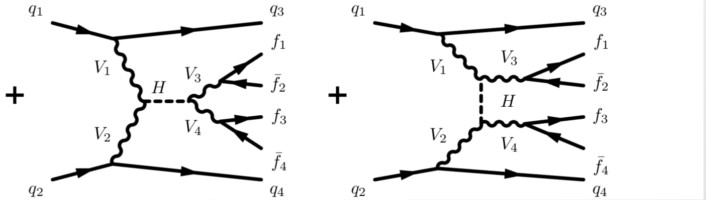




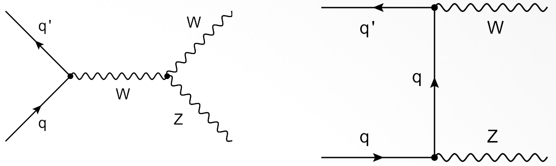
anomalous Self-Gauge Couplings
LEP “lagrangian” couplings
⇒ Effective Filed Theory BSM



important Higgs boson role in triboson production & Vector Boson Scattering
⇒ SM EFT



WZ differential



[arXiv:2110.11231](https://arxiv.org/abs/2110.11231)

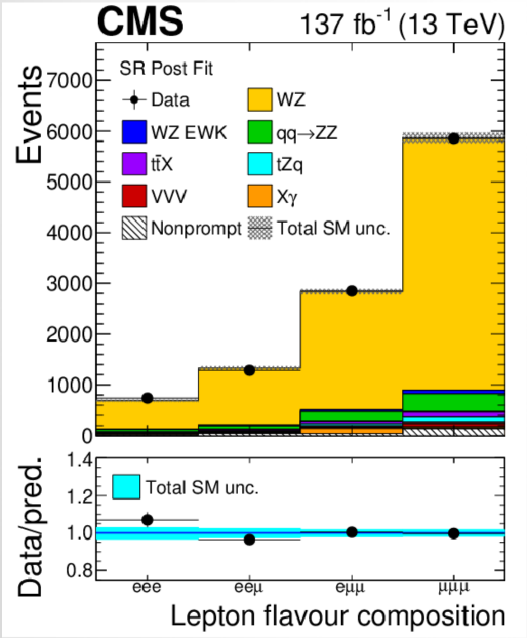
single and double lepton triggers

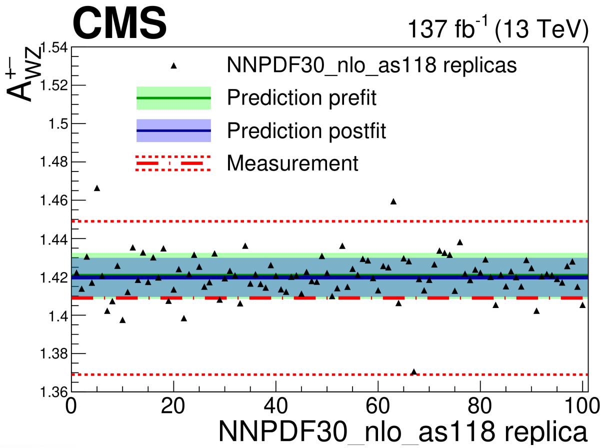
trilepton final states (l_{Z1} l_{Z2} l_W)

Control regions for ZZ, ttZ , non-prompt and conversions

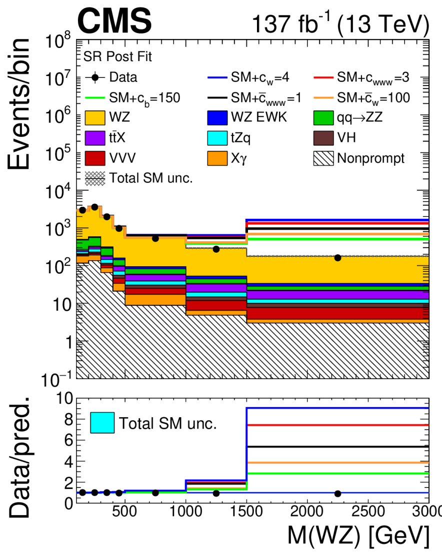
$\sigma(pp \to WZ) = 50.6 \pm 0.8(stat) \pm 1.5(syst) \pm 1.1(lumi) \pm 0.5(theo)$ pb

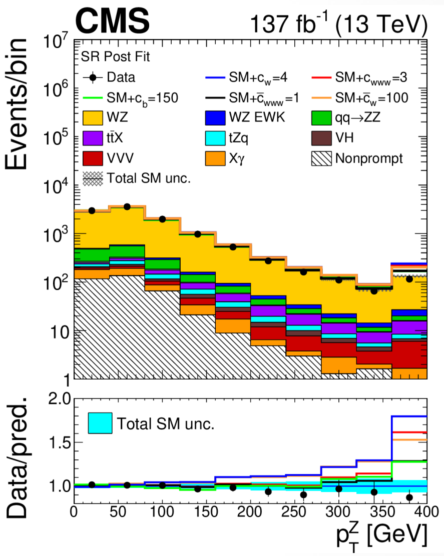
Main backgrounds from ZZ, ttX/tZq and nonprompt

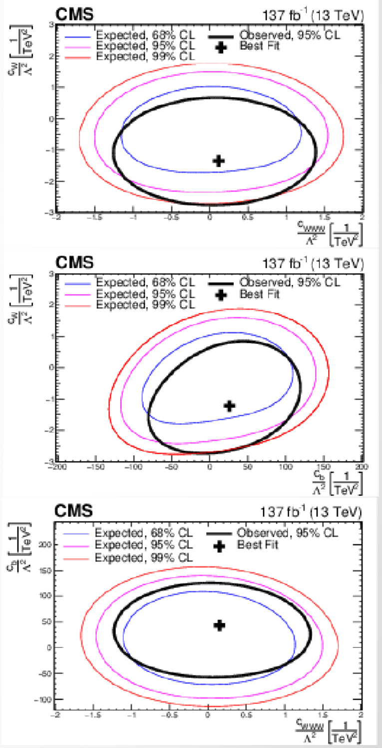




charge asymmetry
⇒ PDF constraints







limits on aTGCs
⇒ EFT Wilson coefficients

ATL-PHYS-PUB-2021-022

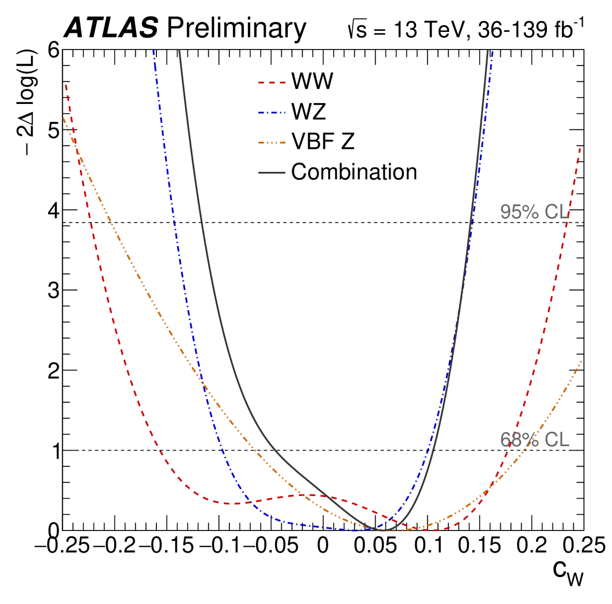
Combined EFT fit

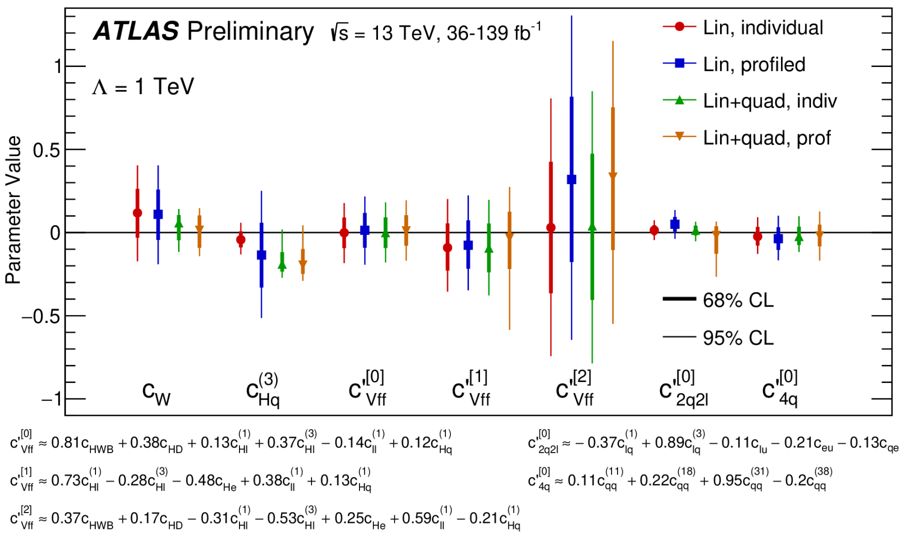
combined fit of WW, WZ, 4ℓ, and VBF Z measurements : **6 differential inputs**

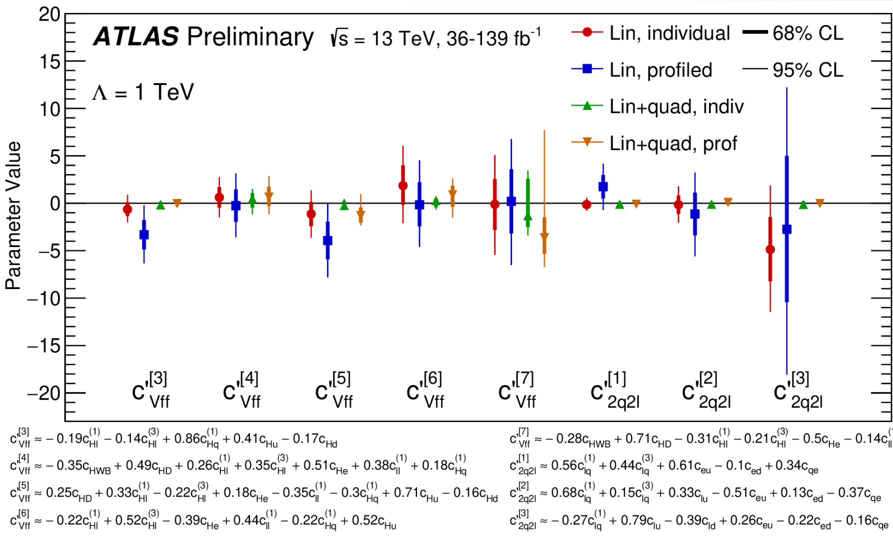
WW ($36fb^{-1}$) : leading lepton pT
WZ ($36fb^{-1}$) : mT(WZ)
4ℓ ($139fb^{-1}$) : m(Z2) in 3 m(4ℓ) regions
VBF Z ($139fb^{-1}$) : ***Δφ***(jj)

dim6 SMEFT re-interpretation (Warsaw basis) : 33 operators considered

constraints derived on 15 WC linear combinations





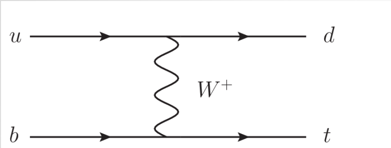


considering both linear-only and also quadratic effects
constrained individually or in combination (*profiled*)

towards an ATLAS global SMEFT interpretation !

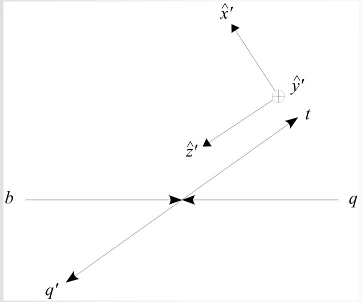
ATLAS-CONF-2021-027

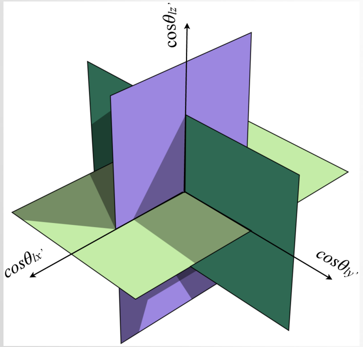
Single top polarization



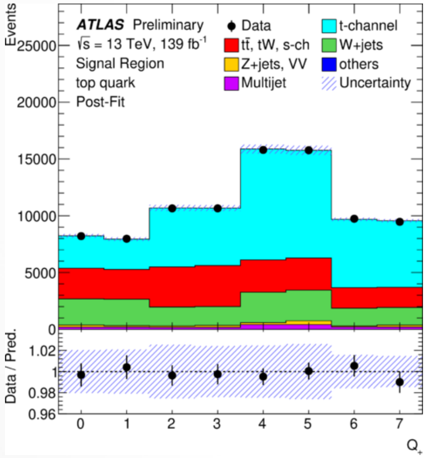
Events with 1 prompt lepton , p_T(miss), 2jets (1*b*-jet)
W+jets and ditop control regions

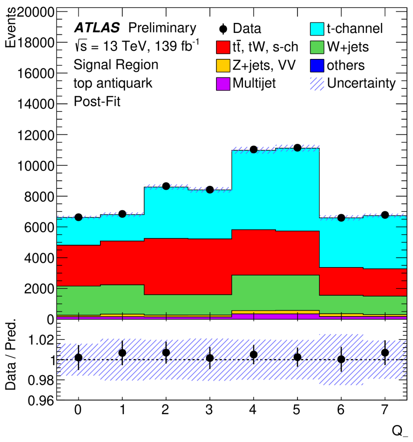
Unfolded particle level angular distributions
➔ Fit for possible EFT effects in the **tWb** vertex





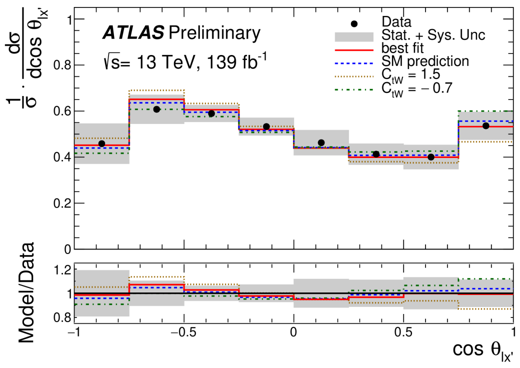
Measurement of 3 polarization components fitting rates of lepton *octant* variables

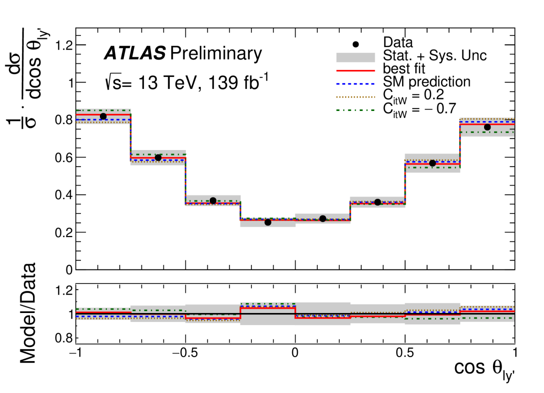


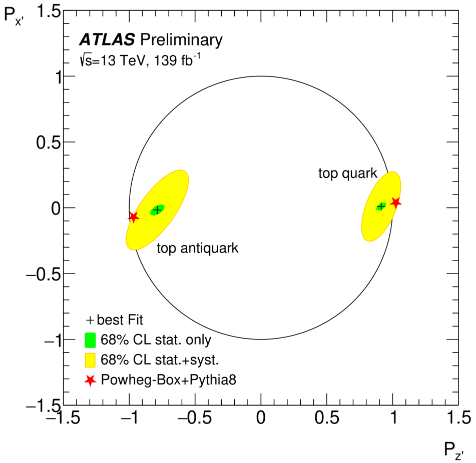


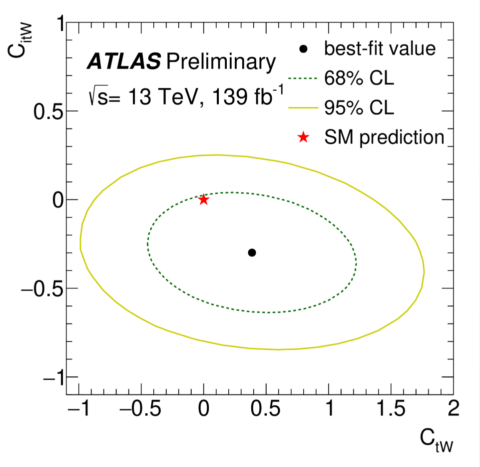
P_x=0.01±0.18
P_y=−0.029±0.027
P_z=0.91±0.10

P_x=−0.02±0.20
P_y=−0.007±0.051
P_z=−0.79±0.16

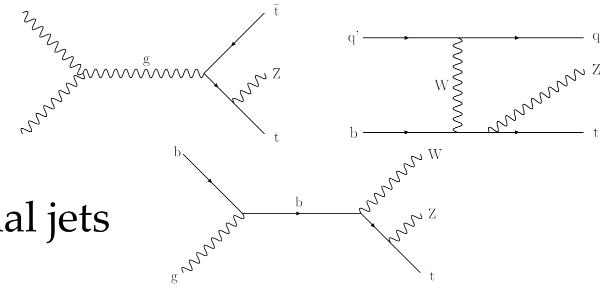








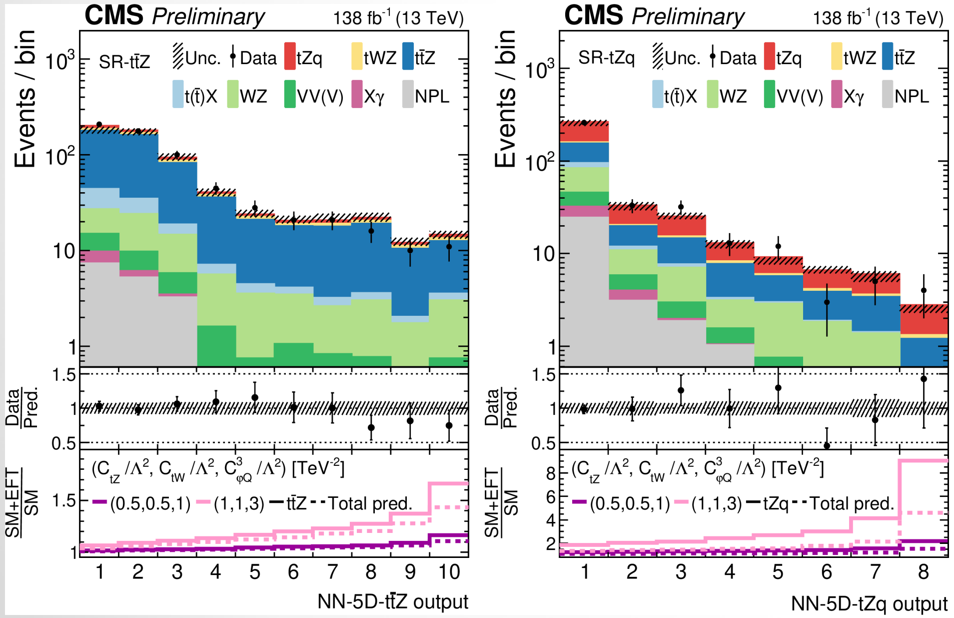
tZ & ttZ EFT limits

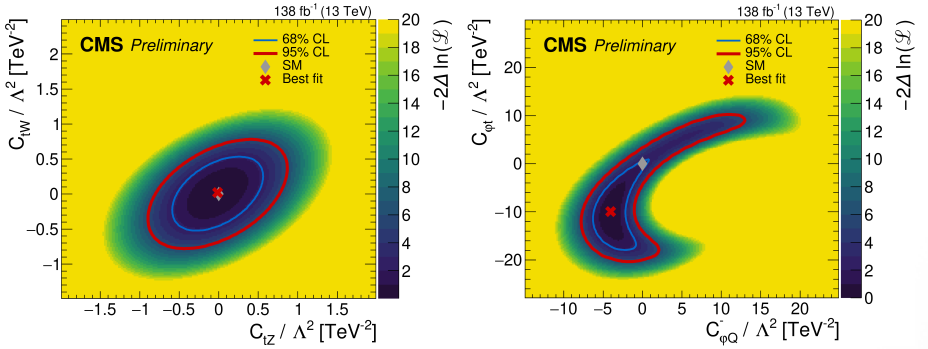


Operator	WC	Mapping to Warsaw-basis coefficients
$\mathcal{O}_{tZ}$	c_{tZ}	$\mathrm{Re}\{-s_W c_{uB}^{(33)} + c_W c_{uW}^{(33)}\}$
$\mathcal{O}_{tW}$	c_{tW}	$\mathrm{Re}\{c_{uW}^{(33)}\}$
$\mathcal{O}^3_{\varphi Q}$	$c^3_{\varphi Q}$	$c_{\varphi q}^{3(33)}$
$\mathcal{O}^-_{\varphi Q}$	$c^-_{\varphi Q}$	$c_{\varphi q}^{1(33)} - c_{\varphi q}^{3(33)}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$c_{\varphi u}^{(33)}$

3/4 prompt leptons, b-jet(s), p_T(miss), additional jets
Control regions for WZ and ZZ backgounds
data-driven nonprompt lepton rates

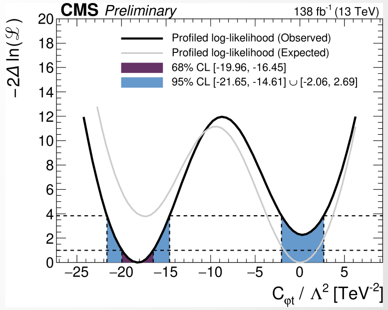
NNs trained to separate SM processes, and events generated with BSM contributions





All results consistent with SM @95% CL

$C_{\varphi t}$ BSM minimum preferred by data but SM still within 95%CL

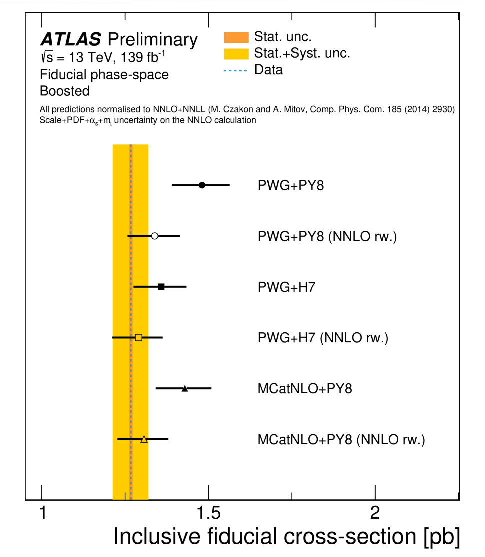


ATLAS EXPERIMENT

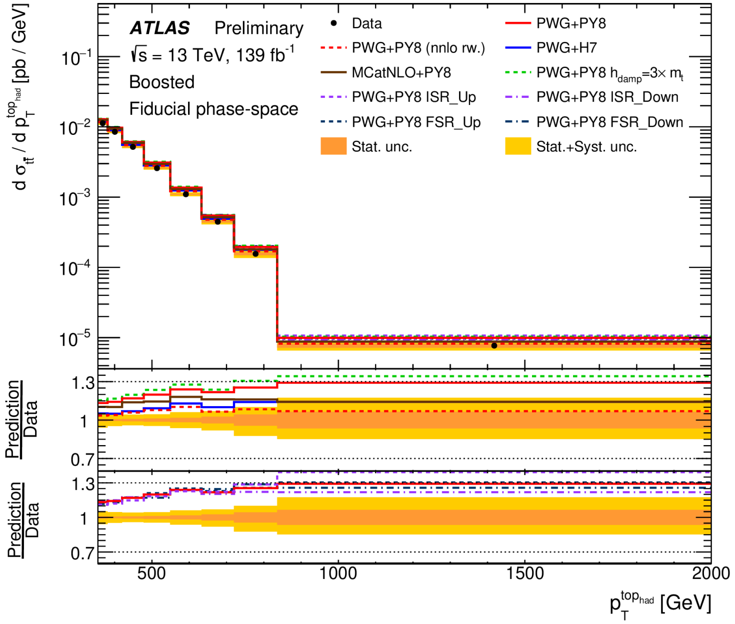
[ATLAS-COM-CONF-2021-031](#)

high p_T top

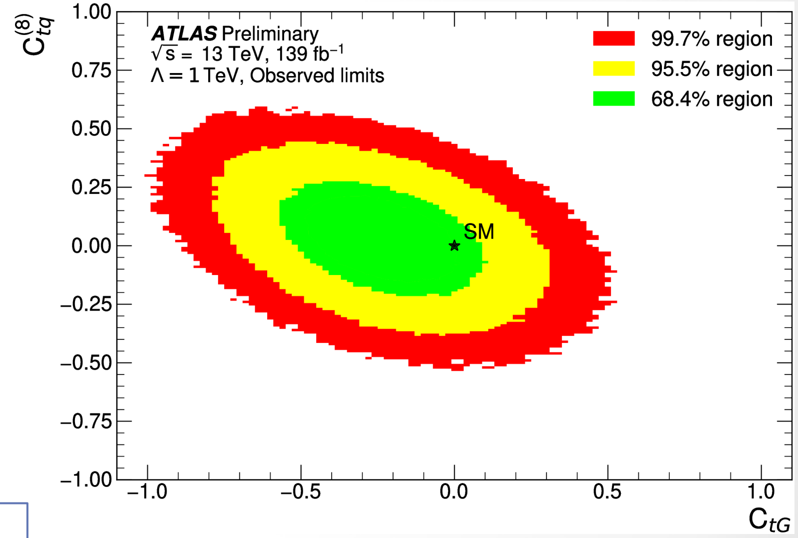
Events with 1 lepton, 2 b-jets, 1 top-tagged large jet (R=1, containing 1 b-jet) $p_T > 355$ GeV
main bkg single top (2%) & ttV (1%)



fiducial σ = 1.267 ± 0.005 ± 0.053 pb



Limits on EFT operators from hadronic top pT



NNLO QCD + NLO EW improve agreement with data

Differential measurements in many observables
including properties of additional jet activity

stringent constraining power on C(8)tq ∈ [−0.30, 0.36]
improving global fit results in [arXiv:2105.00006](#)

ATLAS EXPERIMENT

all-hadronic boosted top quarks

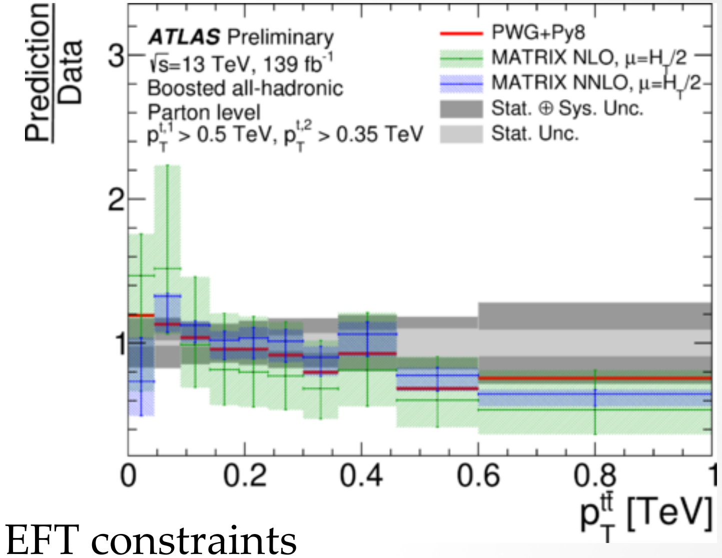
NEW

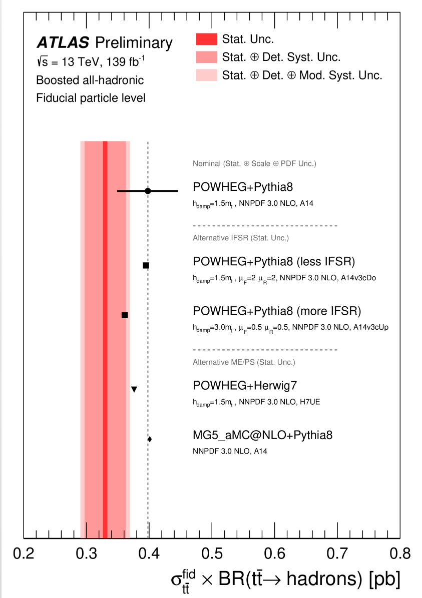
large *R=1.0* jets : p_T > 500, 350 GeV
NN for substructure top tagging

QCD multijet background estimated and validated with 16 CRs

σ_{fid} = 330 ± 3(stat) ± 38(syst) fb.

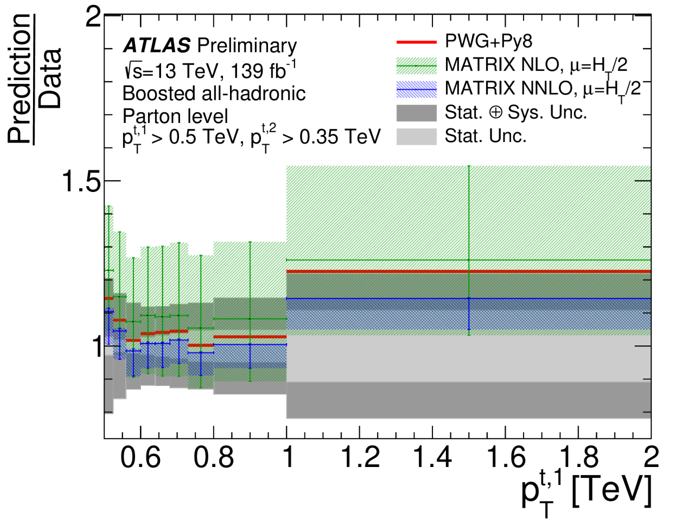
Source	Event Yields
$t\bar{t}$ (all-hadronic)	16 200 ± 2000
$t\bar{t}$ (non-all-hadronic)	625 ± 91
Single top-quark	220 ± 120
$t\bar{t}+W/Z/H$	114 ± 16
Multijet events	2900 ± 230
All Backgrounds	3900 ± 300
Prediction	20 000 ± 2200
Data (139 fb^{-1})	17 261

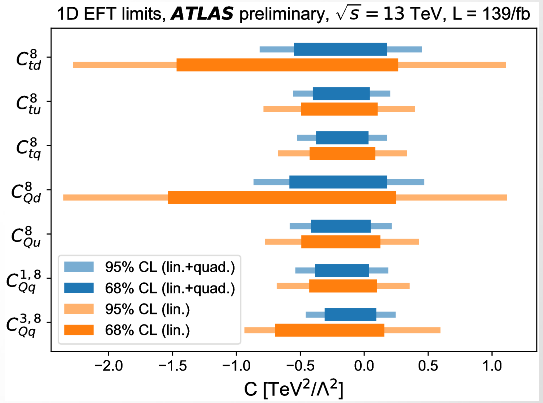




Source	Relative Uncertainty [%]
Top-tagging	±7.8
JES ⊕ JER	±4.2
JMS ⊕ JMR	±1.1
Flavor tagging	±2.9
Alternative hard-scattering model	±0.9
Alternative parton-shower model	±4.3
ISR/FSR + scale	±4.9
PDF	±0.8
Luminosity	±1.7
Monte Carlo sample statistics	±0.5
Systematics	±11.6
Statistics	±1.0
Total Uncertainty	±11.7

p_T(t,1) used to set EFT constraints





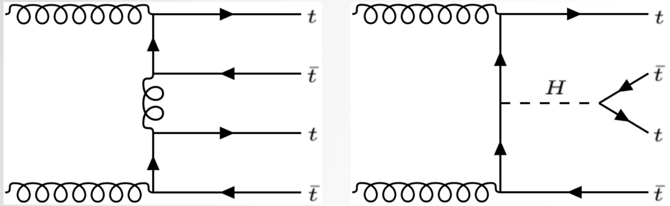
stringent limits

Exploration of rare processes

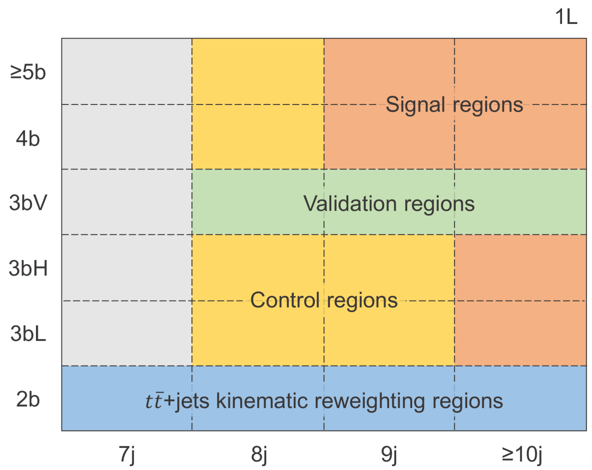
arXiv:2106.11683

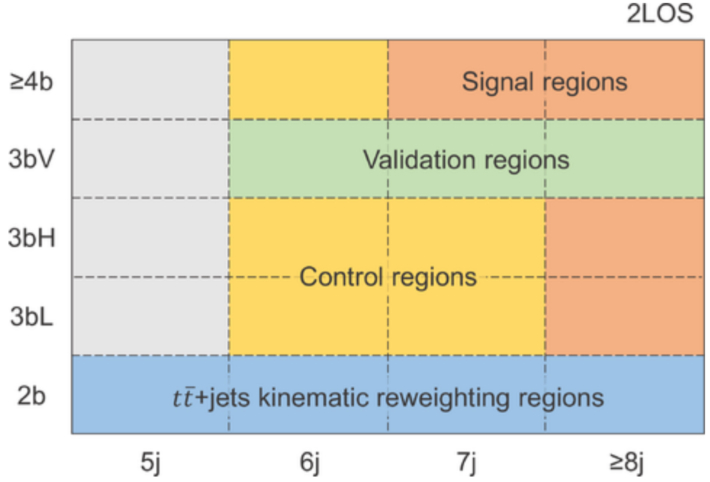
4top production

1L/2LOS + jets (combined with 2LSS/3L arXiv:2007.14858)

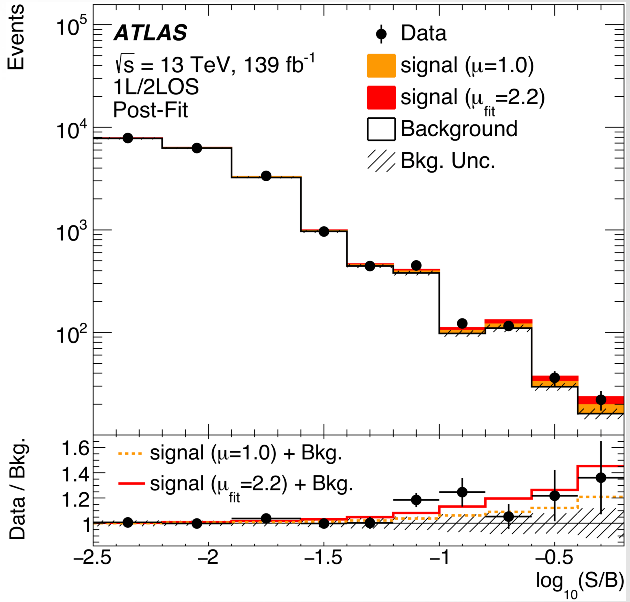


Very large jet multiplicity
Mostly ttbb background
21 regions used in the fit



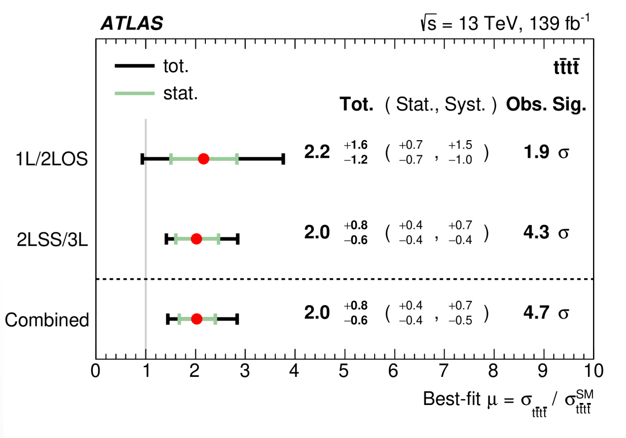


Uncertainty source	$\Delta\sigma_{t\bar{t}t\bar{t}}$ [fb]	
Signal Modelling		
$t\bar{t}t\bar{t}$ modelling	+8	−3
Background Modelling		
$t\bar{t}$+≥1b modelling	+8	−7
$t\bar{t}$+≥1c modelling	+5	−4
$t\bar{t}$+jets reweighting	+4	−3
Other background modelling	+4	−3
$t\bar{t}$+light modelling	+2	−2
Experimental		
Jet energy scale and resolution	+6	−4
b-tagging efficiency and mis-tag rates	+4	−3
MC statistical uncertainties	+2	−2
Luminosity	< 1	
Other uncertainties	< 1	
Total systematic uncertainty	+15	−12
Statistical uncertainty	+8	−8
Total uncertainty	+17	−15



Signal discrimination with 6 BDTs (14 inputs)

Combined results



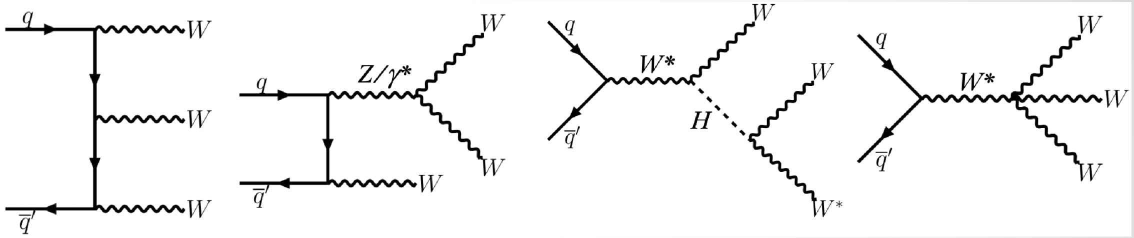
Dominant systs from theory signal and ttbb modelling,

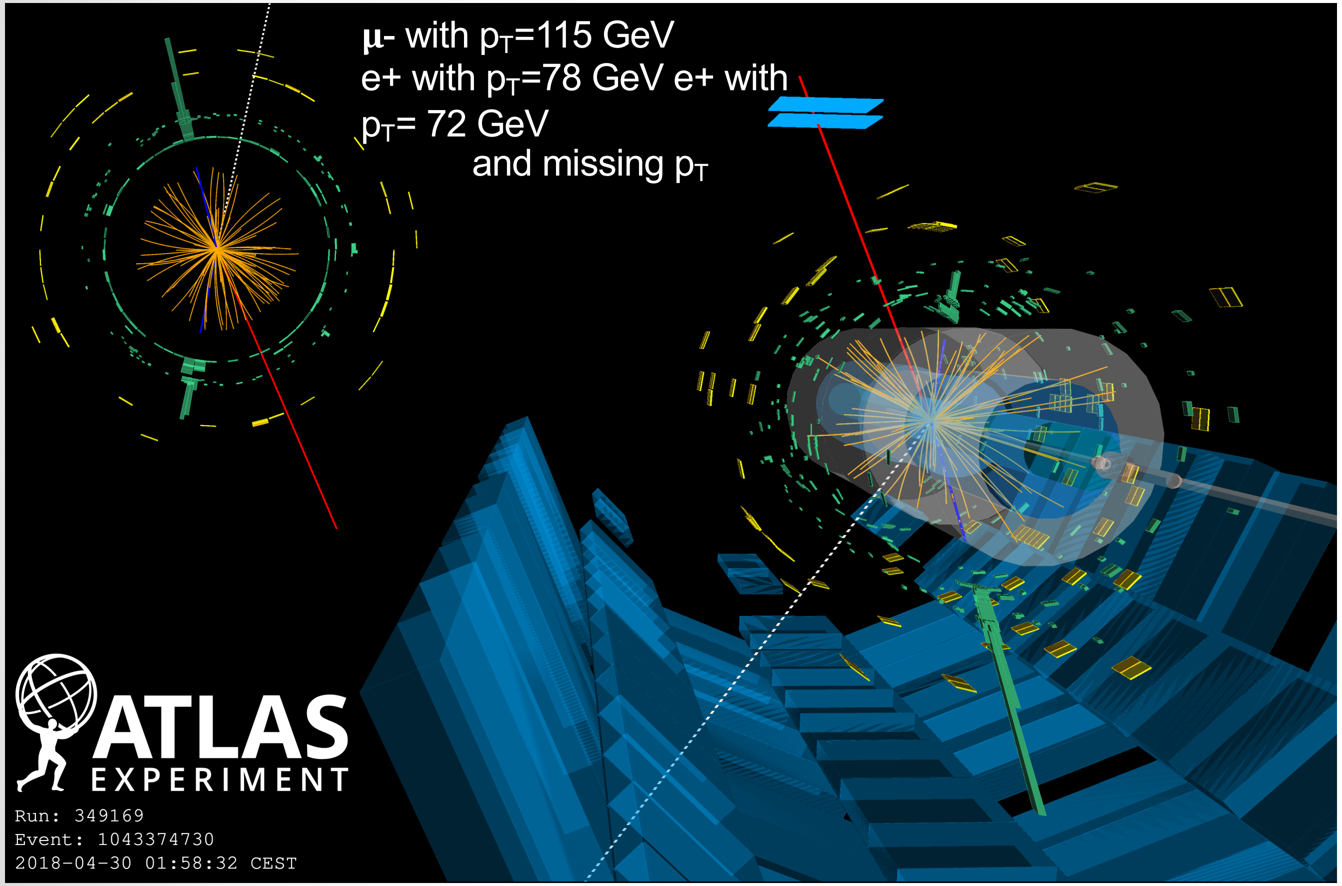
$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8\,(\text{stat.})\,^{+15}_{-13}\,(\text{syst.})\,\text{fb} = 26\,^{+17}_{-15}\,\text{fb}$$

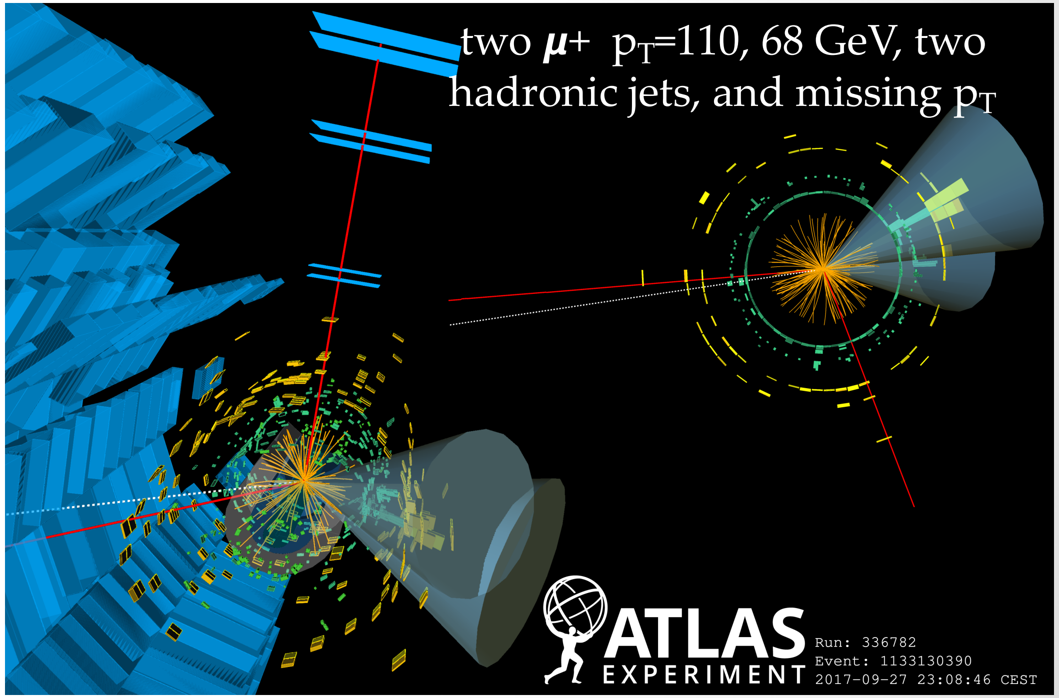
$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.})\,\text{fb} = 24\,^{+7}_{-6}\,\text{fb}.$$

ATLAS-CONF-2021-039

Observation of WWW



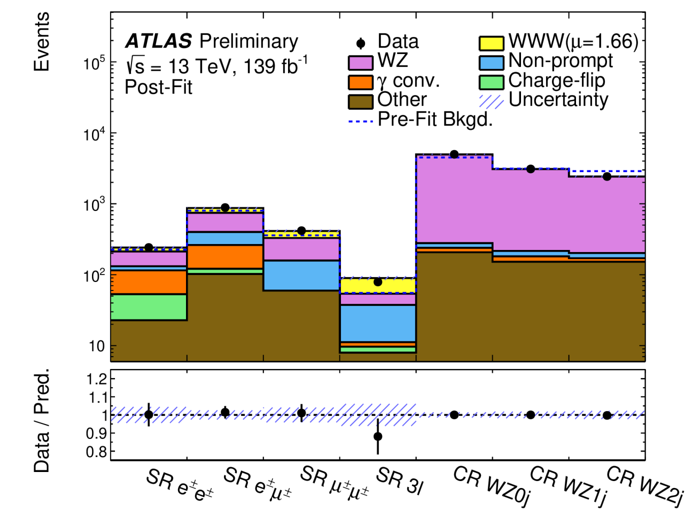




earlier observation by the CMS Collaboration of inclusive three weak boson production (VVV).

Observation of WWW

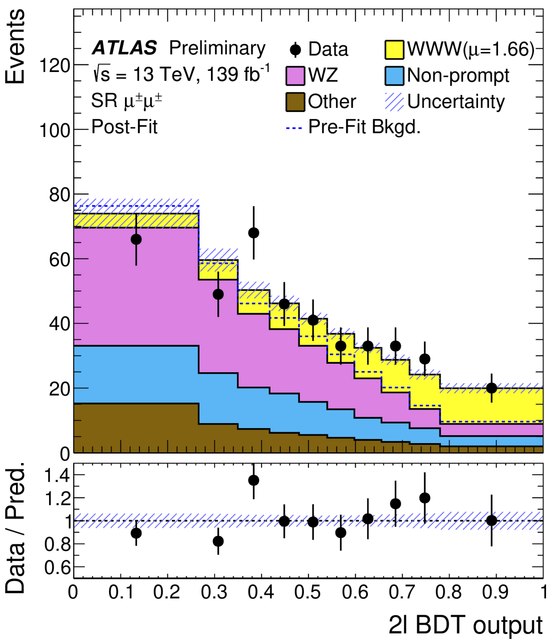
Events with 2SS leptons (e/μ) + ≥2 jets, or with 3 leptons (no SFOS pairs)
dominant bkg WZ → $\ell\nu\ell\ell$ estimated with 3 CRs
data-driven non-prompt , γ-conversions, and charge-flip

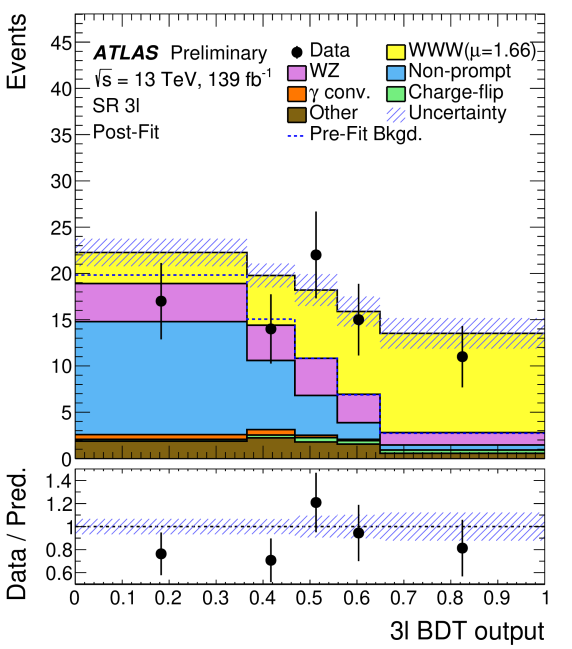


significance 8.2 sd
(5.4 sd expected)
➔ **first observation**

Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	**1.66 ± 0.28**

Two dedicated 2ℓ & 3ℓ BDT trained for signal discrimination





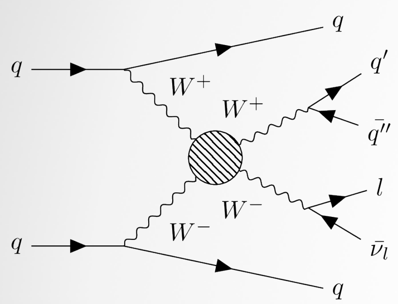
σ_{WWW}= 850 ± 100 (stat.) ± 80 (syst.) fb
signal includes off shell WH(WW*)

arXiv:2112.05259

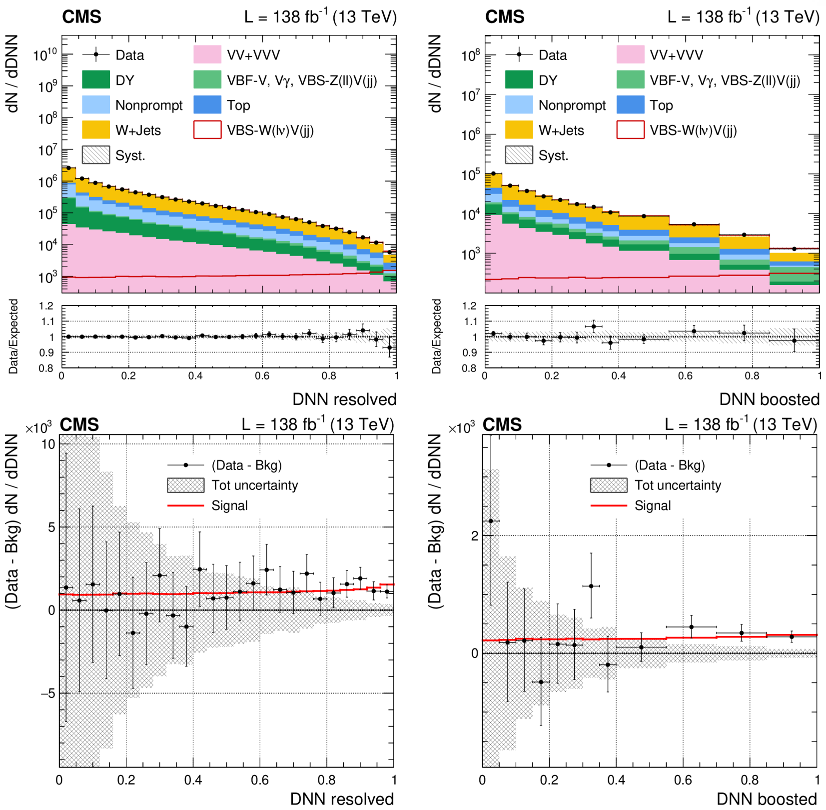
Semileptonic WV VBS

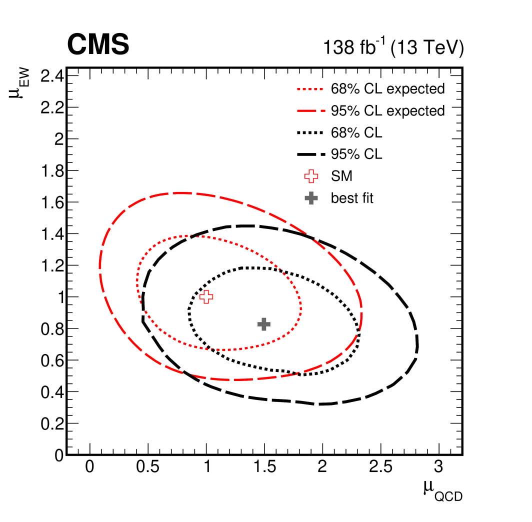
e and μ channels. Resolved and boosted categories

Signal is a mixture of $W^{\pm}W^{\pm}$ $W^{\pm}W^{\mp}$ (SS+OS) and WZ



W+jets and top pair backgrounds estimated with dedicated control regions





DNN inputs

Variable	Resolved	Boosted
Lepton pseudorapidity	✓	✓
Lepton transverse momentum	✓	✓
Zeppenfeld variable for the lepton	✓	✓
Number of jets with $p_T > 30$ GeV	✓	✓
VBS leading tag-jet p_T	-	✓
VBS trailing tag-jet p_T	✓	✓
Pseudorapidity interval between VBS tag-jets	✓	✓
Quark Gluon discriminator of the highest p_T jet of the VBS tag-jets	✓	✓
Azimuthal angle distance between VBS tag-jets	✓	✓
Invariant mass of the VBS tag-jets pair	✓	✓
p_T of jets from V_{had}	✓	-
Pseudorapidity difference between V_{had} jets	✓	-
Quark Gluon discriminator of the V_{had} jets	✓	-
V_{had} p_T	-	✓
Invariant mass of the V_{had}	✓	✓
Zeppenfeld variable for the V_{had}	-	✓
V_{had} centrality	-	✓

$\mu_{EW} = \sigma/\sigma_{SM} = 0.85{+0.24}{-0.20} = 0.85{+0.21}{-0.17}$ (syst.) $\pm$ 0.12(stat.)

σ $_{EW}$ = 1.9 ± 0.5 pb ➔ **4.4** (5.1) observed (expected) standard deviations

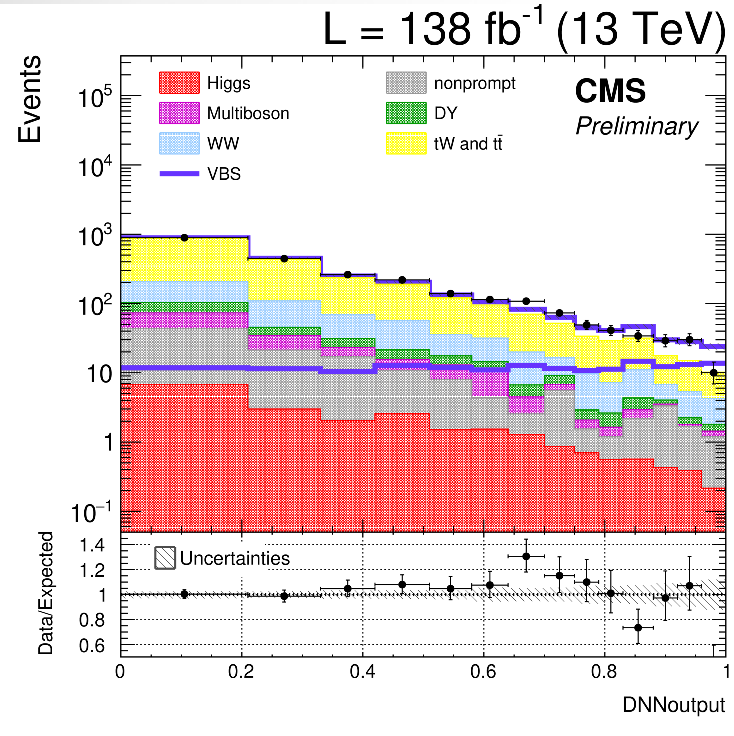
first evidence for EW WV plus two jets **in the semi-leptonic channel**

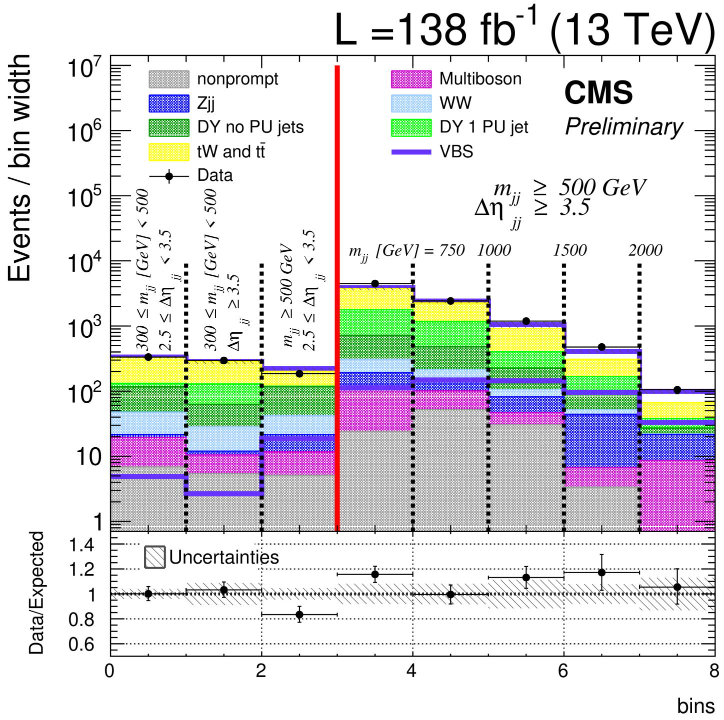
NEW

Opposite sign WW VBS

two OS leptons (electrons or muons) , two jets with large **$\Delta\eta$**(jj) and m(jj), and pT(miss)

Large background from ditop decays, DY plus jets in the SF channels : estimated from control regions





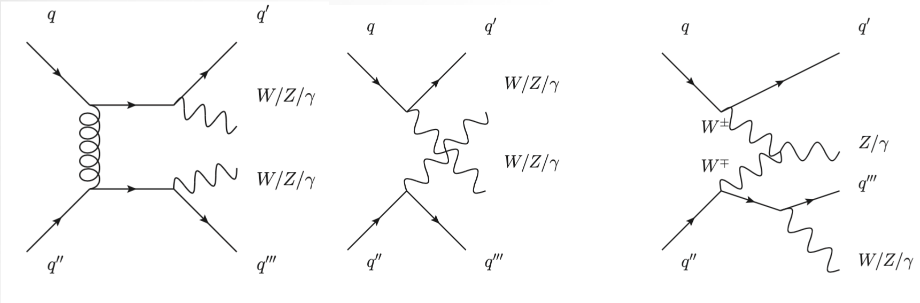
DNN for the eμ events
m(jj), $\Delta\eta$(jj) bins for ee and $\mu\mu$

Uncertainty source	Impact
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ QCD scale	5.1%
QCD factorisation scale for VBS signal	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Prefiring corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
p_T^{miss} energy scale	2.4%
QCD-induced W^+W^- QCD scale	2.1%
Luminosity	2.1%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	$<$ 1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%

first observation : significance 5.6 standard deviations (5.2 exp)
inclusive **σ**=99±20 fb (89±5 fb expected) - fiducial **σ**=10.2±2.0 fb

ATLAS-CONF-2021-038 + arXiv:2109.00925

EW $Z\gamma$ + 2 jets



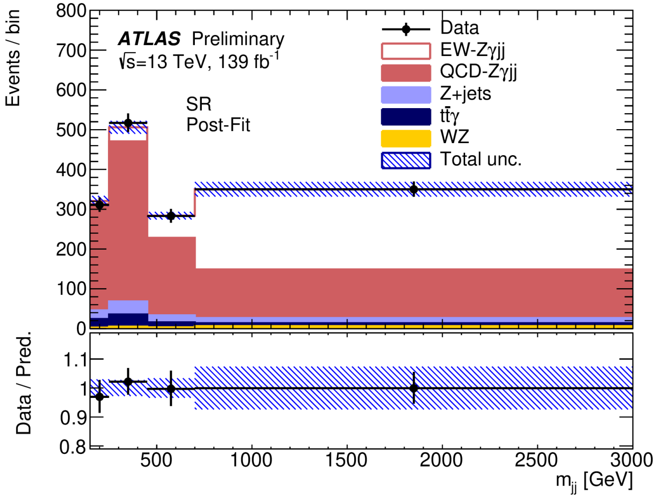
Full 13 TeV data (139 fb^{-1})

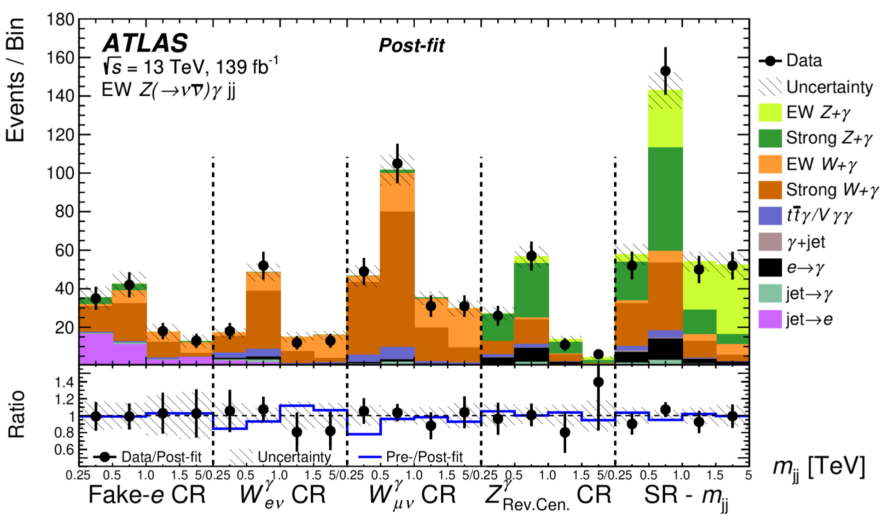
$Z \to \nu\nu$ particularly interesting for BSM

CR for main QCD $Z\gamma jj$ bkg, and $tt\gamma$. Data-driven non-prompt γ

fit to m(jj) distributions
→ μ_{EW} = 0.95+0.14-0.13
significance 10 sd (11 exp)

$Z \to \ell\ell$





→ μ_{EW} = 1.03 ± 0.25

significance 5.2 sd (5.1)

fiducial
σ(EW) = 4.49±0.40(stat.)±0.42(syst.)fb
σ(EW+QCD)= 20.6±0.6(stat.)+1.2 (syst.)fb

fiducial
σ(EW) = 1.31 ± 0.20(stat) ± 0.20(syst) fb

arXiv:2111.05370

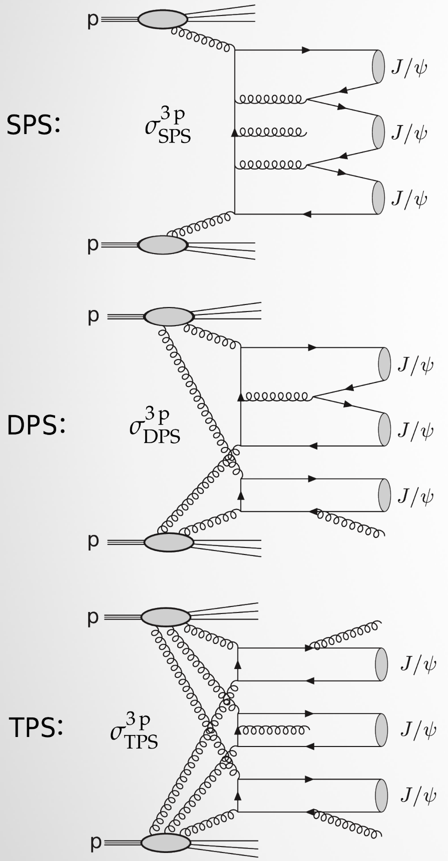
Observation of triple J/ψ

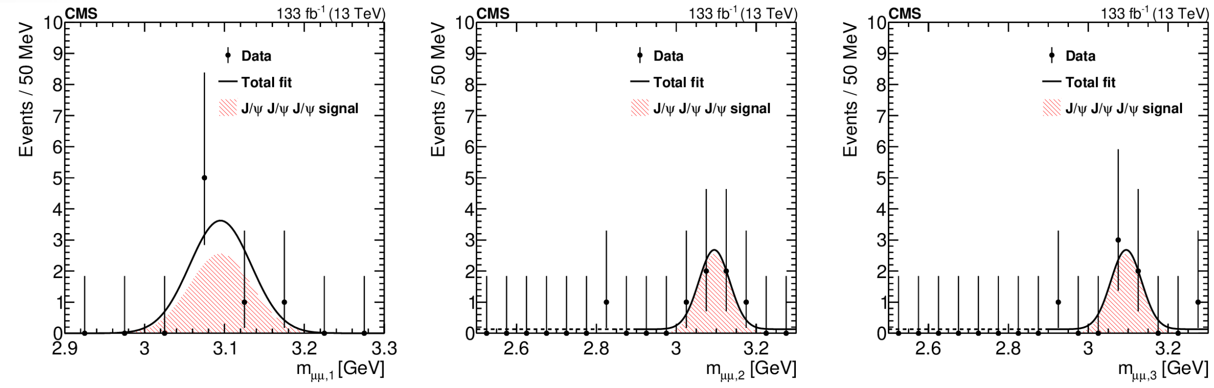
Select 6μ events consistent with 3 J/ψ decays.

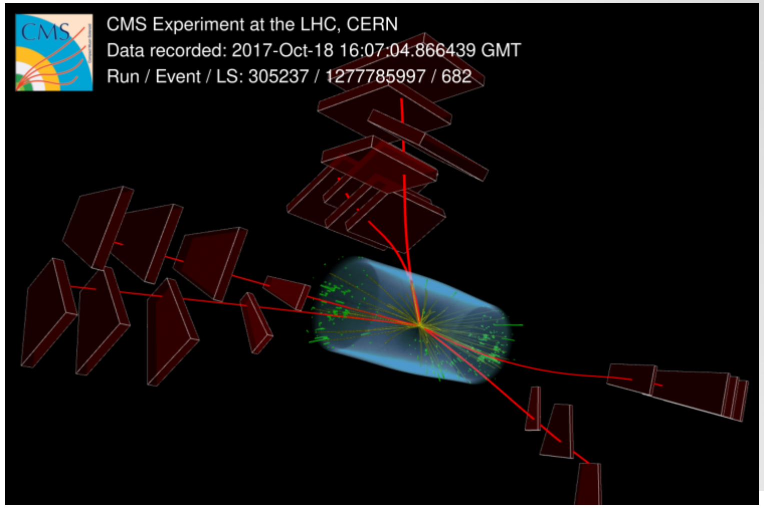
golden channel for TPS

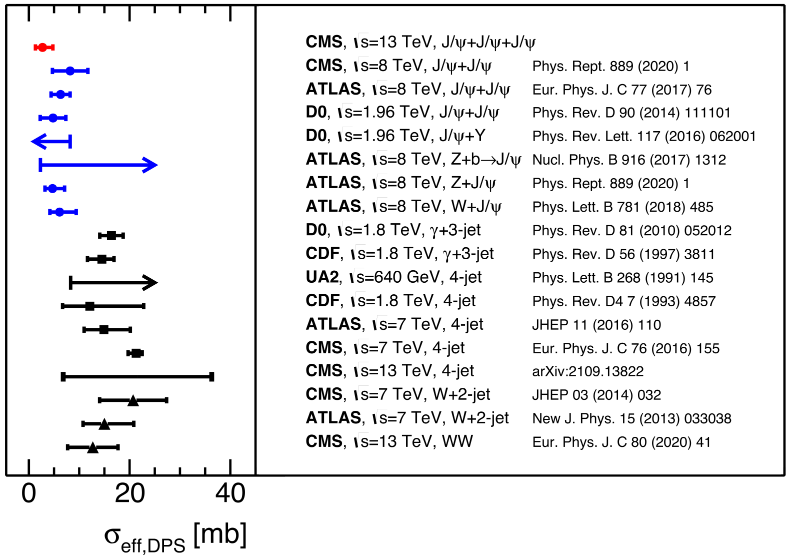
$$\sigma_{TPS}^{pp\to\psi_1\psi_2\psi_3+X} = \left(\frac{m}{3!}\right)\frac{\sigma_{SPS}^{pp\to\psi_1+X}\,\sigma_{SPS}^{pp\to\psi_2+X}\,\sigma_{SPS}^{pp\to\psi_3+X}}{\sigma_{eff,TPS}^2}$$

Pure prompt:









6 events in data : fit yields $N(3J/\psi)$ = 5.0+2.6-1.9 (1.0 bkg)
signal significance >5 sd

σ(pp→J/ψ J/ψ J/ψ X)=272−104+141 (stat) ± 17 (syst) fb

σ_{eff}(DPS)= 2.7+1.4−1.0 (exp) +1.5−1.0 (theo) mb

consistent with σ_{eff} from double-quarkonium
smaller than σ_{eff} from other double-particles

Summary & outlook

- Great times for precision SM measurements and explorations with LHC Run2 (3) data
- Mounting precision on differential and associated processes allow **stringent SM tests** owing also to theory advancements
- Reducing **systematic** uncertainties (theo & exp) is the challenge to harvest impactful results with most inclusive data
- **Rare processes** benefit from statistics increase and also provide great insight towards possible BSM effects (with Higgs sector interplay)
- Many **new measurements** ideas and methods emerge that are/can/will be pursued, also with the coming data

precision measurements led & can lead to the next discoveries