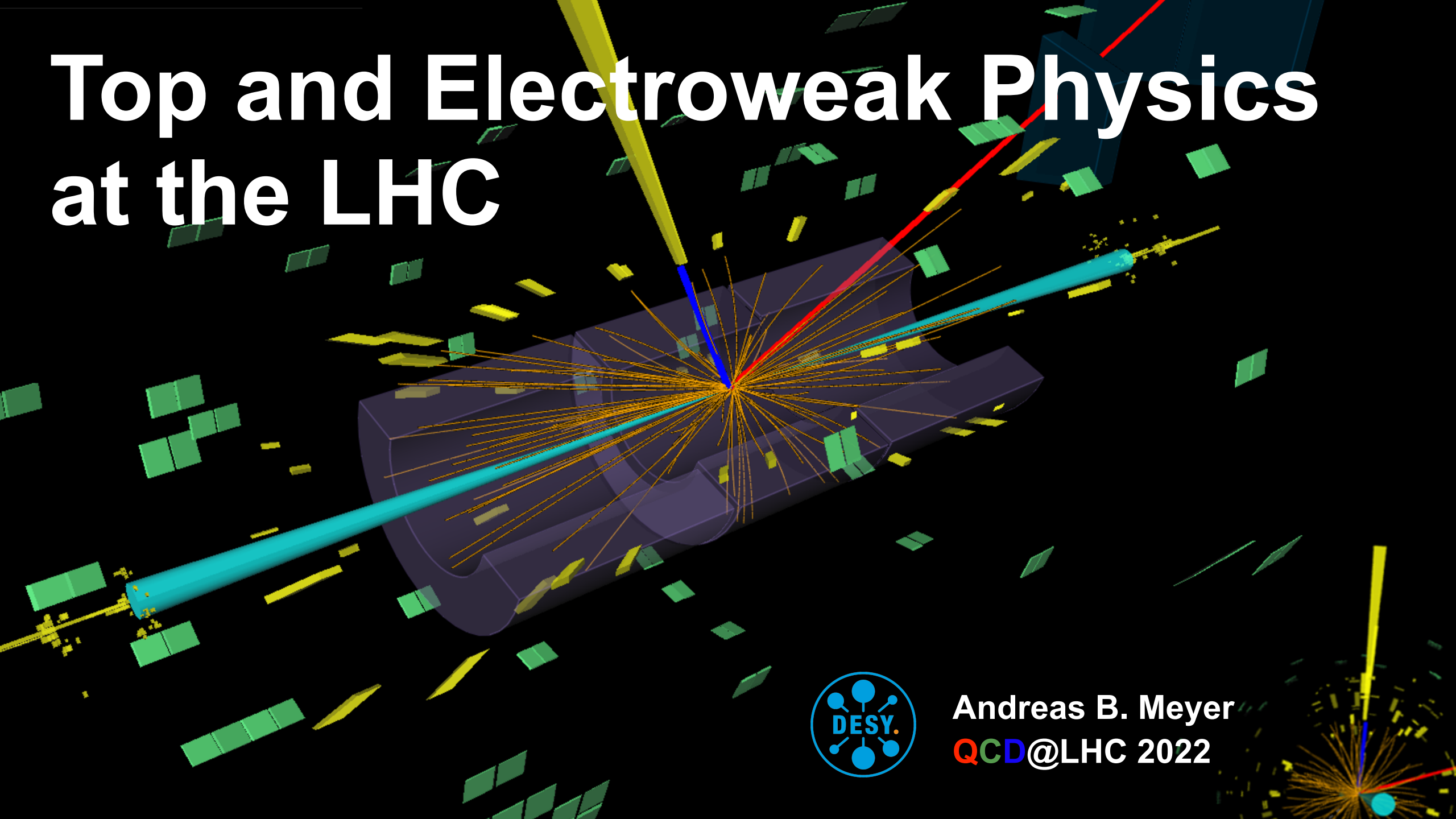
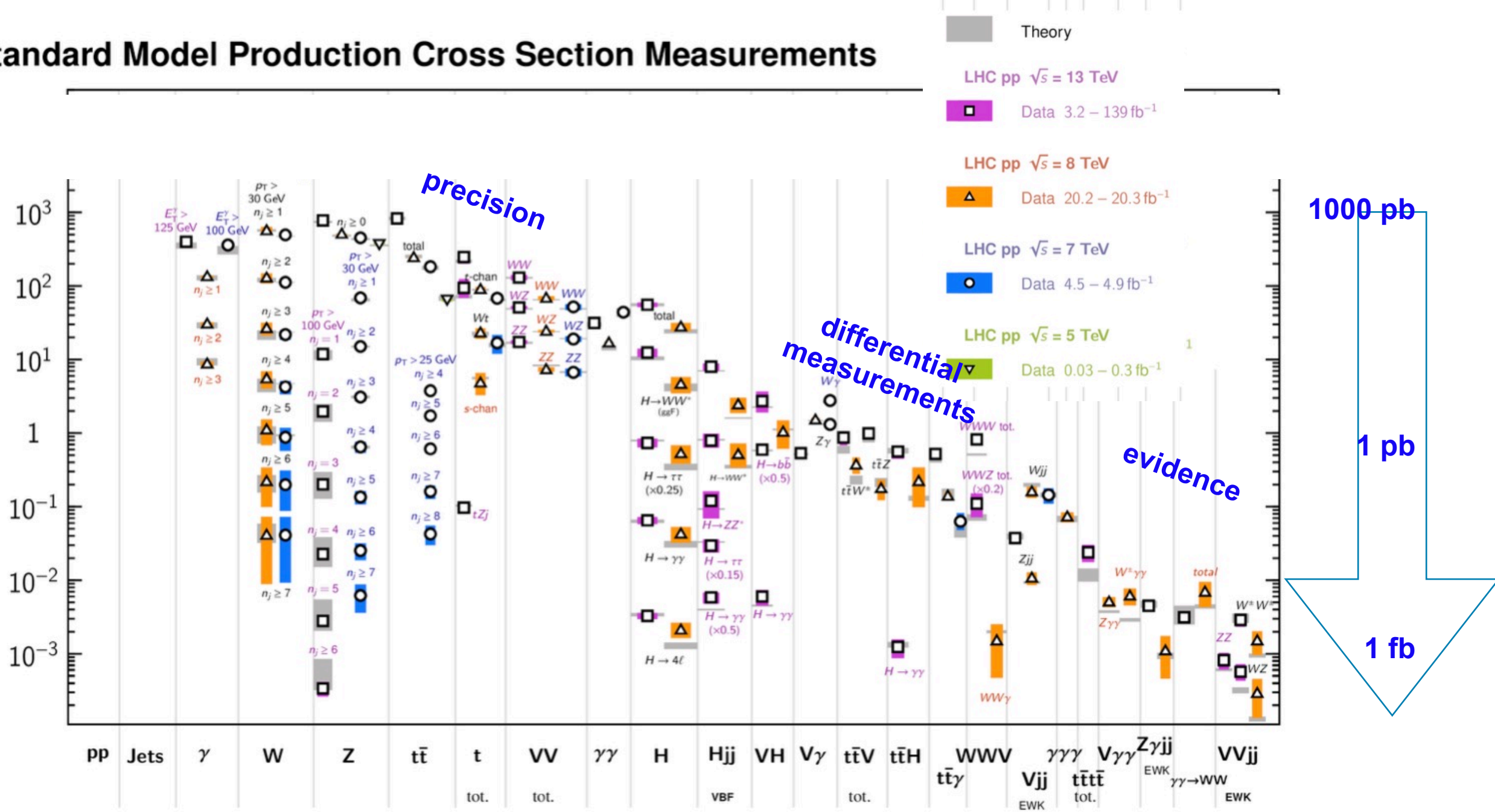
Top and Electroweak Physics at the LHC



Andreas B. Meyer

QCD@LHC 2022

Standard Model Production Cross Section Measurements



Introduction

Outline

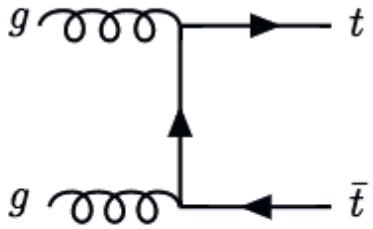
Top:

- Precision Frontier
  - Cross sections and mass (and α_S, pdf, V_{tb})
  - Angular distributions => bare-quark properties
- Evidence and first differential
  - t(t)+X (X=j, b, c, γ, W, Z, tt)
- Direct searches / top as a tool
  - FCNC, Lepton-flavour violation, CP-violation

Electroweak:

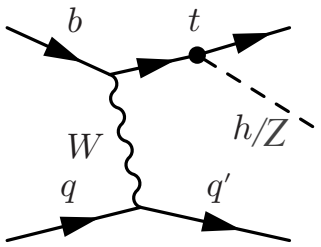
- Vector boson scattering
- VVV production
- Inclusive VV production and polarization

strong

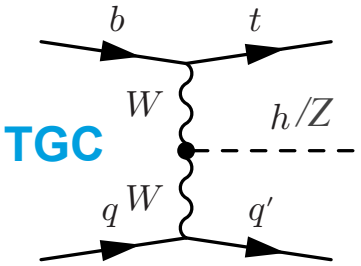


1000 pb

EW-top

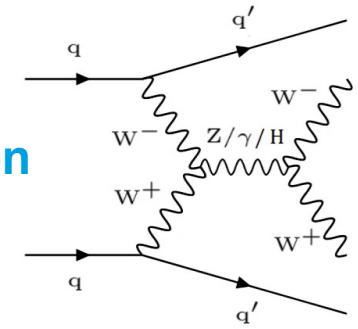


TGC

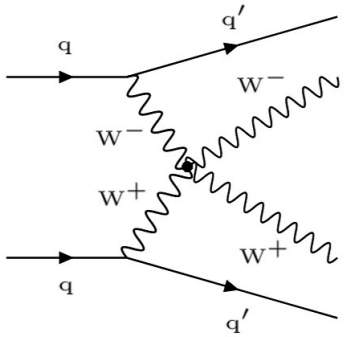


1 pb

Multi-boson



TGC



QGC

1 fb

VBS

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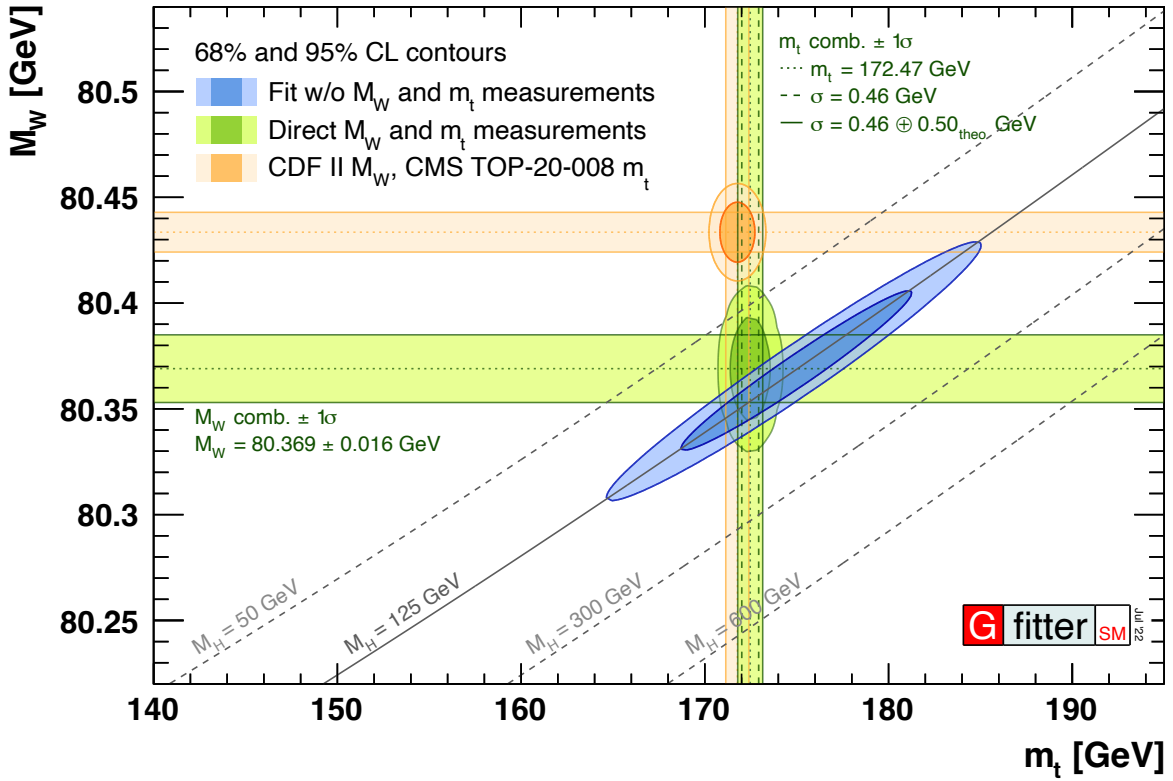
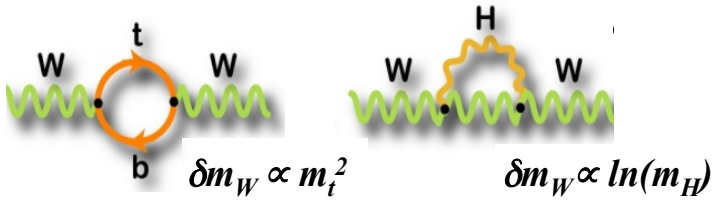
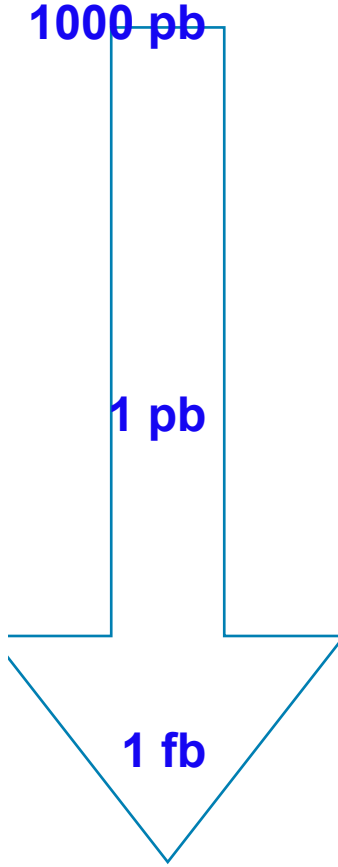
- (Inclusive) VV **production** and polarization

[R.Kogler, ICHEP 2022]



Top quark mass relates Higgs and W masses





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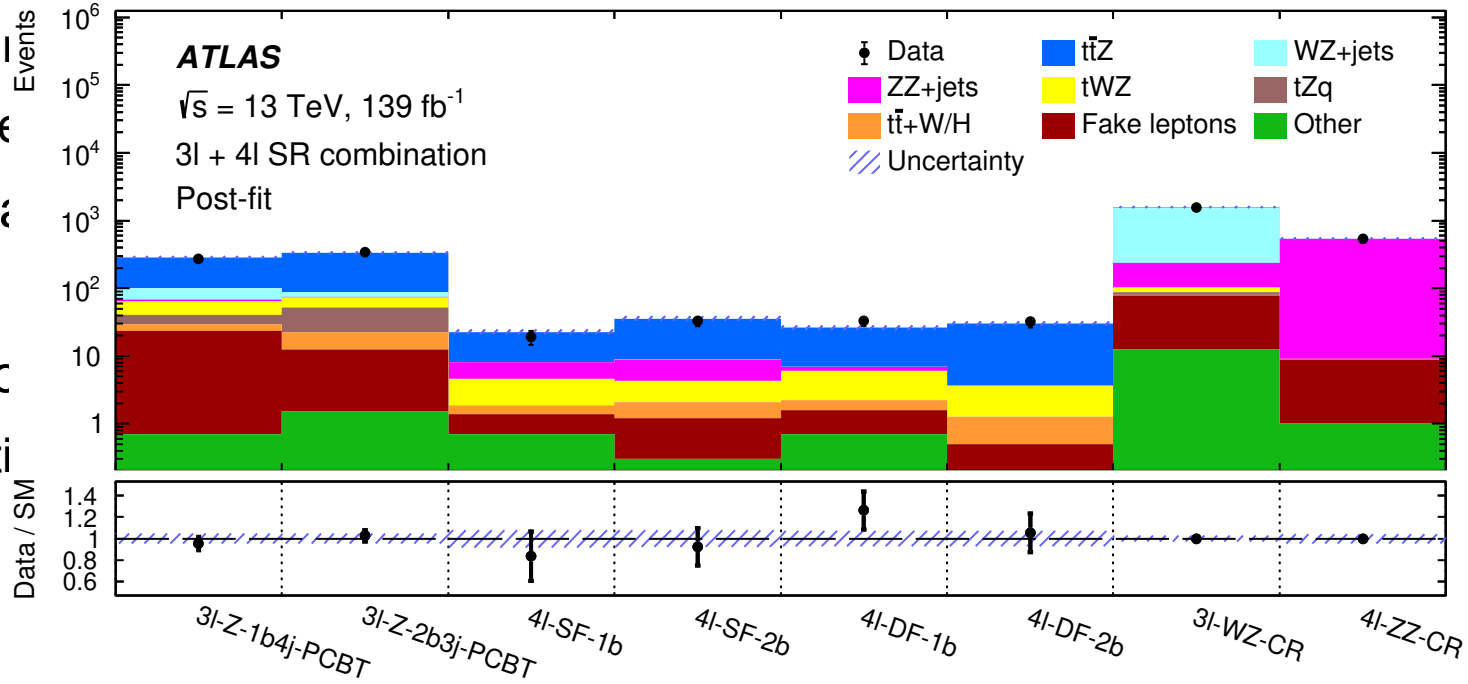
- **(Inclusive) VV production** and polarization

Inclusive and differential ttZ cross section: arXiv:2103.12603



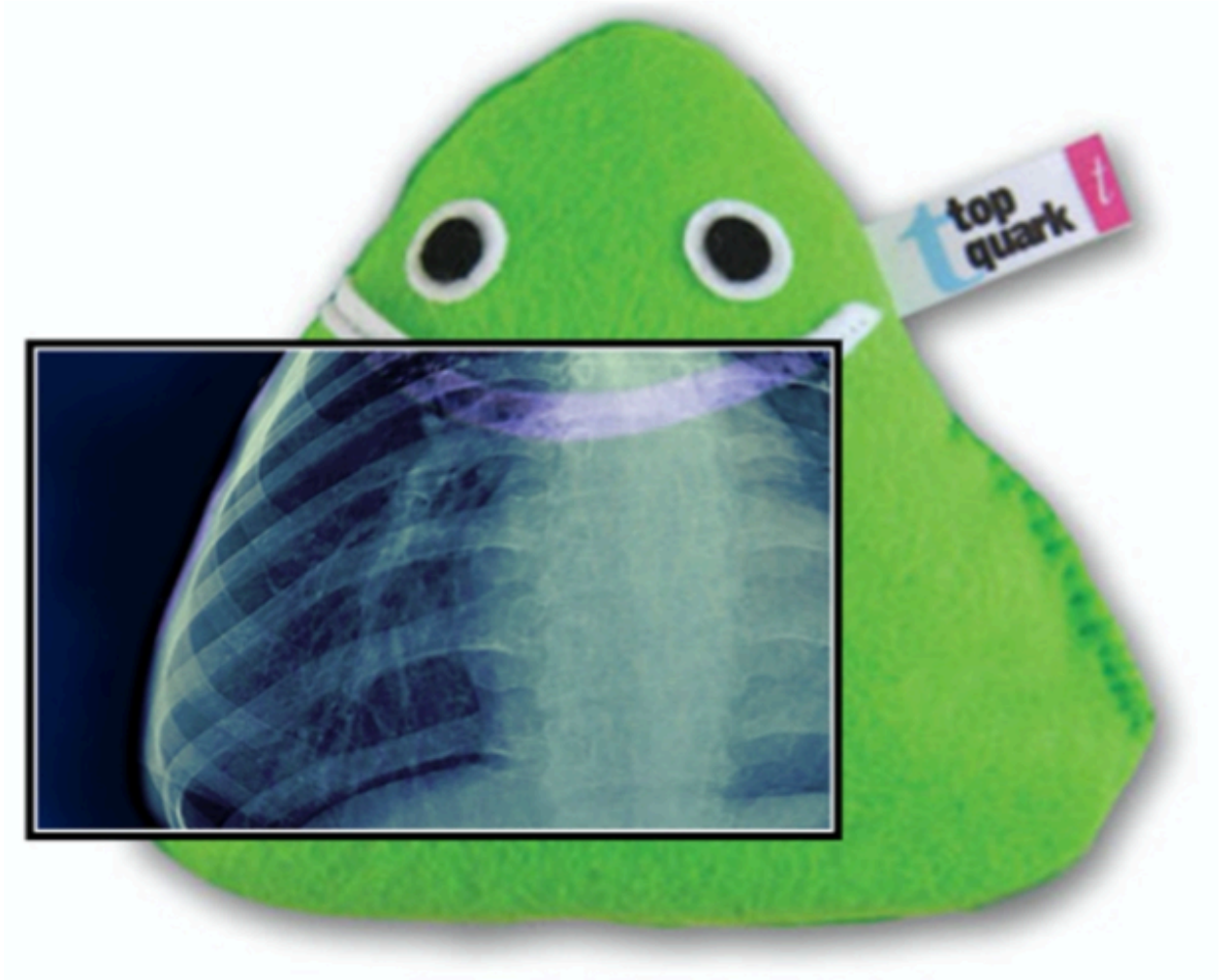
1000 pb

1 pb

1 fb

Experimentally, ttV, tV and VV are mutual backgrounds

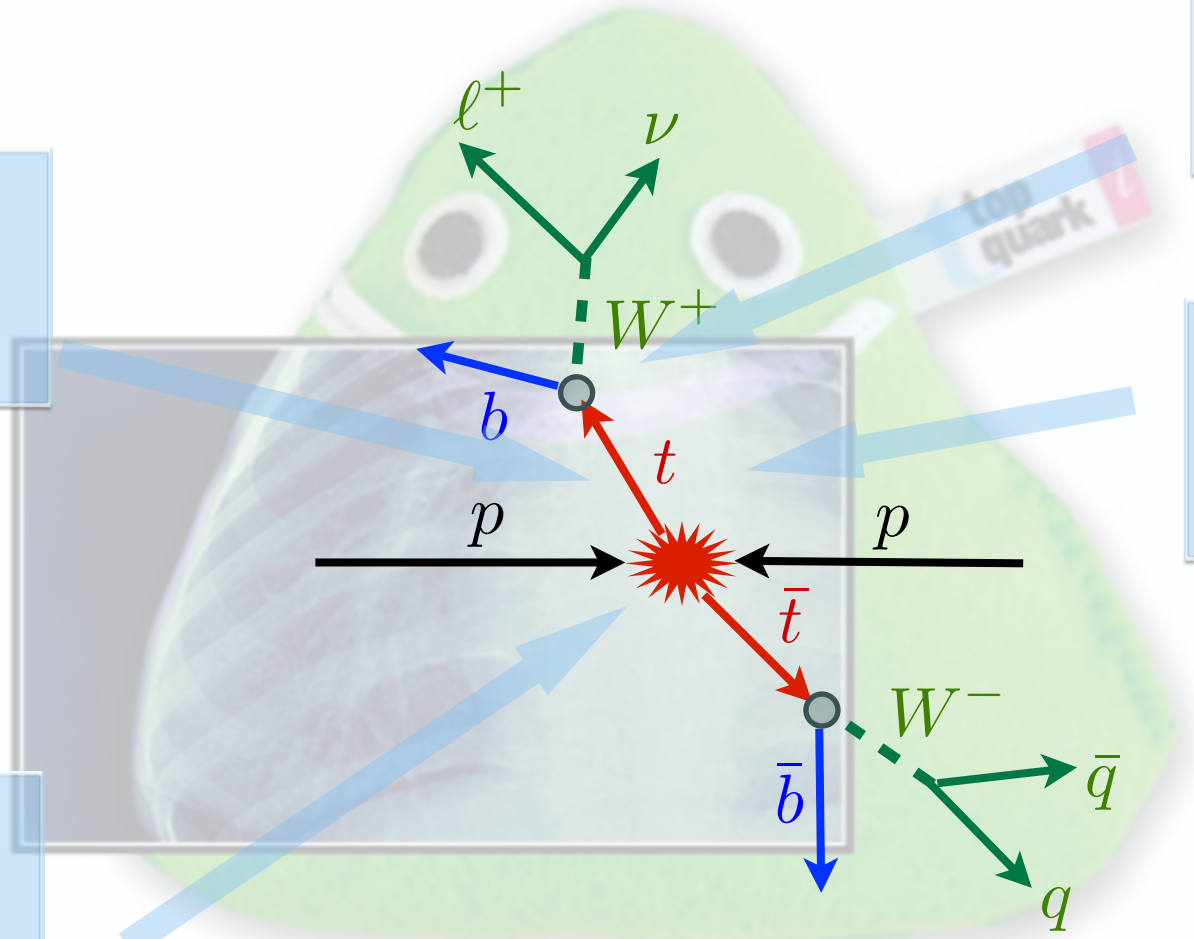
Top



- Farida Fassi: 4-Top probes of new physics *Tue afternoon*
- Alexander Paasch: Top mass with boosted jets *Wed afternoon*
- Agostino de Iorio: Differential top production *Fri morning*

Top

Spin correlations
polarisation
asymmetries



W-helicity fractions
branching ratios, V_{tb},
rare decays, FCNC

Mass
mass difference,
width, charge

Cross sections,
QCD parameters,
resonances,
new particles

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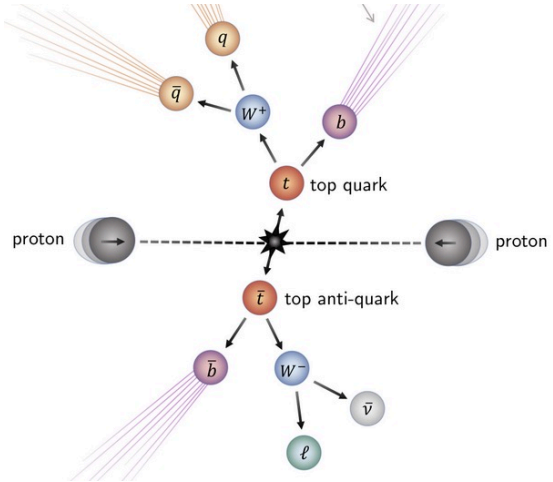
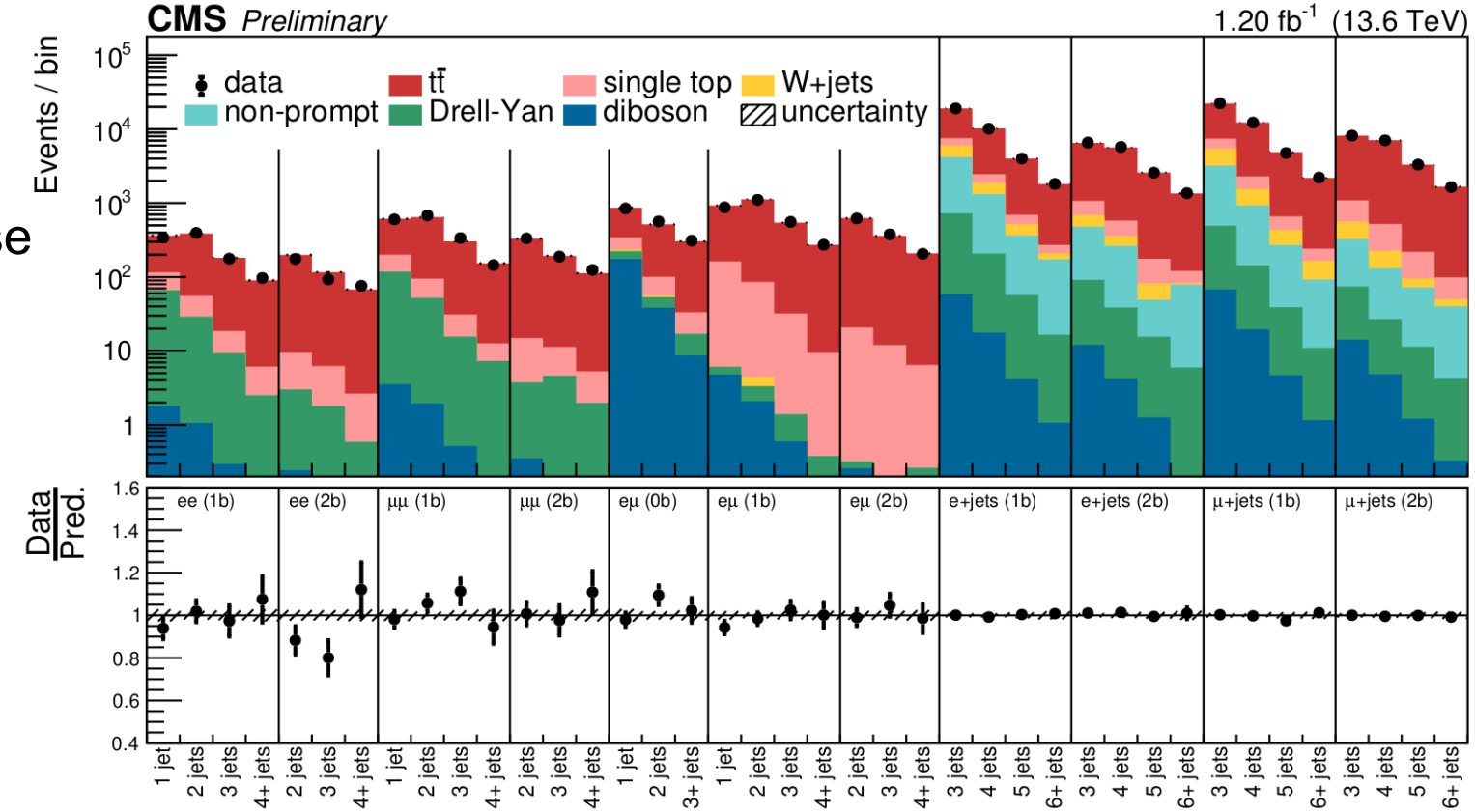
$t\bar{t}$ Cross Section

First Run-3 result

CMS PAS TOP-22-012

- Confirm expected cross section rise
- Top quark events: leptons, jets, b-tags, W-boson, top mass





- In-situ calibration and efficiencies from combination of 5 channels
- Luminosity from emittance scans, cross checked using Z-bosons

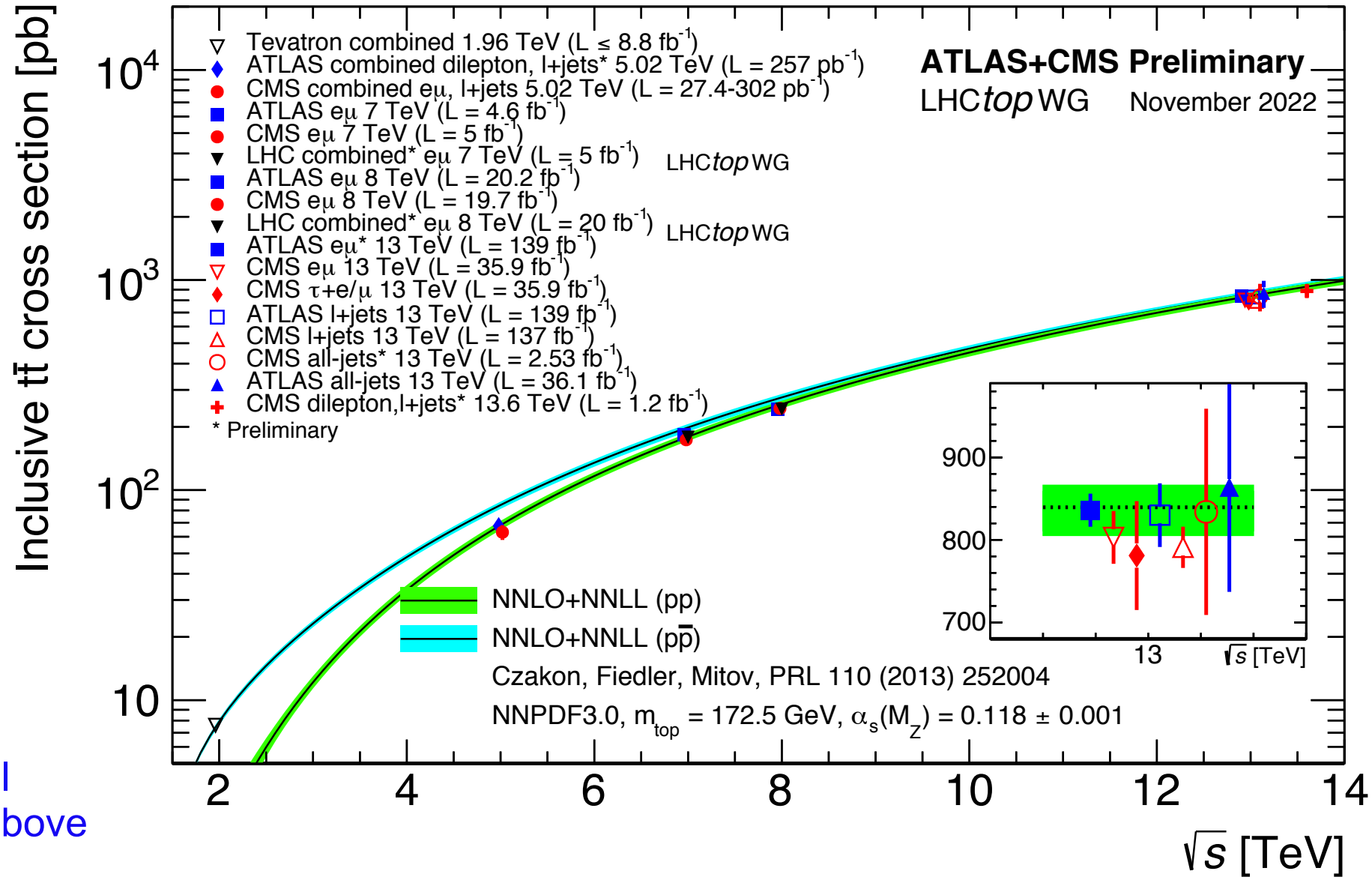
$$887\,^{+43}_{-41}\,(\text{stat}+\text{syst})\pm 53\,(\text{lumi})\,\text{pb}$$

Source	Uncertainty (%)
Lepton ID SF	3.4
Jet energy scale	1.6
b tagging SF	1.5
ME/PS matching	1.1
Drell-Yan background	0.9
Pileup	0.7
combined likelihood fit	4
Jet calibration (external)	2
luminosity (external)	6

$t\bar{t}$ Cross Section

All inclusive measurements

- Dominant uncertainties:
  - luminosity
  - lepton ID
  - MC modelling
- For further experimental progress, work on the above



$t\bar{t}$ Cross Section

Final word on Run-1

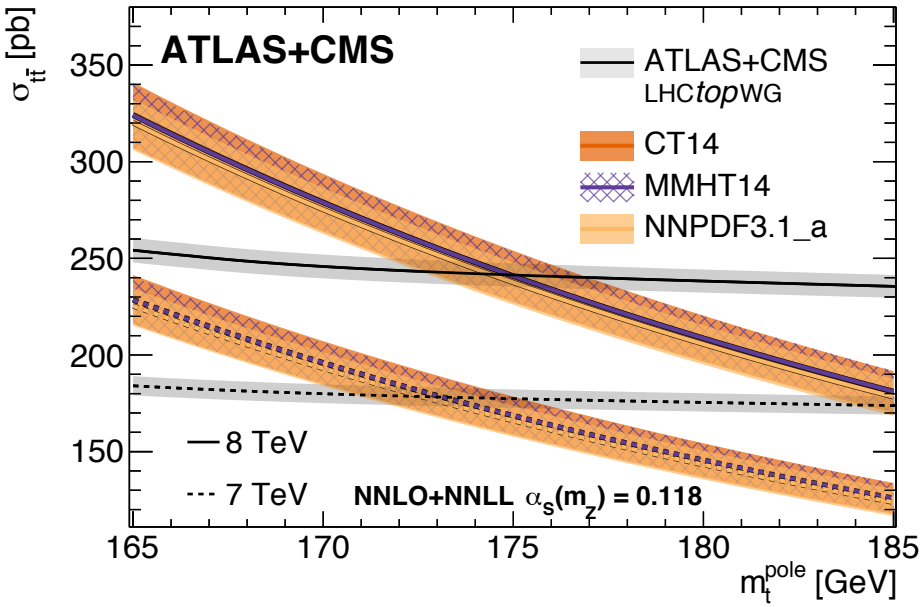
arXiv:2205.13830

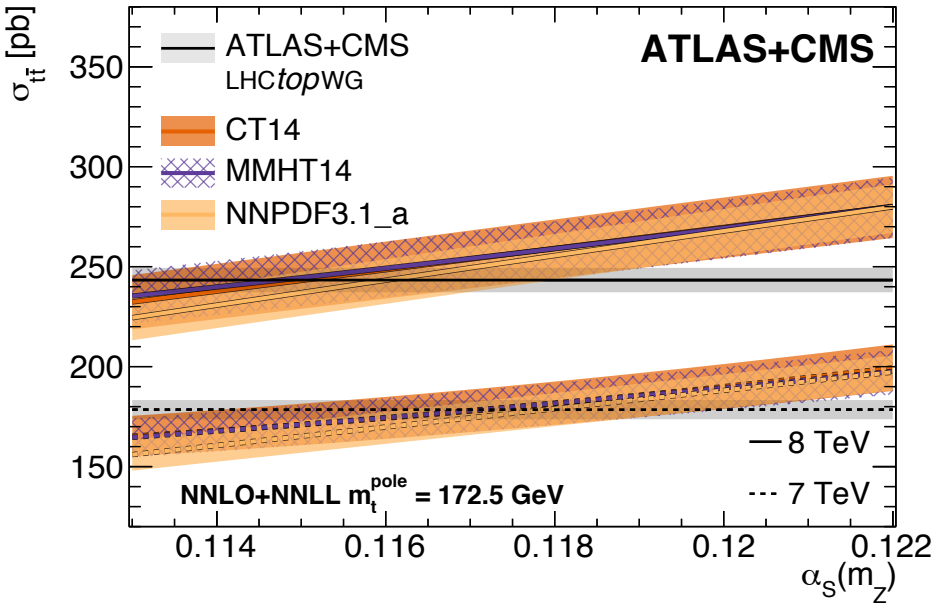
- ATLAS+CMS $t\bar{t}$ cross sections at 7 and 8 TeV:

$$\sigma_{t\bar{t}}\,(\sqrt{s} = 7\,\text{TeV}) = 178.5 \pm 4.7\,\text{pb}$$
$$\sigma_{t\bar{t}}\,(\sqrt{s} = 8\,\text{TeV}) = 243.3^{+6.0}_{-5.9}\,\text{pb}.$$

- Combined systematic uncertainty: 2.6% (down from 3.5%)
- Extract top quark pole mass and α_S

PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0\,^{+2.3}_{-2.3}$ GeV	$0.1161\,^{+0.0030}_{-0.0033}$
MMHT2014	$174.0\,^{+2.1}_{-2.3}$ GeV	$0.1160\,^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4\,^{+1.8}_{-2.0}$ GeV	$0.1170\,^{+0.0021}_{-0.0018}$





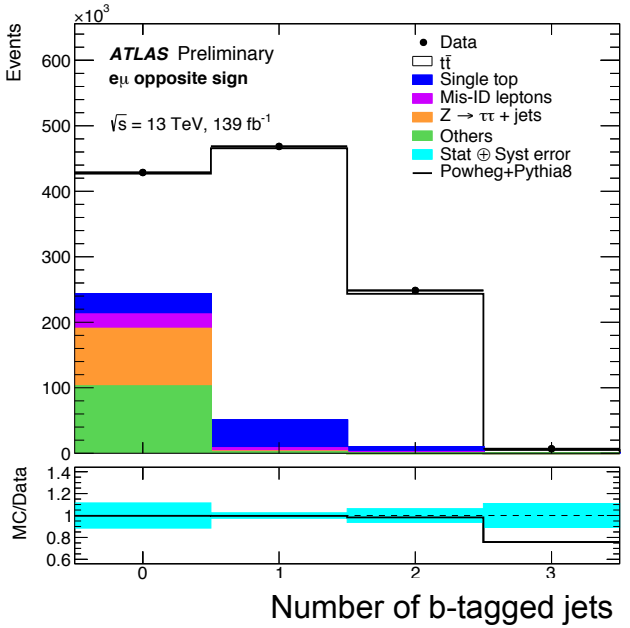
$t\bar{t}$ Cross Section

Run-2: very high statistics => even smaller systematics

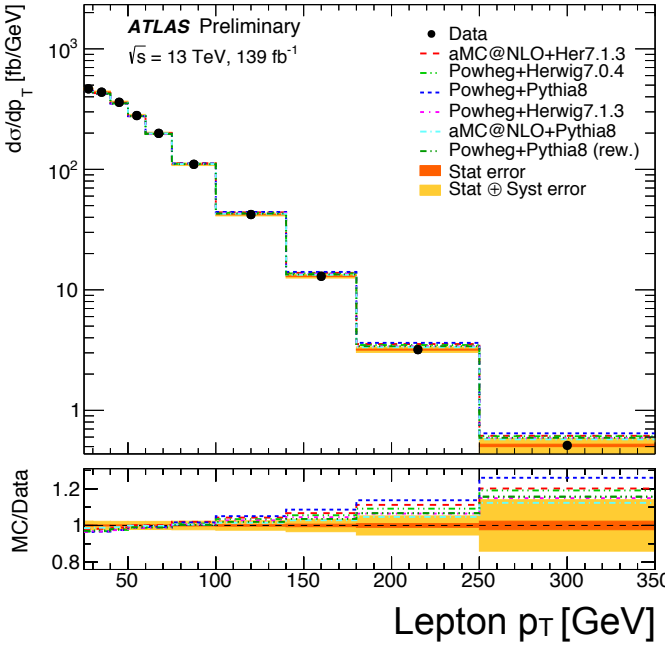
- In-situ determination of b-tag and lepton ID efficiency (as in Run-1)

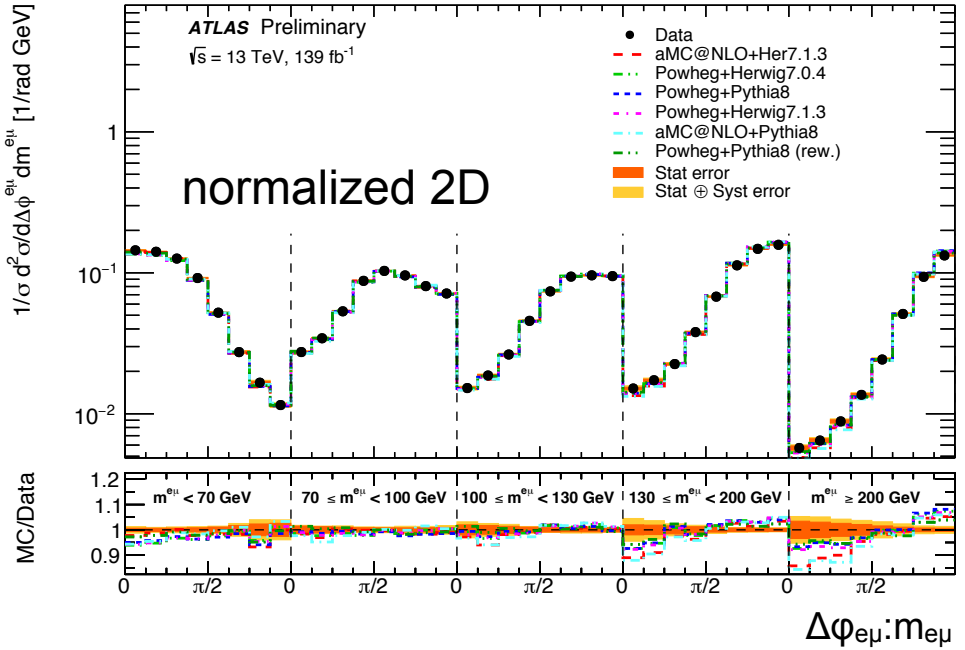
$$\sigma_{t\bar{t}} = 836 \pm 1\ (\text{stat}) \pm 12\ (\text{syst}) \pm 16\ (\text{lumi}) \pm 2\ (\text{beam})\ \text{pb}$$

- Uncertainty: 2.4%
- Dominant uncertainties: luminosity, lepton-ID, $t\bar{t}$ modelling



- Also measured: fiducial, differential- and double differential cross sections
- Known trends:
  - lepton-p_T
  - $\Delta\varphi$

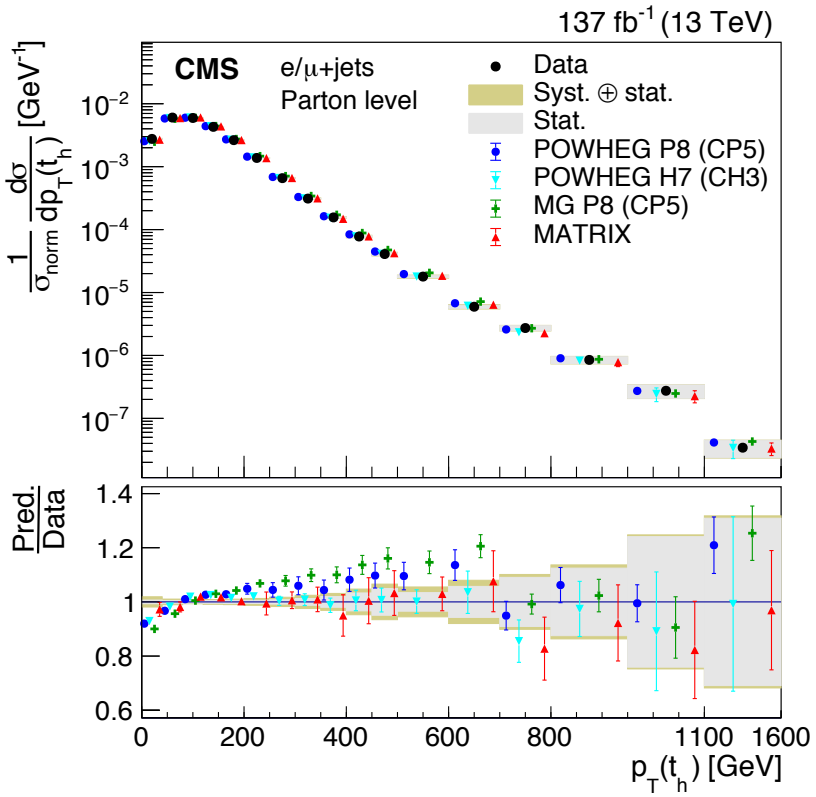




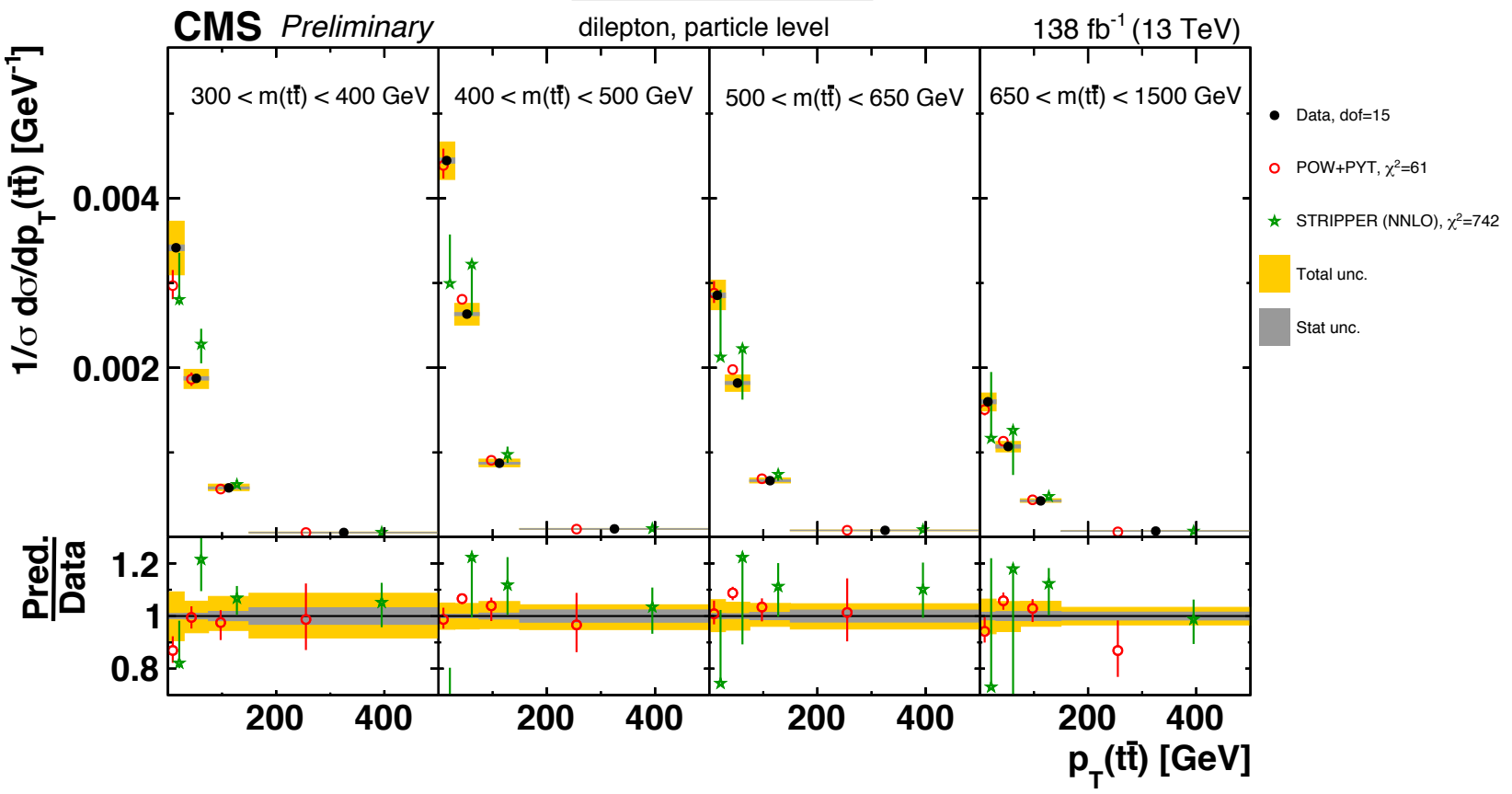
$t\bar{t}$ Differential Cross Sections

Up to 3D

arXiv:2108.02803



CMS PAS TOP-20-006



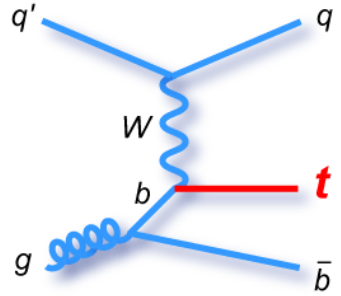
- Precise differential cross sections:
  - very large statistics => reach very high p_T
  - measured and calculated at NNLO, up to 3D
- NNLO calculations:
  - clear improvement over NLO, still residual slope
  - differential lepton distributions also available
  - large uncertainty towards $p_T(t\bar{t})\rightarrow 0$

LHCTopWGSummaryPlots

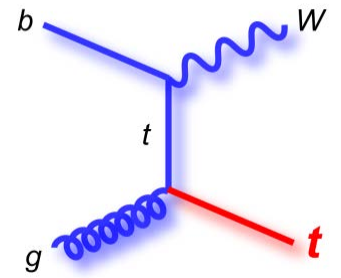
Electroweak Top-Quark Production

Single Top

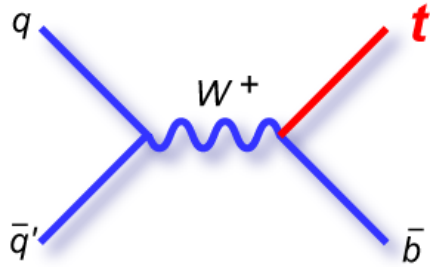
- t-channel



- tW-channel

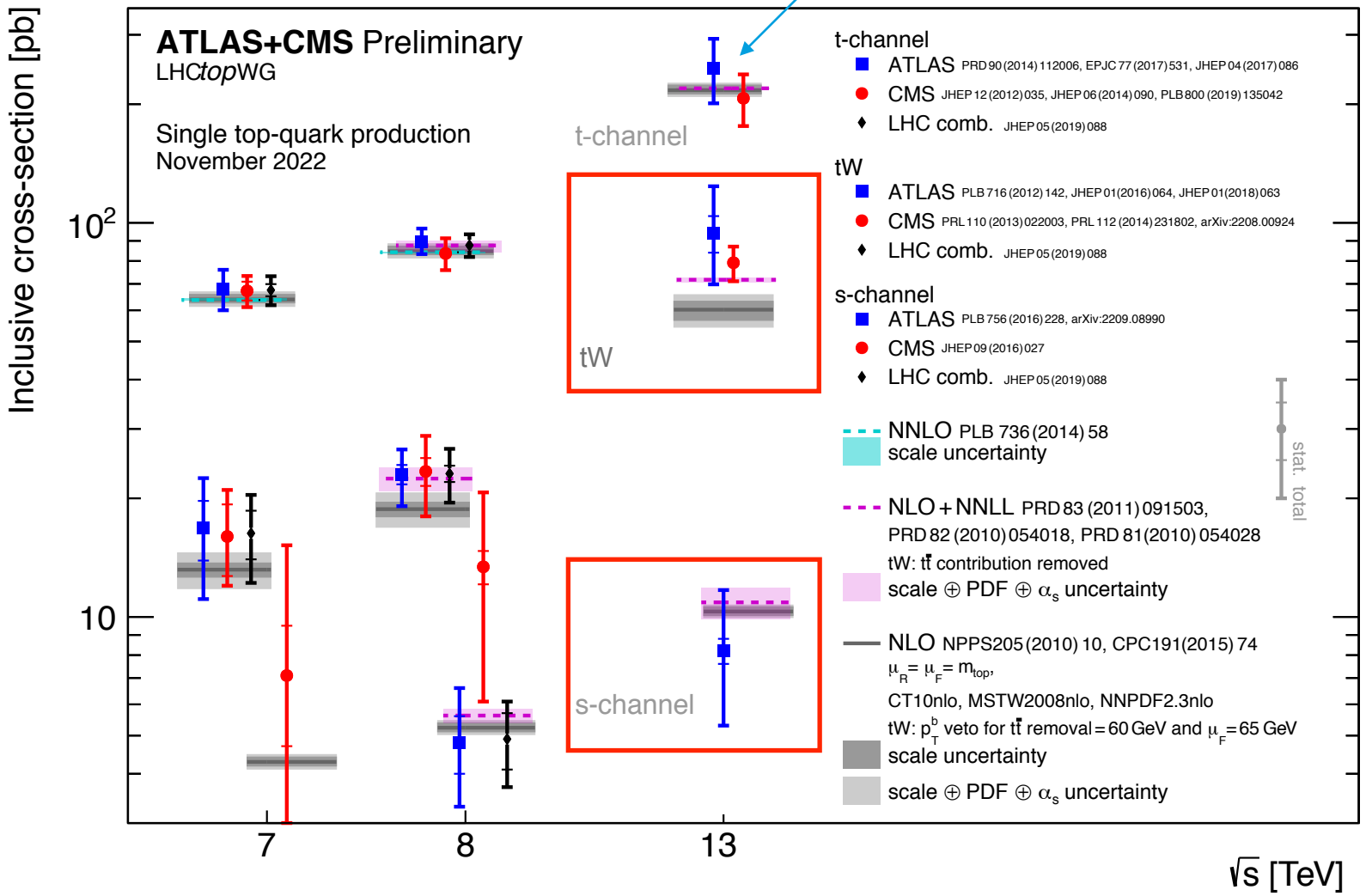


- s-channel



t-channel: detailed and precise differential measurements (not shown)

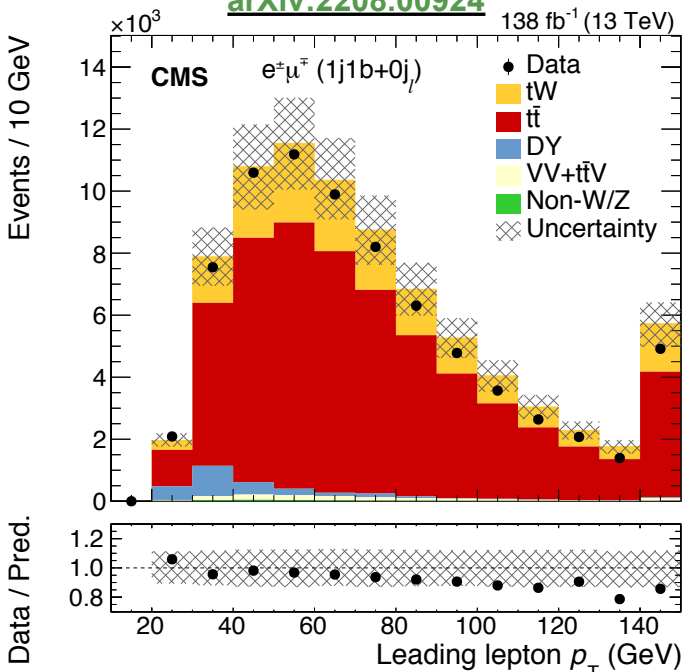
arXiv:2202.11382

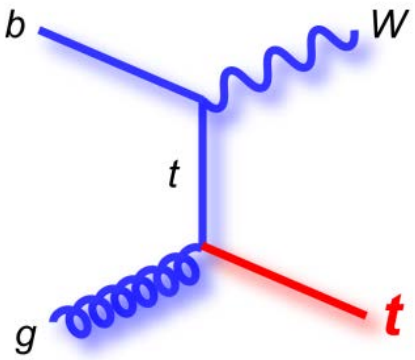


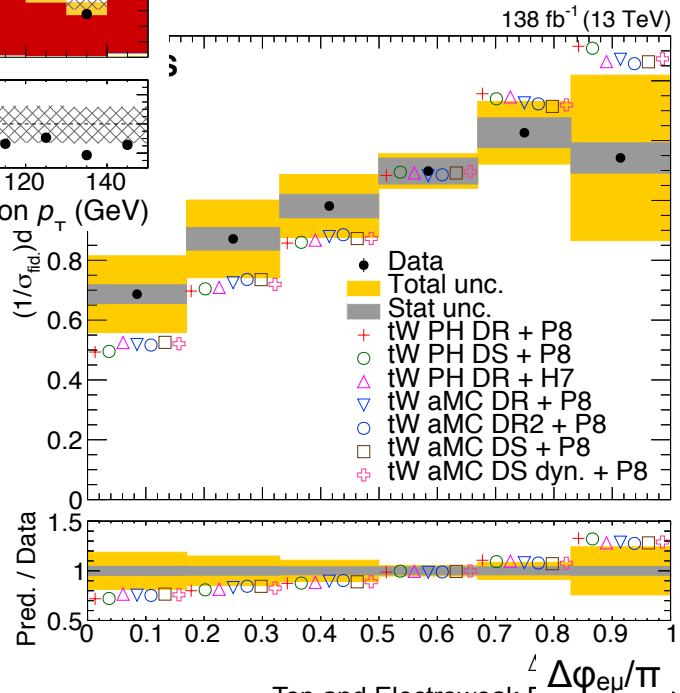
Single Top

Recent firsts

arXiv:2208.00924

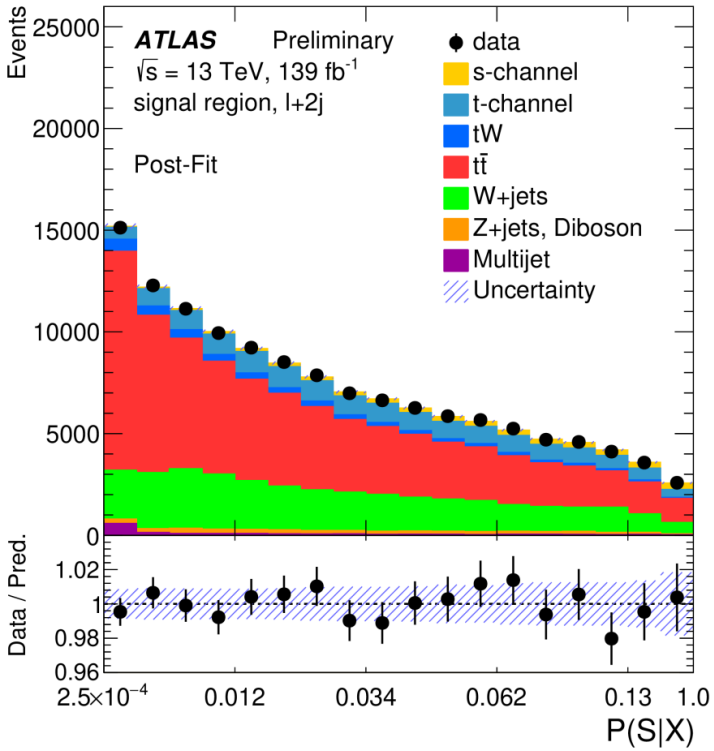


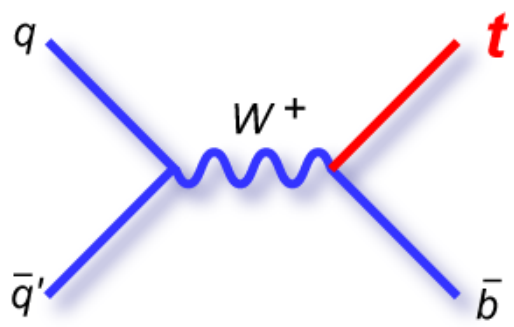


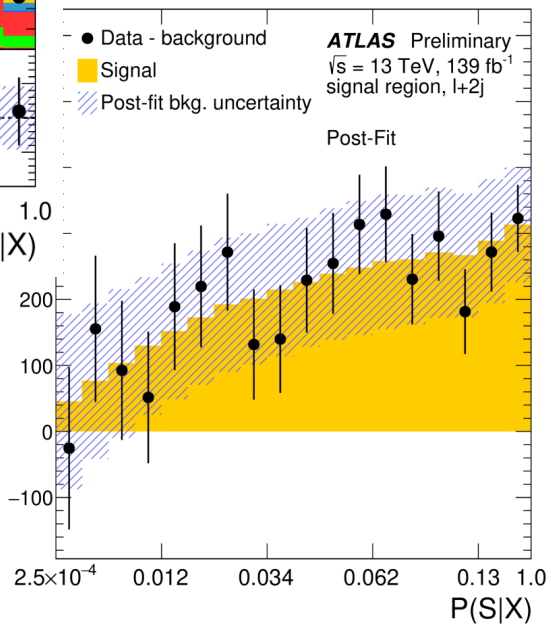


- Differential tW cross section
- Trends (like in tt̄):
  - lepton-p_T
  - Δφ

arXiv:2209.08990





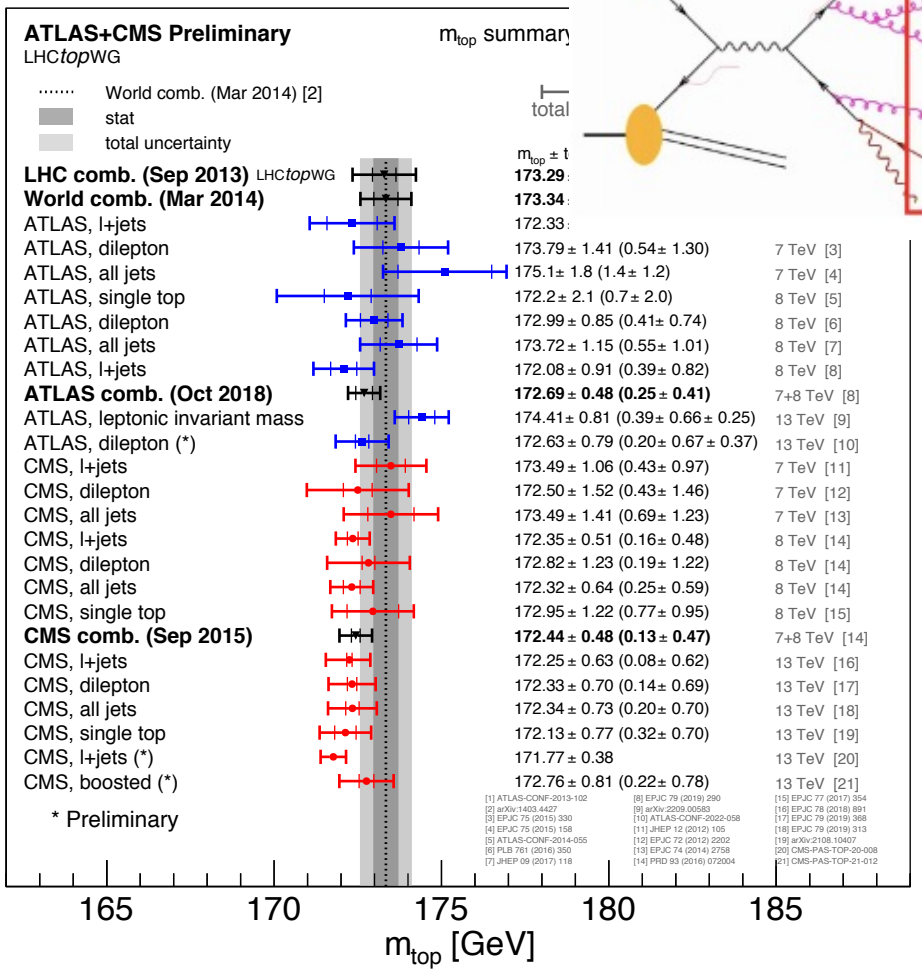


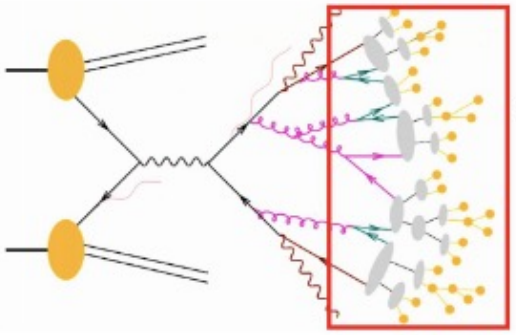
- s-channel:
  Matrix-element discriminant to separate signal from background:

1st evidence at 13 TeV:
3.3(3.9)σ obs(exp)

$$\sigma = 8.2^{+3.5}_{-2.9}\ \text{pb}$$

Top Quark Mass





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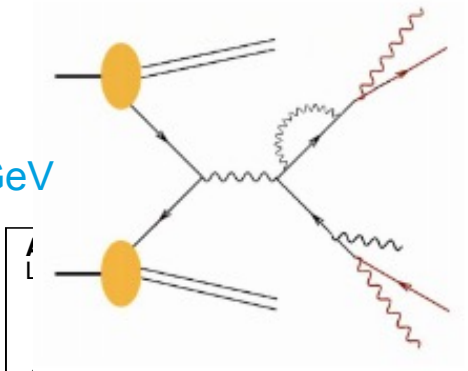
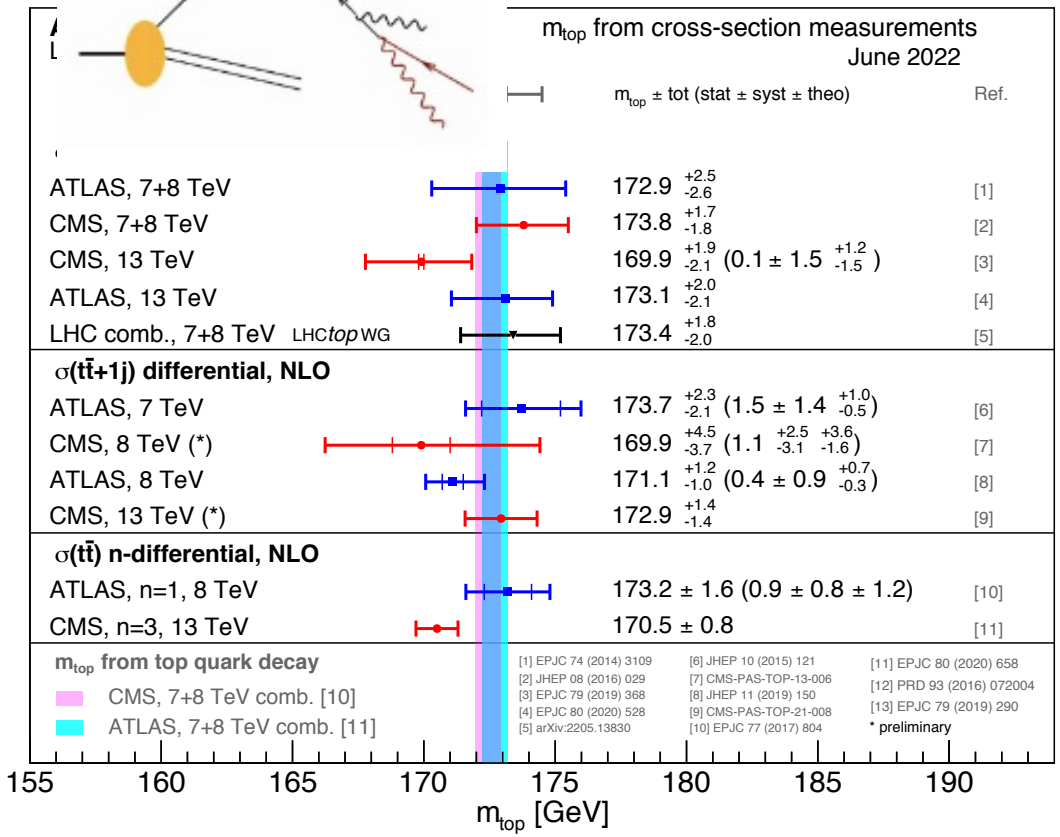
within ~1 GeV

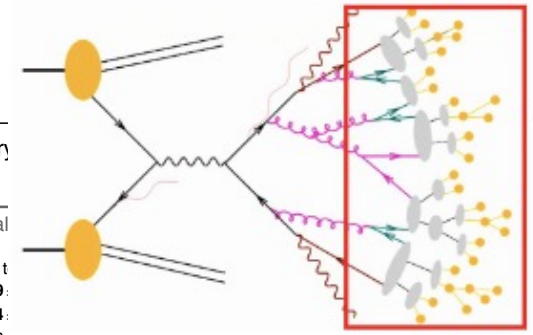




- "Direct": experimentally most precise
  - from observables (kin.rec, jet mass, $m_{\ell b}$, $m_{\ell\ell}$)
  - MC modelling of non-pert. details: "MC mass"

- "Indirect": theoretically well defined
  - from cross sections calculable in fixed-order (pole, $\overline{\text{MS}}$, MSR schemes)

Top Quark Mass



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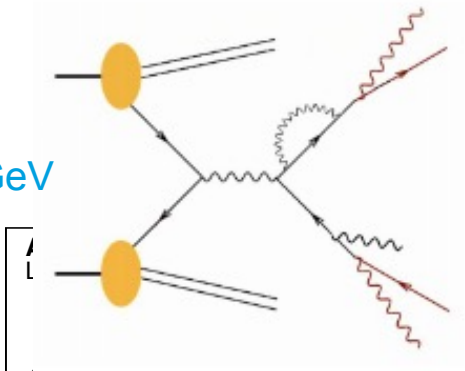

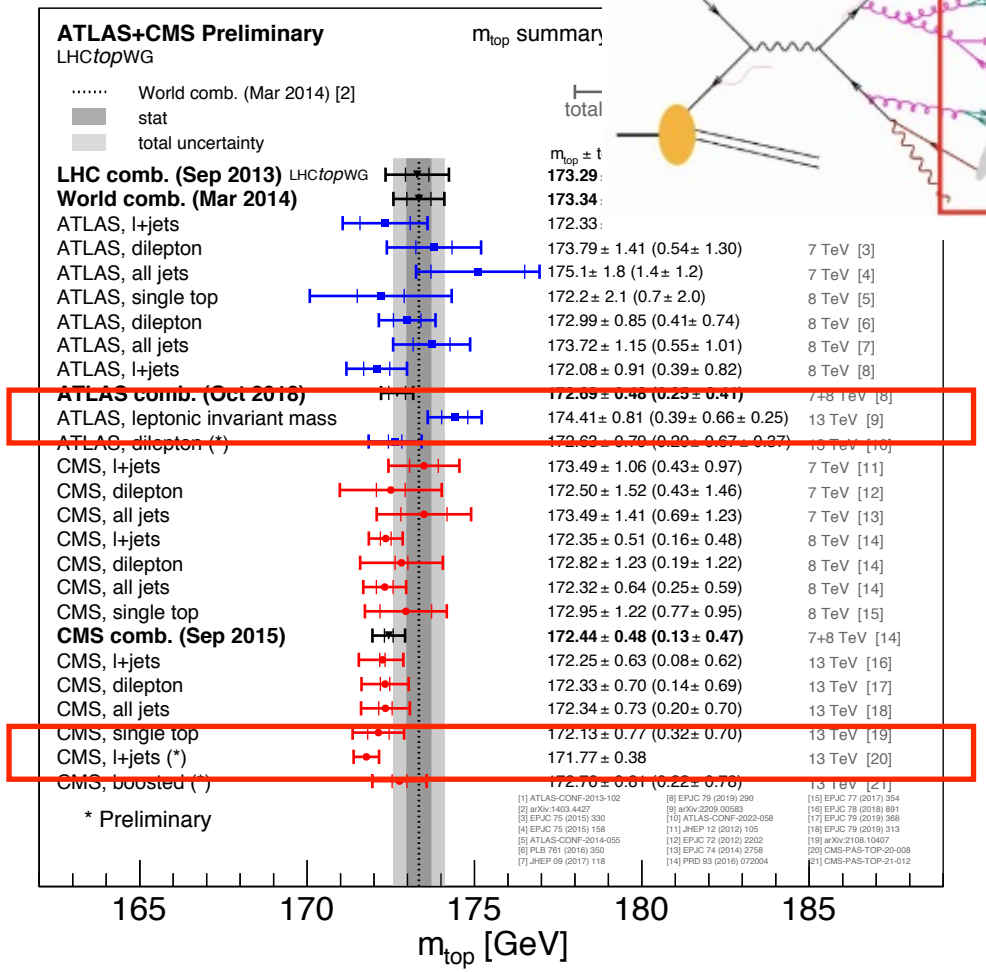

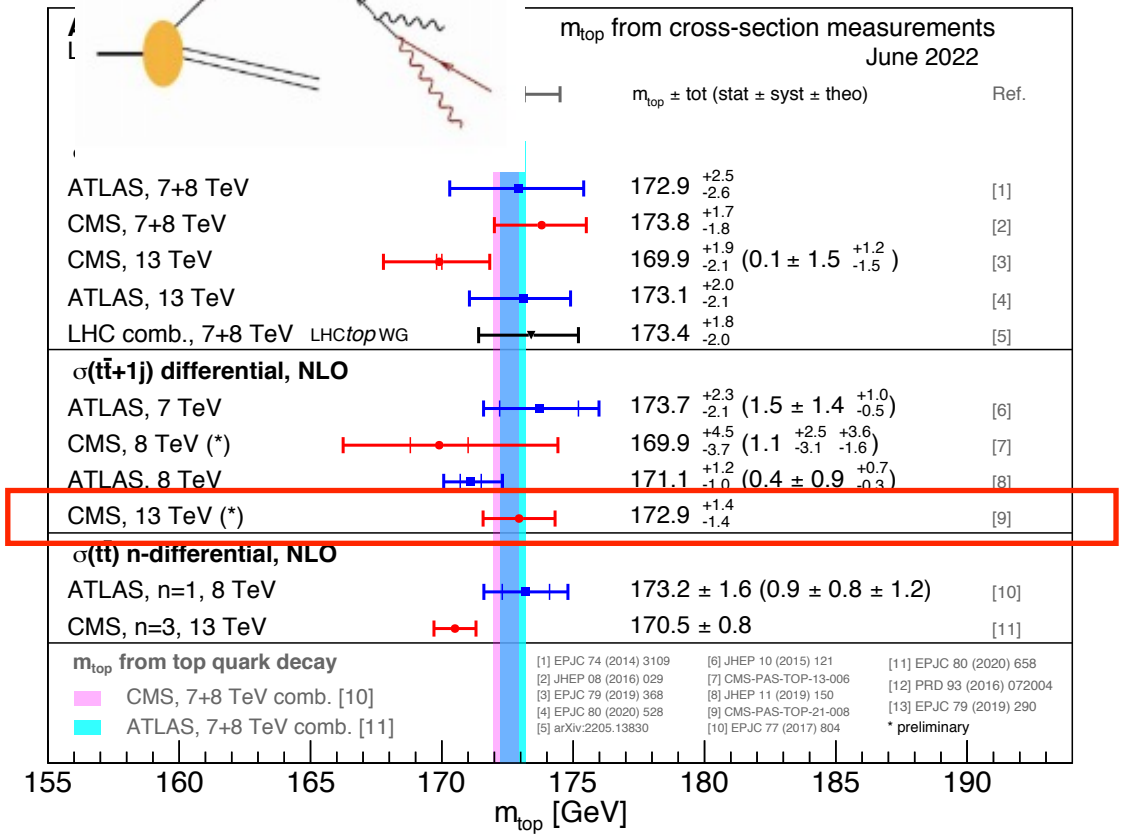

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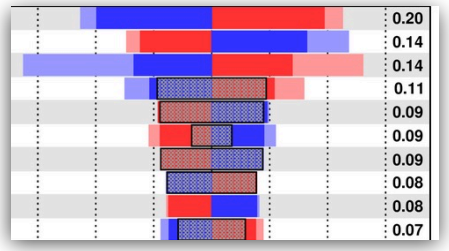
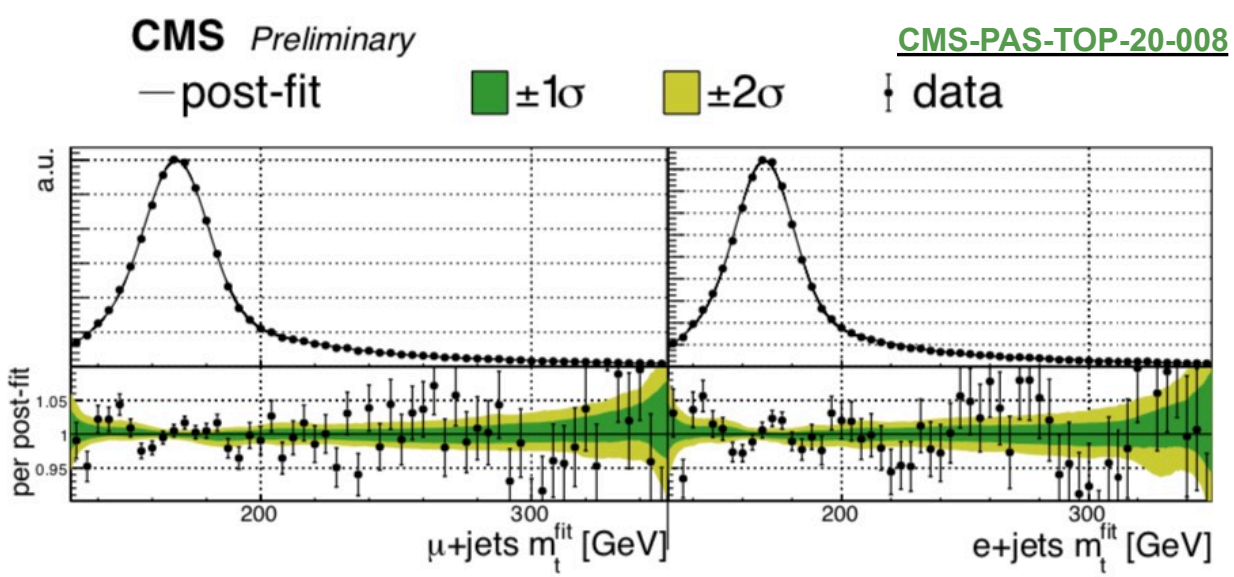
Top Quark Mass

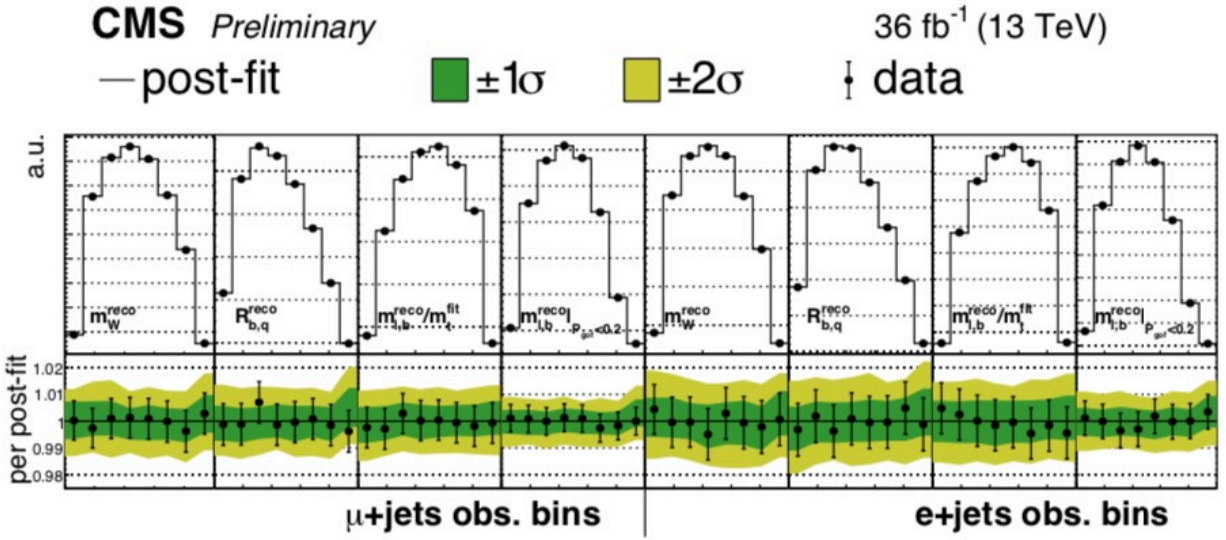
From 5D profile likelihood ratio

- Previously:
  - 2D (or 3D) constraining (b) jet energy from W mass (and the ratio R_{bq}) $R_{bq}^{\mathrm{reco}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{q_1} + p_{\mathrm{T}}^{q_2}}$
  - Systematic uncertainties assumed uncorrelated
- New:
  - 5D (additional variables: $m_{\ell b}/m_{\mathrm{fit}}$ and $m_{\ell b}|p_{\mathrm{gof}}<0.2$)
  - Profile likelihood ratio, accounting for correlations
- Dominant uncertainties (as previously)
  - b-jet energy scale
  - FSR PS scale
  - Color reconnection
  - Underlying event



- Expect further improvements from “differential” measurements



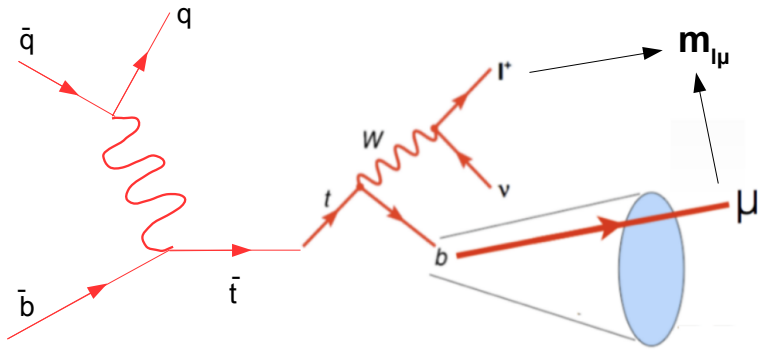


$$m_{\mathrm{t}}^{\mathrm{5D}} = 171.77 \pm 0.38\,\mathrm{GeV}.$$

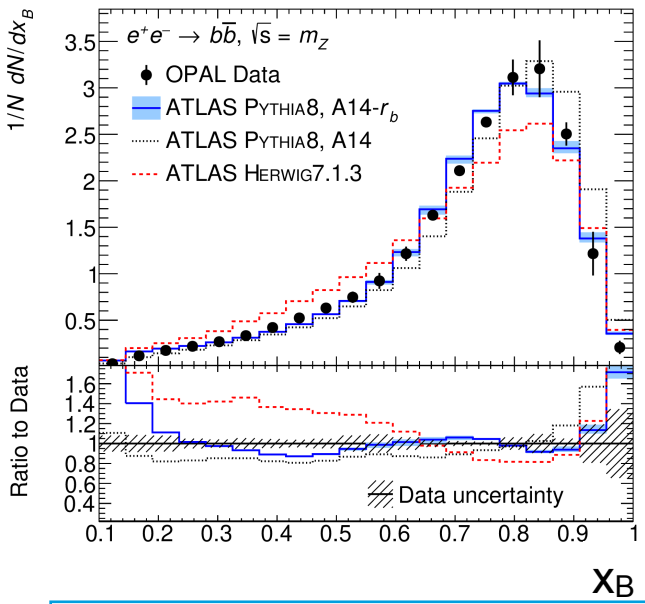
most precise result as yet (still with 2016 data only)

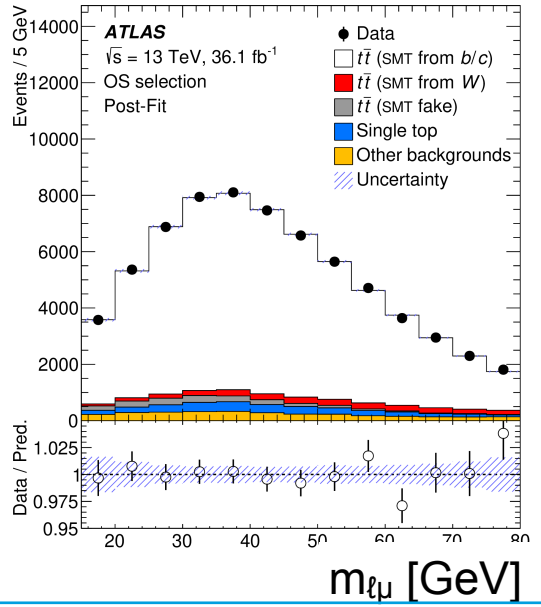
Top Quark Mass

Soft-muon mass $m_{\ell\mu}$

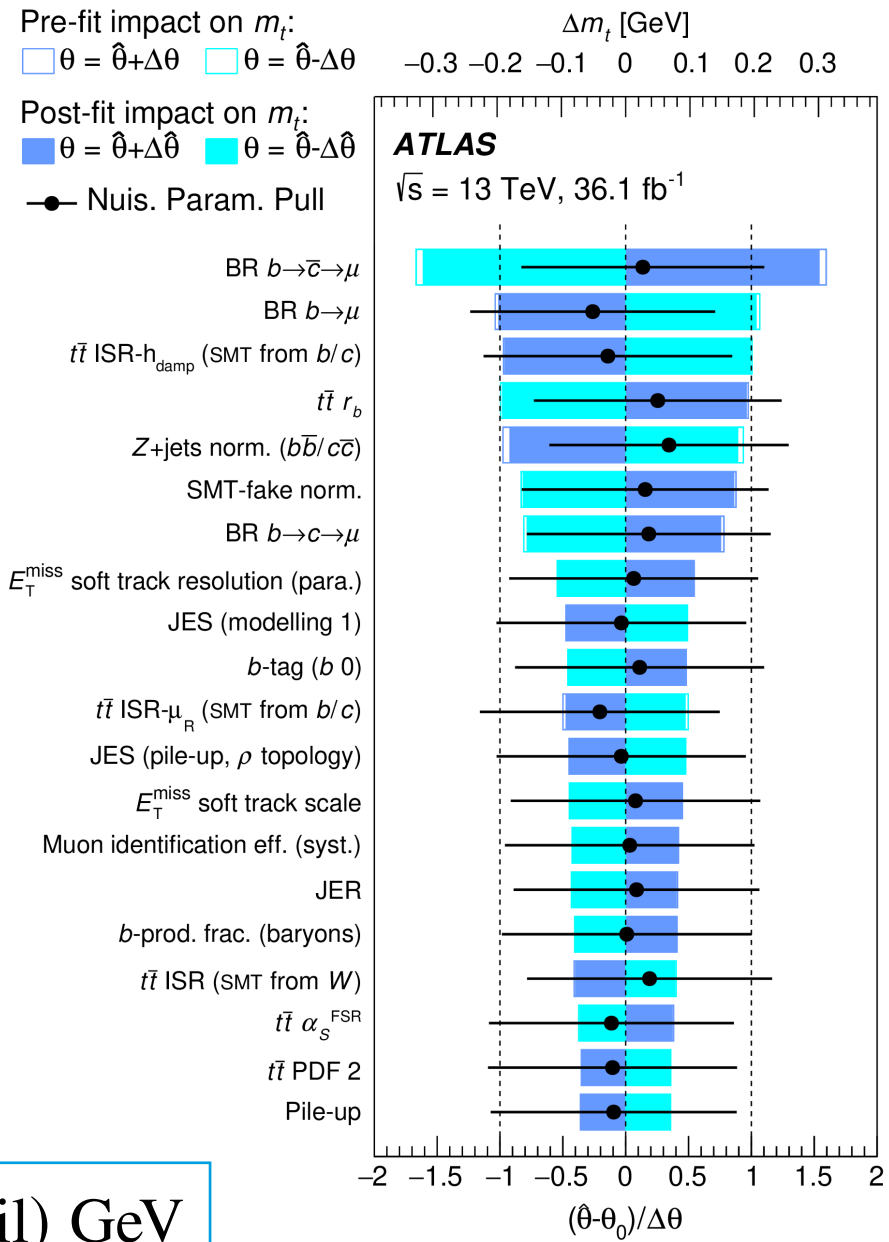


- less sensitive to jet energy scale
- more sensitive to fragmentation function, analysis includes:
  - Refit of Lund-Bowler parameter r_b in Pythia8 using LEP data
  - Additional uncertainty from gluon recoil scheme impacting x_B





arXiv.2209.00583



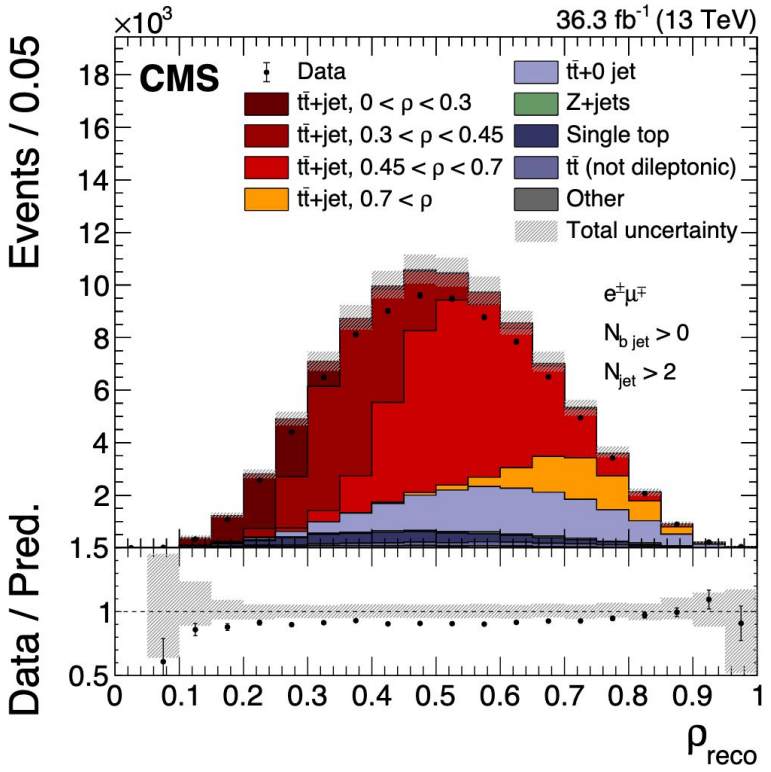
$$m_t = 174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.}) \pm 0.25\ (\text{recoil})\ \text{GeV}$$

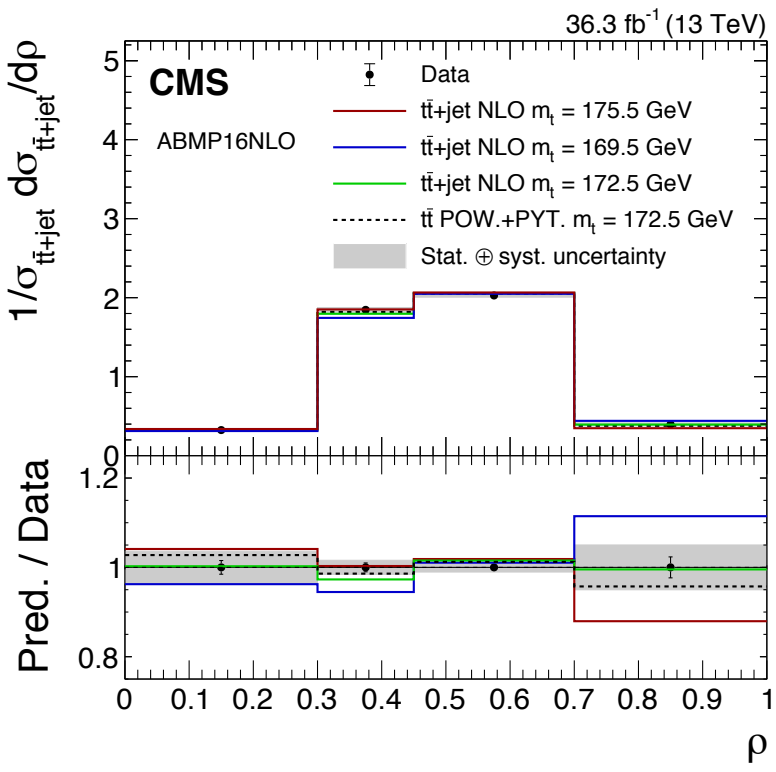
Top Quark Mass

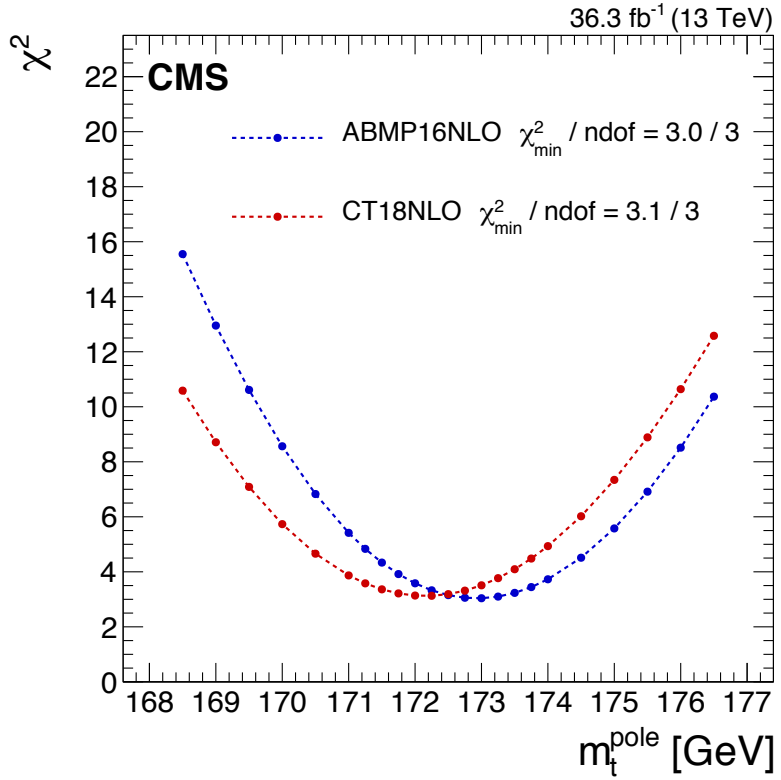
arXiv:2207.02270

"Indirect Mass" from differential $t\bar{t}$+1jet cross section

$$\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}$$







- Differential $t\bar{t}$+1jet cross section as a function of ρ_s
- Enhanced sensitivity as gluon (jet) kinematics depends top-quark mass
- Dedicated calculation at NLO+PS arXiv:1303.6415

$$m_t^{\text{pole}} = 172.94 \pm 1.27\,(\text{fit})\,^{+0.51}_{-0.43}\,(\text{scale})\,\text{GeV}$$ ABMP16

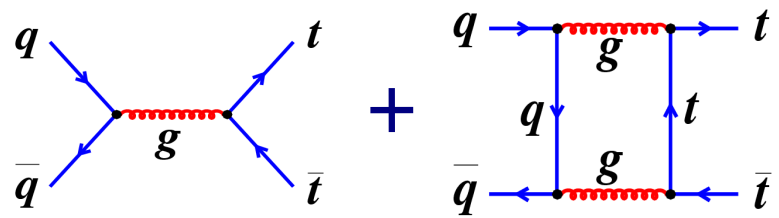
$$m_t^{\text{pole}} = 172.16 \pm 1.35\,(\text{fit})\,^{+0.50}_{-0.40}\,(\text{scale})\,\text{GeV}.$$ CT18

Charge Asymmetry

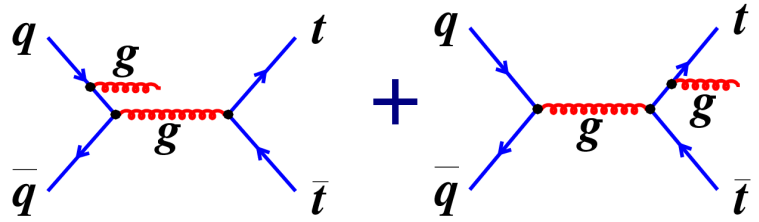
Inclusive $t\bar{t}$

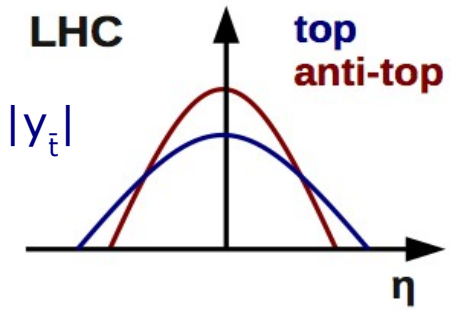
- Contributions from $q\bar{q}$
  - LO: No charge asymmetry expected
  - NLO: interference between $q\bar{q}$ diagrams

positive asymmetry



negative asymmetry

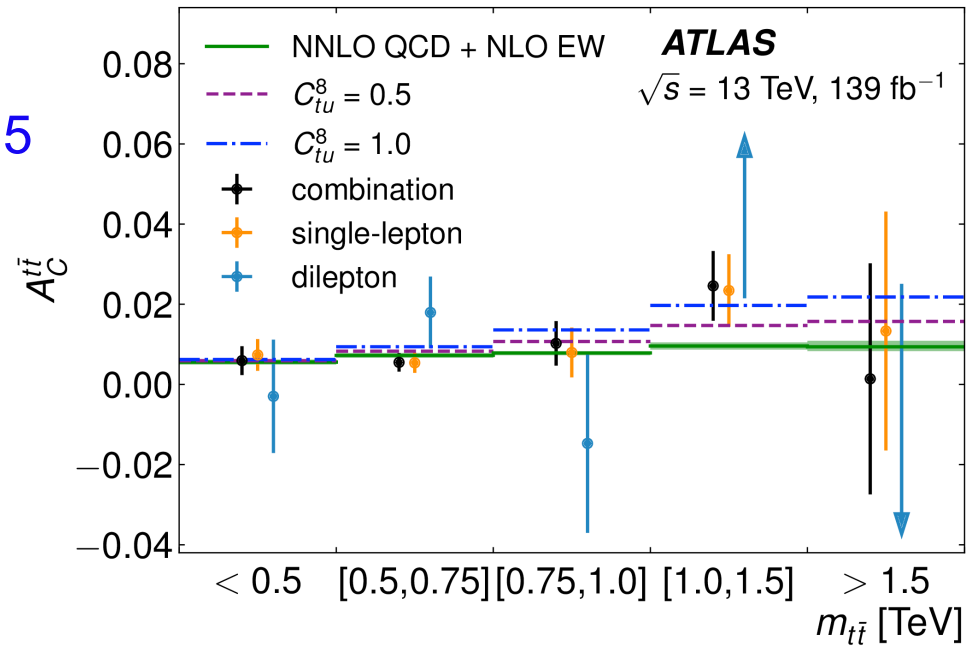




$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

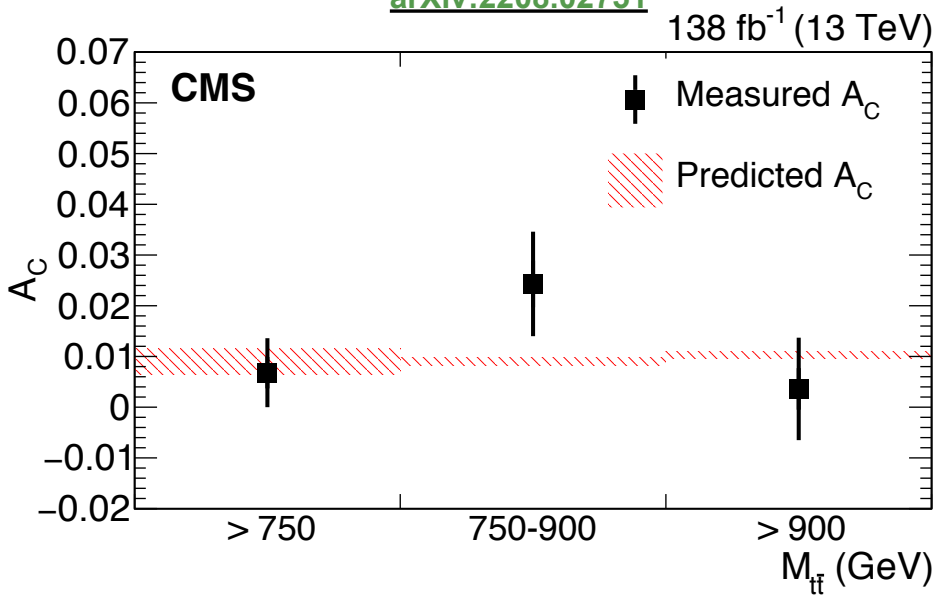
- inclusive A_C = 0.0068 ± 0.0015 **(4.7σ)**

arXiv:2208.12095



- Boosted top: enhanced $q\bar{q}$ at large $m_{t\bar{t}}$

arXiv:2208.02751

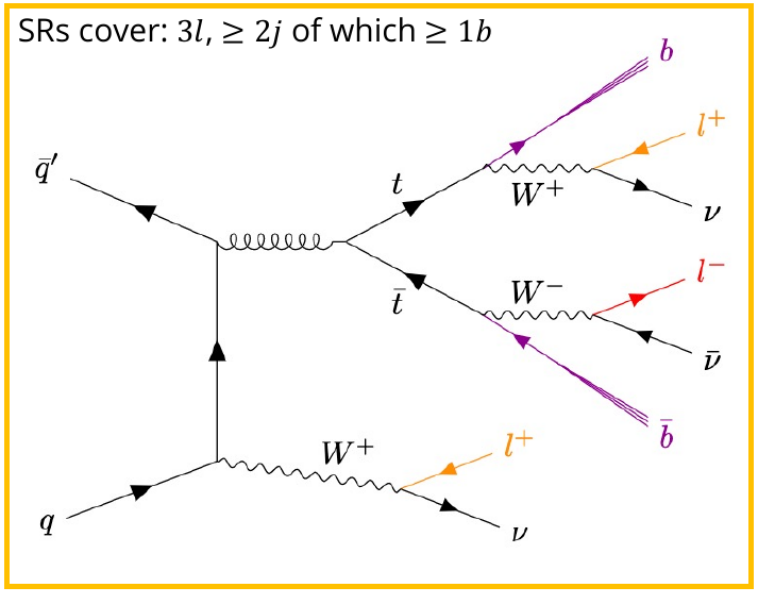


Charge Asymmetry

$t\bar{t}+\gamma$, $t\bar{t}+W$, $t\bar{t}+$jets

tt+jets: arXiv:2110.05453
tt+γ: ATLAS-CONF-2022-049

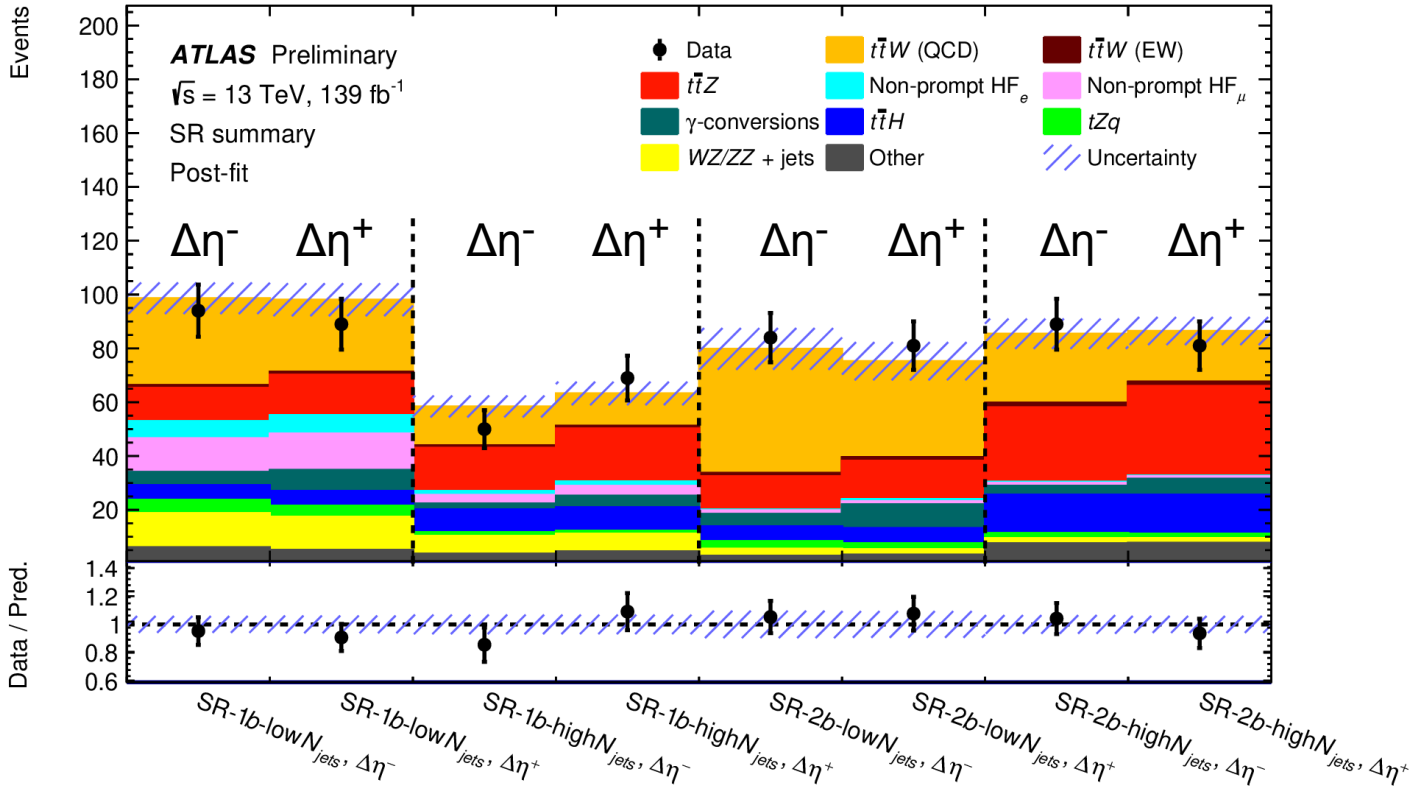
- $t\bar{t}+\gamma$ and $t\bar{t}+W$: enhance $q\bar{q}'$ initial state
- $t\bar{t}+$jets: also contributions from gq



Odd lepton: always from (anti)top quark
Even leptons: need to select the correct one

- BDT to identify ℓ from additional W

ATLAS-CONF-2022-062



$$A_c^{\ell}(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.}),$$

$$A_c^{\ell}(t\bar{t}W)_{\text{SM}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.}).$$

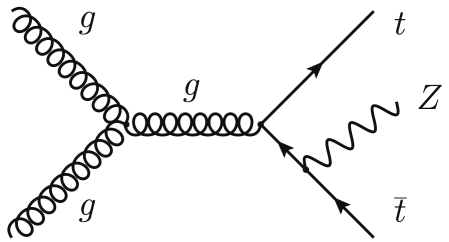
Results consistent with SM within large statistical uncertainties

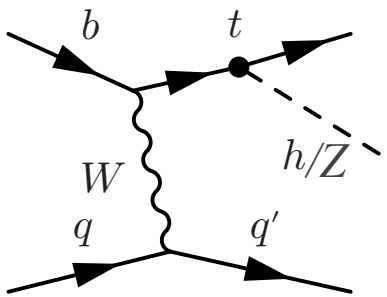
LHCTopWGSummaryPlots

Top + V

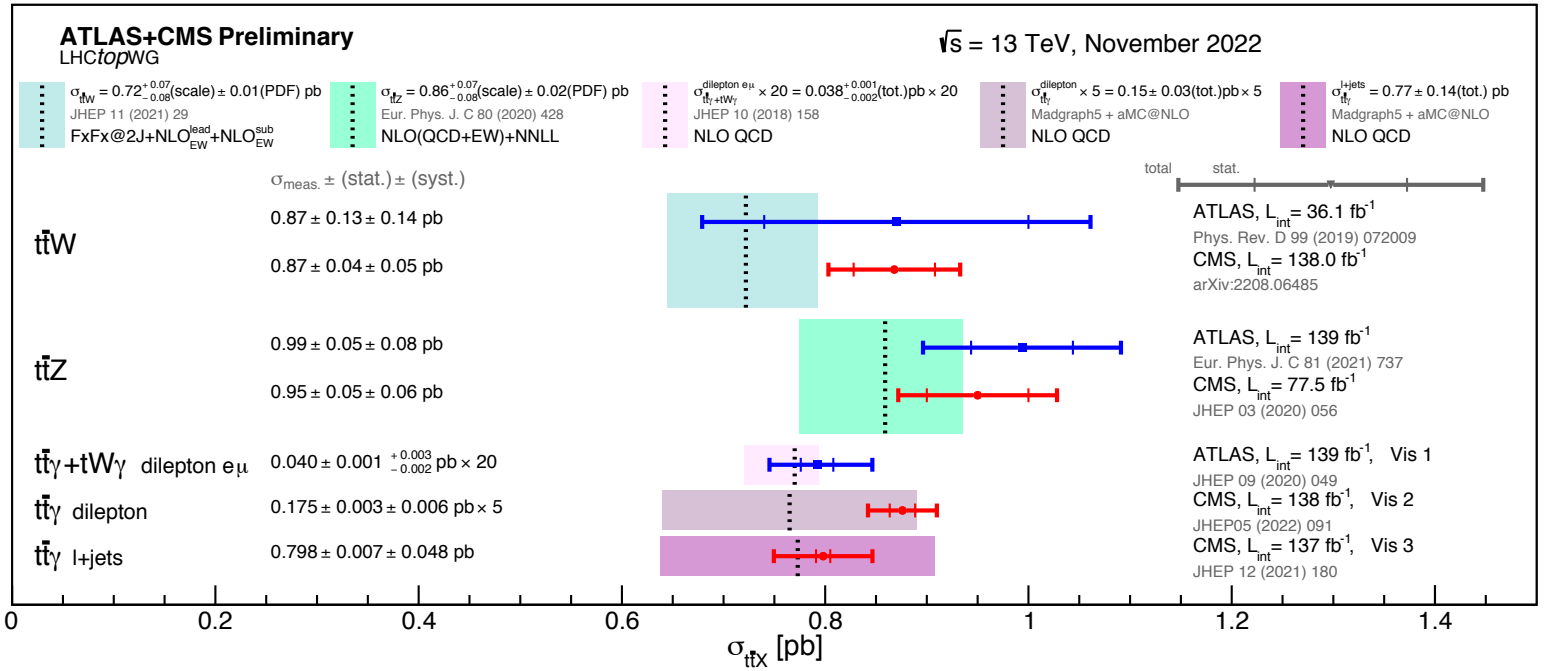
V = γ, W, Z

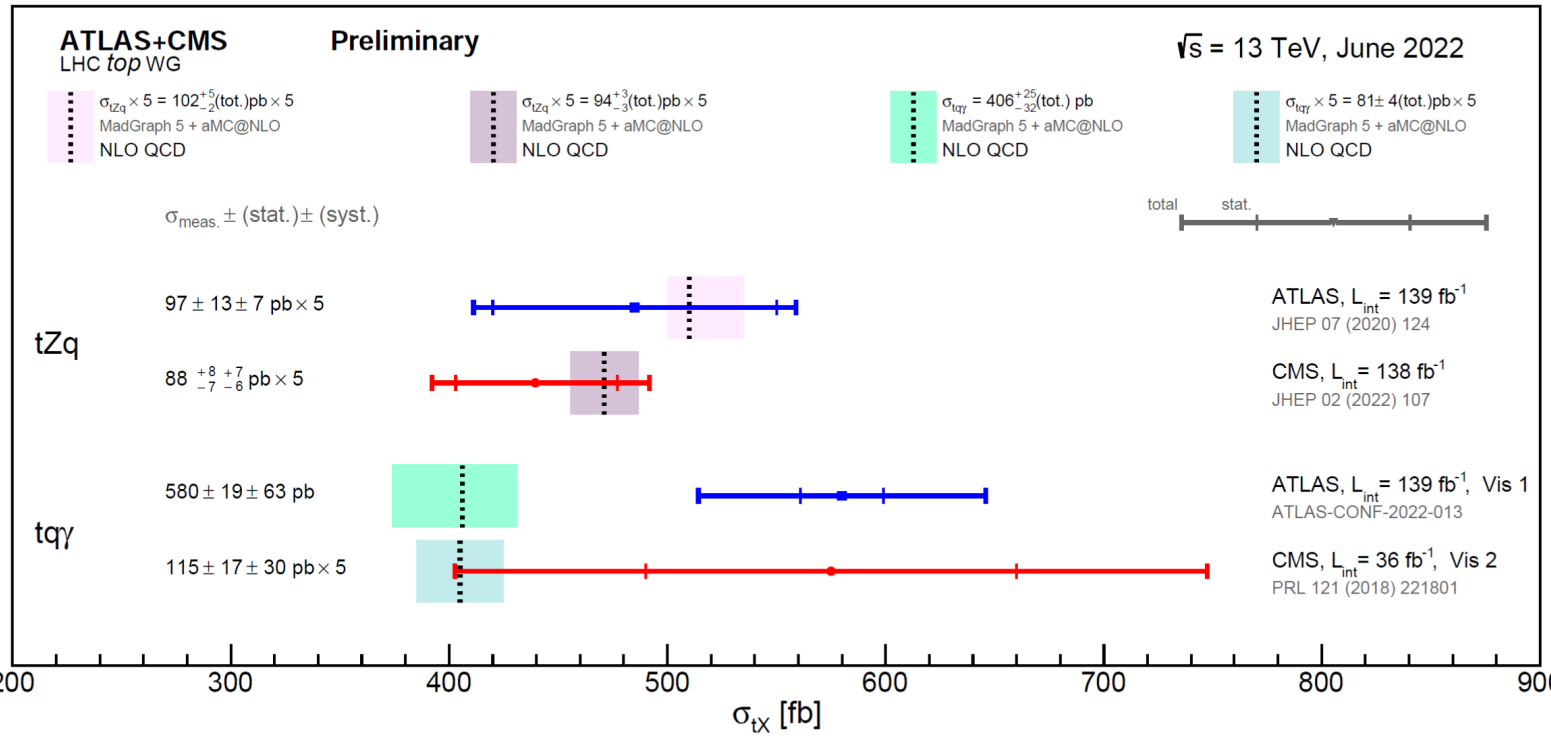
- tVq and tt̄V: similar cross sections (0.4…1 pb)





- 1st differential measurements: good understanding established



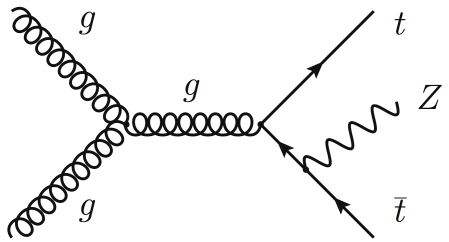


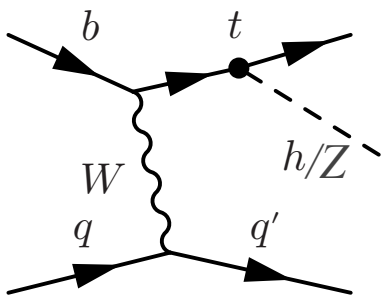
LHCTopWGSummaryPlots

Top + V

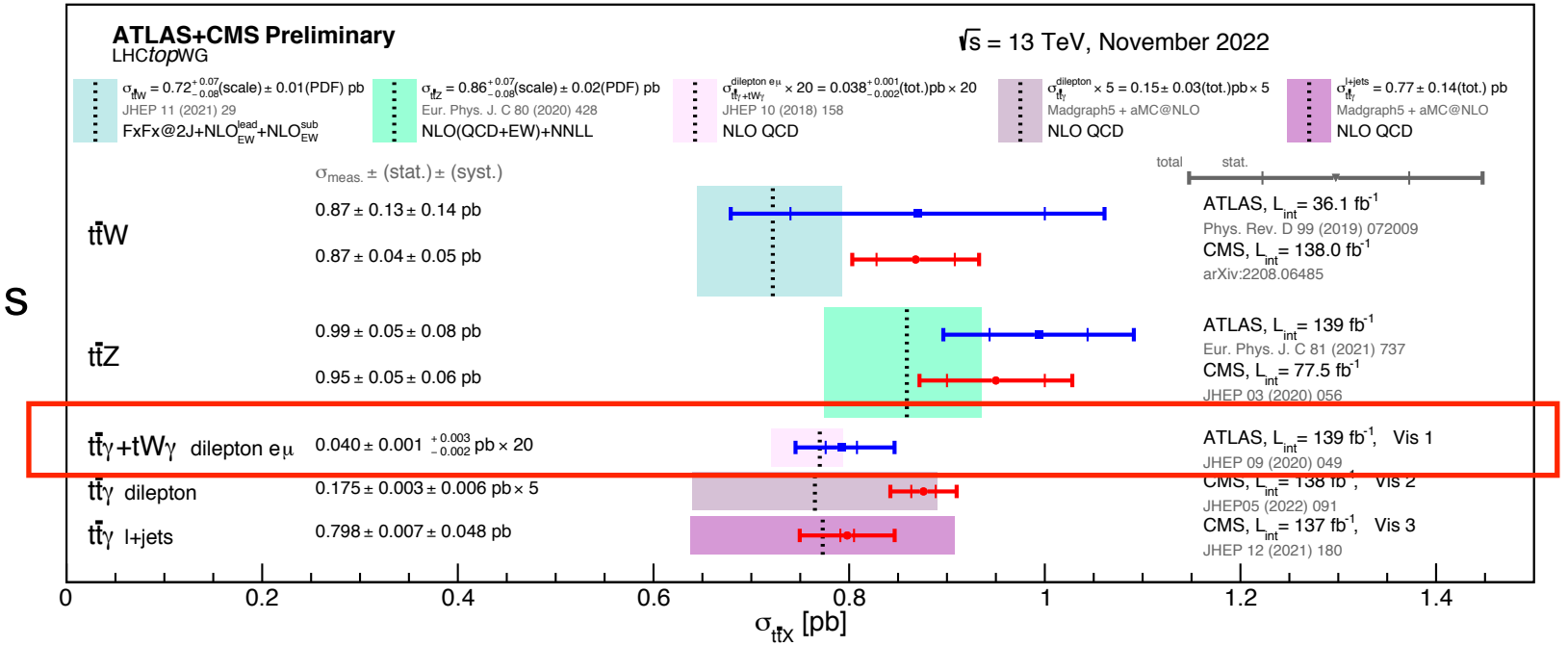
V = γ, W, Z

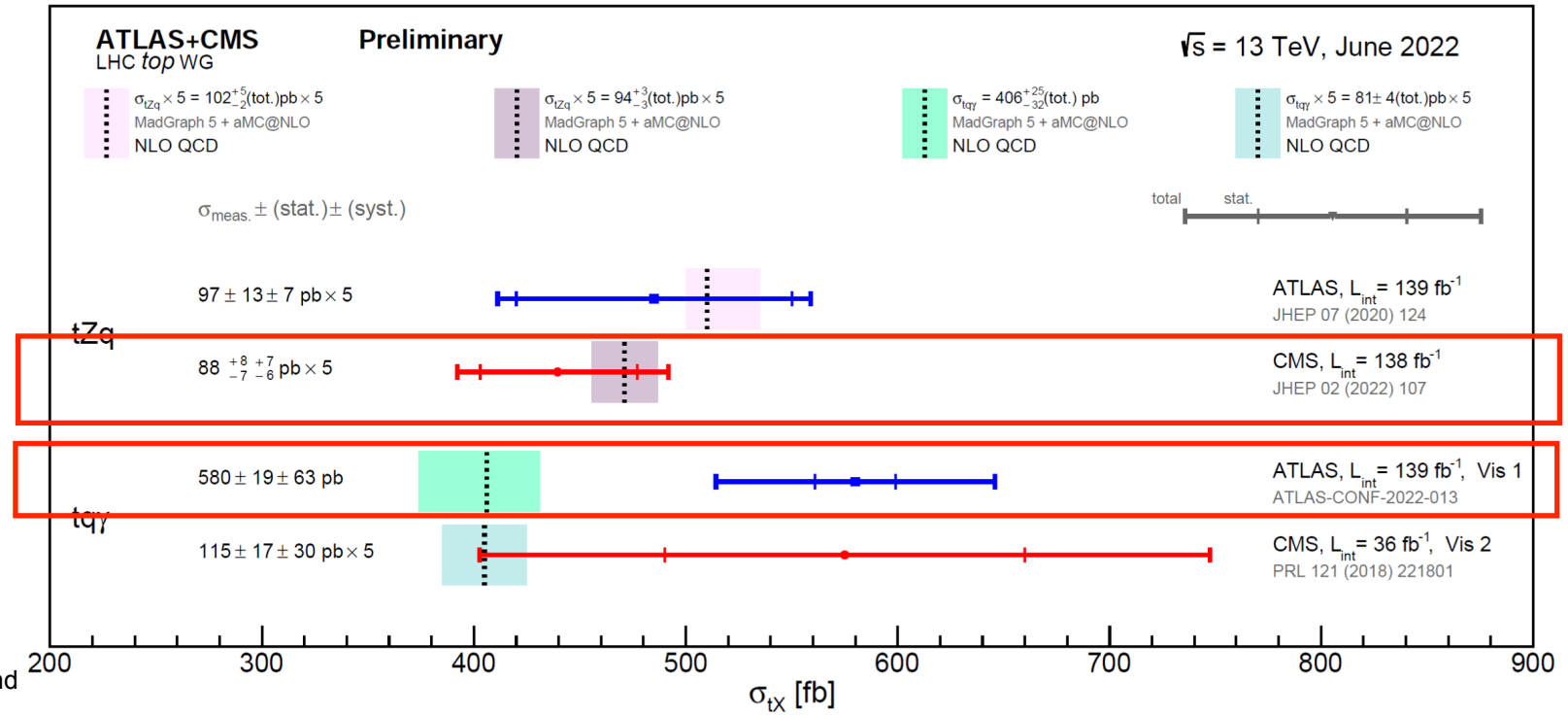
- tVq and tt̄V: similar cross sections (0.4…1 pb)





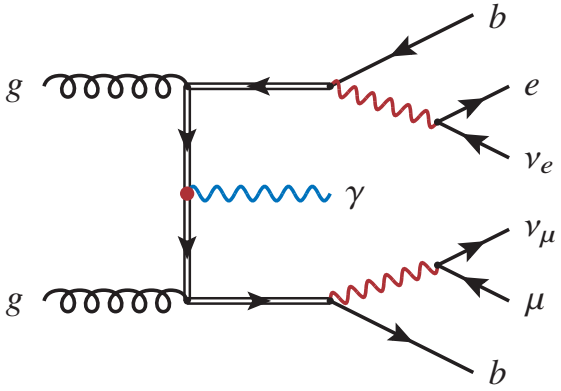
- 1st differential measurements: good understanding established





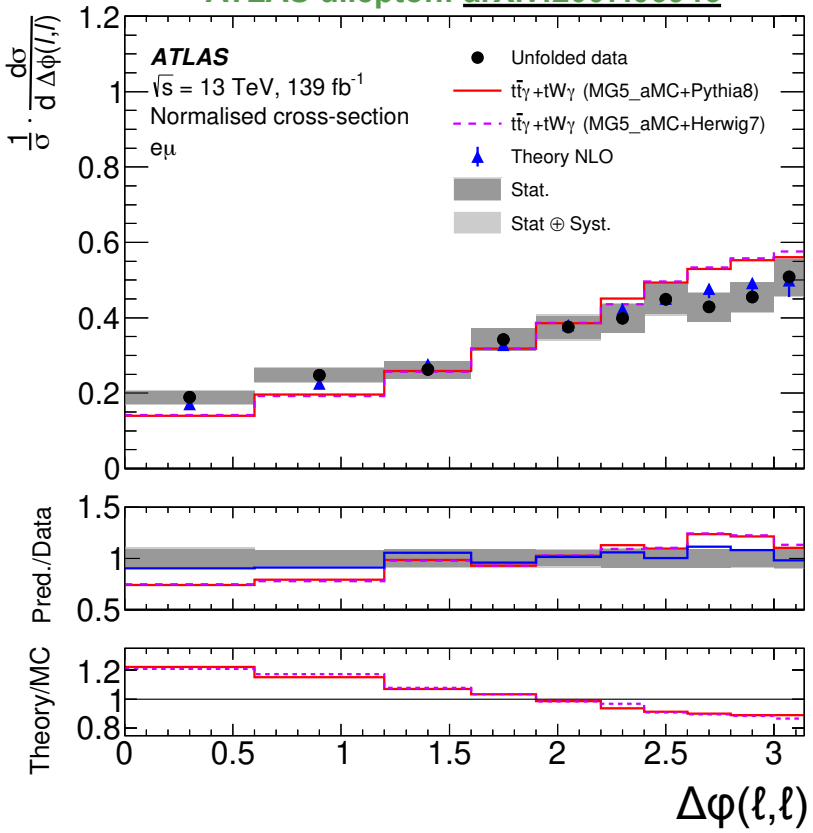
Top + γ

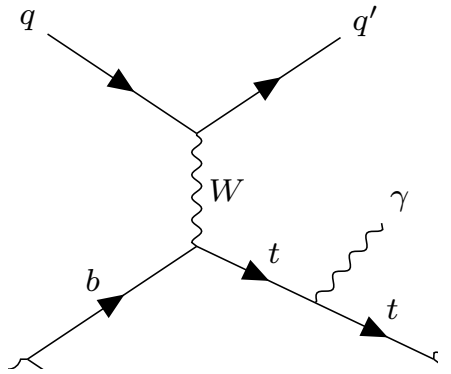
$t\bar{t}\gamma$ and tqγ



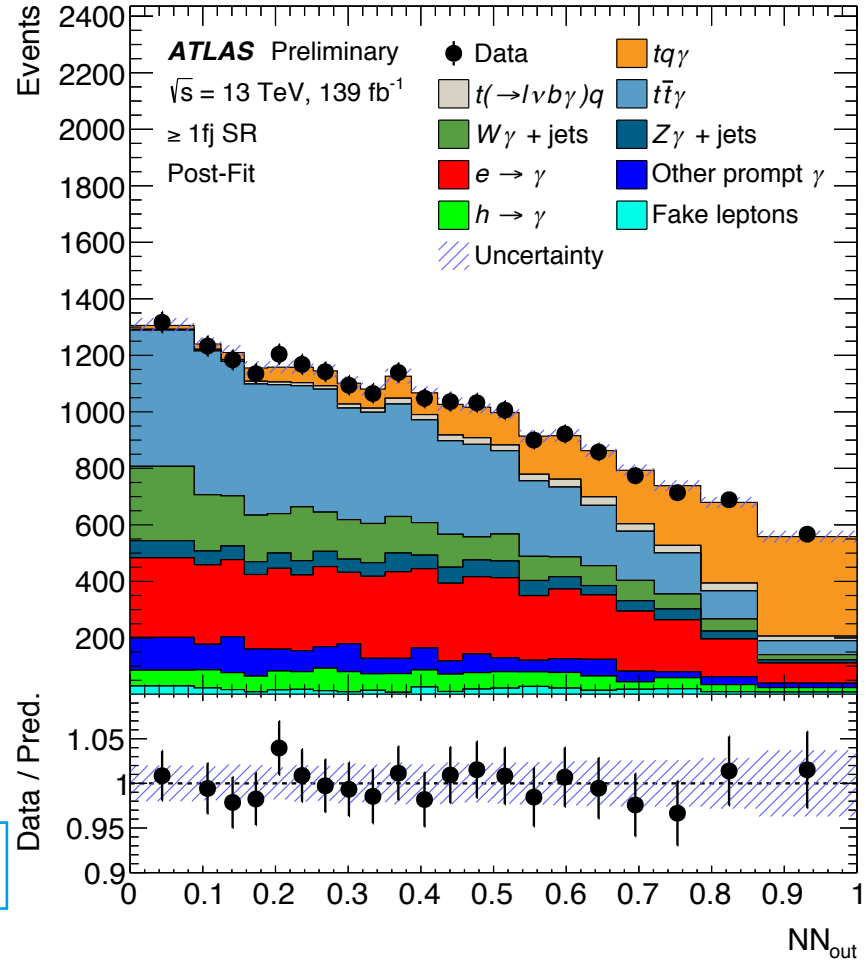
ATLAS dilepton: arXiv:2007.06946
CMS l+jets: arXiv:2107.01508
CMS dilepton: arXiv:2201.07301

ATLAS dilepton: arXiv:2007.06946





ATLAS-CONF-2022-013

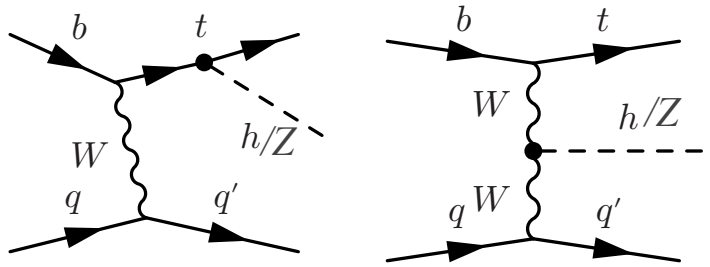


- ttγ: differential measurements show importance of NLO
  - very high precision: 4%
  - Dominant uncertainties: luminosity, background, signal modelling
- Observation of tqγ at 9.1(6.7)σ

$\sigma_{tq\gamma} \times BR = 580 \pm 19_{stat} \pm 63_{sys}$ fb

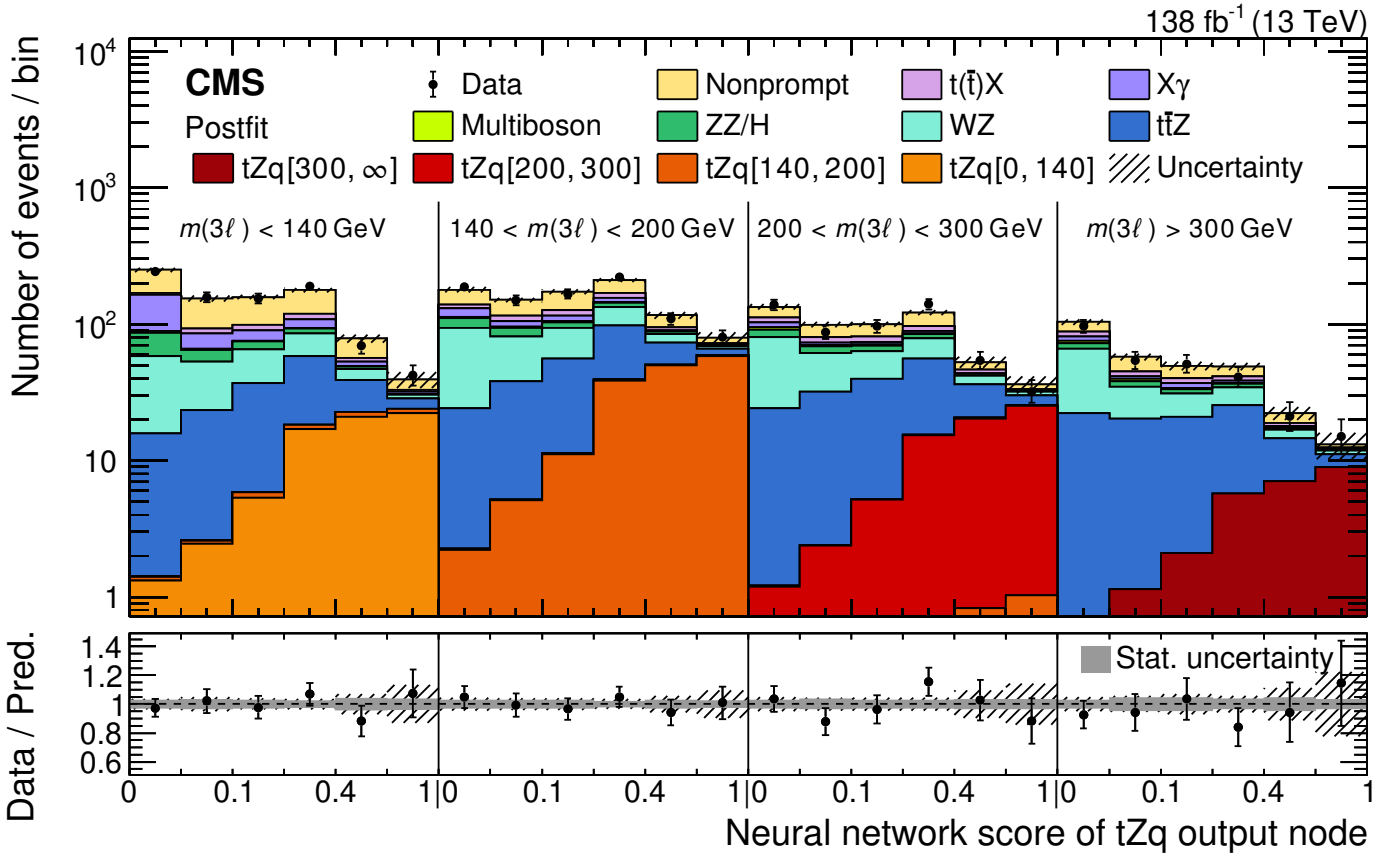
Top + Z

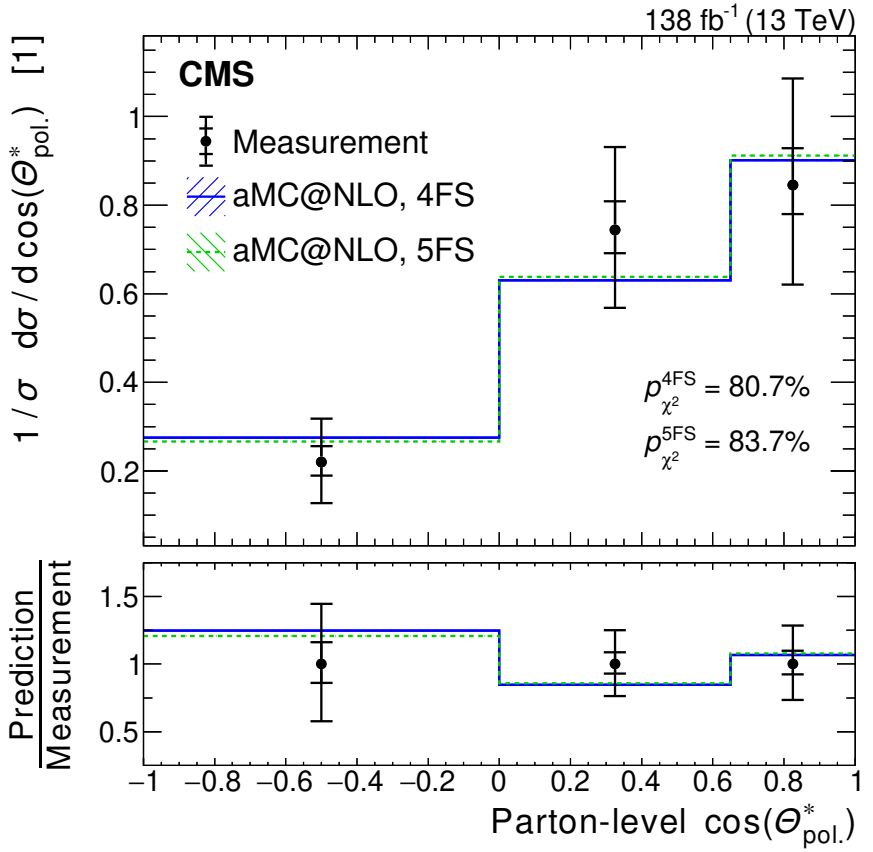
First differential measurement



arXiv:2111.02860

- Inclusive cross section: measured to ~10%
- Dominant from fake leptons and multi boson





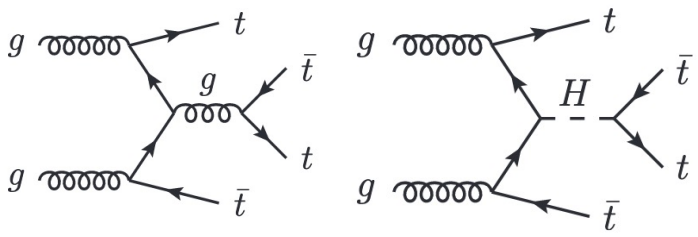
- Top quark spin polarisation from asymmetry in cosθ* distribution

$$A_\ell = 0.54 \pm 0.16\,(\text{stat}) \pm 0.06\,(\text{syst})$$

A_ℓ(SM) = 0.45

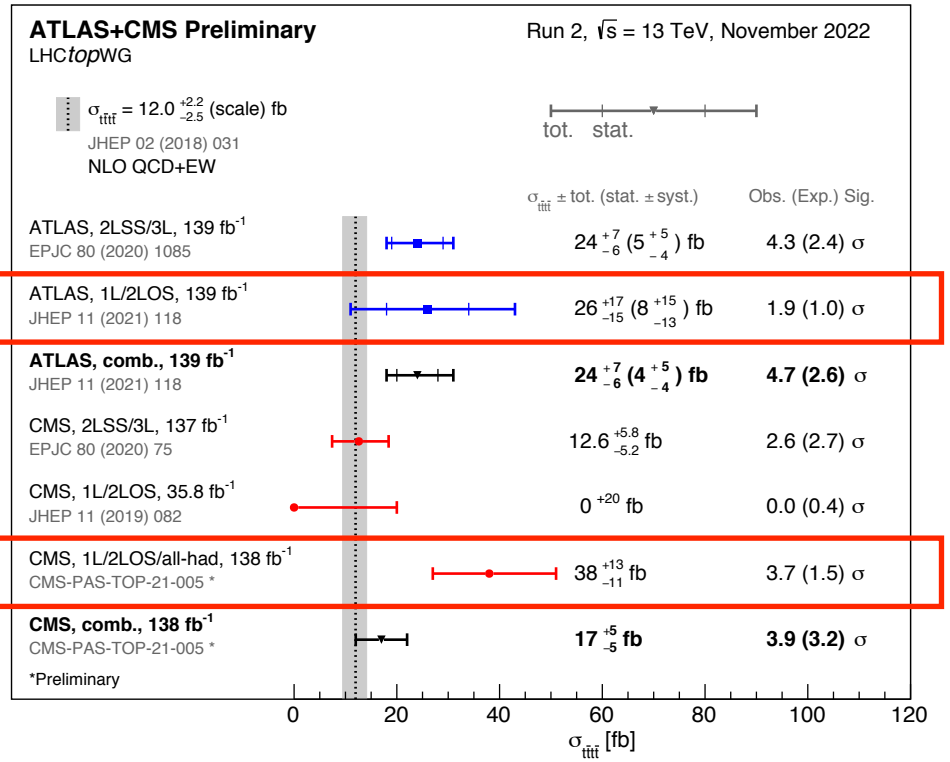
4 Tops

Evidence consolidated



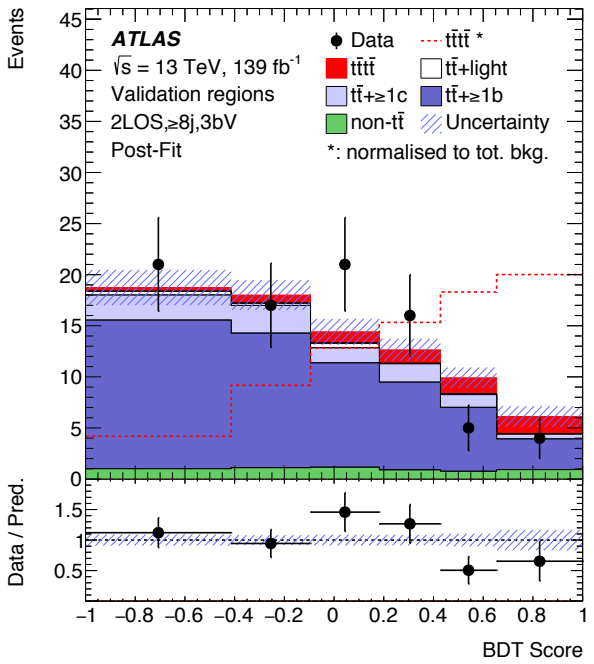
- In 2019/2020, ATLAS and CMS established evidence of 4-top production using multilepton channels

LHCTopWGSummaryPlots



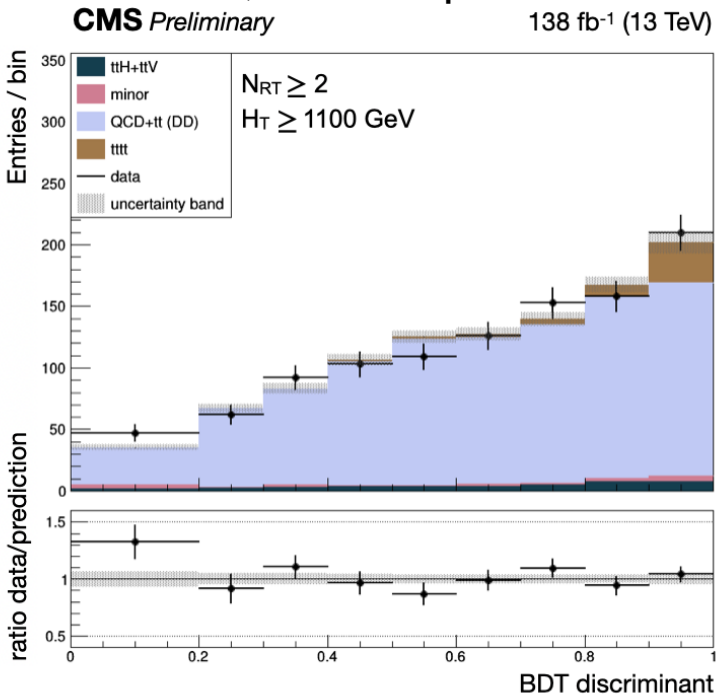
arXiv:2106.11683

1 or 2 OS leptons

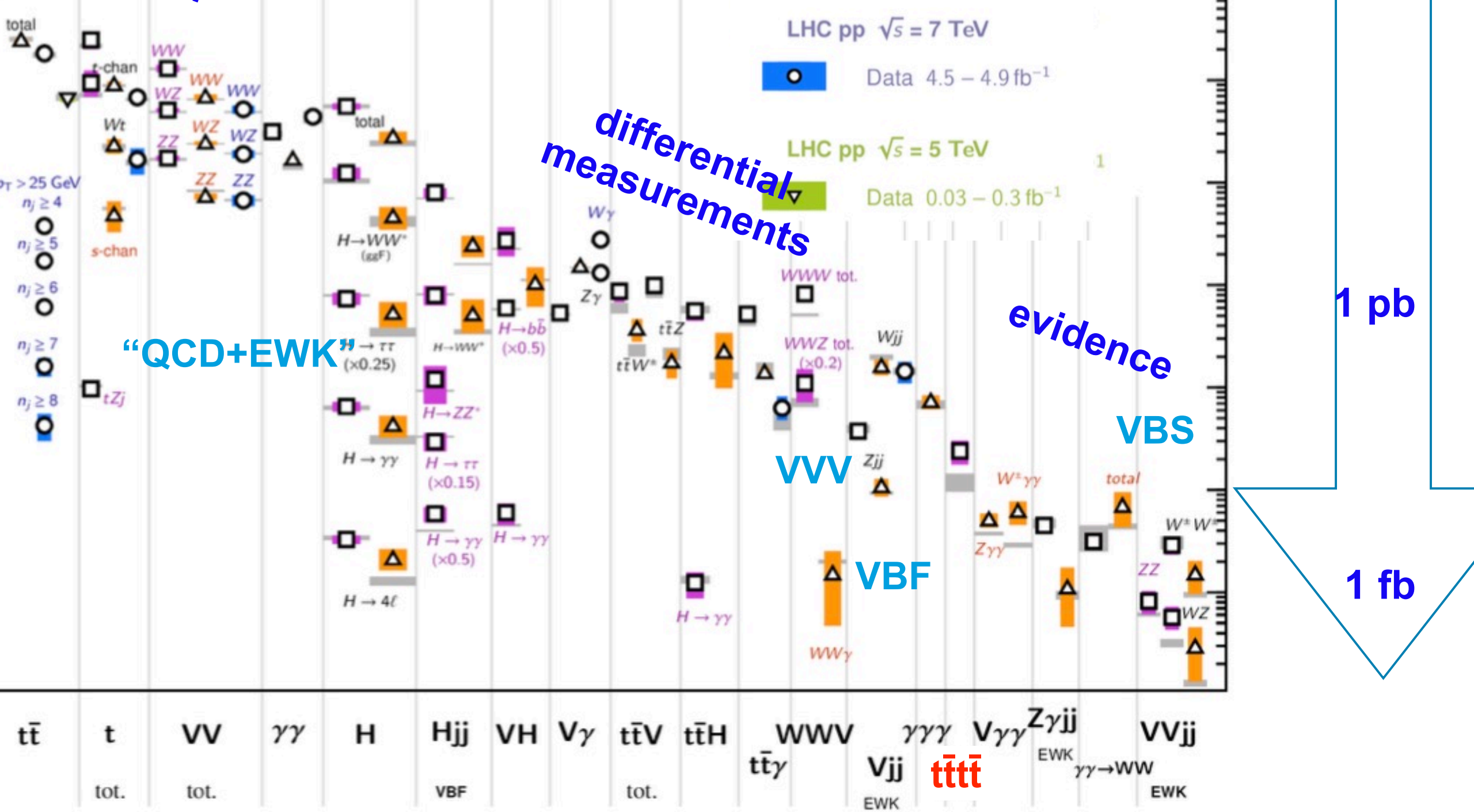


CMS-PAS-TOP-21-005

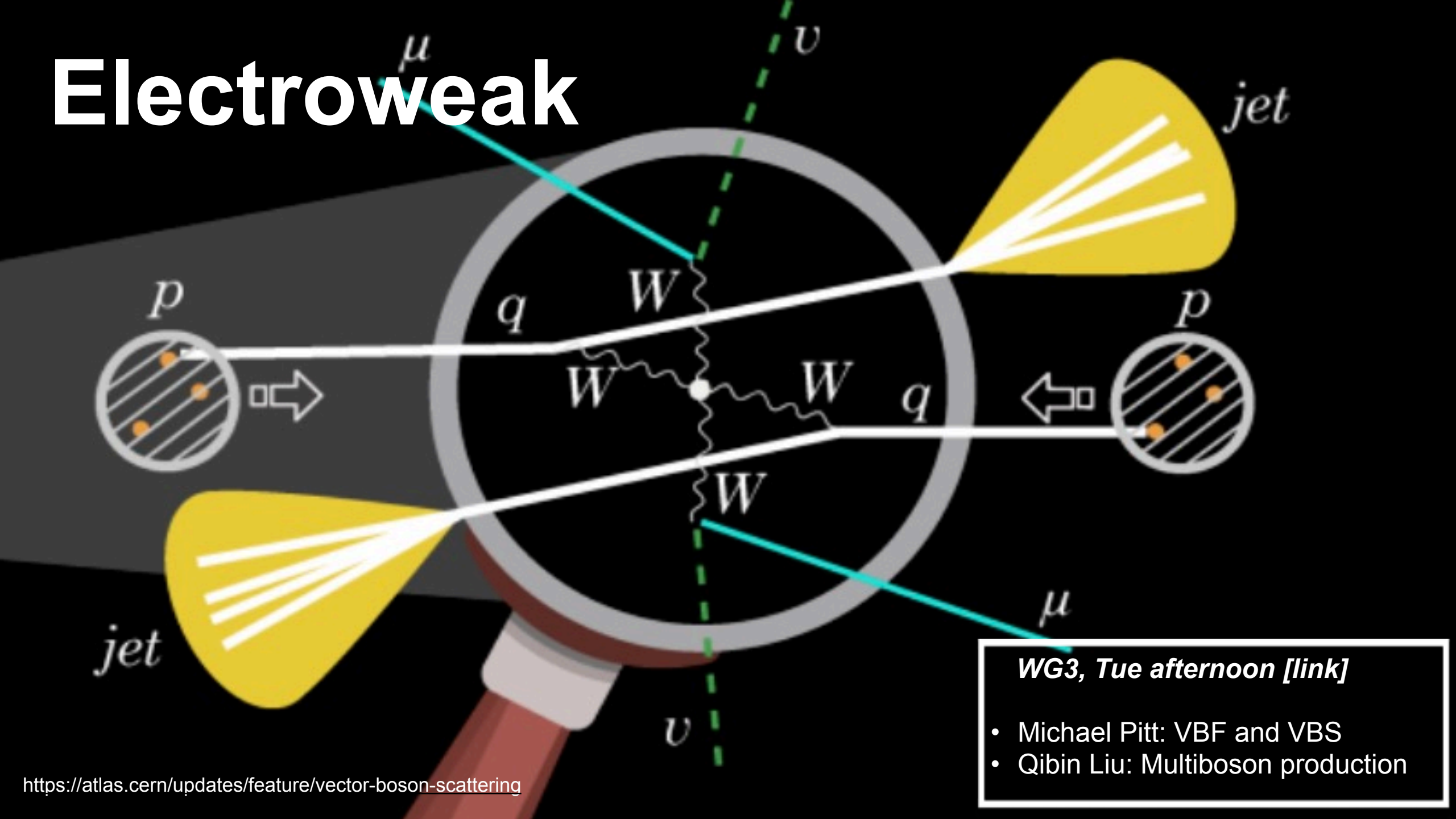
0, 1 or 2 leptons



- Predicted 4-top quark cross section: 12 ± 2.5 fb
- Measured signal strength μ:
  - ATLAS (combined): μ = 2.0 +0.8 -0.6 **4.7(2.6)σ**
  - CMS (combined): μ = 1.4 ± 0.4 **3.9(3.2)σ**


LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
"QCD+EWK"
differential measurements
evidence
VBS
VVV
VBF
1 pb
1 fb
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
WWV
γγγ
Vγγ
Zγjj
VVjj
tt̄γ
Vjj
tttt̄
tot.
VBF
EWK
γγ→WW

Electroweak



WG3, Tue afternoon [link]

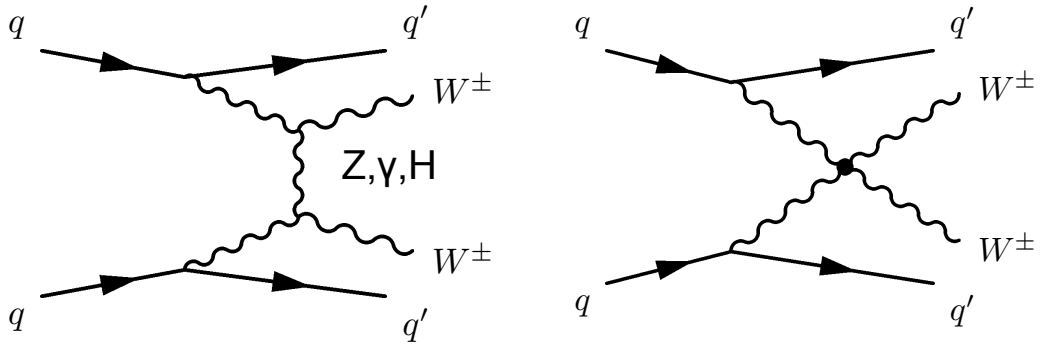
- Michael Pitt: VBF and VBS
- Qibin Liu: Multiboson production

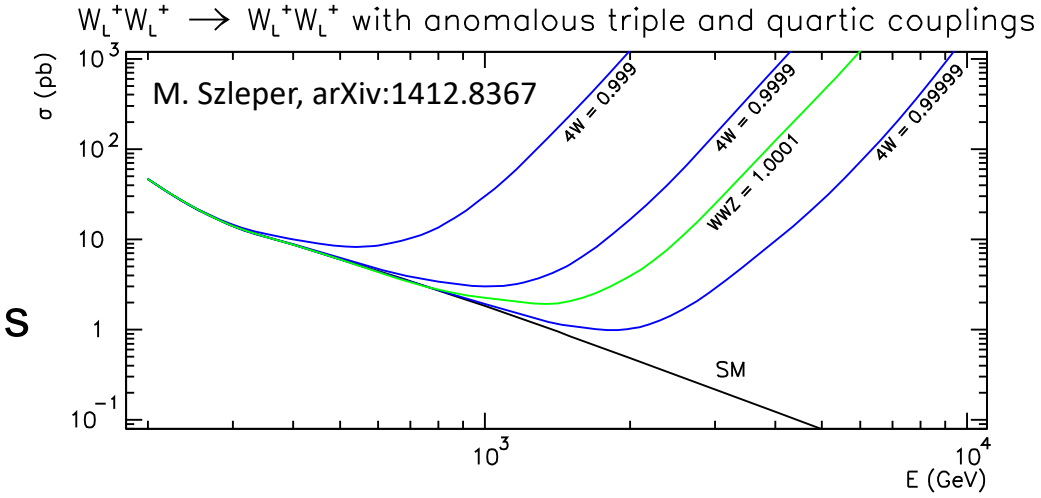
https://atlas.cern/updates/feature/vector-boson-scattering

Vector Boson Scattering (VBS)

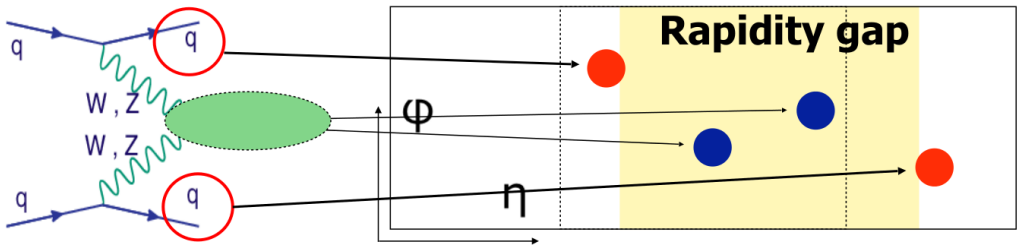
Same-sign WW + 2 jets: the lowest hanging fruit

- Higgs boson expected to unitarize $V_LV_L \rightarrow V_LV_L$ amplitude
  Higgs boson cancels cross section divergence exactly.
- Probing the Higgs mechanism without looking at the Higgs

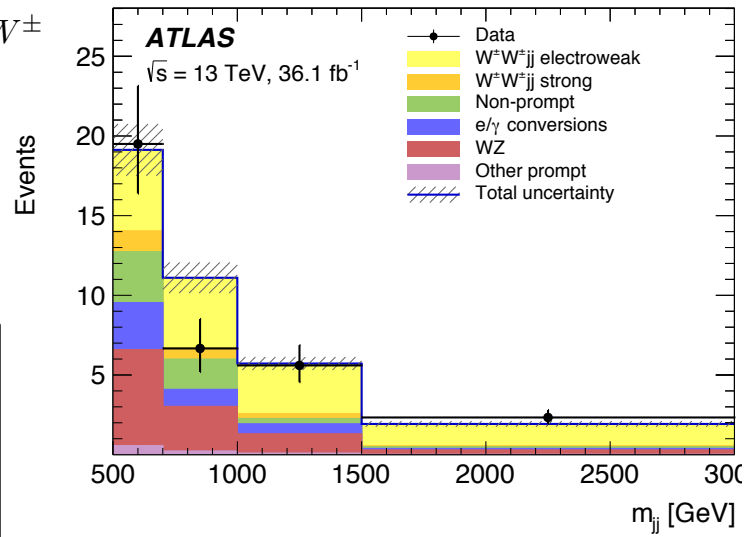




- Experimentally:
  - Signature: 2 jets, large rapidity gap, high m_{jj}

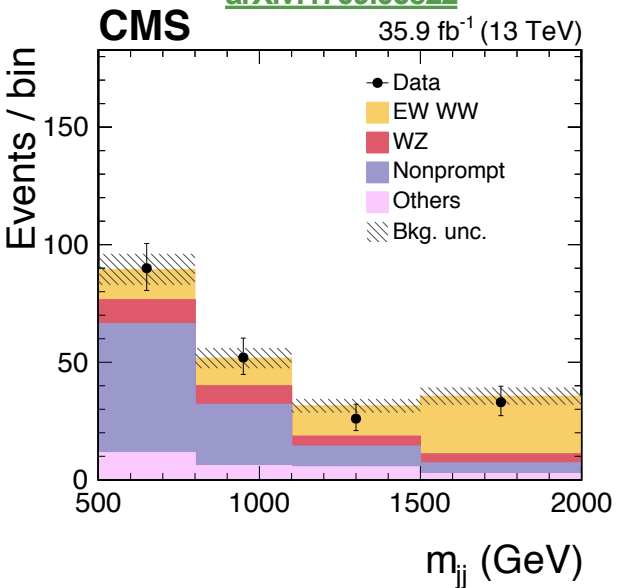


arXiv:1906.03203



6.5(4.4)σ obs(exp)

arXiv:1709.05822

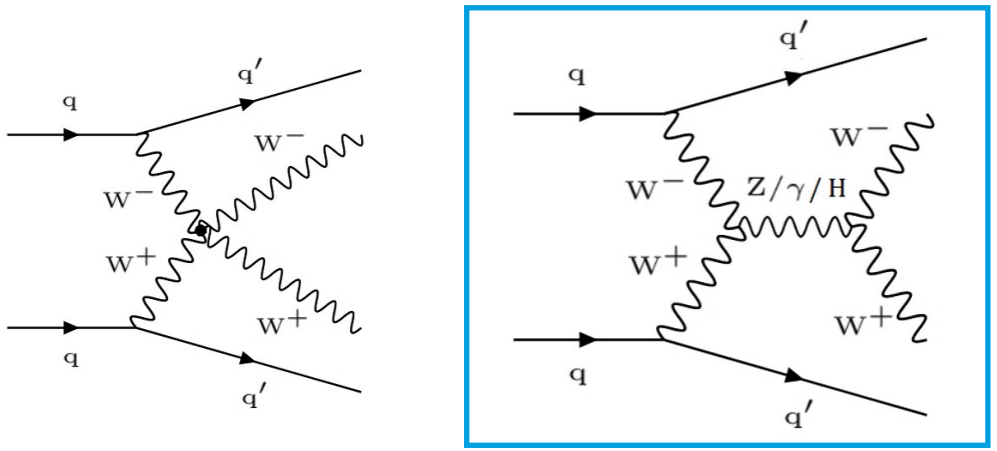


5.5(5.7)σ obs(exp)

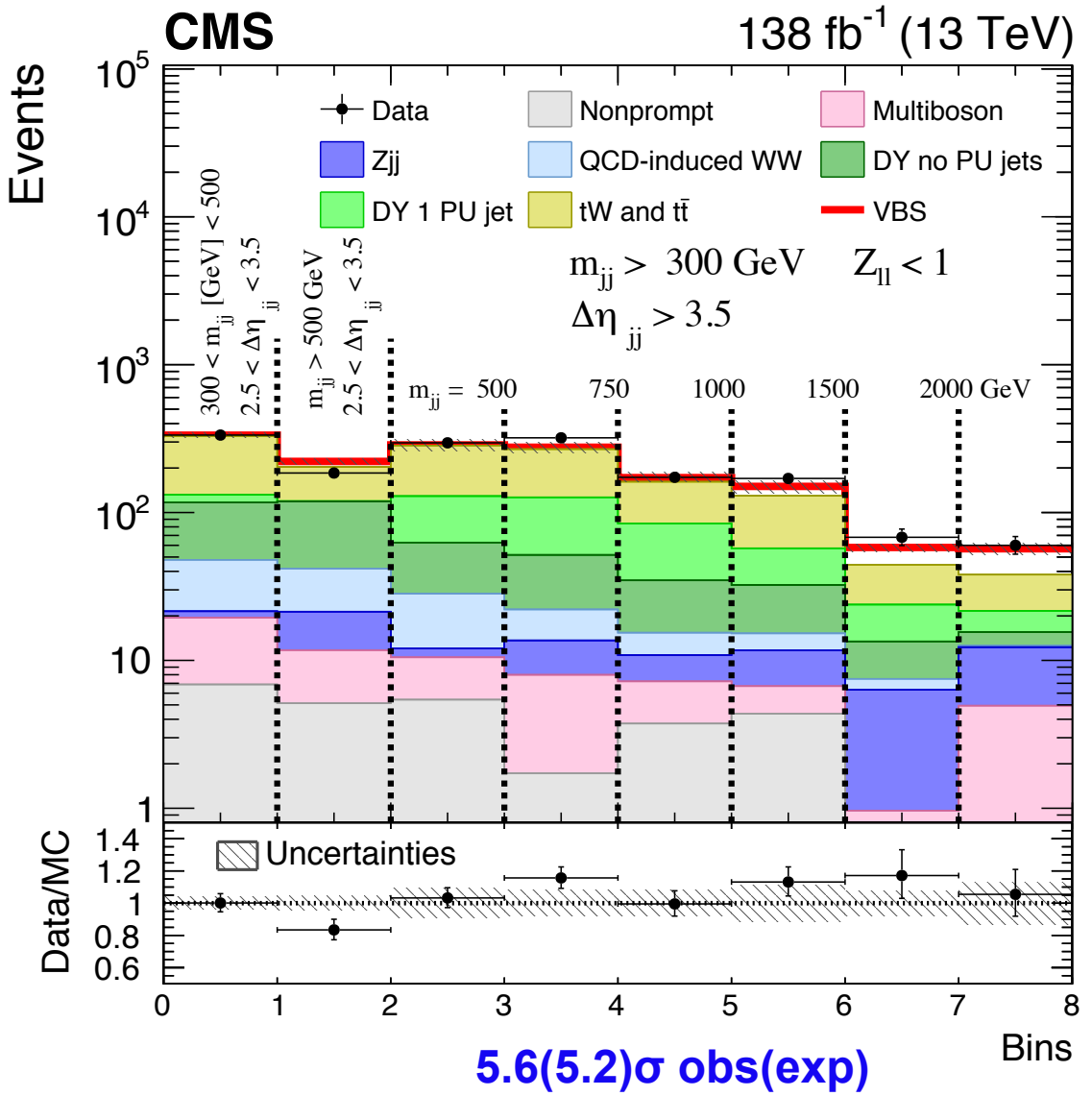
arXiv:2205.05711

Vector Boson Scattering (VBS)

Opposite-sign $W^{\pm}W^{\mp}$ + 2 jets



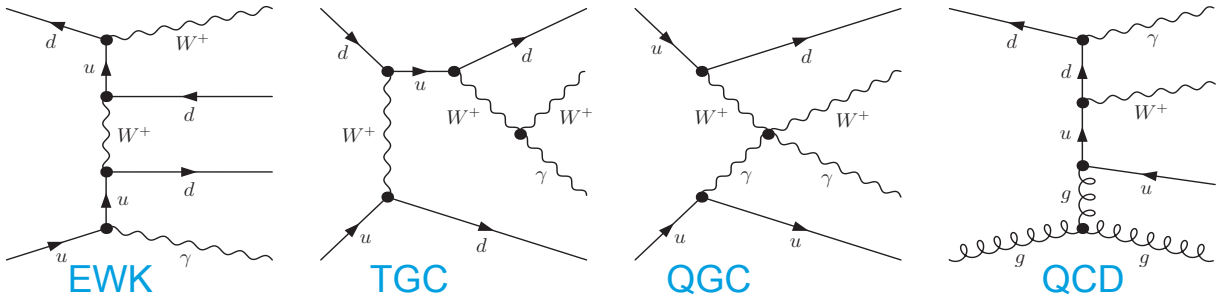
$W^{\pm}W^{\pm}$: s-channel diagram



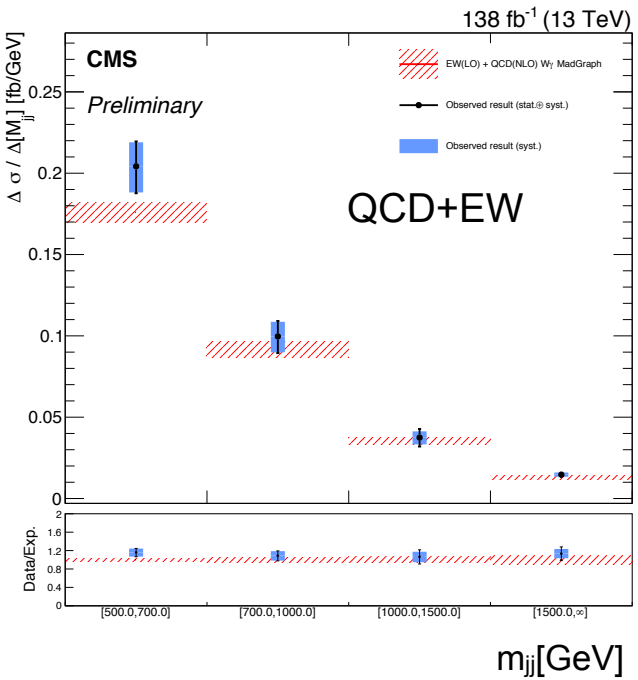
5.6(5.2)σ obs(exp)

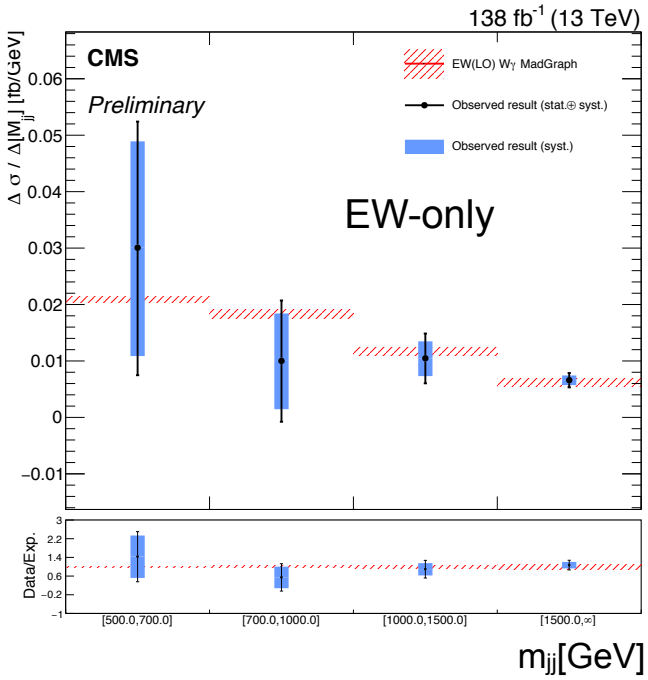
- Includes s-channel Higgs contribution
- Recent calculation at NLO A.Denner et al
- Experimentally, large bg from top and Drell-Yan
- Measured cross section: **10.2 ± 2.0 fb**
- Predicted: 9.1 ± 0.6 fb

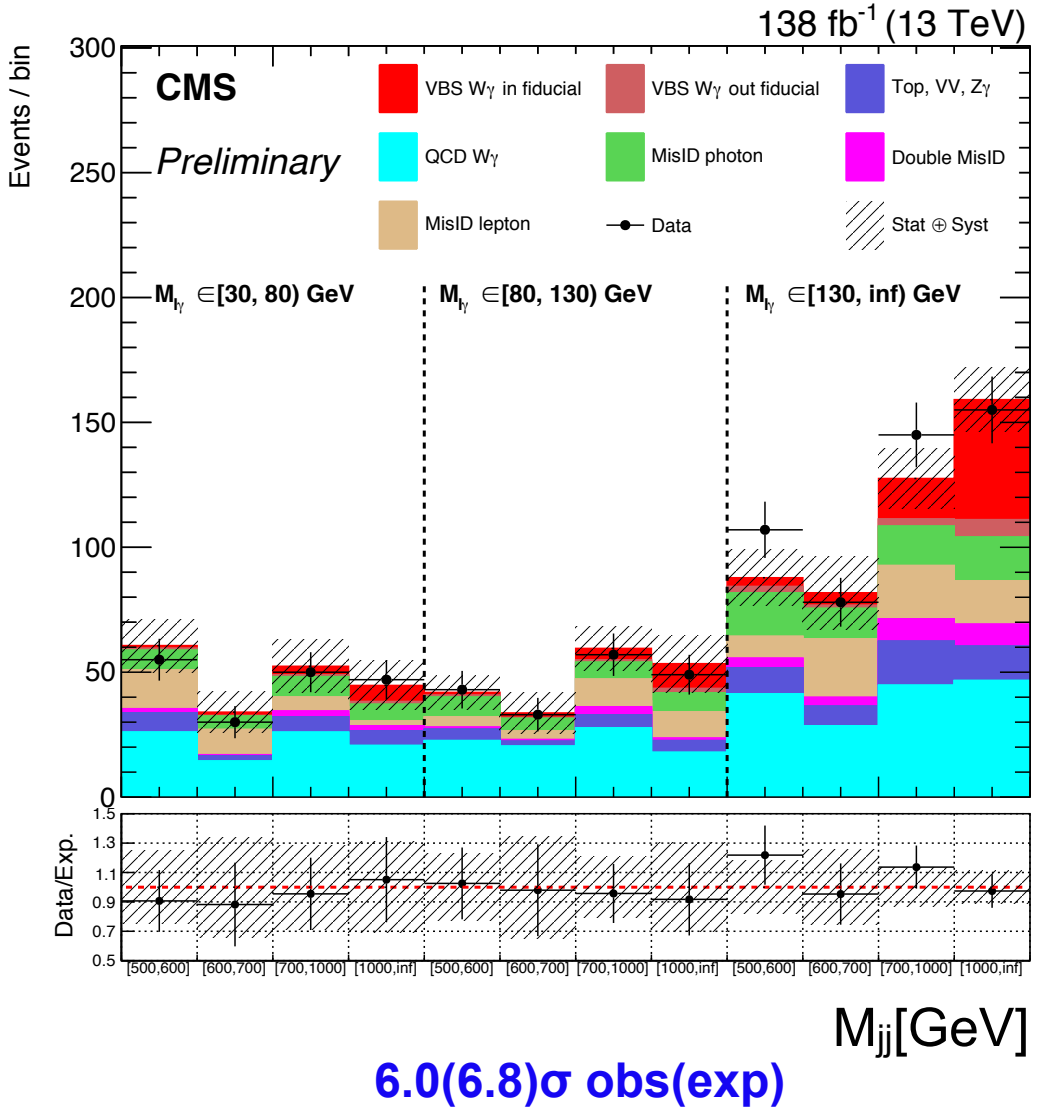
Wγ + 2 Jets



- Measured EW cross section: 19 ± 4 fb
- First differential cross sections





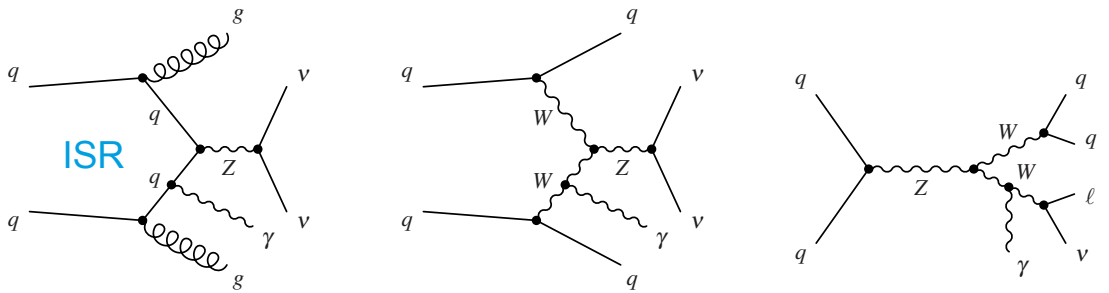


6.0(6.8)σ obs(exp)

arXiv:2106.11082 arXiv:2109.00925 ATLAS-CONF-2021-038

Zγ Production

Differential measurements in Z→ℓℓ and first observation in Z→νν + 2 jets

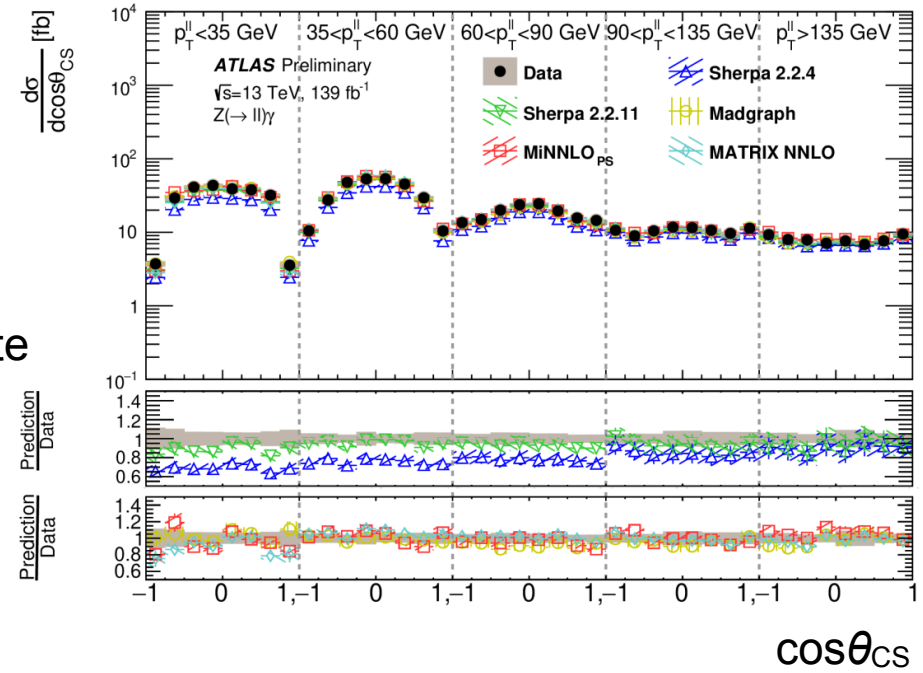


(a) Strong diagram (b) VBF electroweak diagram (c) Triboson diagram

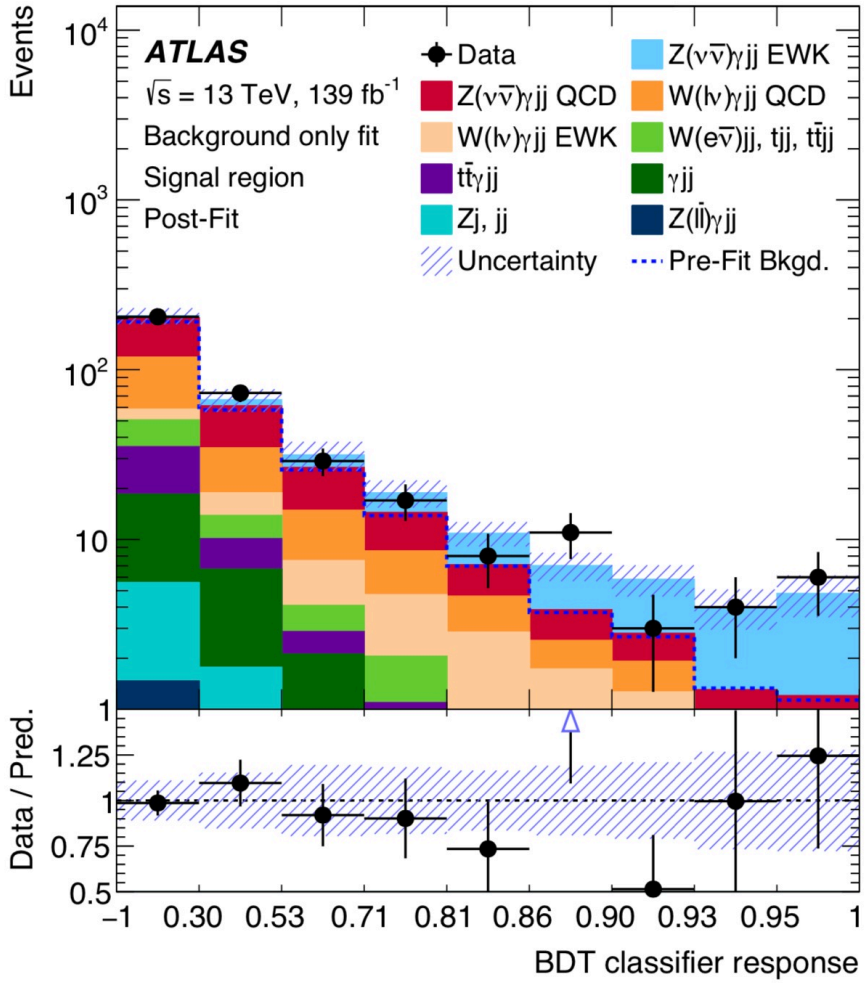
- Differential Zγ, ISR-enriched
  - many distributions measured (1D and 2D)
  - Test of QCD radiation in color singlet final state
  - Polarisation

Good agreement by theory up to NNLO+PS

ATLAS-CONF-2022-047



arXiv:2208.12741

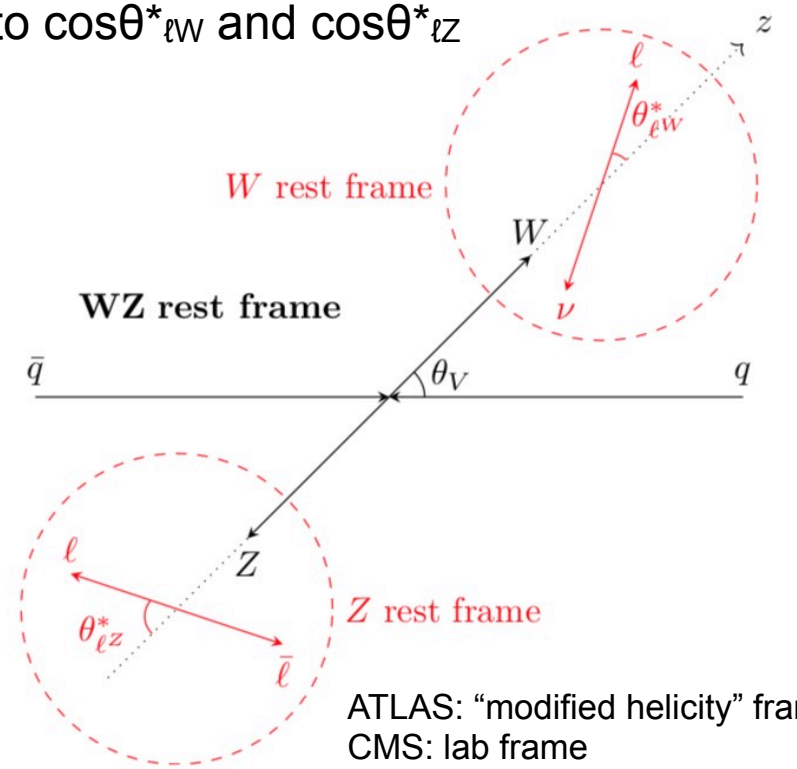


Z(→νν)γ significance: 6.3(6.6)σ

WZ Polarization

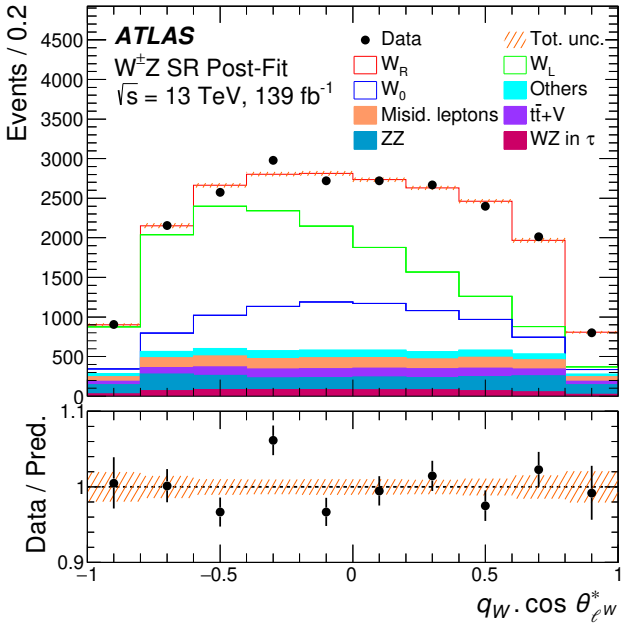
Single-boson polarization

- $V_0V_0 \rightarrow V_0V_0$ beyond reach for now
- Recent theory calculations, NLO QCD A.Denner, G.Pelliccioli and NLO QCD+EW D. Ninh Le, J.Baglio
- Helicity fractions extracted from template fits to $\cos\theta^*_{\ell W}$ and $\cos\theta^*_{\ell Z}$

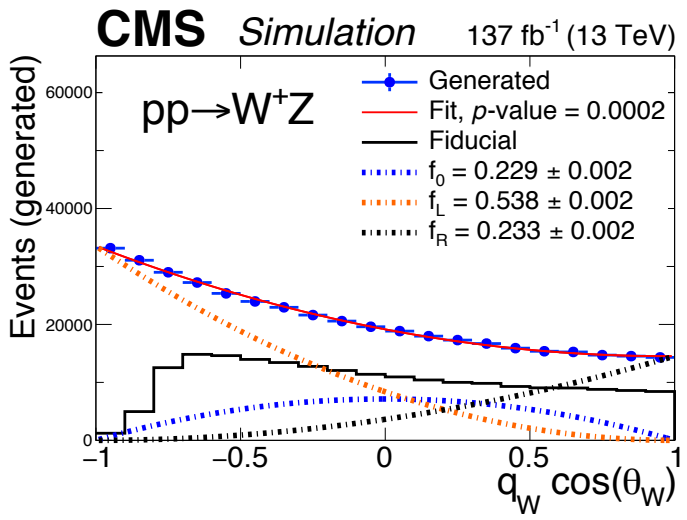


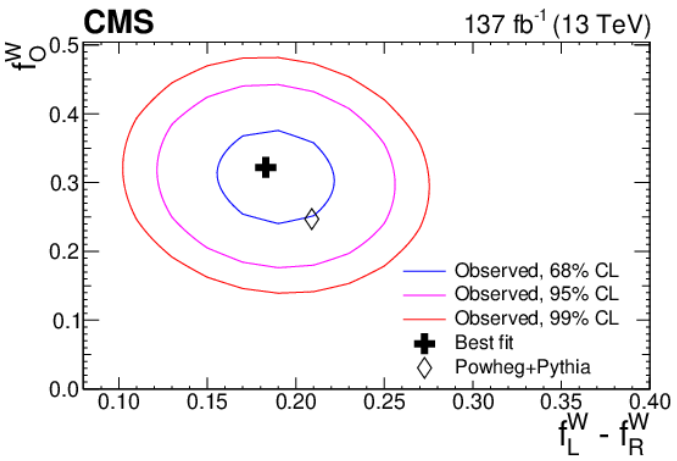
ATLAS: "modified helicity" frame
CMS: lab frame

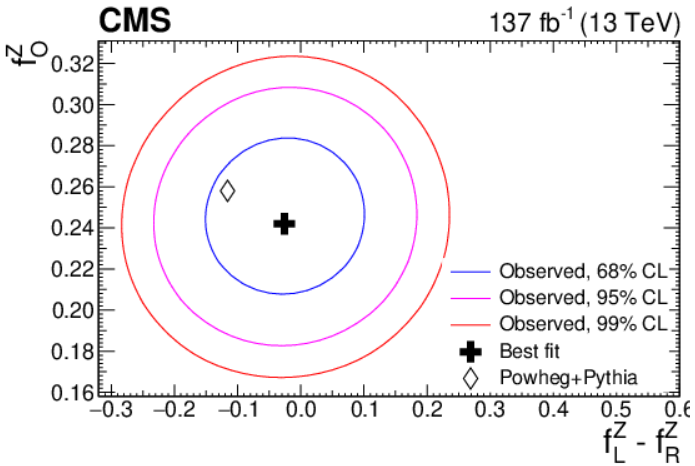
arXiv:2211.09435



arXiv: 2110.11231







f_0 significance over transverse-only hypothesis:

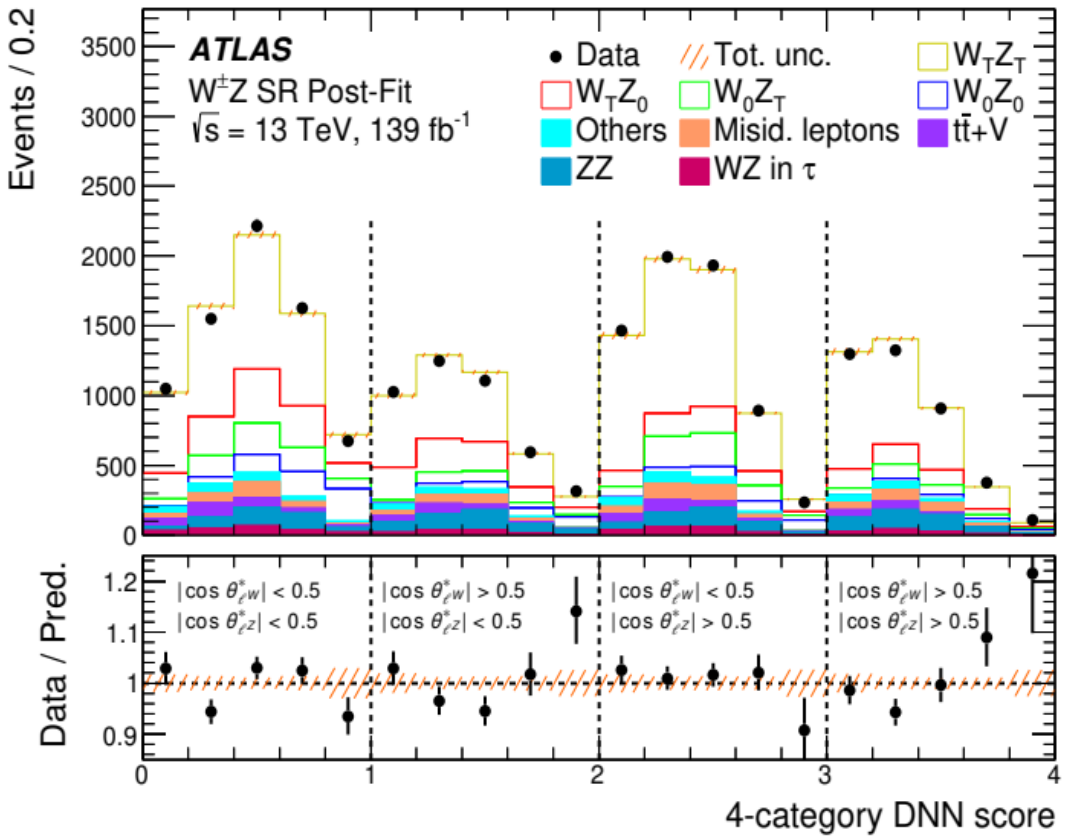
W: 5.6(4.3)σ **Z: ≫5σ**

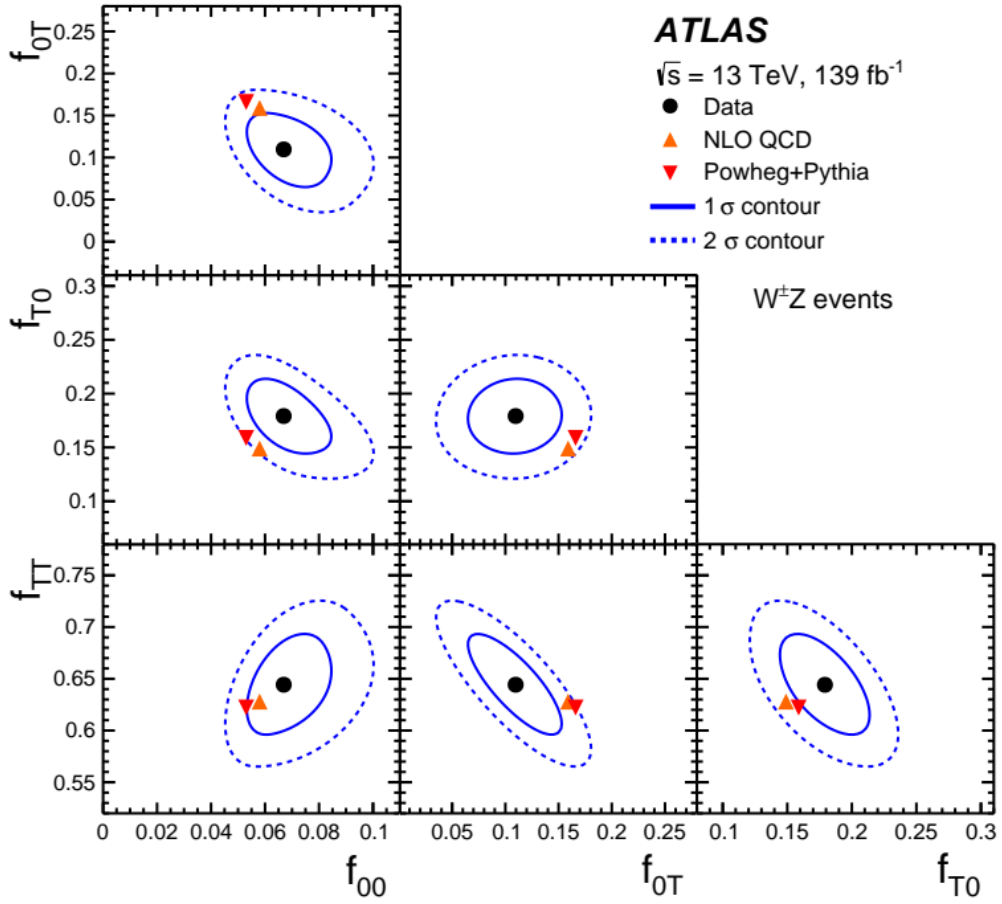
arXiv:2211.09435

WZ Polarization

Joint polarization measurement

- Measure polarisation of both bosons simultaneously.
- DNN score to maximize sensitivity



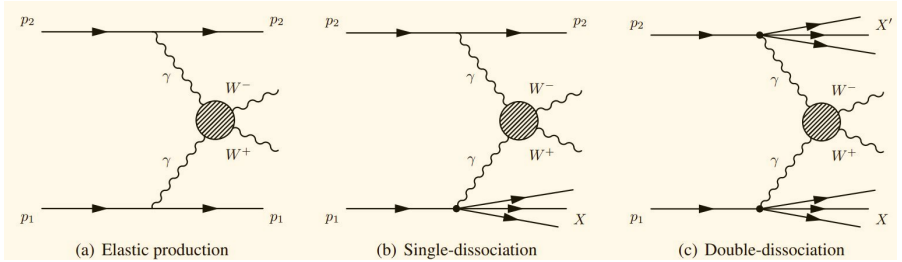


- Four linear combinations of spin density ME: f_{TT}, f_{T0}, f_{0T} and f_{00}
  - Significance on f_{00} **7.1σ**
  - Significance on f_{TT} and f_{T0} **>5σ**

Exclusive Production γγ→VV

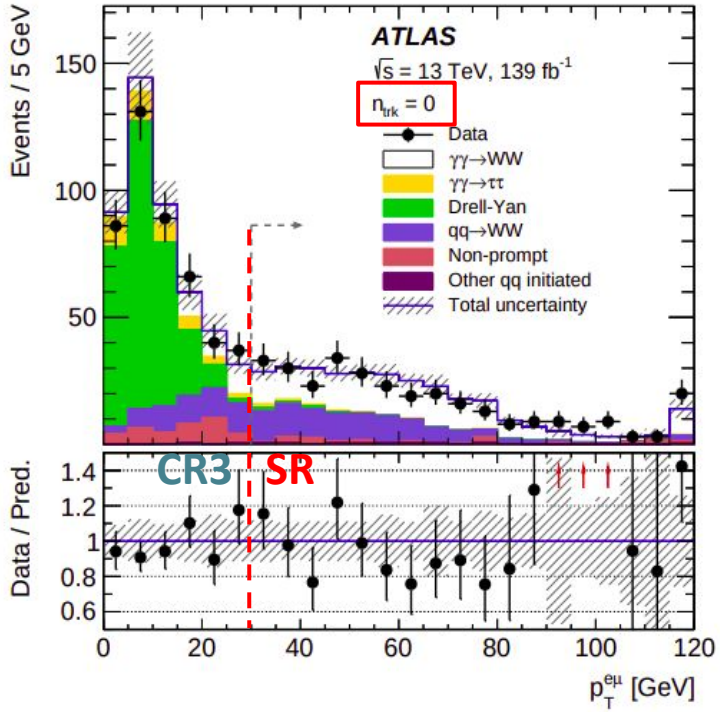
Photon-photon fusion at the LHC

arXiv:2010.04019



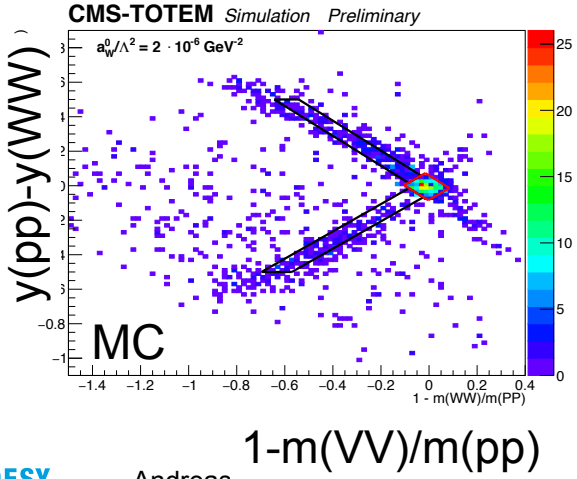
- 1st observation WW→eμ(νν)
  - Elastic + p-dissociative
  - Main signal requirement:
    no additional tracks near eμ vertex
  - Main background: qq→WW

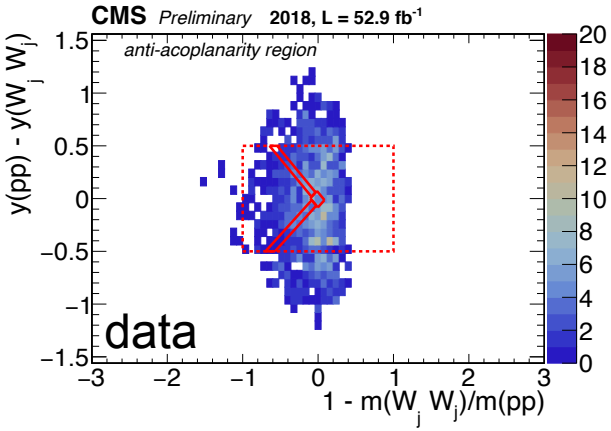
$\sigma_{fid} = 3.13 \pm 0.31 \pm 0.28$ fb

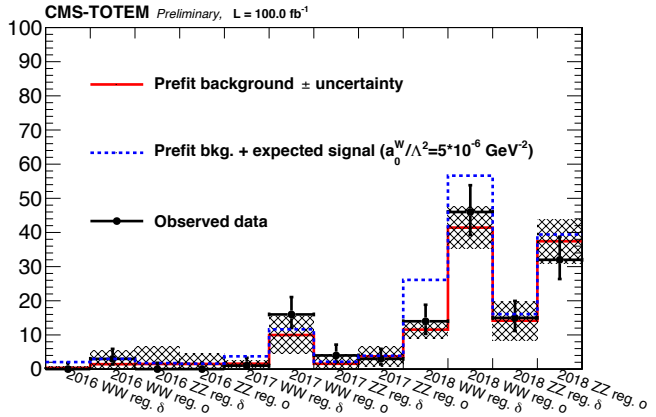


- Elastic VV→jj (boosted) using Proton Spectrometer (PPS)
  - Main background: QCD multijet pileup with protons

CMS-SMP-21-014





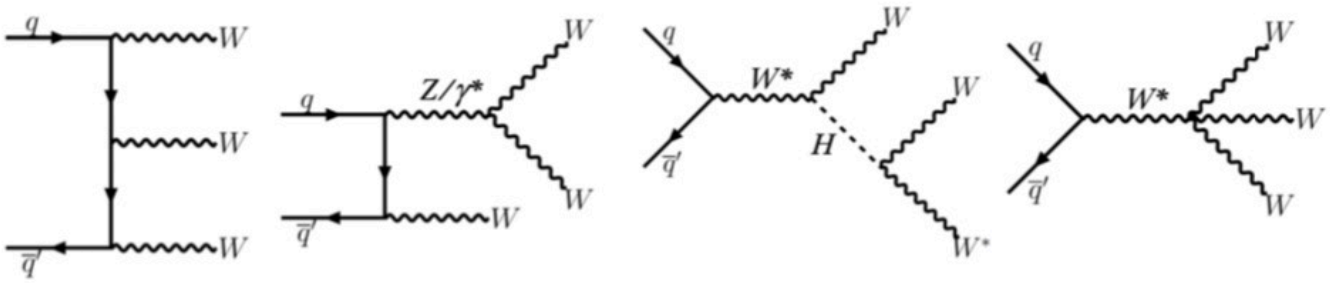


Upper limits @95CL
on σ_{fid}(pp→pVVp)

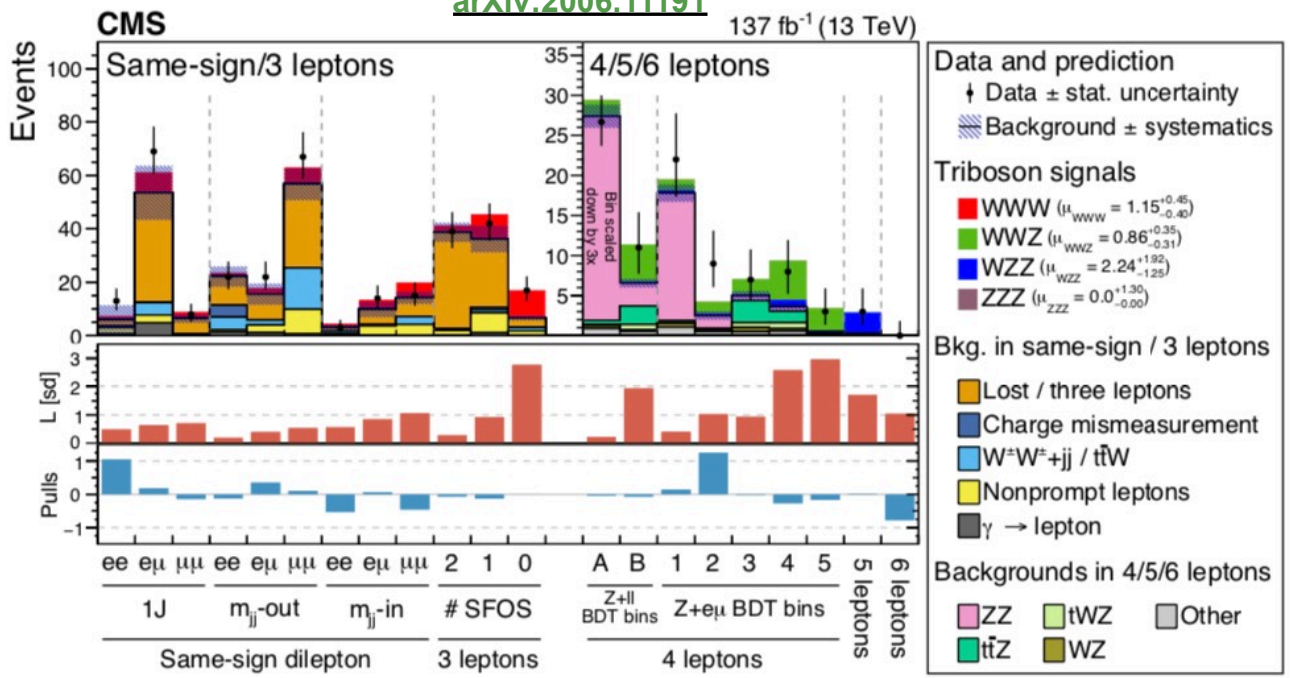
WW: < 67 fb
ZZ: < 43 fb

Triple Boson Production

Quartic Gauge Coupling

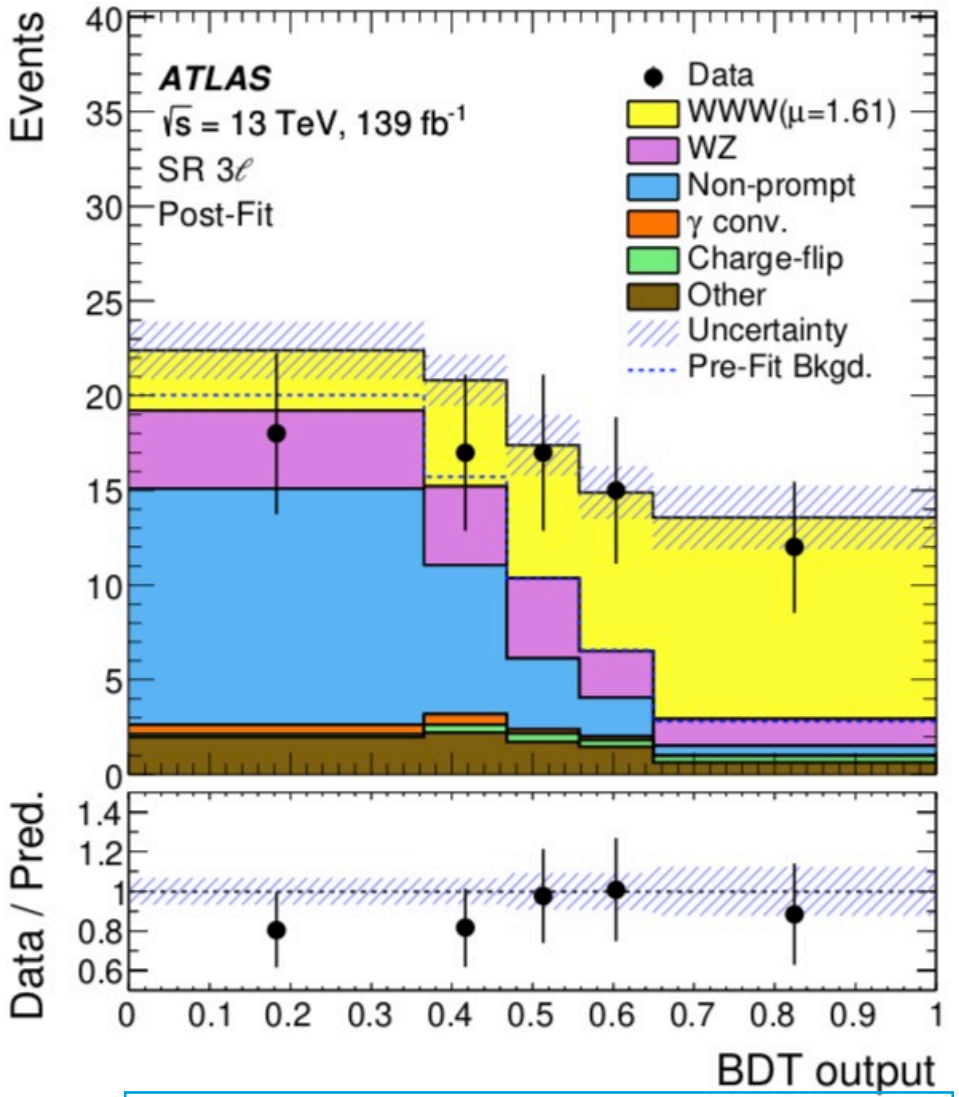


arXiv:2006.11191



5.7(5.9)σ

arXiv:2201.13045

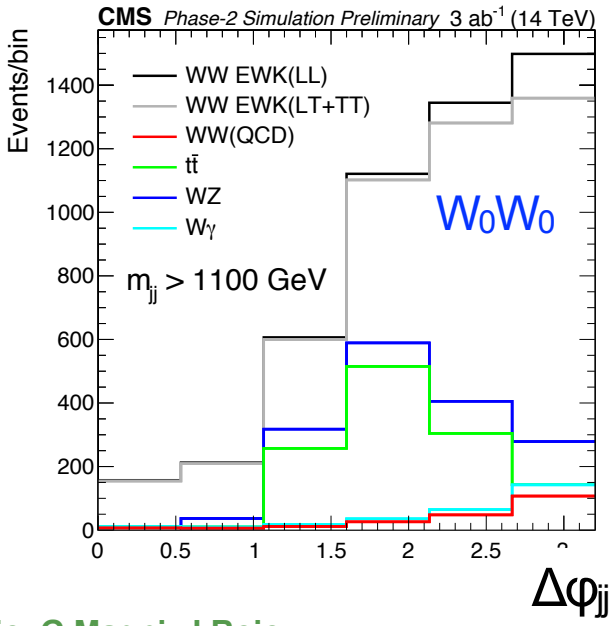


Inclusive WWW cross section:
820 ± 100 (stat.) ± 80 (syst.) fb

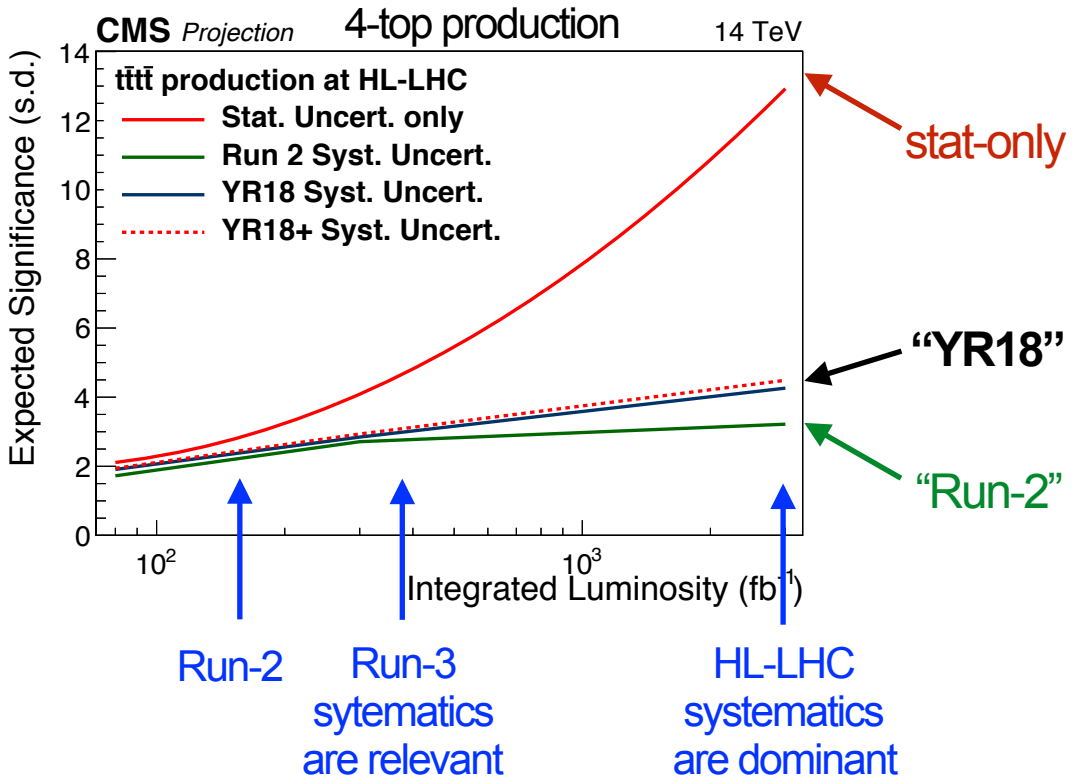
Outlook: Run3 and HL-LHC

- We are ahead of recent projections for Run-3 and HL-LHC
- Systematic uncertainties will be limiting factor for more and more measurements
- V_0V_0 remains hard, but still room for 2-3 orders in SMEFT coefficients

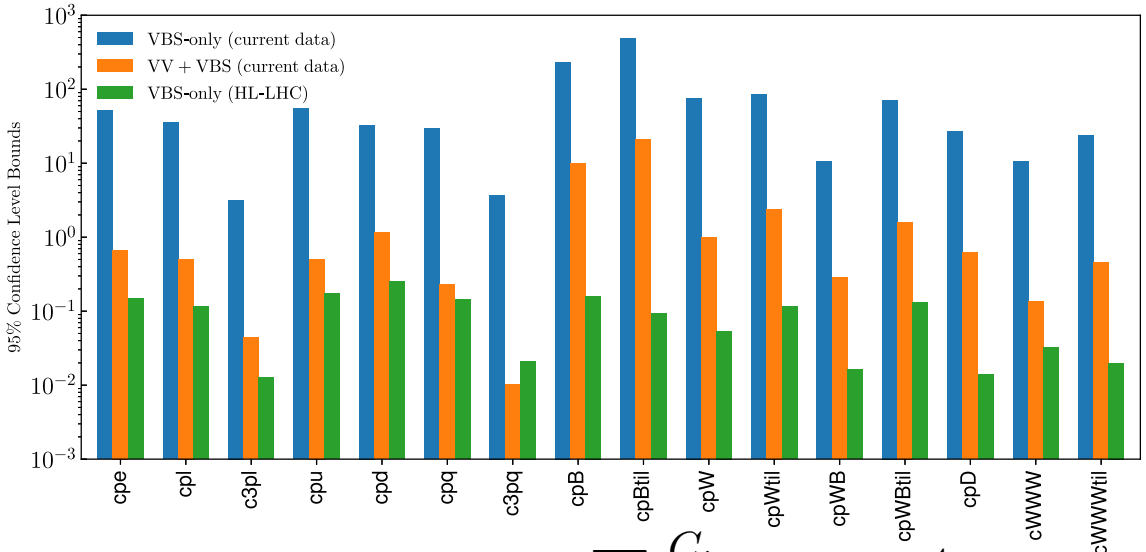
CMS-FTR-18-005



CMS-FTR-18-031



J.J.Ethier, R.Gomez-Ambrosio, G.Magni, J.Rojo



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-4}).$$

Summary

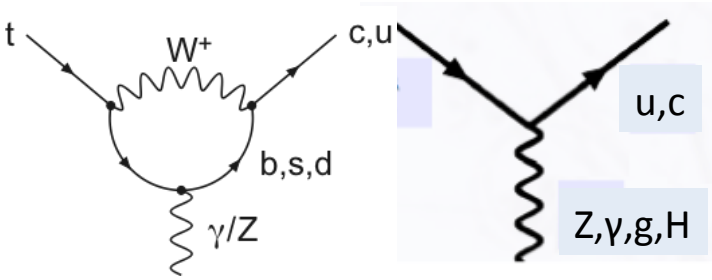
- Top quarks
  - Ever increasing precision: multidifferential cross sections, mass and properties
  - **First observations and differential measurements for t(t)X**
  - Top as a tool: FCNC, flavour-violation, …
- Electroweak multiboson production
  - Unpolarized VBS and VVV established in many channels
  - **Not-so-low-hanging fruit being harvested in VBS**
  - First polarisation results, for inclusive VV
- Run-3 and beyond
  - First results coming out
  - More data, better detectors, further improved analyses
  - Continued interplay between experiment and theory
  - Push for discovery through precision

Backup

Flavour Violations

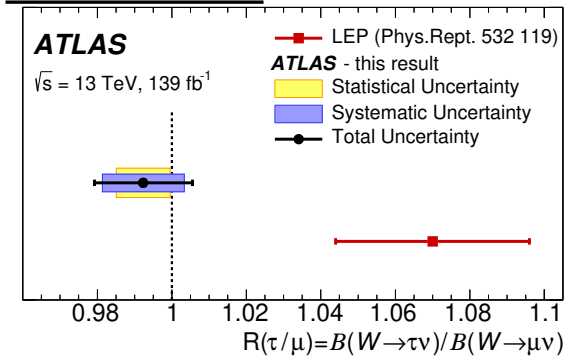
Lepton Flavour

Flavour Changing Neutral Currents

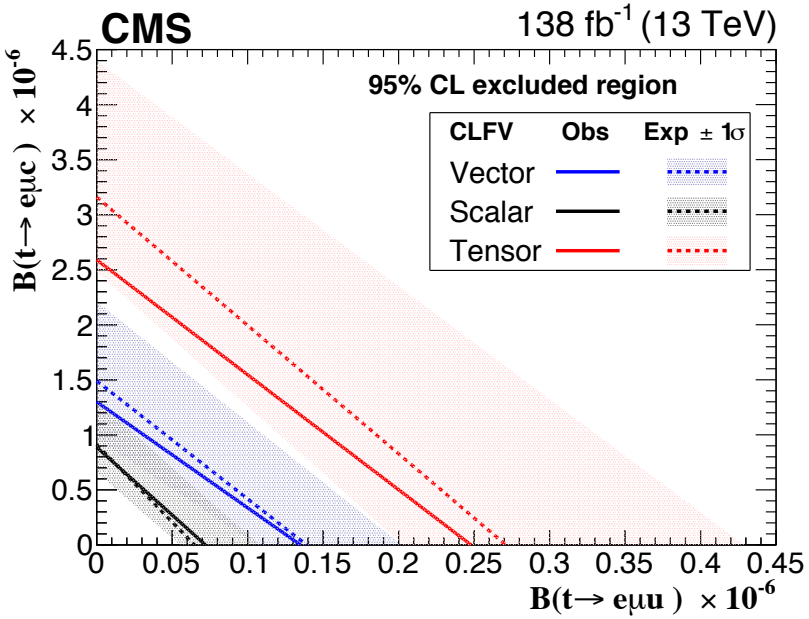


CMS: arXiv:2111.02219: tH(H→γγ)
CMS: arXiv:2112.09734: tH(H→bb)
ATLAS: arXiv:2208.11415: tH(H→ττ)
ATLAS: ATLAS-CONF-2021-049: tZ
ATLAS: arXiv:2205.02537: tγ
ATLAS: arXiv:2112.01302: tg

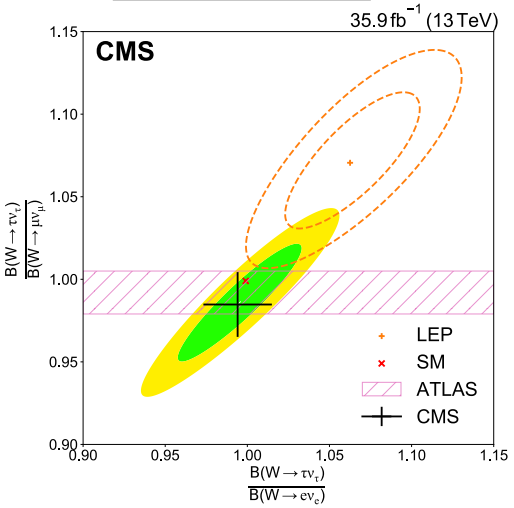
ATLAS: *Nat. Phys.* 17, 813–818 (2021)
arXiv:2007.14040

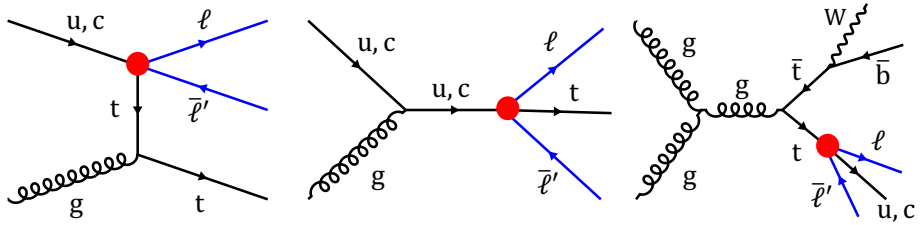


arXiv:2201.07859: t → eμq



arXiv:2201.07861





LHCTopWGSummaryPlots