THE UNIVERSITY of EDINBURGH

EW and QCD Measurements

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On behalf of the ATLAS and CMS Collaborations

La Thuile - Les Rencontres de Physique de la Valle d’Aoste

7th March 2024

Overview

- Several recent **EWK and QCD** results from **ATLAS and CMS**:
  - provide precise measurements of **fundamental SM parameters**
  - probe the mechanism of **EW symmetry breaking**
  - offer **sensitivity to BSM physics**
  - test state-of-the-art **perturbative QCD calculations**
  - provide measurements of **proton PDFs**
  - provide important **input for the development of MC simulations**
  - search for **rare SM decays**
  - introduce and develop interesting experimental techniques

***new for La Thuile**

ATLAS EXPERIMENT

- ***RAZ effect and polarisation in WZ production**
- ***Wγjj fiducial and differential x-sections**
- ***MET+jets differential x-sections**
- ***Lund subjet multiplicities**
- Search for exclusive hadronic W decays

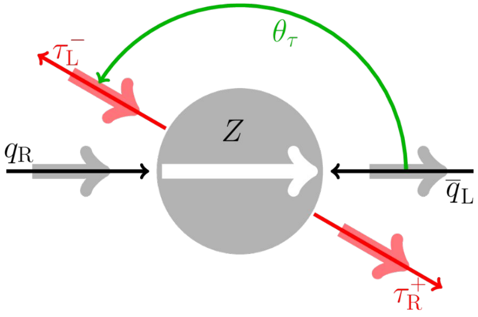
CMS

- Multidifferential dijet x-sections
- Azimuthal jet correlations → determination of α_s
- Tau lepton polarisation → determination of $\sin\theta_W$

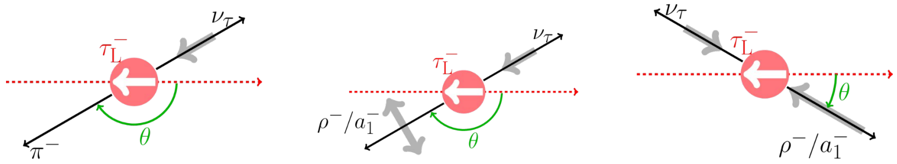
- Weak mixing angle ($\sin\theta_W^{eff}$) leads to different coupling of Z boson to RH and LH fermions - described by asymmetry parameter A_f
- From **τ polarisation in Z→ττ decays can determine $\sin\theta_W^{eff}$**

$$P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_{\tau^2}} \approx -2.\frac{v_\tau}{a_\tau} = -2(1-4\sin^2\theta_W^{eff})$$

$$P_\tau = \frac{\sigma(\tau_R)-\sigma(\tau_L)}{\sigma(\tau_R)+\sigma(\tau_L)}$$



- **More challenging than measurement at LEP**
  - hard to determine polar emission angle
  - average over limited range of √s of the qq pair
  - comparisons are test of lepton universality of weak neutral current



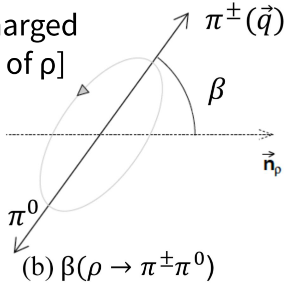
Measurement of τ lepton polarisation

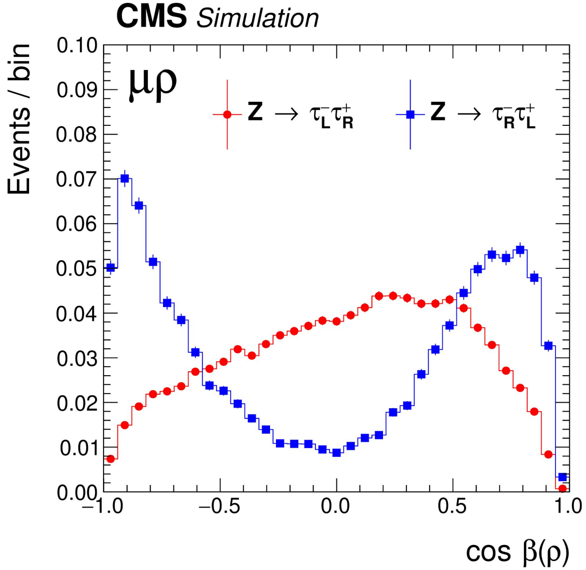
JHEP 2401 (2024) 101

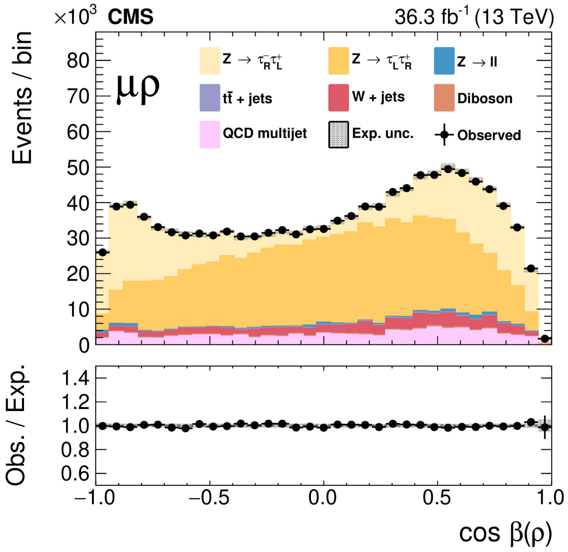
- **11 categories** depending on
  - hadronic/leptonic tau
  - decay mode of hadronic tau ($\tau \to h\nu$, with $h = \pi, \rho, a_1$)
- Discriminant observable maximising sensitivity for helicity for each category → **fit with template & extract helicity fractions**

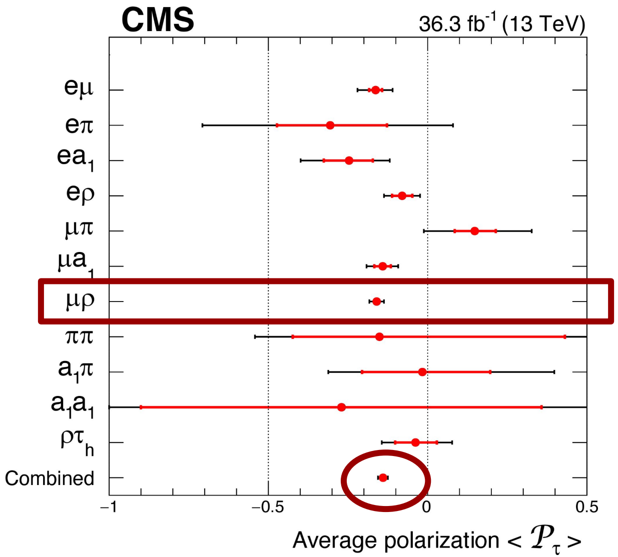
[β - angle between direction of charged pion in ρ rest frame and direction of ρ]

$$P_\tau = \frac{\sigma(\tau_R) - \sigma(\tau_L)}{\sigma(\tau_R) + \sigma(\tau_L)}$$









Measurement of τ lepton polarisation

- Average polarisation extracted from fits

$$\langle P_\tau \rangle = -0.140 \pm 0.006\ \text{(stat)} \pm 0.014\ \text{(syst)}$$

- Correct to value at Z pole - allow comparison with LEP measurement

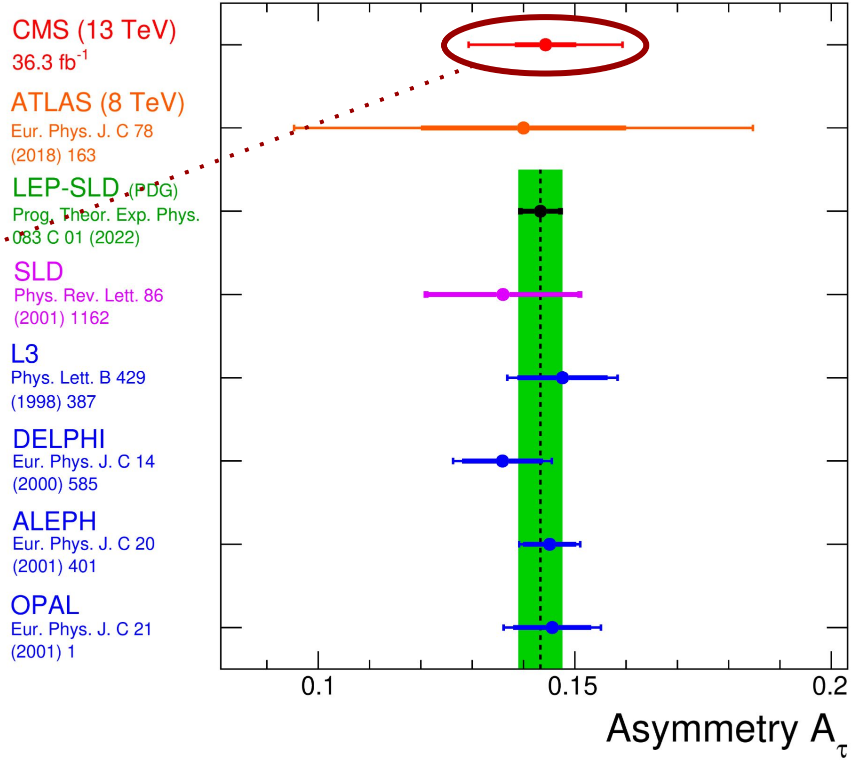
$$P_\tau(Z_0) = -0.144 \pm 0.006\ \text{(stat)} \pm 0.014\ \text{(syst)}$$

from A_τ can determine:

$\sin^2\theta_W = 0.2319 \pm 0.0008\ \text{(stat)} \pm 0.0018\ \text{(syst)}$

most precise result at hadron colliders!

All plots & tables here



RAZ effect and polarisation in WZ production

NEW FOR LA THUILE

ATLAS EXPERIMENT

arXiv:2402.16365

- WZ polarisation measurements probe the nature of EW symmetry breaking
- Use **WZ→lνl'l'** (l, l'=e, μ) production to study:

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- Use **WZ→lνl’l’** (l, l’=e, μ) production to study:
  - **energy dependence of diboson polarisarion fractions**

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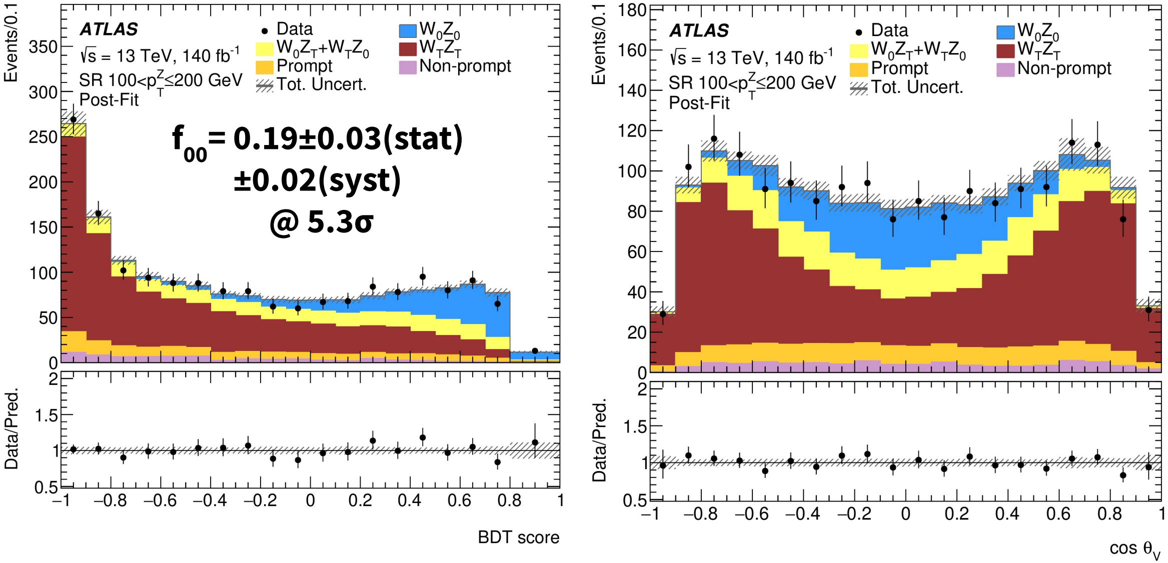
WZ polarisation @ high p_T

- Diboson polarisation fractions in inclusive WZ are dominated by TT events with low momentum bosons
- Target events with **high p_T Z bosons**
- **BDT** trained to separate 00 polarisation state from others
- Fit to BDT score to extract polarisation fractions in two bins of **p_T(Z)** (100-200 GeV & >200 GeV)

non-0 f_{00} for 100 < p_T^Z < 200 GeV w/ >5σ significance

[0 - longitudinal, T - transverse]



RAZ effect and polarisation in WZ production

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- WZ polarisation measurements probe the nature of EW symmetry breaking
- Use **WZ→lνl'l'** (l, l'=e, μ) production to study:
  - **Radiation Amplitude Zero effect**

arXiv:2402.16365

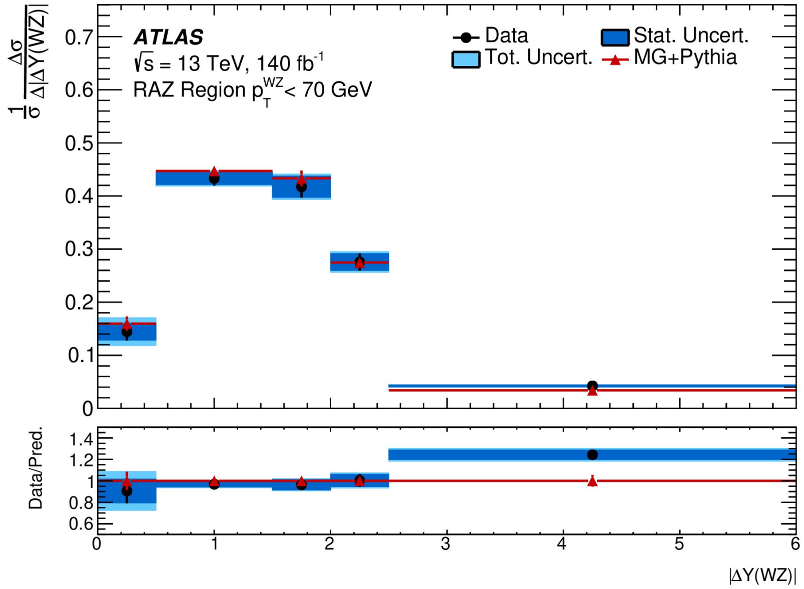
All plots & tables here

[0 - longitudinal, T - transverse]

RAZ Effect

- **Radiation Amplitude Zero effect: exact 0 for TT amplitude in the region where cos θ_W ~ 0**
- Observed using rapidity differences - causes dip at 0
  - $\Delta Y(WZ)$, $\Delta Y(l_W Z)$
- **Requirement on p_T(WZ)<x ,** to reduce jet activity and increase significance of dips
- Measurements corrected for detector effects and compared to SM predictions

First study of this effect in WZ production!



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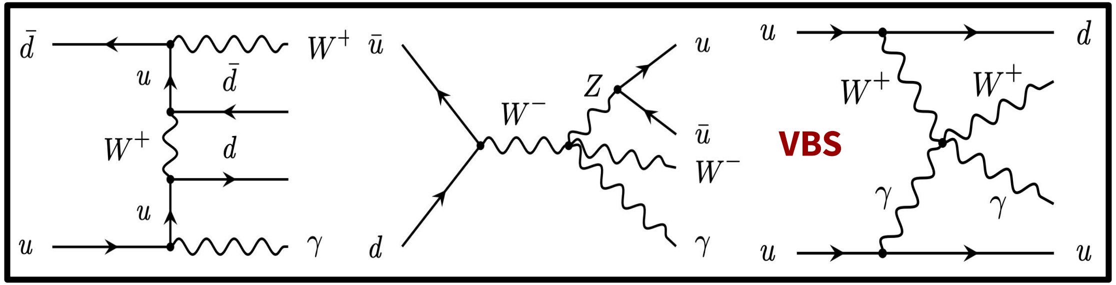
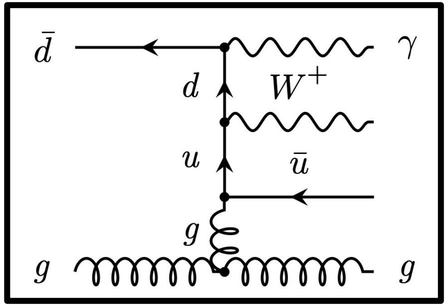


EW Wγjj signal

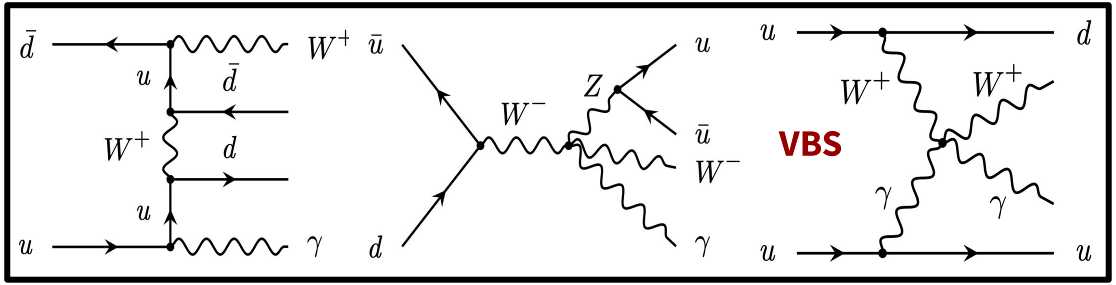


QCD Wγjj bkgd

- Measurement of fiducial and differential x-sections of **EW Wγjj**
  - VBS process sensitive to **quartic gauge couplings** & probe of **EW gauge symmetry breaking**
  - Corrected for detector effects

Wγjj x-section @ 13 TeV

All plots & tables here



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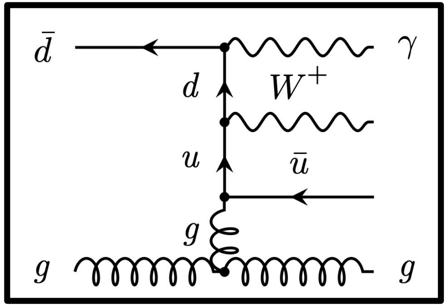
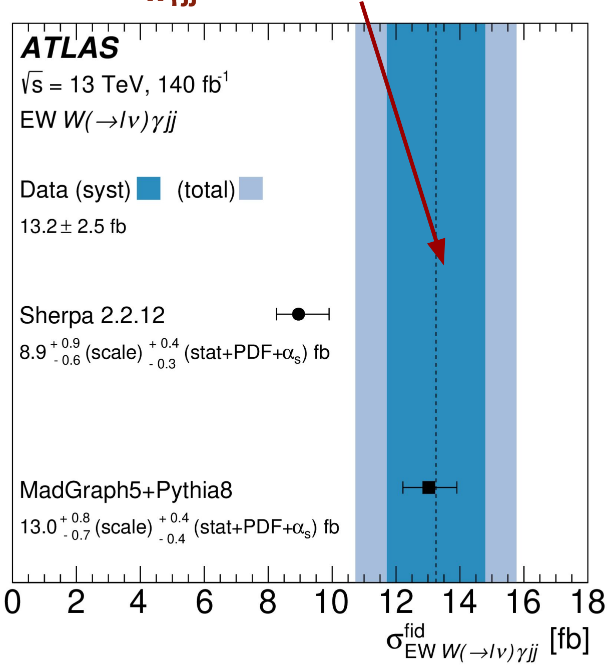


QCD Wγjj bkgd

- Measurement of fiducial and differential x-sections of **EW Wγjj**
  - VBS process sensitive to **quartic gauge couplings** & probe of **EW gauge symmetry breaking**
  - Corrected for detector effects
- **Fiducial x-section measurement:**
  - **NN** used for **signal/bkgd classification** in VBS enhanced phase space
- **Differential x-section measurements:**
  - **VBS observables (m_{jj}, p_T^{jj}, p_T^{l}, $m_{l\gamma}$) -** sensitive to **aQGCs** & used to constrain **EFT operators**
  - **CP observables ($\Delta\Phi_{jj}$,$\Delta\Phi_{l\gamma}$) -** probe CP structure

1st observation of Wγjj production at ATLAS!

$\sigma_{W\gamma jj}^{fid} = 13.2 \pm 2.5$ pb



Wγjj x-section @ 13 TeV

arXiv:2403.02809

NEW FOR LA THUILE

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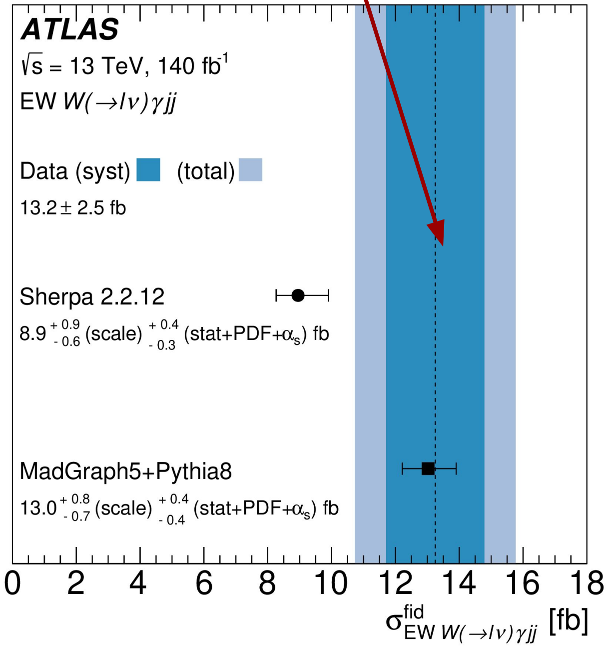
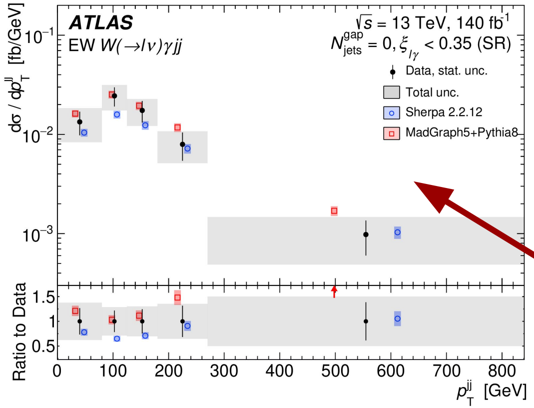
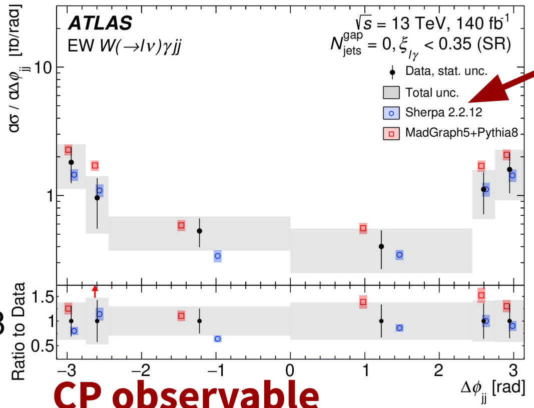


VBS observable



Differential x-section measurements



CP observable

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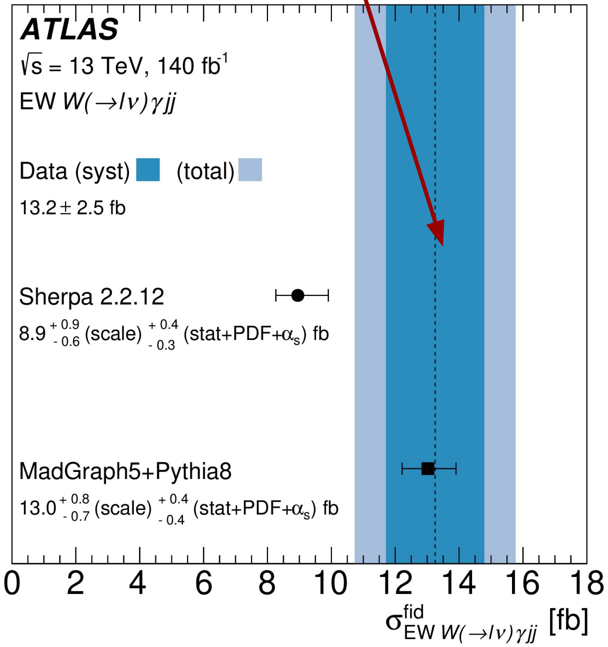
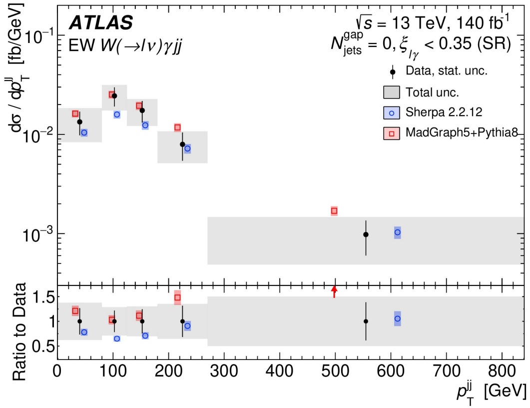
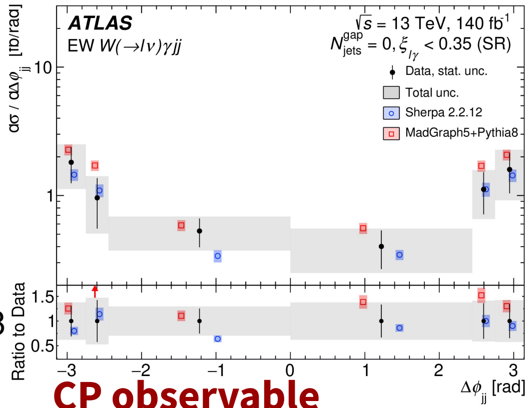


VBS observable





CP observable

- Differential x-section measurements used to **constrain dimension-8 EFT operators** which can change QGC
  - Sensitive to 8 tensor-type operators and 7 mixed-scalar operators

1st limits on f_{T3} and f_{T4} at the LHC!

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)}$$

Coefficients [TeV^{-4}]	Observable	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	[-2.4, 2.4]	[-1.8, 1.8]
f_{T1}/Λ^4	p_T^{jj}	[-1.5, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	[-4.4, 4.7]	[-3.1, 3.5]
f_{T3}/Λ^4	p_T^{jj}	[-3.3, 3.5]	[-2.4, 2.6]
f_{T4}/Λ^4	p_T^{jj}	[-3.0, 3.0]	[-2.2, 2.2]
f_{T5}/Λ^4	p_T^{jj}	[-1.7, 1.7]	[-1.2, 1.3]
f_{T6}/Λ^4	p_T^{jj}	[-1.5, 1.5]	[-1.0, 1.1]
f_{T7}/Λ^4	p_T^{jj}	[-3.8, 3.9]	[-2.7, 2.8]
f_{M0}/Λ^4	p_T^{l}	[-28, 28]	[-24, 24]
f_{M1}/Λ^4	p_T^{l}	[-43, 44]	[-37, 38]
f_{M2}/Λ^4	p_T^{l}	[-10, 10]	[-8.6, 8.5]
f_{M3}/Λ^4	p_T^{l}	[-16, 16]	[-13, 14]
f_{M4}/Λ^4	p_T^{l}	[-18, 18]	[-15, 15]
f_{M5}/Λ^4	p_T^{l}	[-17, 14]	[-14, 12]
f_{M7}/Λ^4	p_T^{l}	[-78, 77]	[-66, 65]

MET+jets differential x-section @ 13 TeV

- **Unfolded differential measurements of p_T^{miss} produced in association with jets**
  - process-specific (**$Z \rightarrow \nu\nu$**)
    - after subtraction of all sub-dominant processes
  - **inclusive measurements**
    - only subtracting fakes from data
    - sensitive to various **DM other BSM models**

- Measurements repeated in auxiliary regions (lepton+jets, photon+jets)
  - Ratios between SR measurement and auxiliary measurements (**R^{miss}**) **allow cancellation of systematics and modelling effects**

Regions

SR: p_T^{miss} + jets	Aux: μ + jets
Aux: e + jets	Aux: 2μ + jets
Aux: 2e + jets	Aux: γ + jets

Phase-spaces	Observables
>= 1 jet	p_T^{miss}
VBF, >= 2 jets	p_T^{miss}, m_{jj} and $\Delta\Phi_{jj}$

arXiv:2403.02793

MET+jets differential x-section @ 13 TeV

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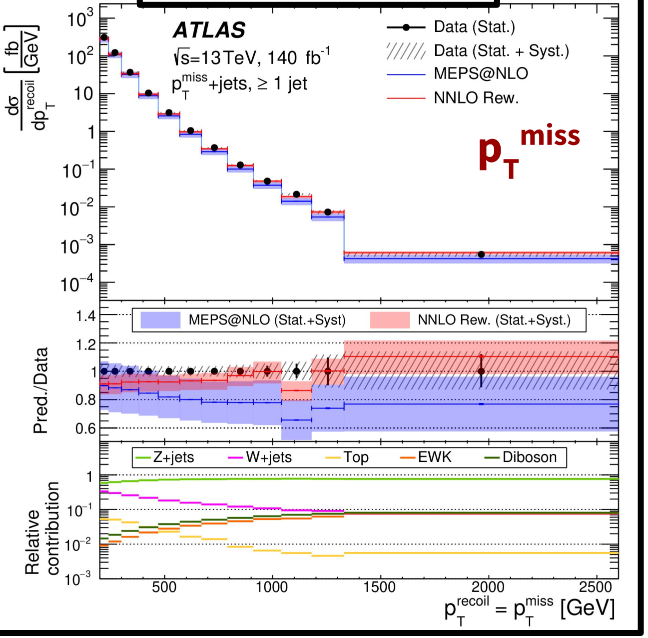
inclusive, >= 1 jet



Generally reasonable agreement with state-of-the-art SM predictions

All plots & tables here

arXiv:2403.02793

MET+jets differential x-section @ 13 TeV

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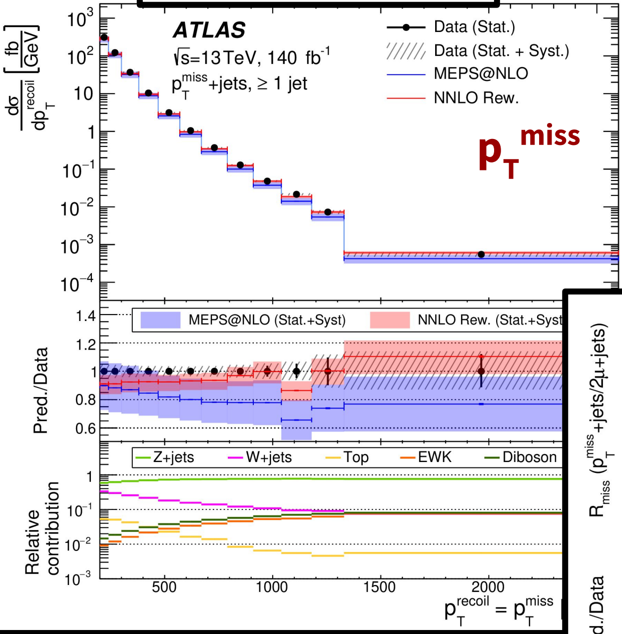
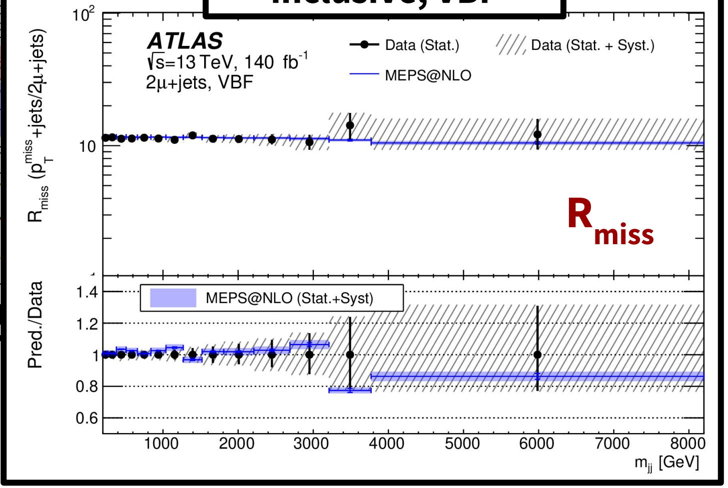


Generally reasonable agreement with state-of-the-art SM predictions except for mjj

- flat pred/data for R_{miss}

inclusive, VBF



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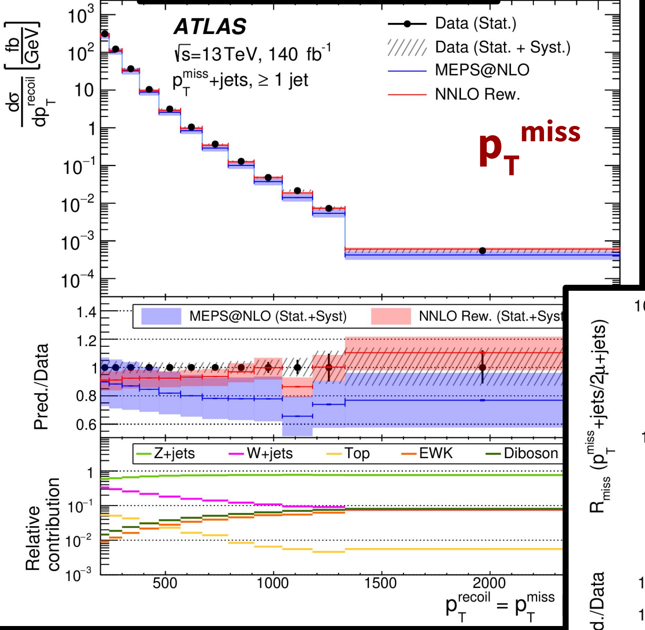
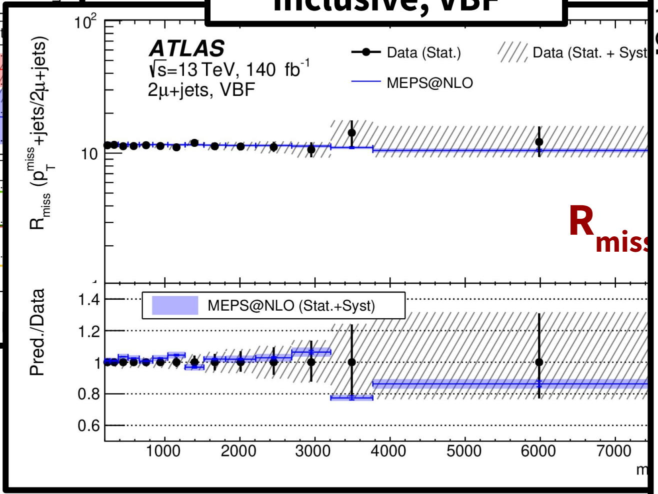


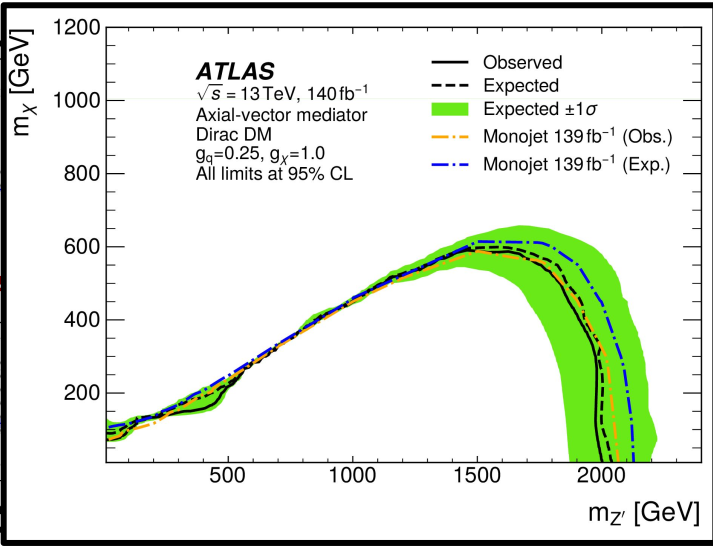
Generally reasonable agreement with state-of-the-art SM predictions except for mjj - flat pred/data for R_{miss}

compared with two DM models comparable sensitivity wrt dedicated searches

highly re-interpretable!

inclusive, VBF





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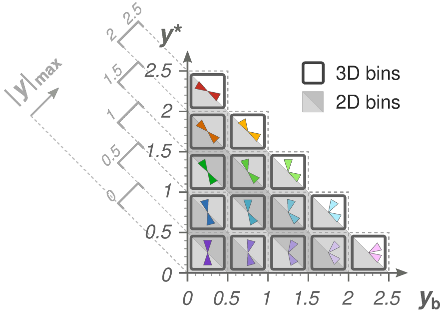
- **2D and 3D measurements of dijet production x-section**
  - anti-k_T jets with $R = 0.4$ and $R = 0.8$



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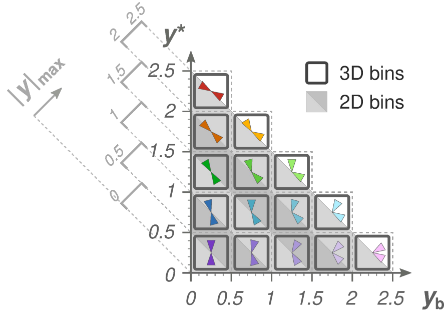
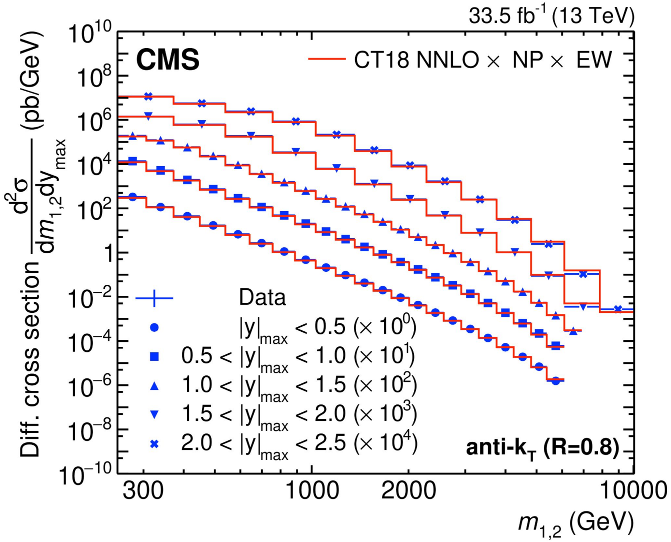
    - $\mathbf{|y|_{max}}$ - largest absolute rapidity of the 2 jets





Multidifferential dijet x-sections @ 13 TeV

arXiv:2312.16669

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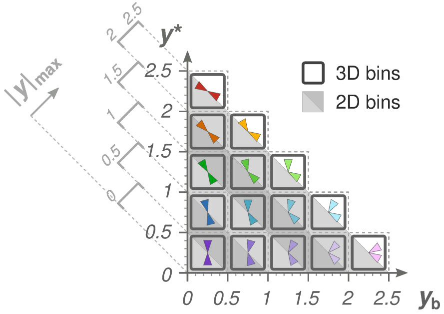
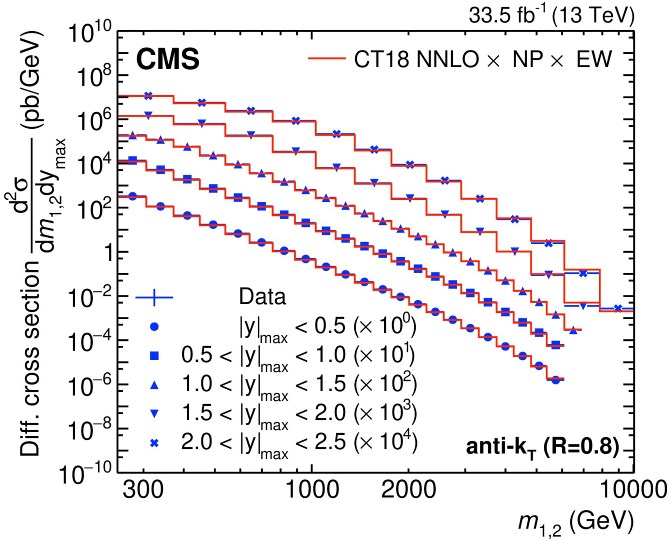
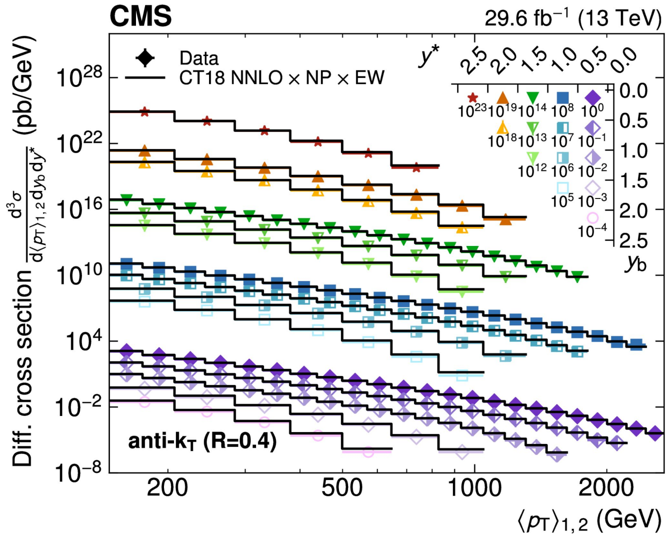
  - 2D spectra: as function of $\mathbf{m_{1,2}}$ in 5 rapidity bins
    - $\mathbf{|y|_{max}}$ - largest absolute rapidity of the 2 jets
  - 3D spectra: as function of $\mathbf{m_{1,2}}$ or $\mathbf{\langle p_T \rangle_{1,2}}$ in 15 rapidity bins
    - $\mathbf{y^*}$ - rapidity separation; $\mathbf{y_b}$ - total boost of dijet system



$$y^* = \frac{1}{2}|y_1 - y_2|$$

$$y_b = \frac{1}{2}|y_1 + y_2|$$





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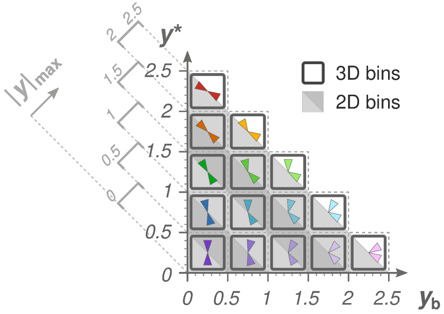
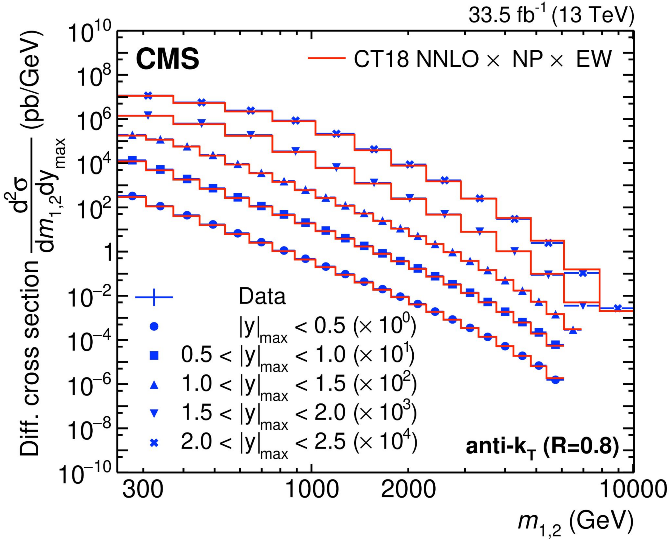
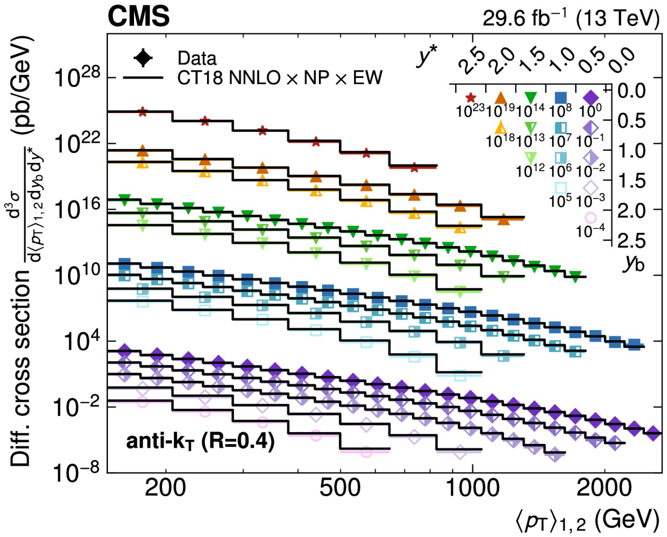


$$y^* = \frac{1}{2}|y_1 - y_2|$$

$$y_b = \frac{1}{2}|y_1 + y_2|$$

- Measurement corrected for experimental effects and compared with **NNLO pQCD predictions - good agreement!**





Multidifferential dijet x-sections @ 13 TeV

arXiv:2312.16669

- Simultaneous determination of proton **PDFs** and $\alpha_s(M_Z)$
  - fitting **HERA ep DIS data** + 2D/3D dijet data
    - only measurements of $m_{1,2}$ for R = 0.8

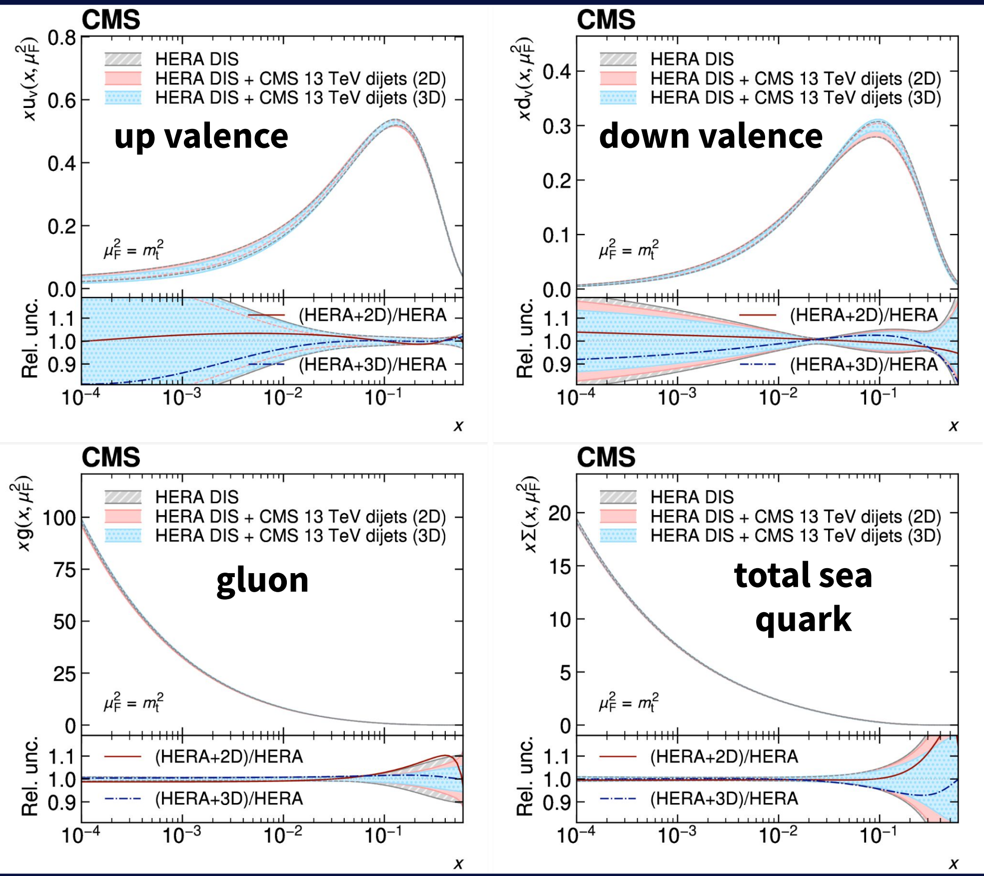
- Inclusion of dijet measurement allows better constraint on PDFs

- Compatible results from fits with 2D/3D measurements

- Slightly more precise $\alpha_s(M_Z)$ value from fit with 2D dijet measurements

$$\alpha_s(M_Z)^{CMS} = 0.1179 \pm 0.0019$$

All plots & tables here



- $R_{\Delta\Phi}(p_T)$ measured over $360 < p_T < 3200$ GeV
  - proportional to $\boldsymbol{\alpha_s^3/\alpha_s^2 = \alpha_s}$
  - leads to cancellation of experimental systematic uncertainties

neighbouring jets around jet i
$p_T > 100$ GeV
$2\pi/3 < \Delta\Phi < 7\pi/8$ - **>= 3 jets**

$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T\text{min}}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

α^3 / α^2

inclusive jets in p_T bin

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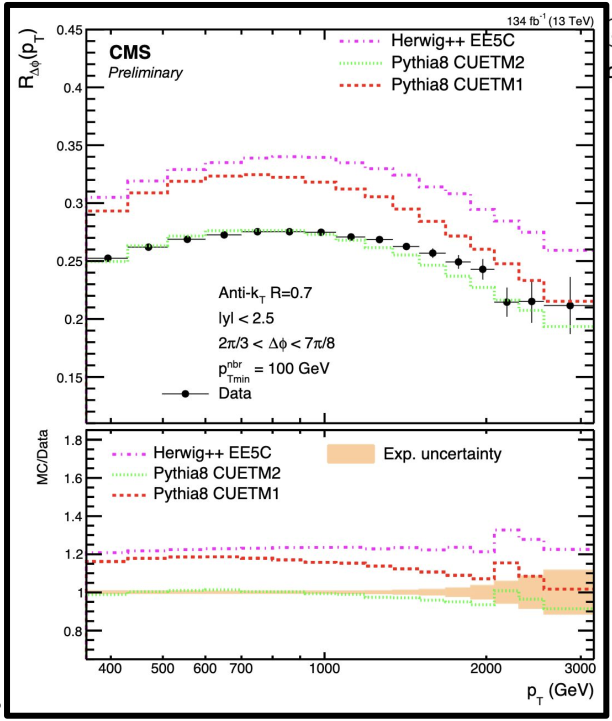
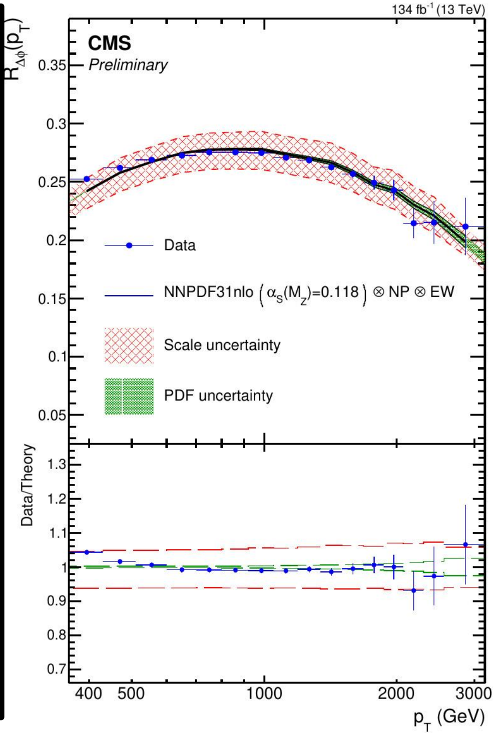
α^3 / α^2

inclusive jets in p_T bin

- Measurement corrected for detector effects and compared with **predictions from MC generators** & NLO pQCD predictions





- **Good description from LO Pythia8 CUETM2**
- **Overestimation from other generators tested**

Azimuthal jet correlations → α_s determination

CMS-PAS-SMP-22-005

- $R_{\Delta\phi}(p_T)$ measured over $360 < p_T < 3200$ GeV
  - proportional to $\boldsymbol{\alpha_s^3/\alpha_s^2 = \alpha_s}$
  - leads to cancellation of experimental systematic uncertainties

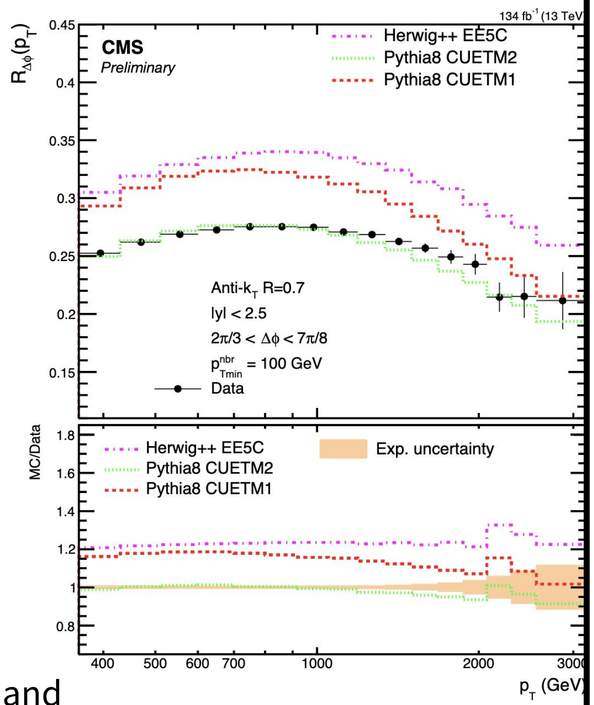
neighbouring jets around jet i
$p_T > 100$ GeV
$2\pi/3 < \Delta\Phi < 7\pi/8$ - **>= 3 jets**

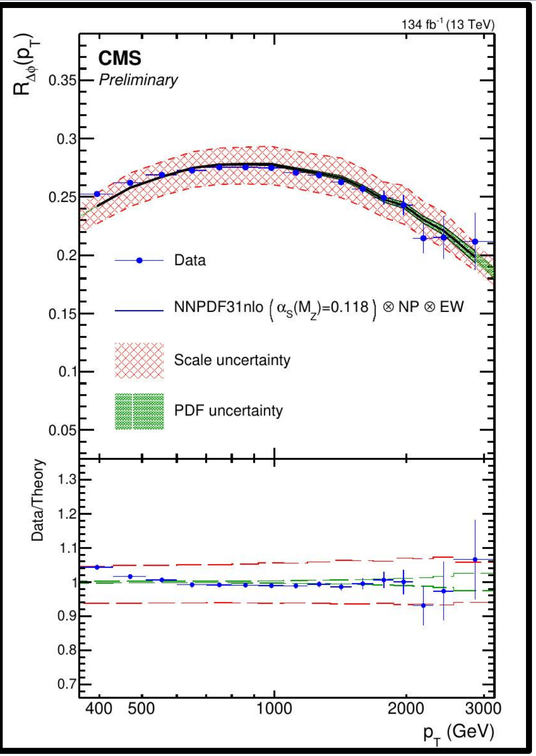
$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T\text{min}}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

α^3 / α^2

inclusive jets in p_T bin

- Measurement corrected for detector effects and compared with predictions from MC generators & **NLO pQCD predictions**

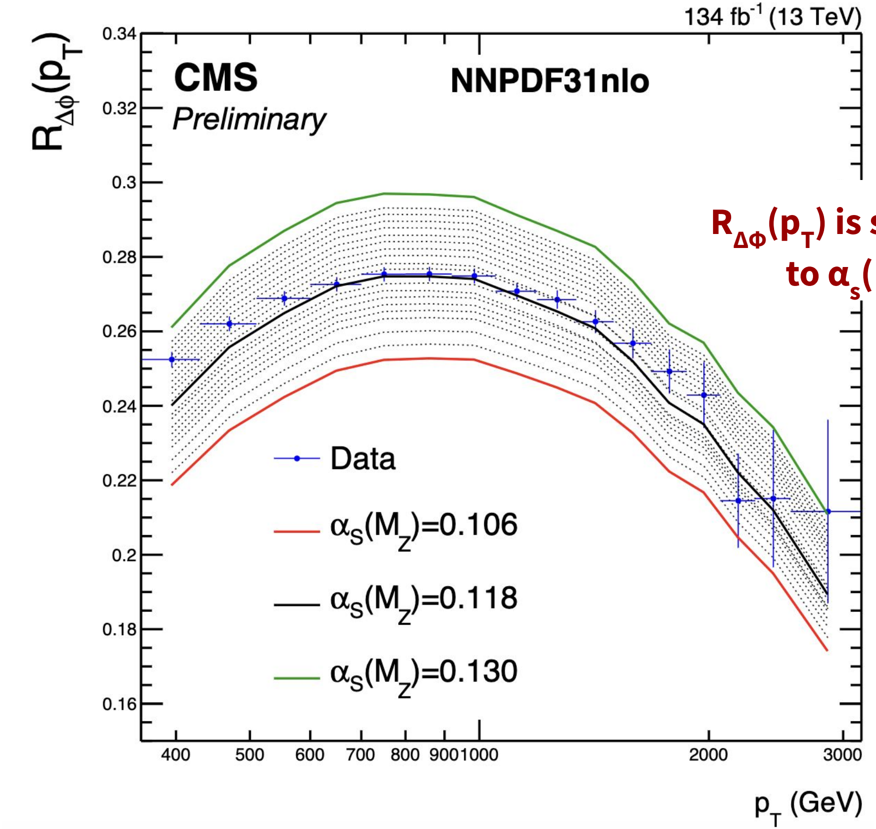




- **Good agreement with NLO pQCD predictions with all PDF sets tested**

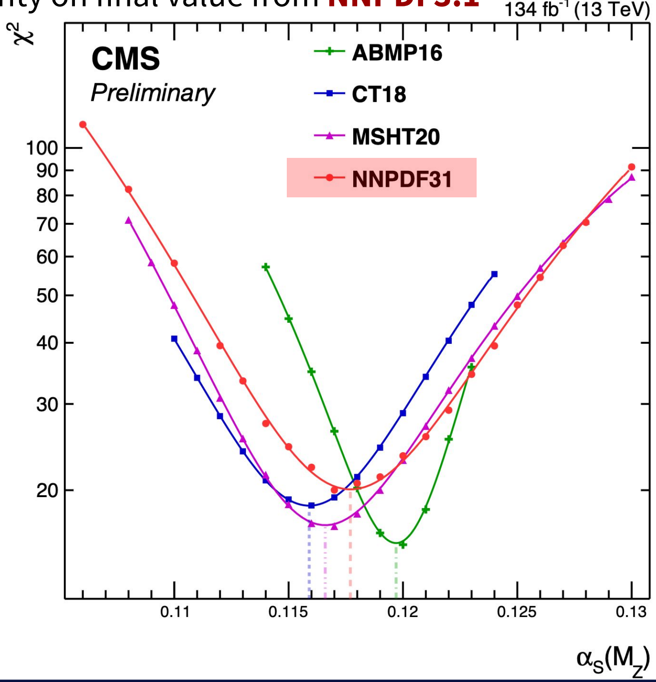
Azimuthal jet correlations → α_s determination

CMS-PAS-SMP-22-005



$R_{\Delta\Phi}(p_T)$ is sensitive to $\alpha_s(M_Z)$!

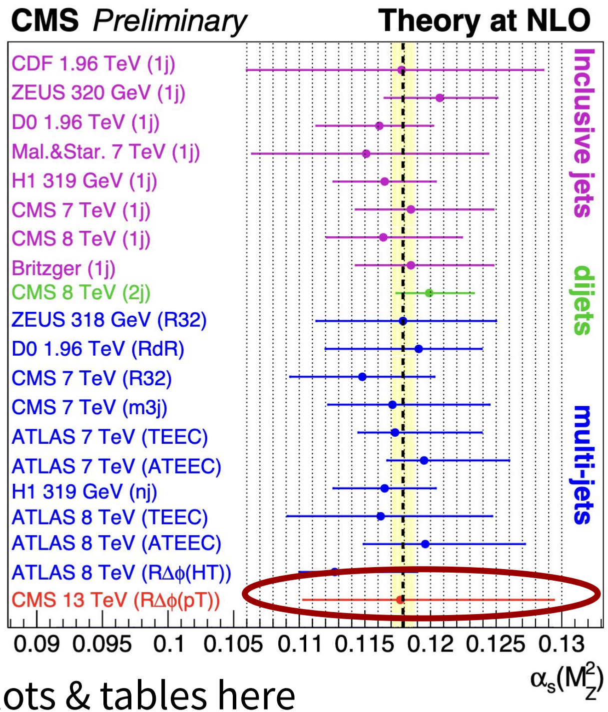
- $\alpha_s(M_Z)$ from χ^2 minimisation between experimental results and theoretical predictions
- Spread of $\alpha_s(M_Z)$ values from different PDF sets is additional uncertainty on final value from **NNPDF3.1**



Azimuthal jet correlations → α_s determination

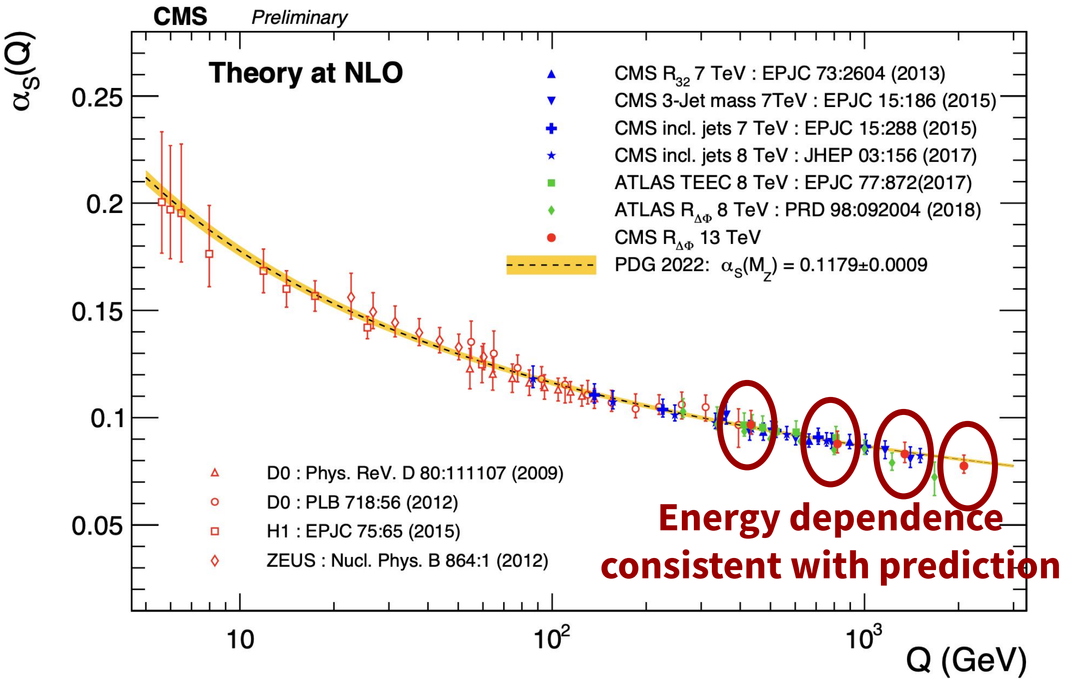
CMS-PAS-SMP-22-005

$\alpha_s(M_Z)^{CMS} = 0.1177^{+0.0117}_{-0.0074}$



All plots & tables here

- **Running of α_s** studied by splitting p_T range into 4 subregions and repeating fitting procedure using **NNPDF3.1** set



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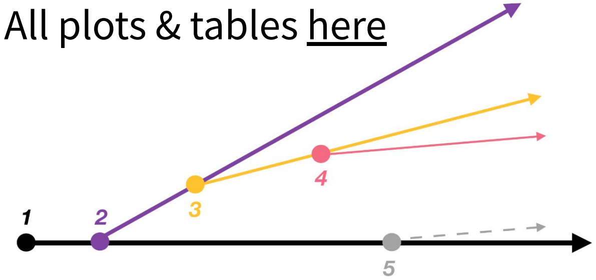
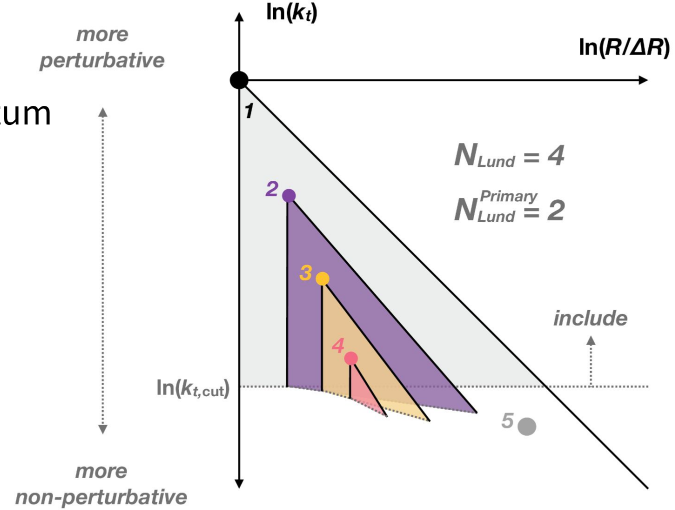


- **Parton shower modelling** is crucial for analyses at hadron colliders
  - different algorithms give different predictions
  - higher order QCD effects, like "double-soft" splittings need to be understood and incorporated
  - affects precision of analyses
- Measurement of **Lund subjet multiplicities** is sensitive to higher order effects
  - number of subjets above a certain jet relative transverse momentum k_t in a jet's angle-ordered clustering history (obtained using Cambridge/Aachen algorithm)
- Measurement done in dijet events

$$k_t = p_T^{\text{emission}} \times \Delta R(p^{\text{emission}}, p^{\text{core}})$$



Lund subjet multiplicities

arXiv:2402.13052

NEW FOR LA THUILE

ATLAS EXPERIMENT

- **Unfolded** differential x-section measurement of $\mathbf{N_{Lund}}$ for different k_t requirements, in jet p_T bins, and in relative rapidity bins

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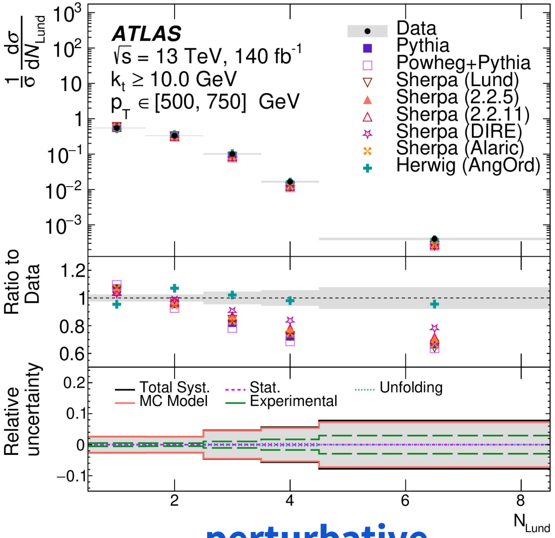
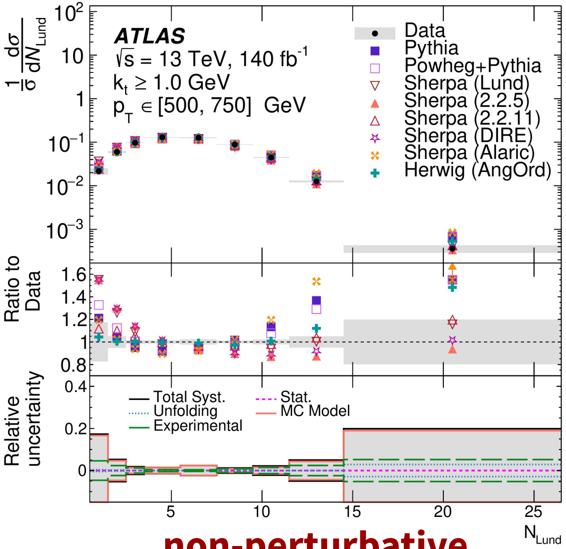
  - **Sherpa** performs best when **non-perturbative** emissions are allowed (k_t < 2 GeV)



perturbative



non-perturbative

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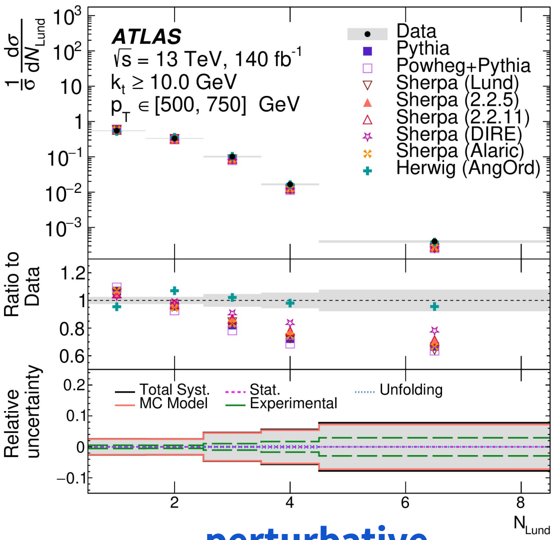
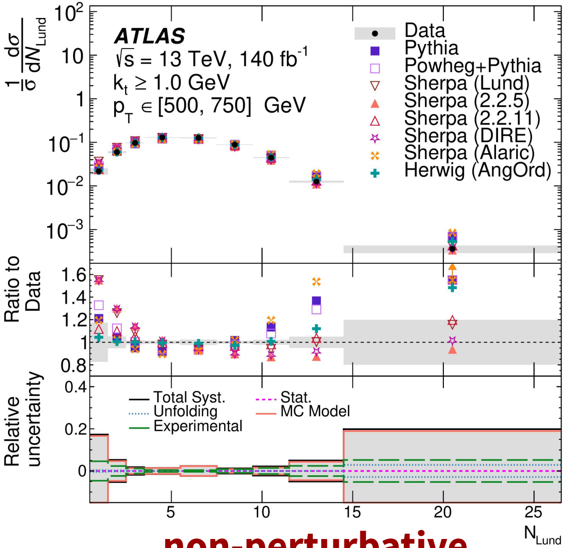


perturbative



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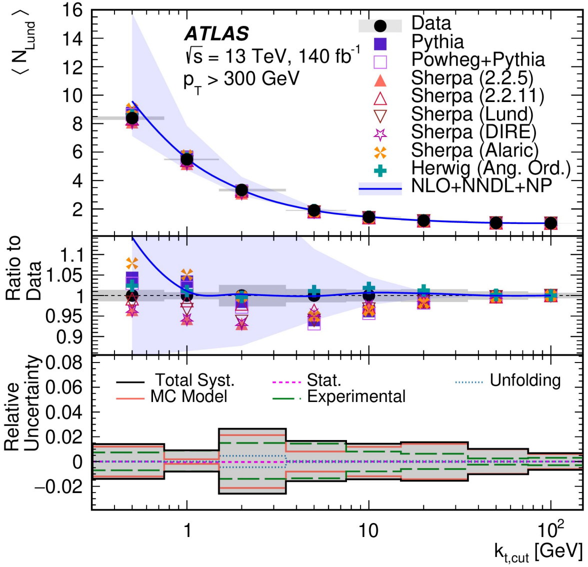

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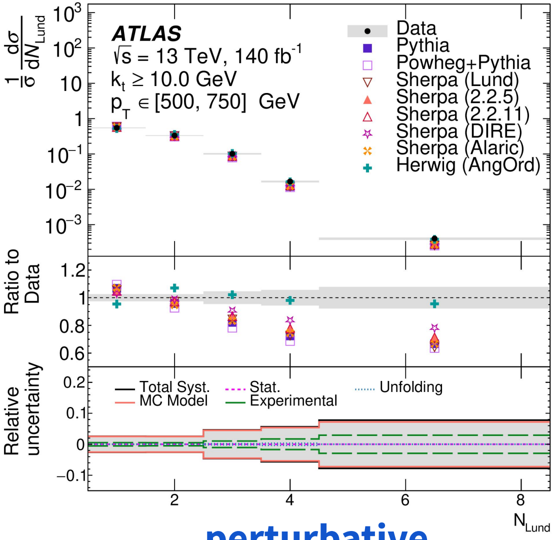
important input for PS algorithms development!



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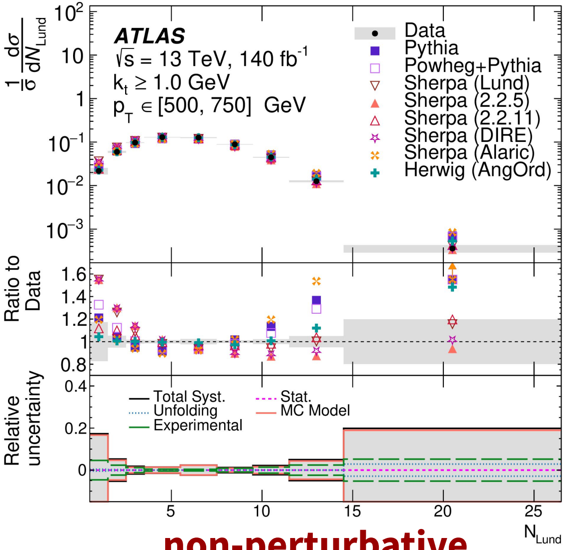

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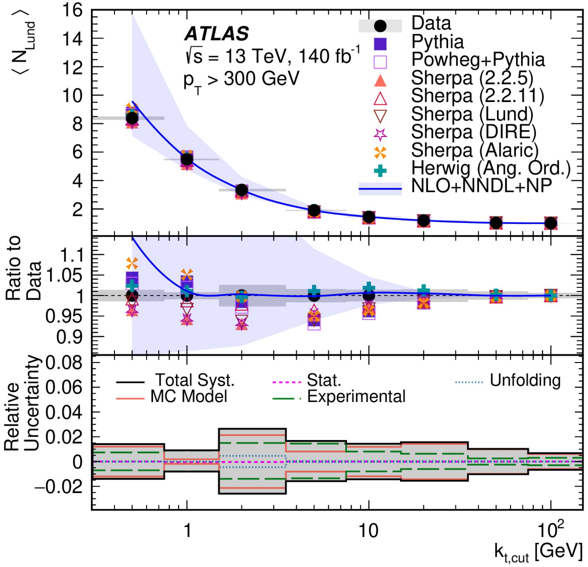


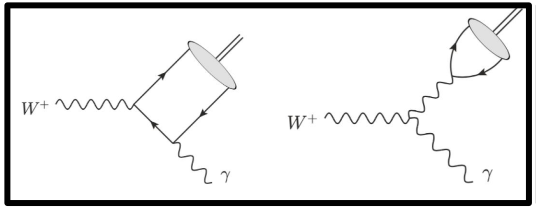
Searches for exclusive hadronic W decays

arXiv:2309.15887

ATLAS EXPERIMENT

- No exclusive hadronic decay of the W boson has been observed to date
- Could offer:
  - Clean **tests of QCD factorisation**
  - **W mass measurement** through fully-reconstructed final state

search for $W^{\pm} \to \pi^{\pm}\gamma$, $W^{\pm} \to \rho^{\pm}\gamma$, $W^{\pm} \to K^{\pm}\gamma$



Decay Channel	SM Branching Fraction
$W^{\pm} \to \pi^{\pm}\gamma$	$(4.0 \pm 0.8) \times 10^{-9}$
$W^{\pm} \to \rho^{\pm}\gamma$	$(8.7 \pm 1.9) \times 10^{-9}$
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Y. Grossman, M. König, M. Neubert

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  - **track+photon** - all decays
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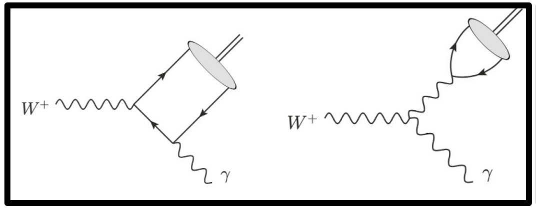

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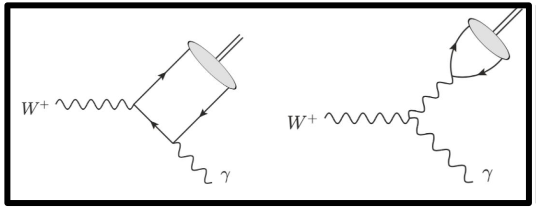
- Modelling of **di-jet** and **jet+photon** background using novel **non-parametric data-driven** technique based on **ancestral sampling** (JHEP10(2022)001) in region with relaxed selection

search for $W^{\pm} \rightarrow \pi^{\pm}\gamma$, $W^{\pm} \rightarrow \rho^{\pm}\gamma$, $W^{\pm} \rightarrow K^{\pm}\gamma$



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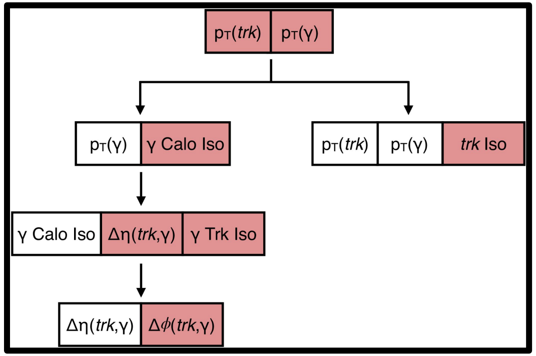
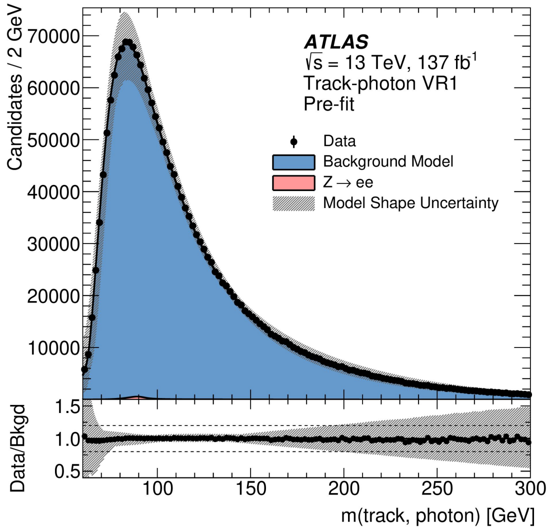
sampling sequence



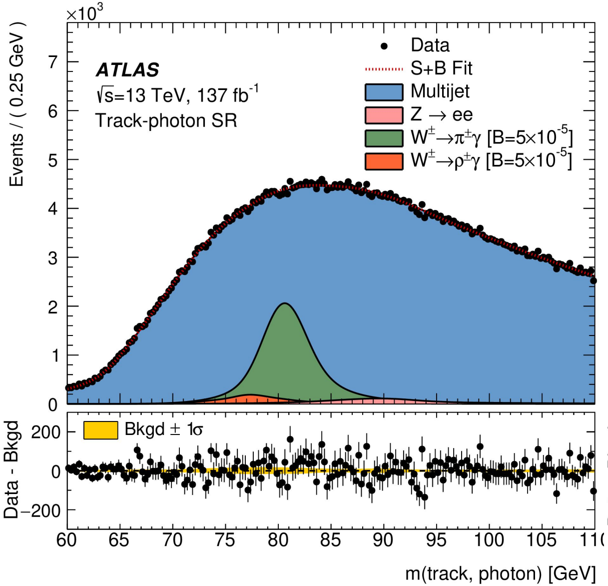


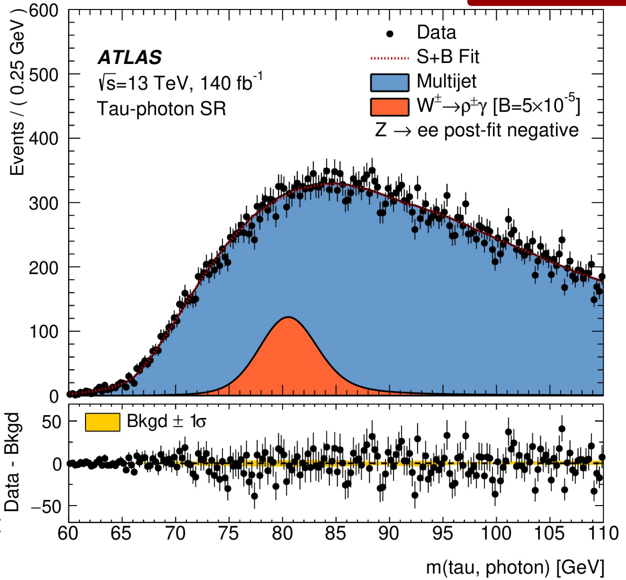
All plots & tables here

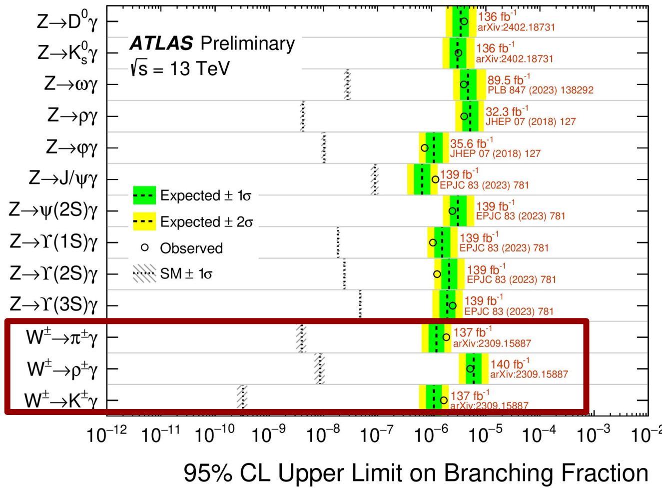
best upper limit on $B(W^{\pm} \rightarrow \pi^{\pm}\gamma)$! (4x improvement)

first limits on $B(W^{\pm} \rightarrow \rho^{\pm}\gamma)$ & $B(W^{\pm} \rightarrow K^{\pm}\gamma)$!

	Expected branching fraction $\times 10^{-6}$	Observed branching fraction $\times 10^{-6}$
$W^{\pm} \rightarrow \pi^{\pm}\gamma$	$1.2^{+0.5}_{-0.3}$	1.9
$W^{\pm} \rightarrow K^{\pm}\gamma$	$1.1^{+0.4}_{-0.3}$	1.7
$W^{\pm} \rightarrow \rho^{\pm}\gamma$	$6.0^{+2.3}_{-1.7}$	5.2







Summary

- Several recent **EWK and QCD** results from **ATLAS and CMS** discussed today
  - further details can be found in the respective publications

ATLAS EXPERIMENT

- RAZ effect and polarisation in WZ production **[Link]**
- Wγjj fiducial and differential x-sections **[Link]**
- MET+jets differential x-sections **[Link]**
- Lund subjet multiplicities **[Link]**
- Search for exclusive hadronic W decays **[Link]**

CMS

- Multidifferential dijet x-sections **[Link]**
- Azimuthal jet correlations → determination of α_s **[Link]**
- Tau lepton polarisation → determination of $\sin\theta_W$ **[Link]**

- Many more interesting results, not covered today, can be found in ATLAS & CMS public pages
  - ATLAS public STDM results: **https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults**
  - CMS public STDM results: **https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html**