QCD Standard Model measurements with the ATLAS Detector

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(on behalf of the ATLAS Collaboration)
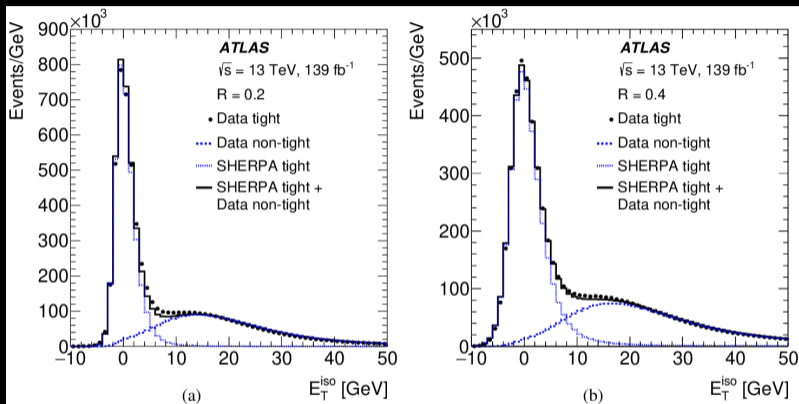
University of Wisconsin-Madison

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Motivation: Precision QCD Measurements at the LHC

- ▶ LHC datasets offer truly unique environment for probing QCD
  - ▶ Tests of perturbative QCD (pQCD) predictions at high scales
  - ▶ Extracting strong coupling constant $\alpha_s(Q)$ and its running
  - ▶ Differential cross-section measurements over multiple orders of magnitude
- ▶ Huge dataset and precise object reconstruction enable increased precision and more granular measurements
  - ▶ Full ATLAS Run-2 dataset ($L = 139$ fb^{-1}) enables precise tests of QCD
  - ▶ Boon for novel techniques sensitive to difficult to model remote areas of QCD phase space
- ▶ Focusing on 3 recent results from ATLAS today:
  - ▶ Inclusive-photon production and its dependence on photon isolation [ATLAS-STDM-2018-39] (arXiv:2302.00510)
  - ▶ Determination of the strong coupling using Transverse Energy-Energy Correlations (TEEC) in multijet events [ATLAS-STDM-2018-51] (arXiv:2301.09351)
  - ▶ Measurements of multijet event isotropies using optimal transport [ATLAS-CONF-2022-056]

Inclusive-Photon Production and its Dependence on Photon Isolation

E_T^{iso} distributions for photon candidates in data for background determination [ATLAS-STDM-2018-39] (arXiv:2302.00510)
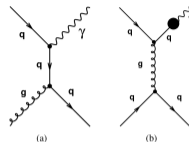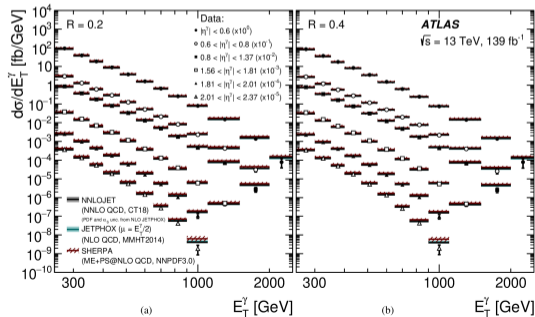

(a)

(b)

New! results from ATLAS using the full Run-2 data set (139 fb^{-1})

▶ Production of prompt (not secondaries from hadron decays) photons at high p_T in p-p collisions, $pp \rightarrow \gamma + X$, provides a testing ground for pQCD in a cleaner environment compared to jet production, as it is less affected by hadronisation effects

▶ Results compared to JETPHOX, SHERPA, NNLOjet MC simulations with different PDF sets for NLO and NNLO comparisons to differential cross sections
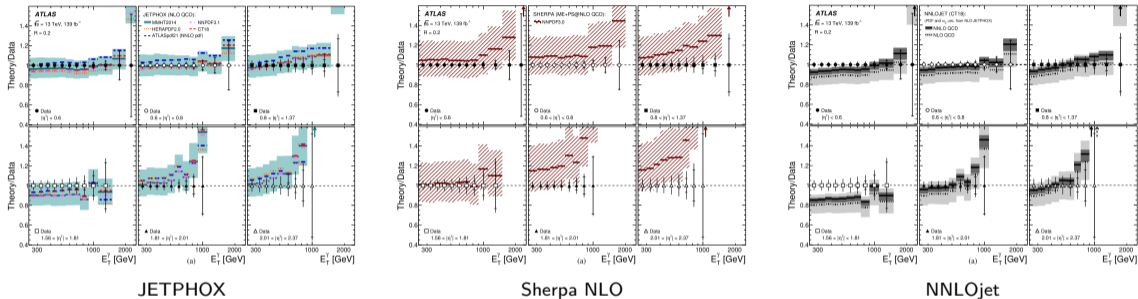

Leading order contributions: direct process and fragmentation process

Differential measurements span nearly 6 order of magnitude

Program	Order in α_s	Fragmentation	Parton shower	Isolation method	PDF	Particle level
JETPHOX	NLO	yes	no	fixed cone	– MMHT2014 – CT18 – NNPDF3.1 – HERAPDF2.0 – ATLASpdf21	no
SHERPA 2.2.2	NLO for $\gamma + (1, 2)$-jet LO for $\gamma + (3, 4)$-jet	no	yes	hybrid	NNPDF3.0	yes
NNLOJET	(N)NLO	yes	no	fixed cone	CT18NNLO	no

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Measurements have potential to further constrain PDFs within global NNLO QCD fit

JETPHOX　　　　　　　　Sherpa NLO　　　　　　　　NNLOjet

- Ratio of the NLO (or NNLO) pQCD calculations from theory and the measured differential cross sections for inclusive isolated-photon production with $R = 0.2$ as functions of E_T^{γ} in different η^{γ} regions
- Experimental systematic uncertainties smaller than theoretical uncertainties over the full investigated phase space
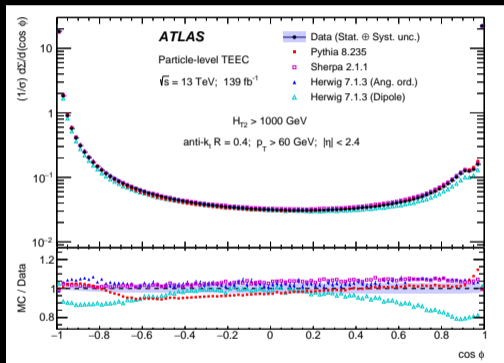- NNLOjet NNLO calculation (solid line) has sizeable reduction of the scale uncertainty!

Ratios provide very stringent test of pQCD, with significantly reduced experimental and theoretical uncertainties

JETPHOX   Sherpa NLO   NNLOjet

- Measured ratios of the differential cross sections for inclusive isolated-photon production for $R = 0.2$ (numerator) and $R = 0.4$ (denominator) as functions of E_T^γ in different η^γ regions.
- Uncertainty bars show combined statistical and systematic. Shaded bands show theoretical uncertainties.

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Determination of the strong coupling using Transverse Energy-Energy Correlations in multijet events

Comparison between the data and the MC expectations for the TEEC for the inclusive H_{T2} bin [ATLAS-STDM-2018-51] (arXiv:2301.09351)

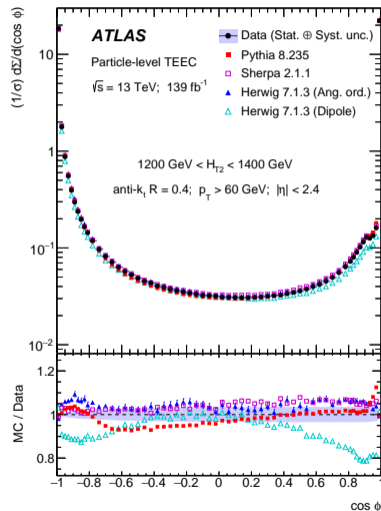**New!** results from ATLAS using the full Run-2 data set (139 fb^{-1})

- Determination of the strong coupling using Transverse Energy-Energy Correlations (TEEC) in multijet events

- E_T-weighted distribution of the $\Delta\phi$ between jet pairs

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{T_i}dx_{T_j}d\cos\phi}x_{T_i}x_{T_j}\cos\phi = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{T_i}^A E_{T_j}^A}{\left(\sum_k E_{T_k}^A\right)^2}\delta\left(\cos\phi - \cos\phi_{ij}\right)$$

- $\cos\phi = -1$: back-to-back jets (dijet-like)

- $\cos\phi = 1$: collinear jets (sensitive to splittings, soft effects)

- Jet radius effect seen in kink at $\cos\phi \approx 0.92$

Generator	ME order	ME partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
PYTHIA 8	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3}^2 \cdot m_{T4}^2)^{\frac{1}{2}}$	0.140
SHERPA	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ [2 → 2] CMW [2 → 3]	0.118
HERWIG 7	NLO	2,3	MMHT2014 NLO	Angular-ordered Dipole	$\max\{p_{Ti}\}_{i=1}^N$	0.120

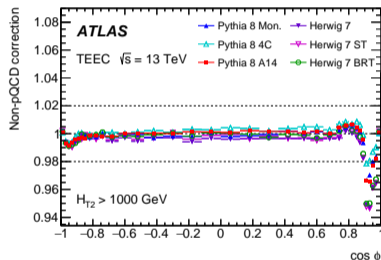Results compared to PYTHIA8, SHERPA, HERWIG7

Comparison of data and MC expectations for TEEC

- ▶ Determination of the strong coupling using Transverse Energy-Energy Correlations (TEEC) in multijet events

- ▶ E_T-weighted distribution of the $\Delta\phi$ between jet pairs

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{T_i}dx_{T_j}d\cos\phi}x_{T_i}x_{T_j}\cos\phi = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{T_i}^A E_{T_j}^A}{\left(\sum_k E_{T_k}^A\right)^2}\delta\left(\cos\phi - \cos\phi_{ij}\right)$$

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Non-perturbative corrections to the TEEC prediction for different tunes of PYTHIA8 and HERWIG7

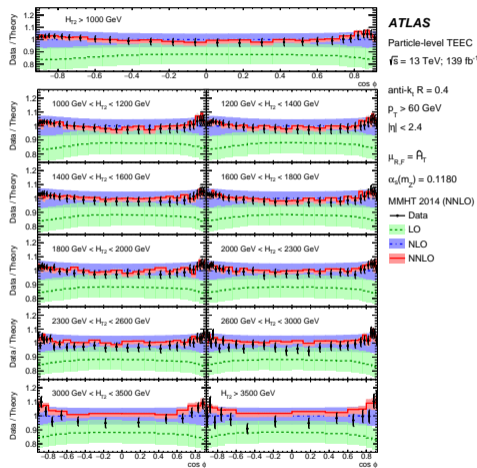| Generator	ME order	ME partons	PDF set	Parton shower	Scales μ_R, μ_F	$\alpha_s(m_Z)$
PYTHIA 8	LO	2	NNPDF 2.3 LO	p_T-ordered	$(m_{T3}^2 \cdot m_{T4}^2)^{\frac{1}{4}}$	0.140
SHERPA	LO	2,3	CT14 NNLO	CSS (dipole)	$H(s,t,u)$ [2 → 2] CMW [2 → 3]	0.118
HERWIG 7	NLO	2,3	MMHT2014 NLO	Angular-ordered Dipole	max $\{p_{Ti}\}_{i=1}^{N}$	0.120

Results compared to PYTHIA8, SHERPA, HERWIG7

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- Used NNLO predictions to extract α_s at scale of Z pole mass and its running via χ^2 fit
- Able to probe α_s at high Q (up to 4 TeV) extending reach of previous measurements

Simultaneous fit to all H_{T2} bins:

$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})$$
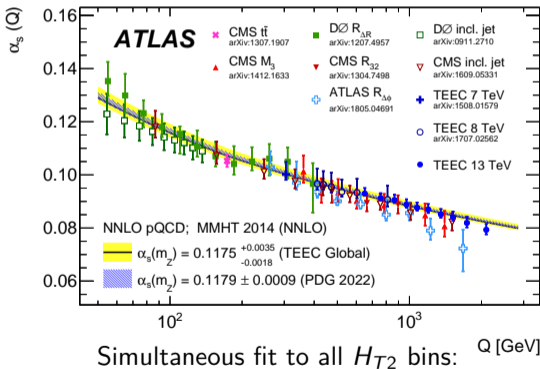

Ratios of theoretical predictions for the TEEC functions at LO and NNLO *to the NLO calculations*, shown with ratios of the *data to NLO predictions*.

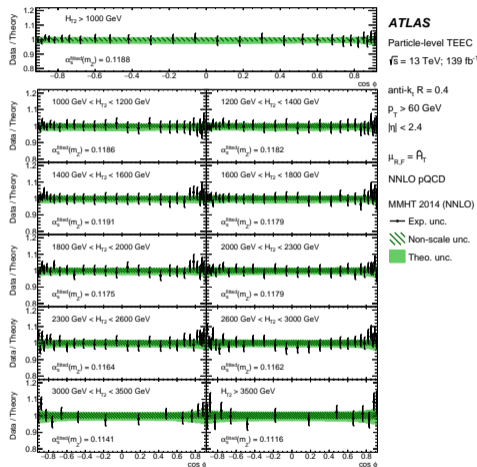▶ Used NNLO predictions to extract α_s at scale of Z pole mass and its running via χ^2 fit

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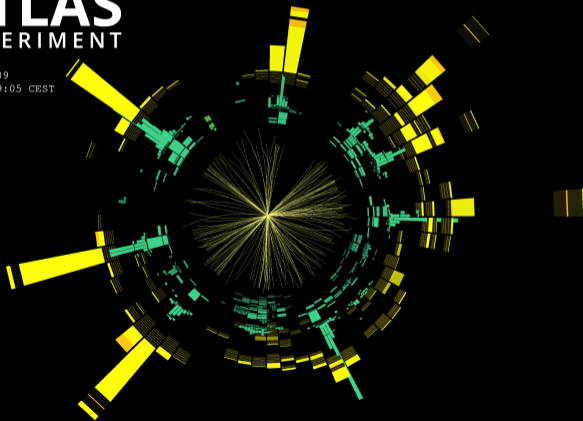

Theory uncertainties dominated by scale variations. JES systematic uncertainty next dominant, followed by MC modeling and JER uncertainties.

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Measurements of multijet event isotropies using optimal transport with the ATLAS detector

Most isotropic event passing the analysis selection (ATLAS LHC Run-2 $N_{jet} = 12$ event) [ATLAS-CONF-2022-056]
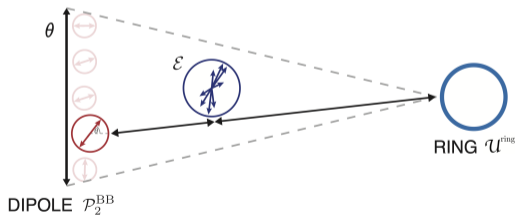
Event Isotropies at 13 TeV

- ▶ Event shapes: observables used to describe the flow of energy in collider events
  - ▶ Designed to probe QCD radiation and compare event similarity to well-balanced dijet events
- ▶ Event isotropy: novel event shape defined as distance collider event is from a symmetric radiation pattern $\mathcal{U}$ in the Wasserstein metric
  - ▶ Wasserstein distances given by Earth Mover's Distance (EMD) from optimal transport problems: minimum required 'work' to transport one event to another with equal energy by movements of energy f_{ij} from particle $i \leq M$ in one event to particle $j \leq M'$ in other
  - ▶ Infrared and colinear safe by construction!

$$\mathrm{EMD}_\beta \left(\mathcal{E}, \mathcal{E}' \right) = \min_{\{f_{ij} > 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} \theta_{ij}^\beta$$

$$\sum_{i=1}^{M} f_{ij} = E_j', \quad \sum_{ij1}^{M'} f_{ij} = E_i, \quad \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} E_i = \sum_{j=1}^{M'} E_j = E_{\mathrm{tot}}$$
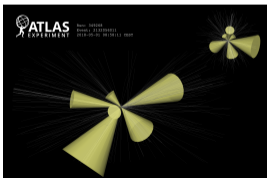
θ_{ij} : pairwise distance "ground measure", $\quad \beta > 0$ (here 2)

$$\mathcal{I} \left(\mathcal{E} \right) = \mathrm{EMD} \left(\mathcal{E}, \mathcal{U} \right)$$
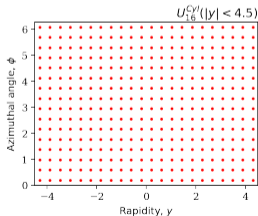

EMD of event $\mathcal{E}$ to the manifold of two-particle back-to-back events ($\mathcal{P}_2^{\mathrm{BB}}$) and to uniform ring-like geometry with $N = 128$ reference particles
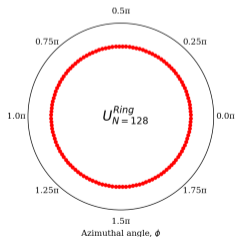
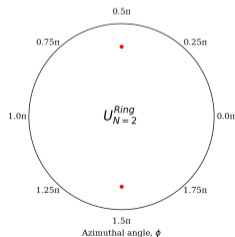| Geometry	Energy Weight	Ground Measure	Radiation Pattern $\mathcal{U}$
Cylinder	$w_i^{\text{cyl}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{cyl}} = \frac{12}{\pi^2 + 16 y_{\max}^2}\left(y_{ij}^2 + \phi_{ij}^2\right)$	$\mathcal{U}_{N=16}^{\text{cyl}}\left(|y| < y_{\max}\right)$
Ring	$w_i^{\text{ring}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{\pi}{\pi - 2}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_{N=128}^{\text{ring}}$
Ring (Dipole)	$w_i^{\text{ring}} = p_{Ti}/p_{T\text{tot}}$	$\theta_{ij}^{\text{ring}} = \frac{1}{1 - \frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_{N=2}^{\text{ring}}$

Event $\mathcal{E}$ with $N_{\text{jet}} = 6$

$\mathcal{I}_{\text{Cyl}}^{16} = \text{EMD}_2\left(\mathcal{E}, \mathcal{U}_{16}^{\text{cyl}}\right)$
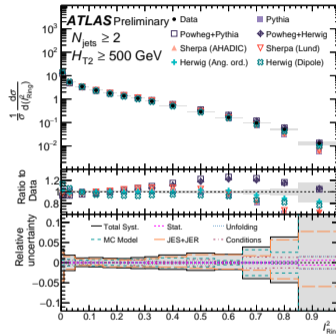
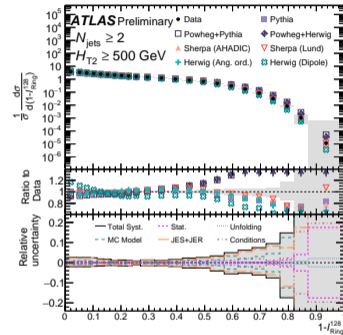$\mathcal{I}_{\text{Ring}}^{128} = \text{EMD}_2\left(\mathcal{E}, \mathcal{U}_{128}^{\text{Ring}}\right)$

$\mathcal{I}_{\text{Ring}}^{2} = \text{EMD}_2\left(\mathcal{E}, \mathcal{P}_2^{\text{BB}}\right)$

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- $\mathcal{I}_{\mathrm{Ring}}^2$: MC generators roughly describe data
  - In isotropic region predictions with best agreement to data are NLO MC generators
- $1 - \mathcal{I}_{\mathrm{Ring}}^{128}$: MC generators modeling of the data degrades at higher isotropic region
  - Generators disagree with each other at higher isotropy

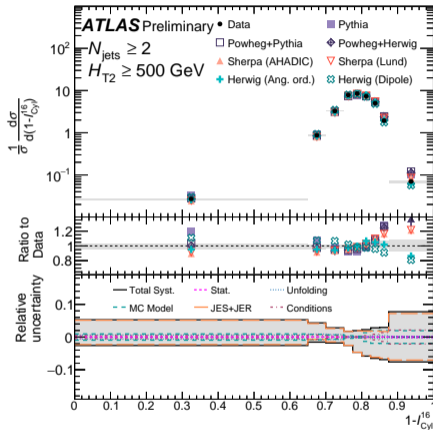Unfolded $\mathcal{I}_{\mathrm{Ring}}^2$ compared to MC

Unfolded $1 - \mathcal{I}_{\mathrm{Ring}}^{128}$ compared to MC

Left side of plot: more back-to-back
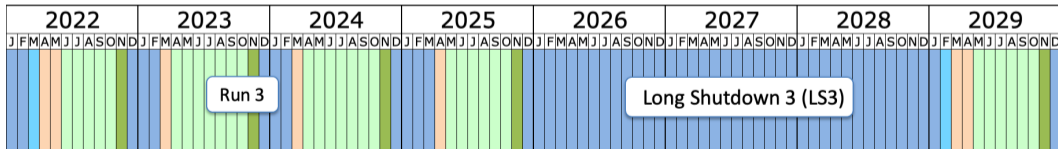**Right side of plot:** more isotropic

- $1 - \mathcal{I}_{\mathrm{Cyl}}^{16}$: None of the MC generators describe the data well
  - Large differences between the parton shower models available in HERWIG
  - Complex observable!
- For all:
  - Agreement best in balanced, dijet-like configurations. Deteriorates in more isotropic configurations.
  - Useful observable for improving simulations at the LHC
  - Can be used in future Monte Carlo tuning campaigns and other QCD studies

    - Capable of exposing a remote piece of QCD phase space difficult to model and relevant to searches for physics beyond the Standard Model

Unfolded $1 - \mathcal{I}_{\mathrm{Cyl}}^{16}$ compared to MC

Left side of plot: more back-to-back
Right side of plot: more isotropic

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Conclusions

- ▶ The LHC provides rich environment for studying QCD
- ▶ Full ATLAS Run-2 dataset ($L = 139$ fb^{-1}) allows for precision measurements of QCD and exploring novel techniques
- ▶ Measurements provide useful inputs for improving understanding of QCD
- ▶ Can be used in future Monte Carlo tuning campaigns and other studies of QCD (including PDF fits)
- ▶ Reminder: We're at the start of LHC Run 3!
  - ▶ More (better) measurements means improved modeling and smaller systematic uncertainties
  - ▶ More to come!

2022	2023	2024	2025	2026	2027	2028	2029
JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND

Run 3

Long Shutdown 3 (LS3)

LHC long term schedule (updated January 2022)

- Single-photon high-level trigger with $E_T^\gamma > 140$ GeV and "loose" photon identification requirements
  - Trigger efficiency for photons with $E_T^\gamma > 250$ GeV close to 100%
- Offline selection from trigger data with:
  - at least one reconstructed primary vertex
  - at least two associated tracks of $p_T > 500$ MeV
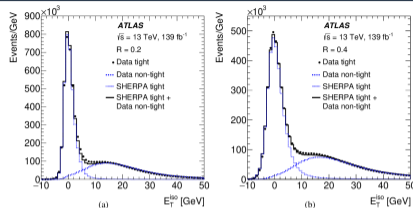 - consistent with the average beam-spot position

- Multi-jet background from events passing event selection but failing tight photon identification and isolation requirements.

- ABCD method used
  - A: Signal region (tight, isolated)
  - B: Control region with non-isolated background events (contains tight and non-isolated photon candidates)
  - C: Control region with non-tight background events (contains isolated and non-tight photon candidates)
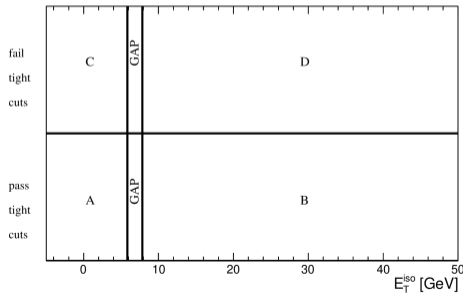 - D: Control region with non-isolated and non-tight photon candidates

$$N_A^{\mathrm{sig}} = N_A - R^{\mathrm{bg}} \cdot \left(N_B - f_B N_A^{\mathrm{sig}} \right) \cdot \frac{\left(N_C - f_C N_A^{\mathrm{sig}} \right)}{\left(N_D - f_D N_A^{\mathrm{sig}} \right)}$$

$$R^{\mathrm{bg}} = \frac{N_A^{\mathrm{bg}} \cdot N_D^{\mathrm{bg}}}{N_B^{\mathrm{bg}} N_C^{\mathrm{bg}}}$$

- Signal purity: $P = N_A^{\mathrm{sig}} / N_A > 90\%$

E_T^{iso} distributions for photon candidates in data

ABCD plane. Vertical lines correspond to the requirements on E_T^{iso} for $E_T^{\gamma} = 250$ GeV.

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$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{T_i}dx_{T_j}d\cos\phi}x_{T_i}x_{T_j}\cos\phi = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{T_i}^A E_{T_j}^A}{\left(\sum_k E_{T_k}^A\right)^2}\delta\left(\cos\phi - \cos\phi_{ij}\right)$$

▶ Valid for a sample of N multijet events, labelled by index A, with indices i, j, k running over all jets in a given event

▶ $E_T = E/\cosh y$

▶ $x_{T_i} = E_{T_i}/\sum_k E_{T_k}$: normalized transverse energy of jet i

▶ ϕ_{ij}: angle in the transverse plane between jet i and jet j

▶ Normalization to the total dijet cross-section, σ, ensures the integral of the TEEC function over $\cos\phi$ is unity

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▶ χ^2 function:

$$\chi^2(\alpha_s, \boldsymbol{\lambda}) = \sum_{\text{bins}} \frac{(x_i - F_i(\alpha_s, \boldsymbol{\lambda}))^2}{\Delta x_i^2 + \Delta \xi_i^2} + \sum_k \lambda_k^2$$
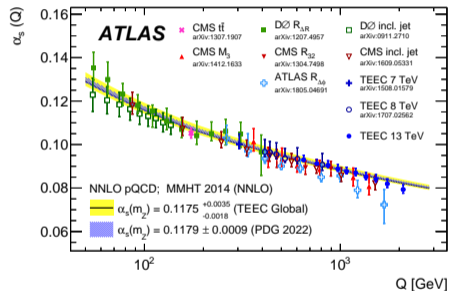
where the theoretical predictions are varied according to

$$F_i(\alpha_s, \boldsymbol{\lambda}) = \psi_i(\alpha_s)\left(1 + \sum_k \lambda_k \sigma_k^{(i)}\right)$$

▶ α_s: $\alpha_s(m_Z)$
▶ x_i: value of the i-th point of the distribution as measured in data
▶ Δx_i: statistical uncertainty of x_i
▶ $\Delta \xi_i$: statistical uncertainty on theory predictions and uncorrelated modelling uncertainty
▶ $\psi_i(\alpha_s)$: analytical expression for dependence of each observable on the strong coupling constant for bin i
▶ λ_k: nuisance parameter associated with each source of experimental uncertainty
▶ $\sigma_k^{(i)}$: relative value of the k-th correlated source of systematic uncertainty in bin i

- The scale Q that $\alpha_s(Q)$ is measured at is ultimately an arbitrary choice
- Selecting the scale to be $Q = m_Z$ is practically useful as it allows comparisons to results from LEP
  - The value of Q for the TEEC 13 TeV points is chosen as half of the average of $\hat{H}_T$ in each H_{T2} bin
- ~ 0.25 of total V production cross-sections at LHC come from processes beyond the Born level, and so depend on QCD coupling value. Calculating V production cross-sections at NNLO for varying $\alpha_s(m_Z)$ can derive value of $\alpha_s(m_Z)$ independent of other current extractions. [arXiv:1912.04387]

Comparison of the values of $\alpha_s(Q)$ determined from fits to the TEEC functions with the QCD prediction using the world average as input (hatched band) and the value obtained from the global fit (solid band).