QCD measurements in pp collisions:

From the underlying event to jets

11th Edition of the Large Hadron Collider Physics Conference

10.03.2023

Armando Bermúdez Martínez

on behalf of the ALICE, LHCb, ATLAS and CMS collaborations

LHCPhysics

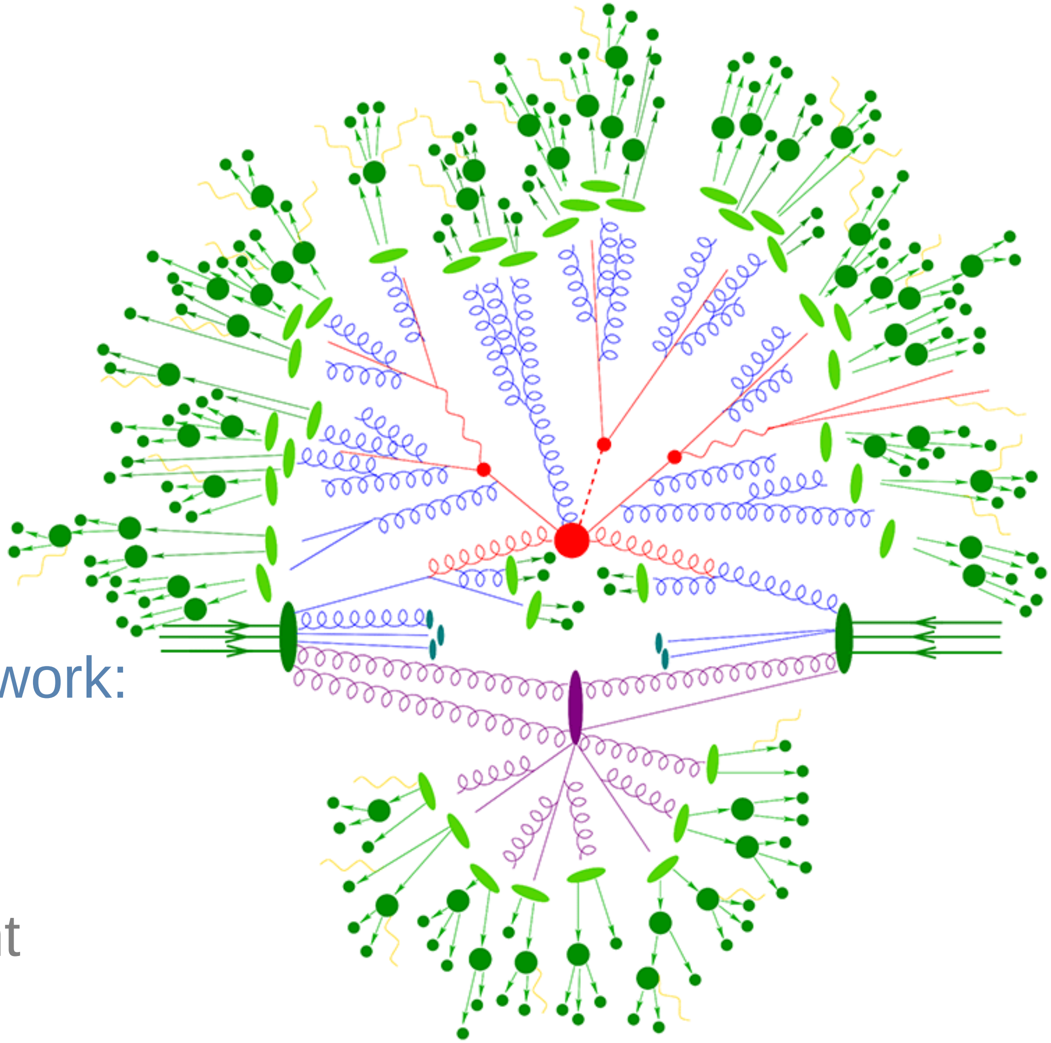
Belgrade, 22 - 26 May 2023

CERN

QCD at the LHC

How we approach the problem:

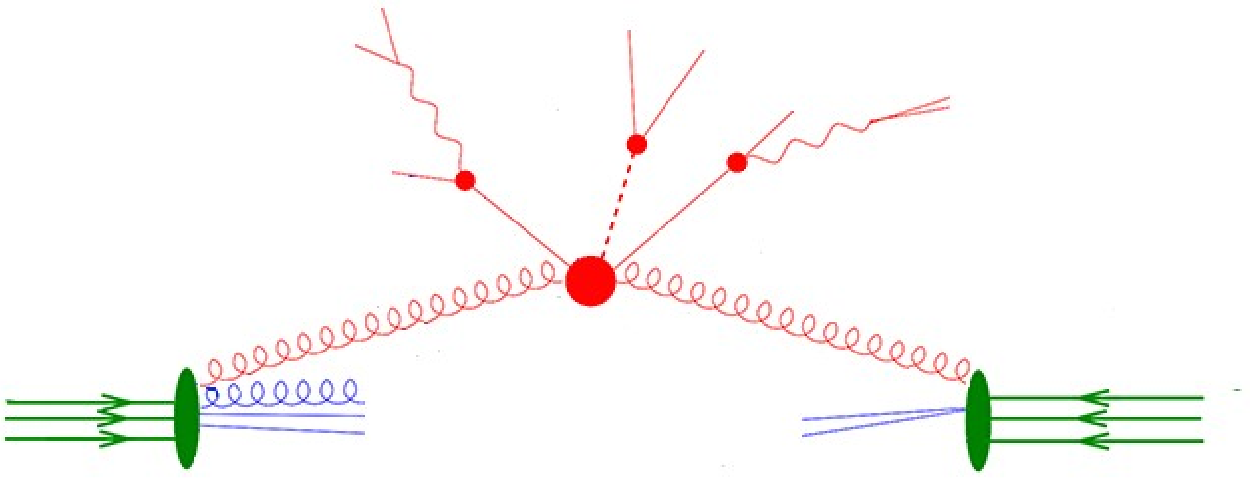
- Hard interaction
- PDFs, TMDs
- Parton Showers
- Multi Parton Interactions
- Fragmentation and Hadronization
- Beam remnants



How we challenge our theory framework:

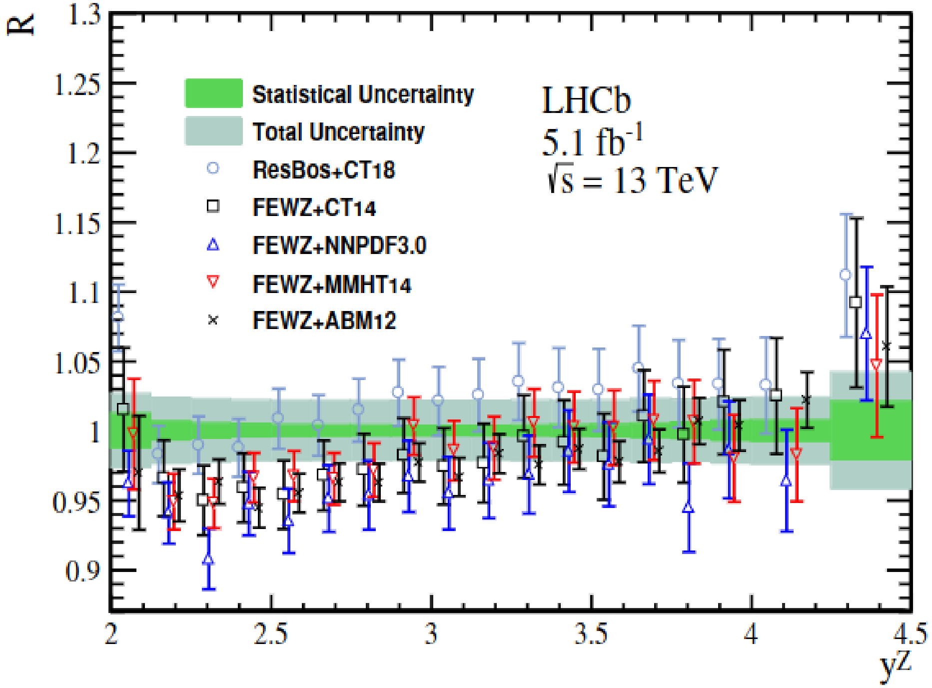
- High presicion measurements of separate components
- Test the interplay between different regimes
- Discriminating between assumptions
- Constraints and input on models

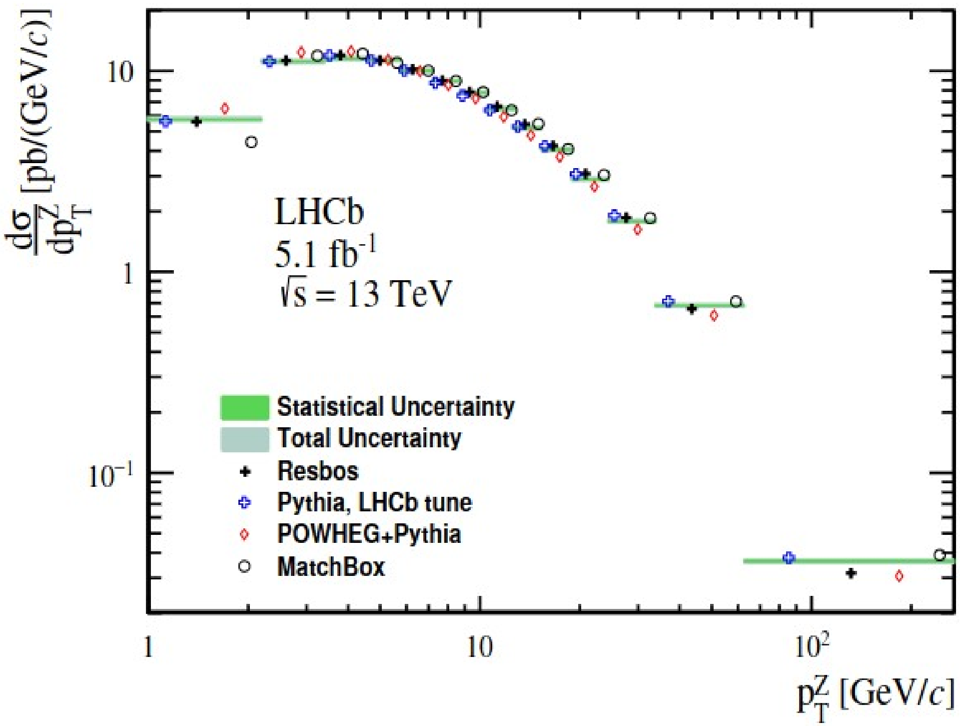
The Hard Process



Forward Z boson production

JHEP 07 (2022) 026

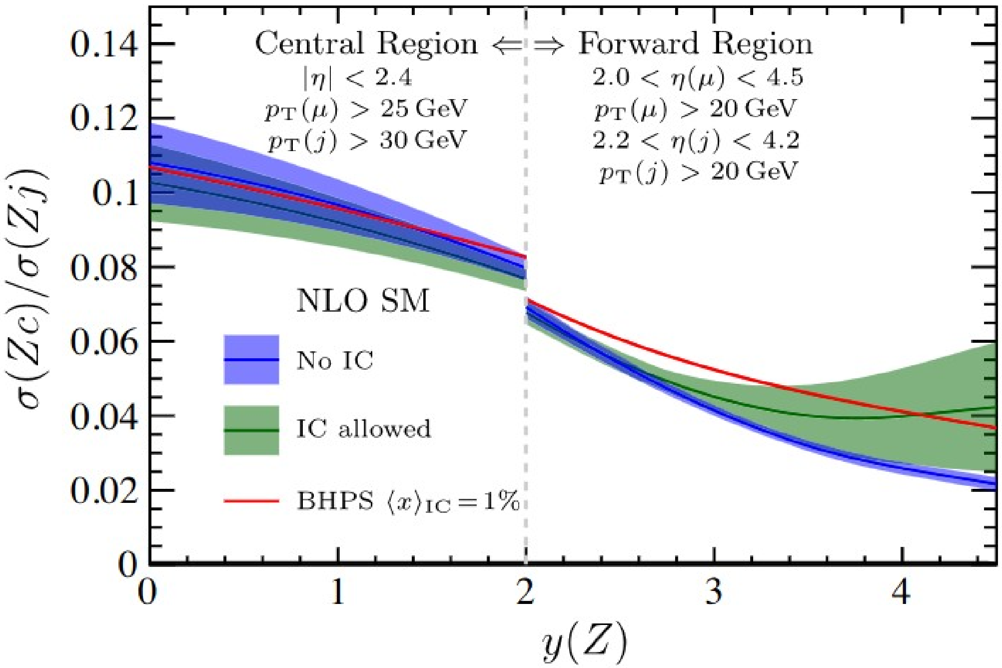


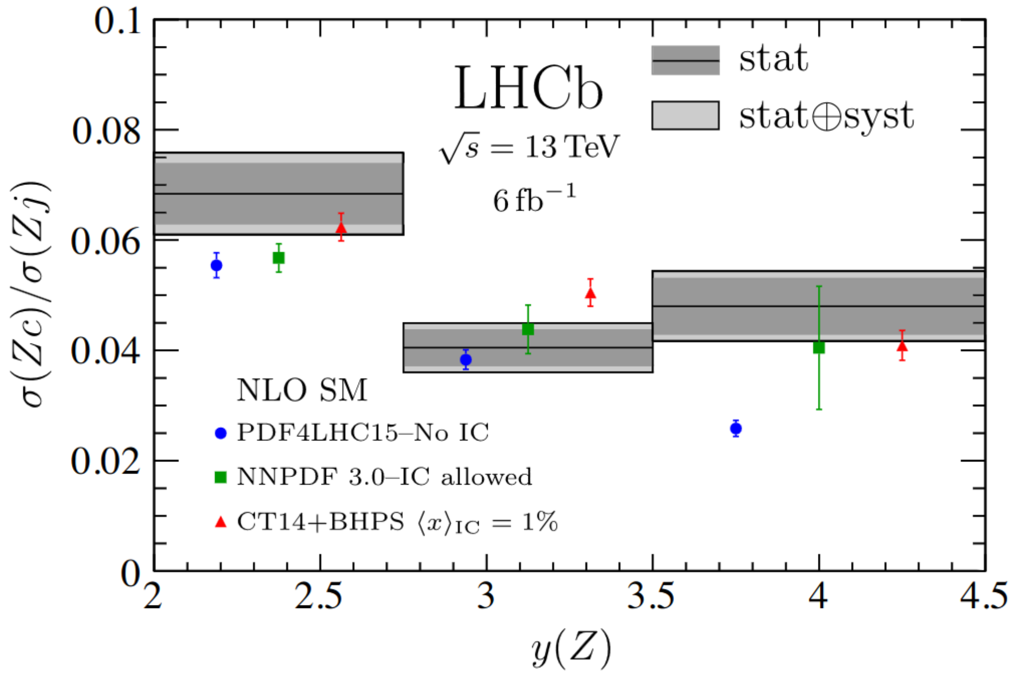


- Differential in y^Z, p_T^Z, ϕ^*_η
- $60 < m_{\mu\mu} < 120$ GeV, $p_T^\mu > 20$ GeV, **$2 < \eta^\mu < 4.5$**
- Data is compared to NLO and NNLO predictions
- **Sensitive to quark PDF at low and high x**
- **Important test of pQCD at high p_T^Z and TMD physics at low p_T^Z**

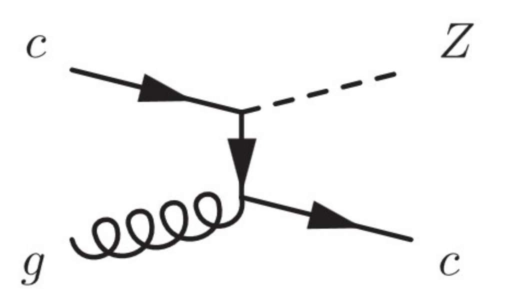
Z boson in association with charm

Phys. Rev. Lett. 128 (2022) 082001





- Fraction of c-jets as a function of y^Z
- $20 < p_T^J < 100$ GeV, $2.2 < \eta^J < 4.2$, $p_T^C > 5$ GeV
- **Probing intrinsic charm**
- **Sizable enhancement is observed at high y^Z**

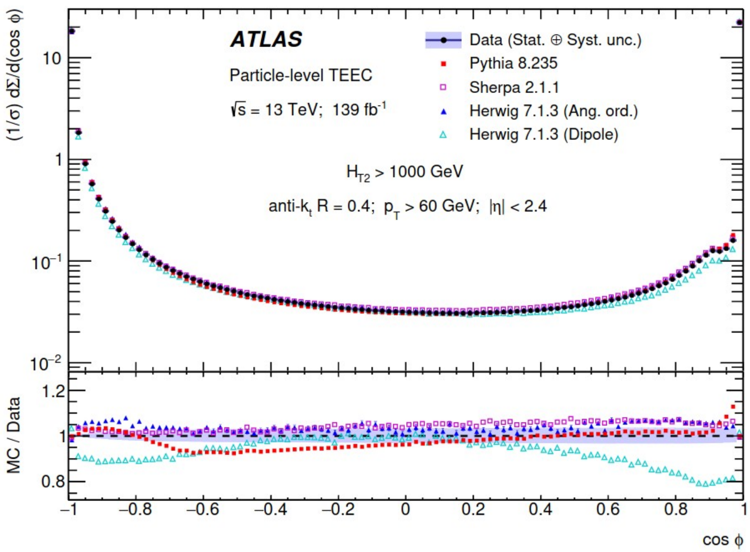


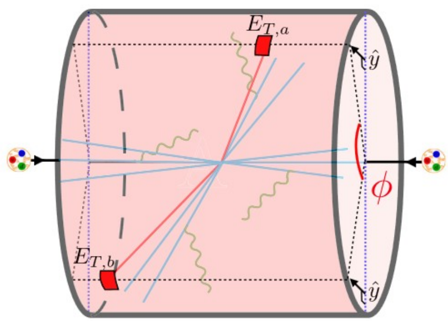
see talk by D. Zuliani

Transverse energy-energy correlations

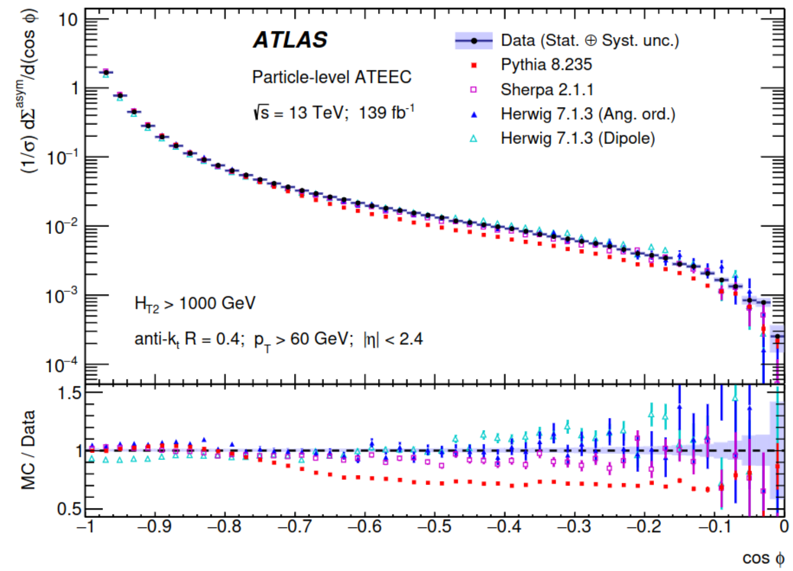
arXiv:2301.09351

Back-to-back ⟷ collinear

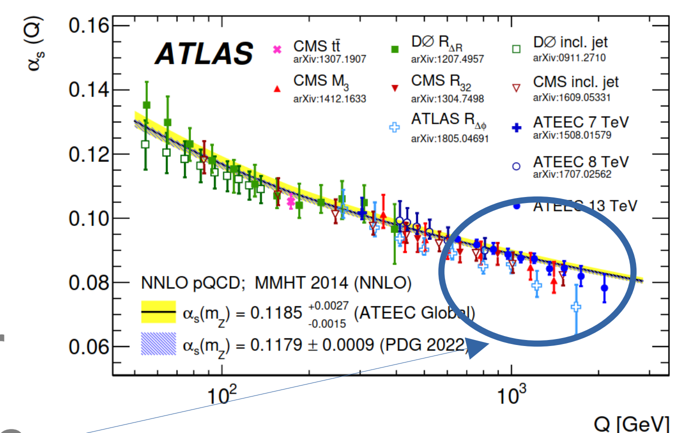




PRL 123 (2019) 062001



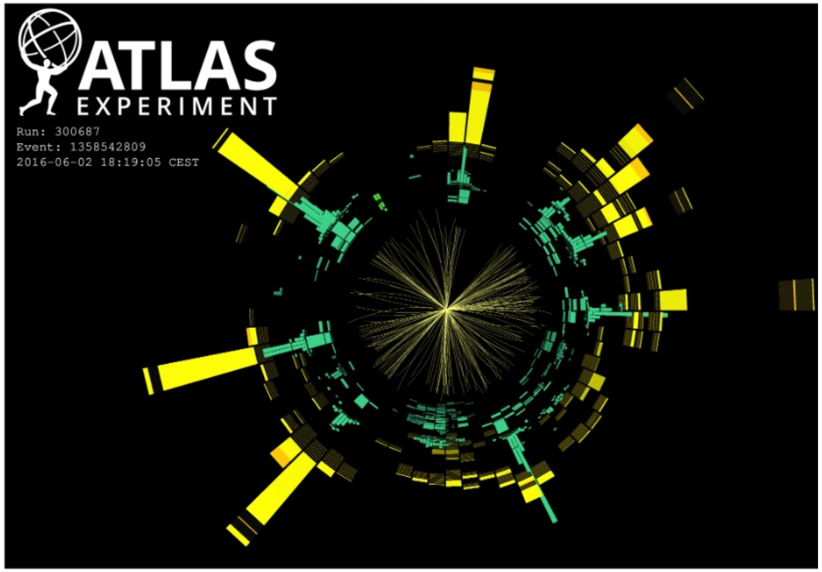
- TEEC and ATEEC in multi-jet events in bins of H_{T2}
- NNLO corrections to 3-jet reduces systematics
- Sensitivity to hard QCD radiation and α_S
- **Factorization formula in the limit $\phi \rightarrow 0$**
- **Best description by angular ordered shower**
- **Probing asymptotic freedom at the TeV scale**

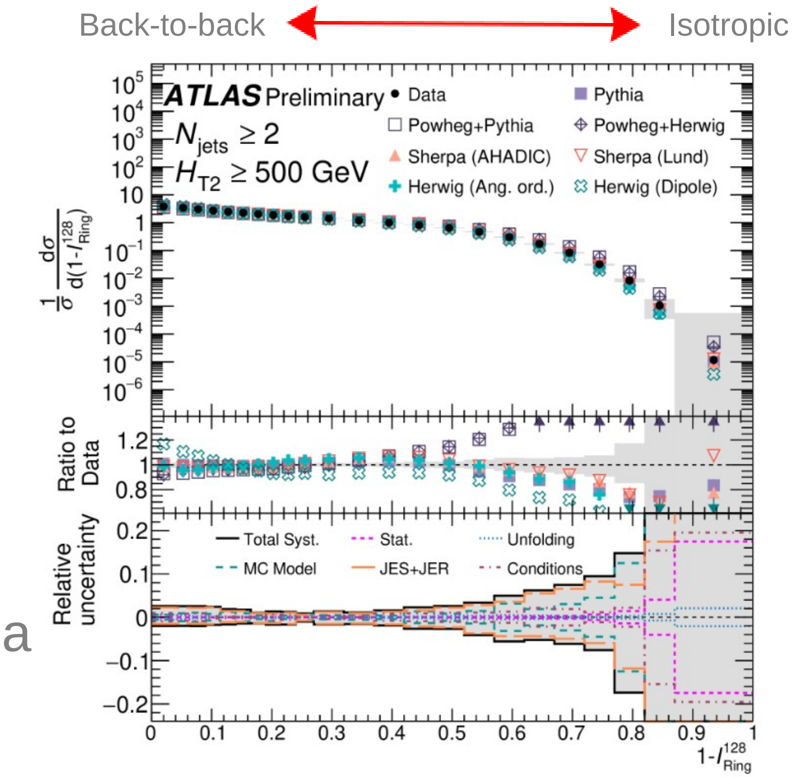


Multi-jet event isotropies

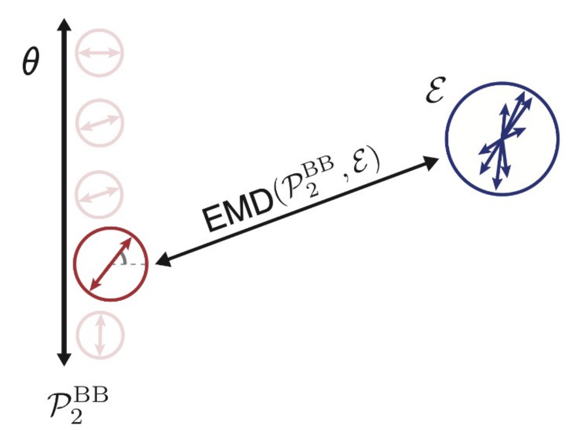
ATLAS-CONF-2022-056

$$1 - I^{128}_{\text{Ring}} = 0.92$$



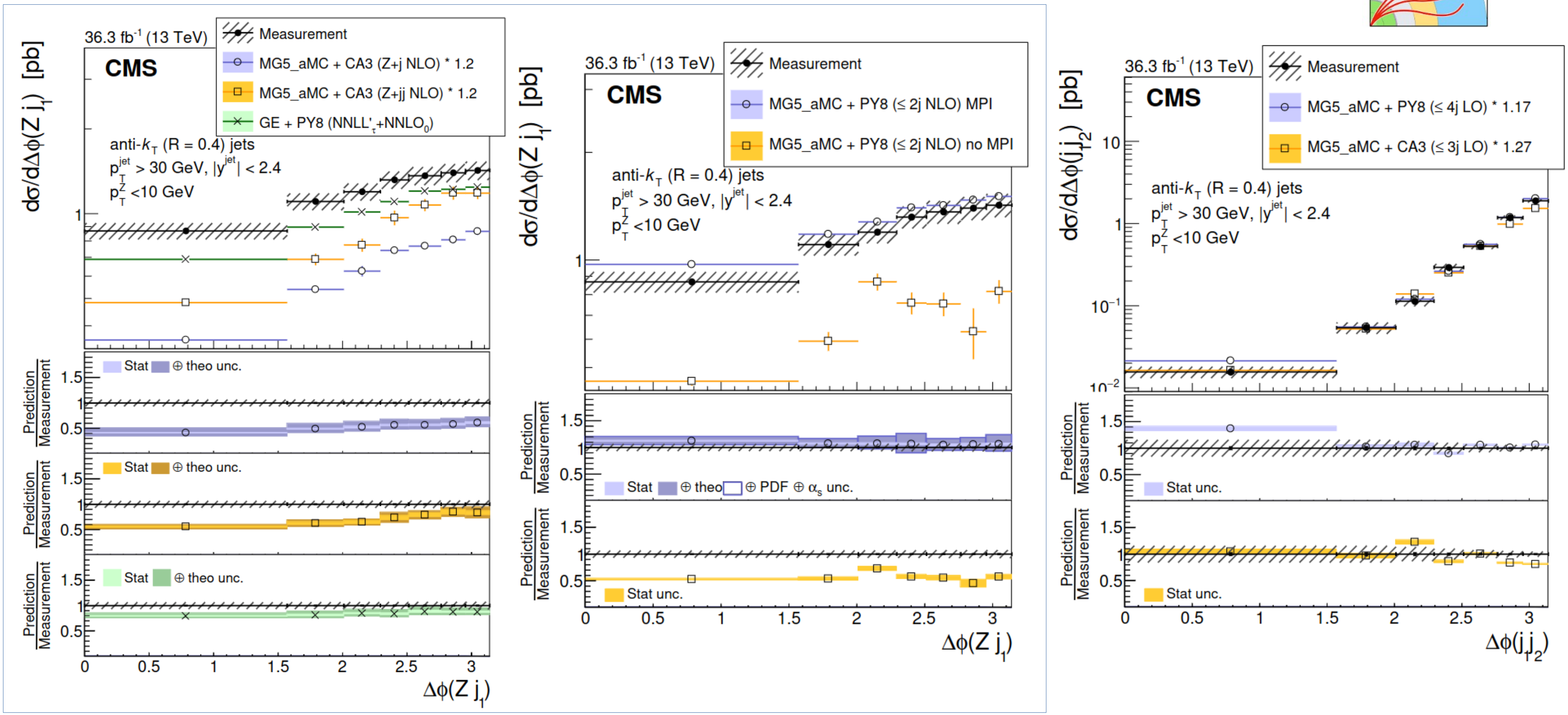


- Event isotropies quantify how far an event is from a symmetric radiation pattern
- Two-points, cylindrical and ring shapes
- $p_T > 60$ GeV, $|y| < 4.4$, bins: $N_{\text{jets}} \geq 2$, $N_{\text{jets}} \geq 5$, $H_{T2} >$ 500, 1000, and 1500 GeV
- Infrared and collinear safe
- **Very sensitive to isotropic events, large dynamic range**
- **Large difference between dipole and angular PS**



Azimuthal correlations in Z+jets

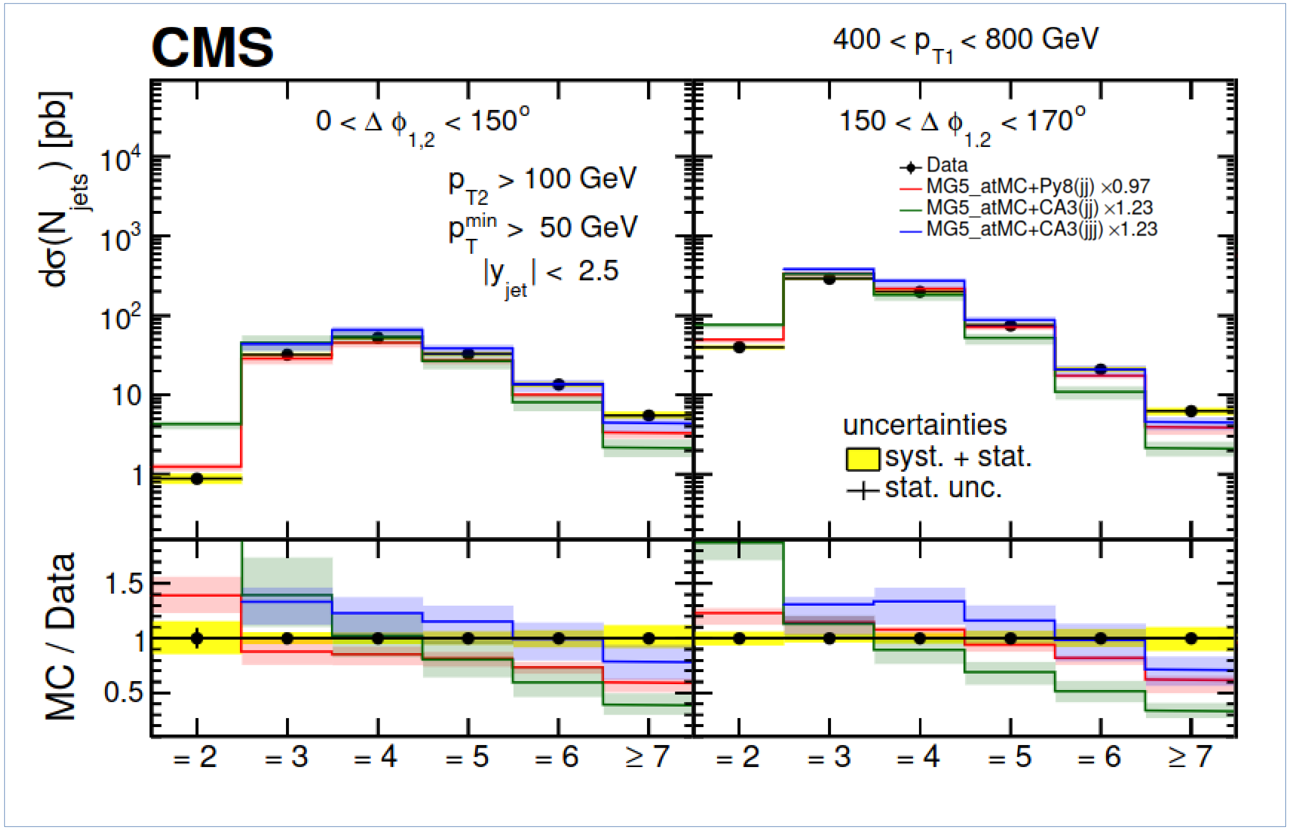
arXiv:2210.16139

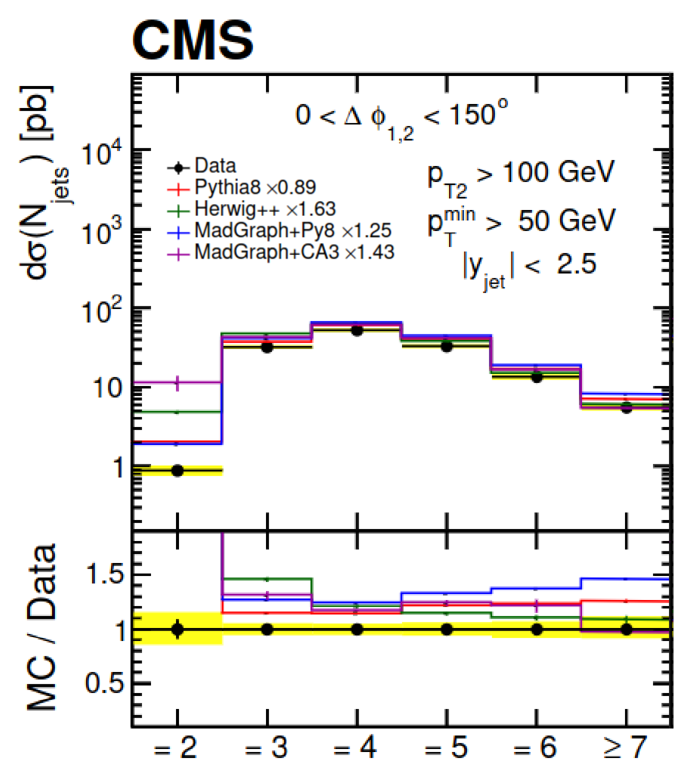


- Azimuthal correlations in bins of p_T^Z
- Sensitive to higher order corrections, resummation and MPI
- Collinear and TMD predictions compared to data
- **MPI contribution significant, smaller for the dijet case**
- **MPI contribution from Pythia8 behaves as multiplicative factor**

Multi-jet correlations and multiplicity

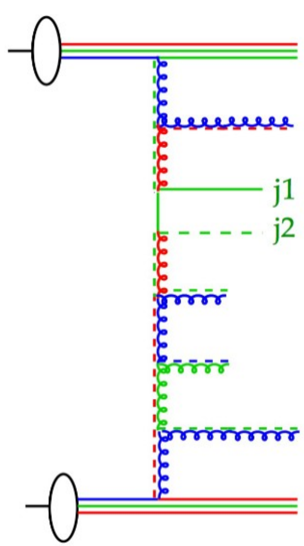
arXiv:2210.13557

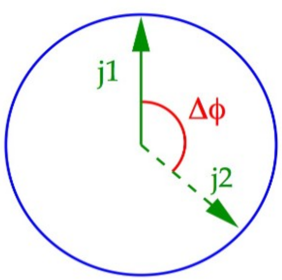




- Jet multiplicity as a function of azimuthal separation
- Sensitive to higher order corrections
- Collinear and TMD predictions compared to data
- **Angular ordered predictions fail to describe large recoils with many jets**

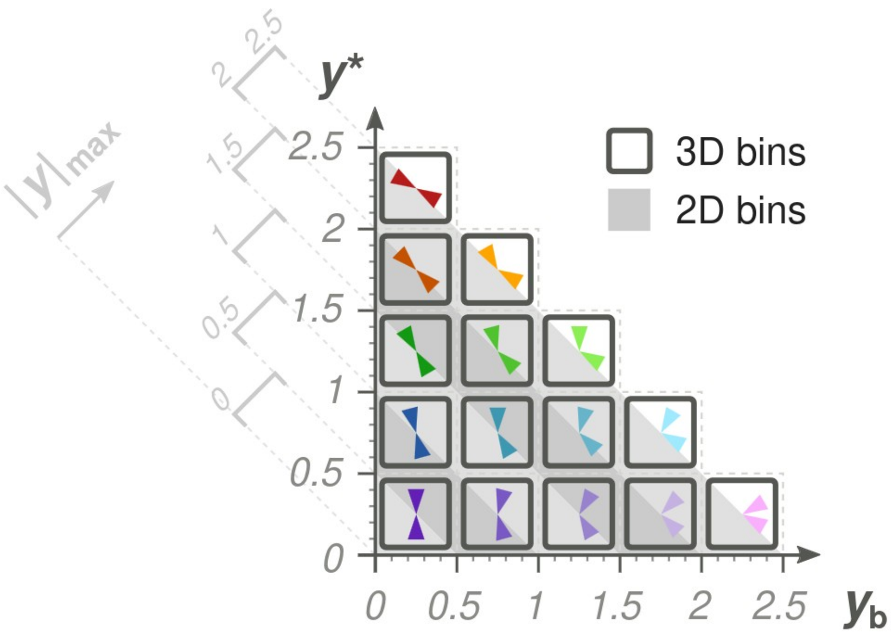
see talk by C. Savoiu

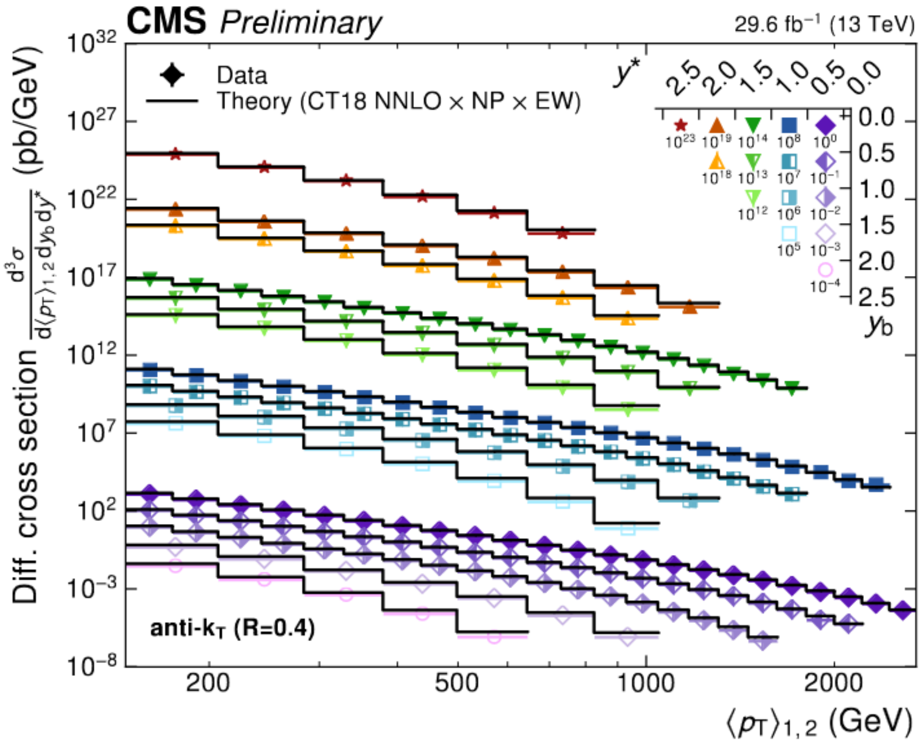




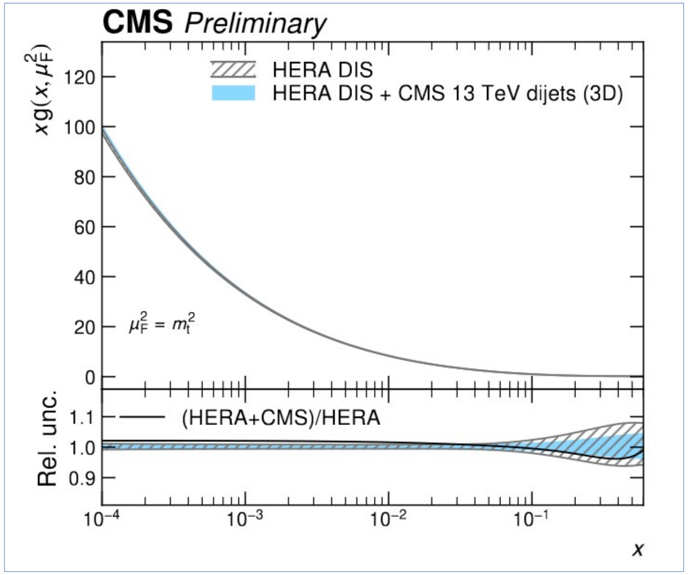
Multi-differential di-jet cross section

CMS-PAS-SMP-21-008



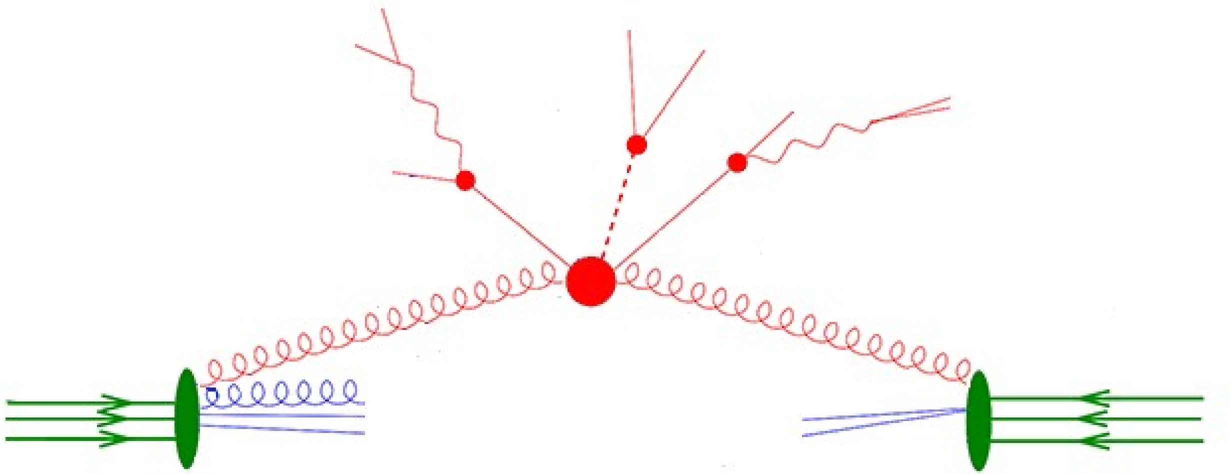


- Differential dijet cross section
- Compared to NNLO in pQCD
- **Sensitive to PDF and strong coupling**
- **Improved constraints on gluon PDFs at high x**

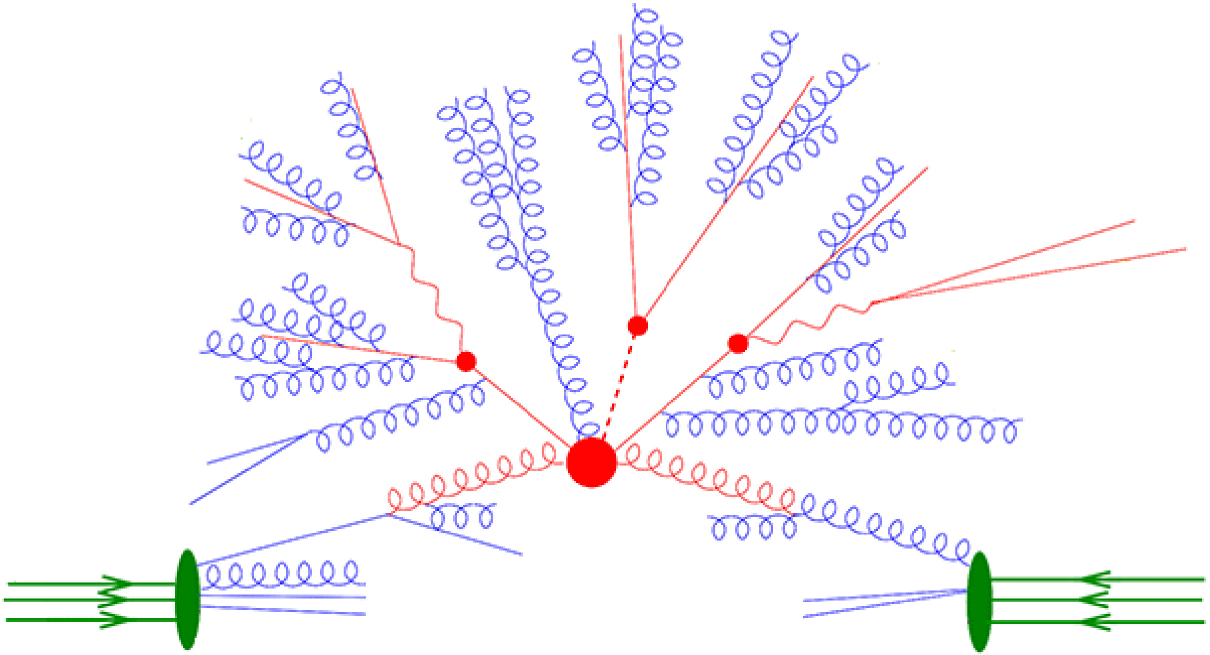


see talk by C. Savoiu

Hard Process

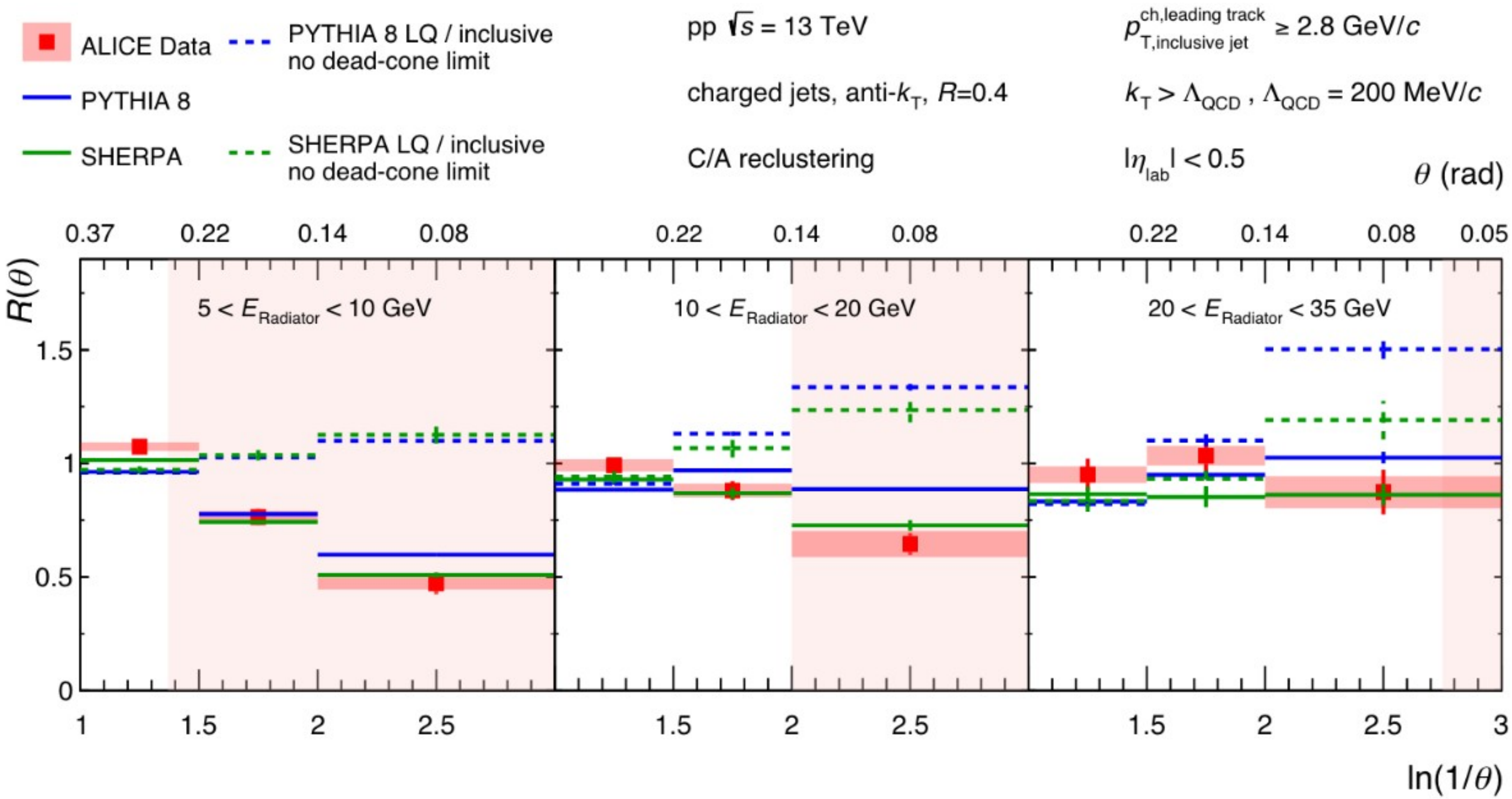


Hard Process + Parton Shower

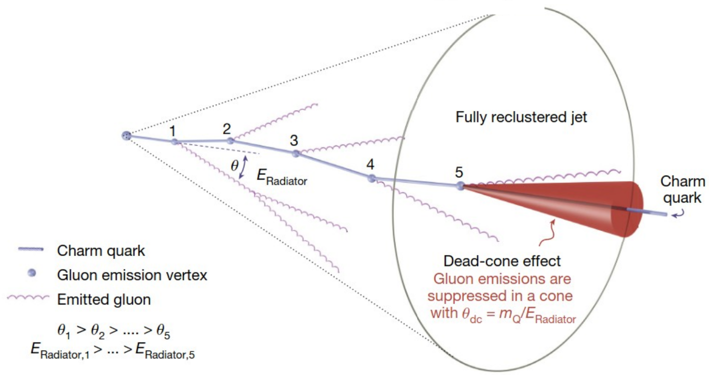


Dead cone effect

Nature 605, 7910 (2022): 440-446

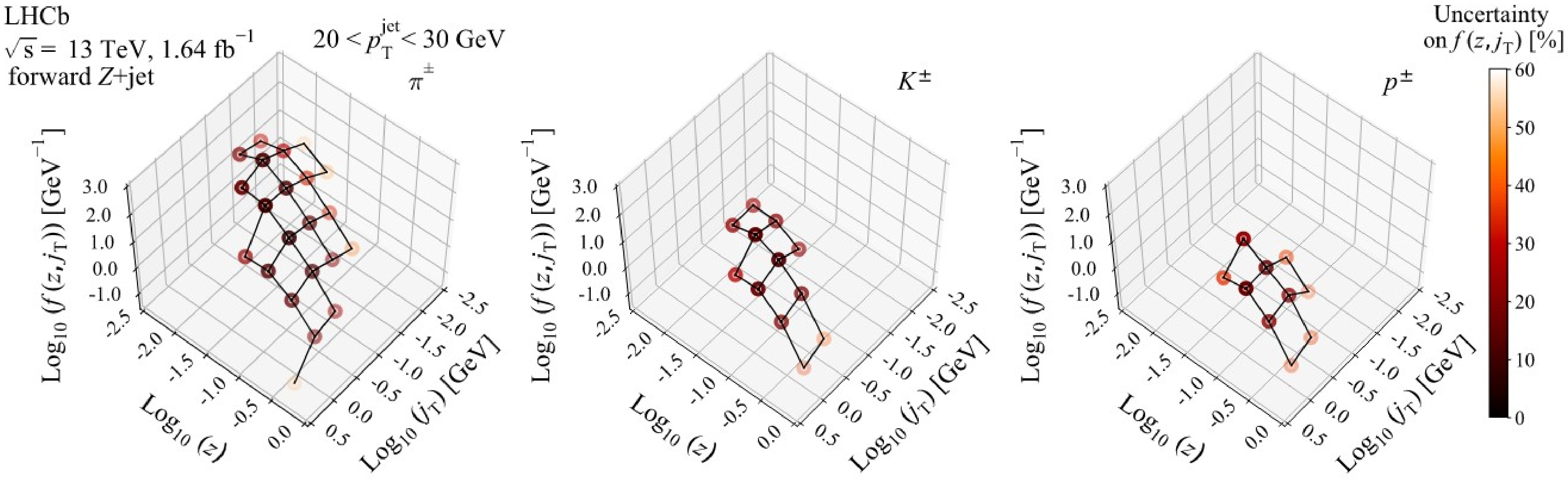


- Ratio of splitting angle distributions for c-jets and inclusive jets
- Suppression of small angle emissions
- **First direct observation of dead cone effect**



Jet substructure in Z-tagged jets

arXiv:2208.11691

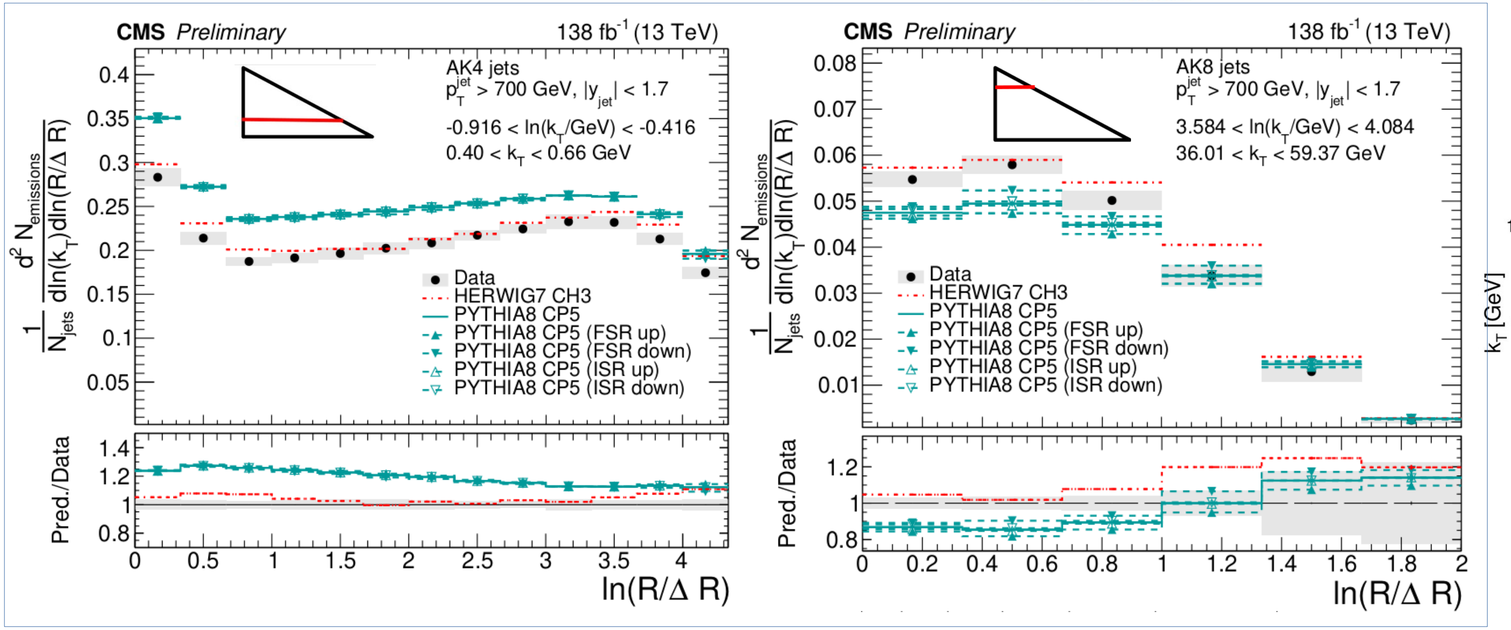


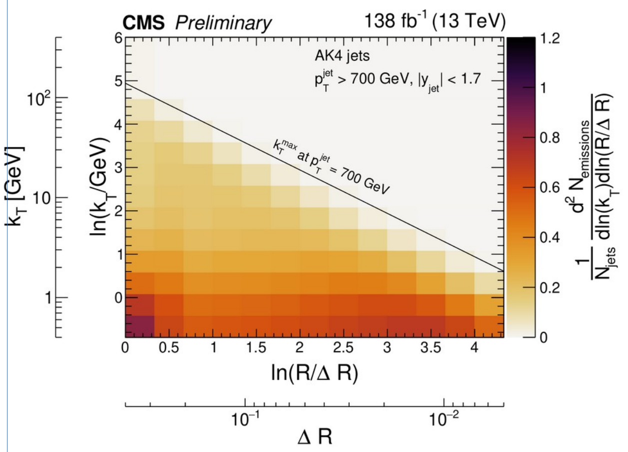
- Charged-hadron distributions as a function of hadron longitudinal momentum fraction, hadron p_T, and jet p_T
- Probing both the longitudinal and transverse profile
- Probing mass hierarchy in the hadronization process
- **Constraints on TMD FFs in new phase space**

PRL 124 (2020) 222002

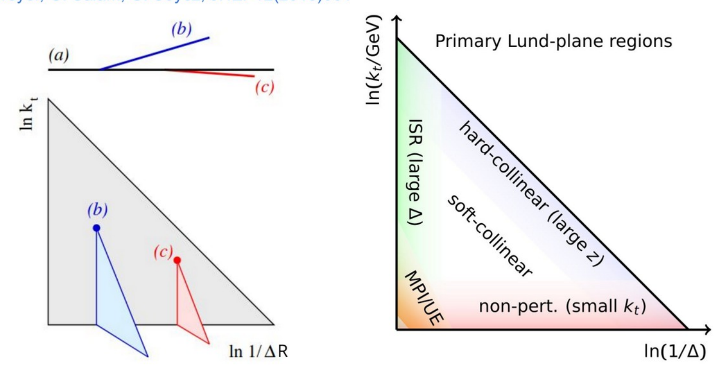
Primary Lund Jet Plane

CMS-PAS-SMP-22-007





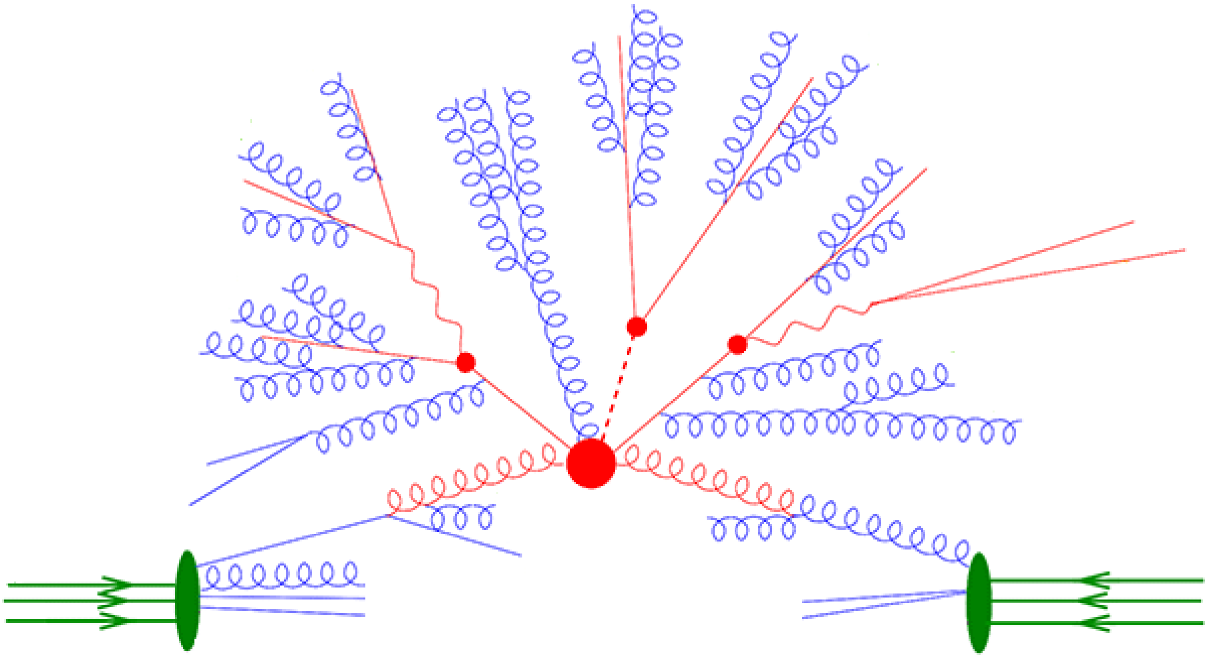
F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064



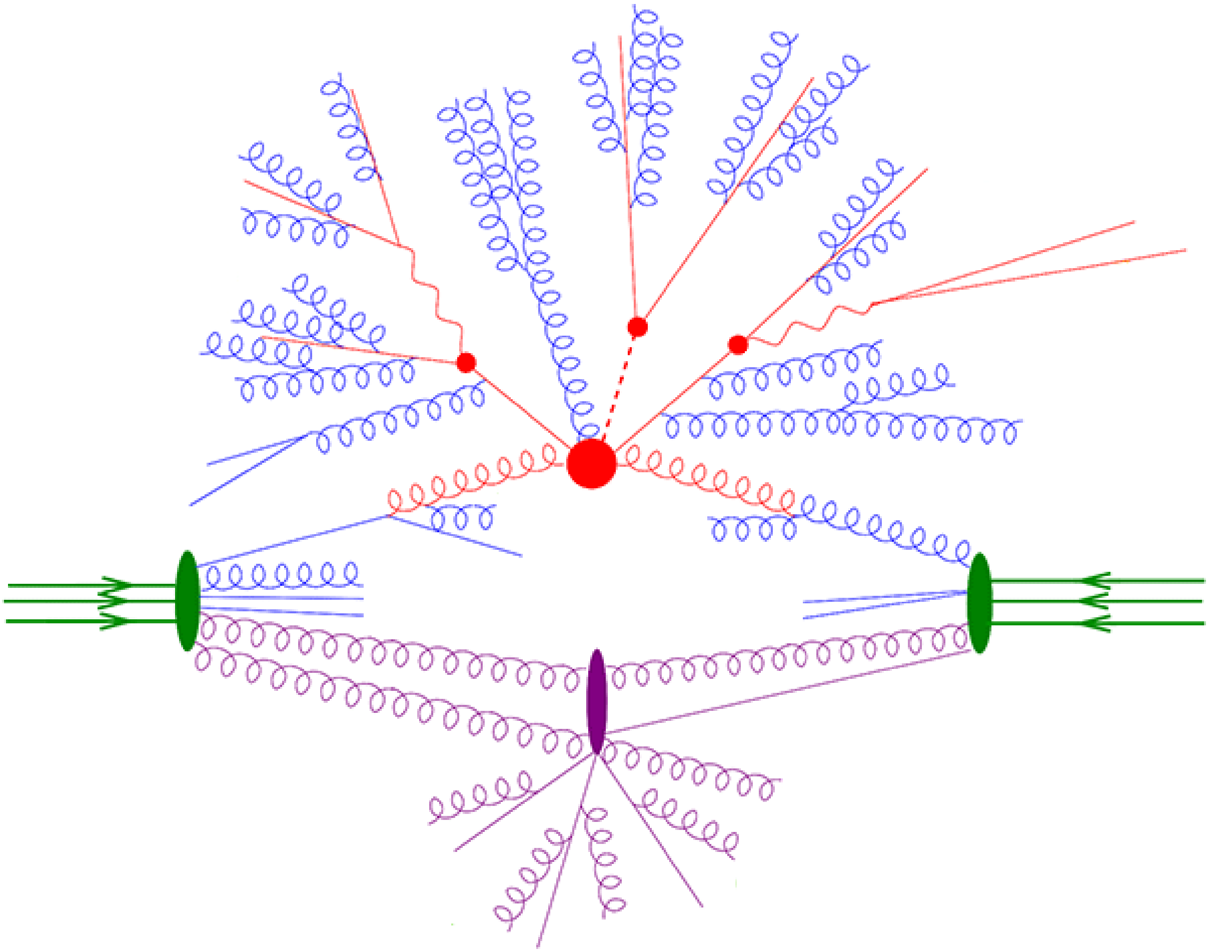
- 2D representation of 1→2 splitting phase space
- Different mechanisms are factorized
- Done in high p_T jets (700 GeV) to open up the phase space for evolution
- Soft- and hard-collinear region similarly described by angular- and pt-ordered showers
- **Wide-angled well described by angular ordered PS**
- **Constraints on MC generators, improvements on jet tagging**

see talk by C. Savoiu

Hard Process + Parton Shower

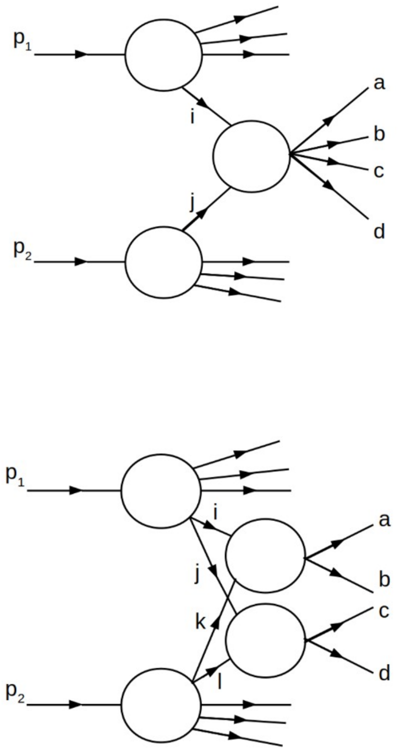


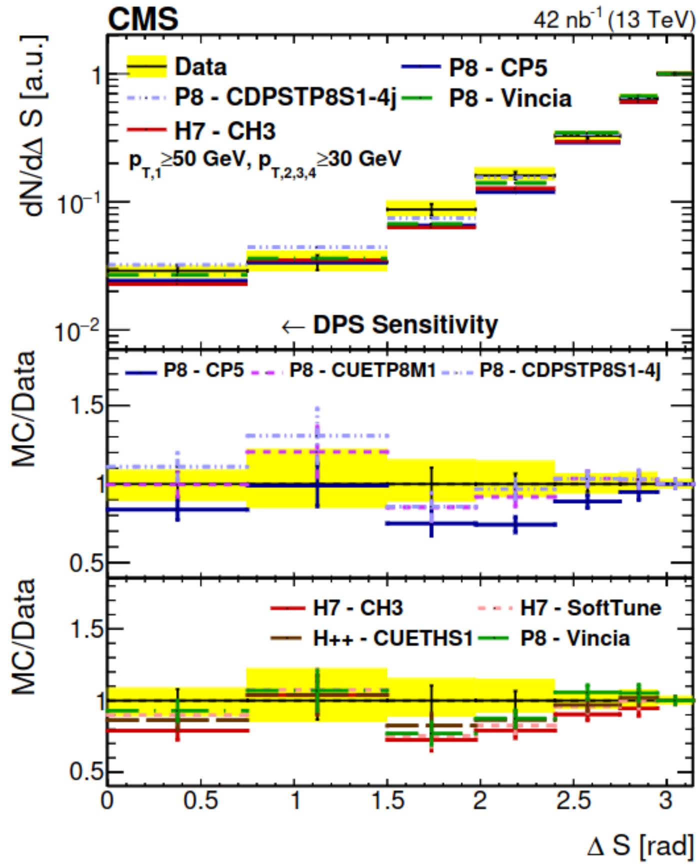
Hard Process + Parton Shower + MPI



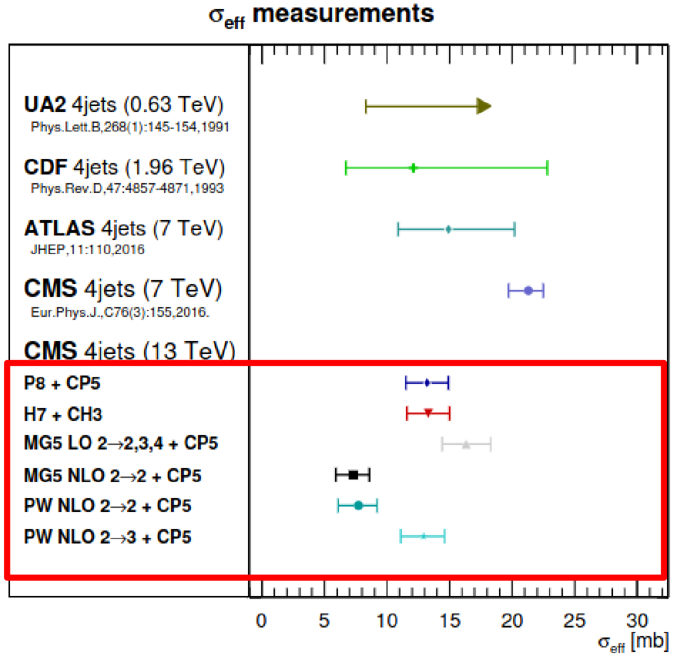
DPS in four jet events

JHEP01(2022)177





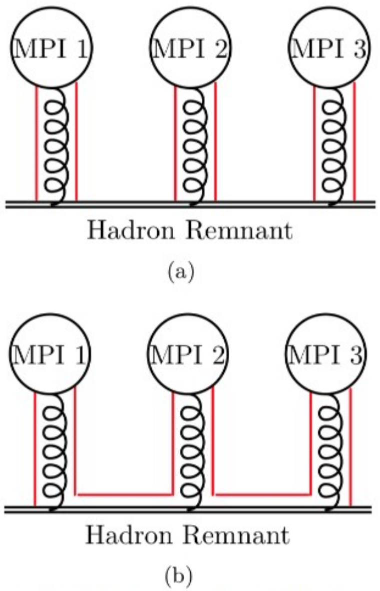
$$\sigma^{\rm DPS}_{\rm A,B} = \frac{m}{2}\frac{\sigma_{\rm A}\sigma_{\rm B}}{\sigma_{\rm eff}}$$



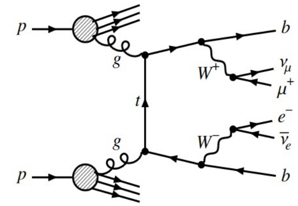
- Study of observables sensitive to DPS
- MPI important for describing measurements
- ΔS least sensitive to shower model, used to determine $\sigma_{\rm eff}$
- **Background modeling difficult especially when jets are present**
- **Need to improve the underlying models**

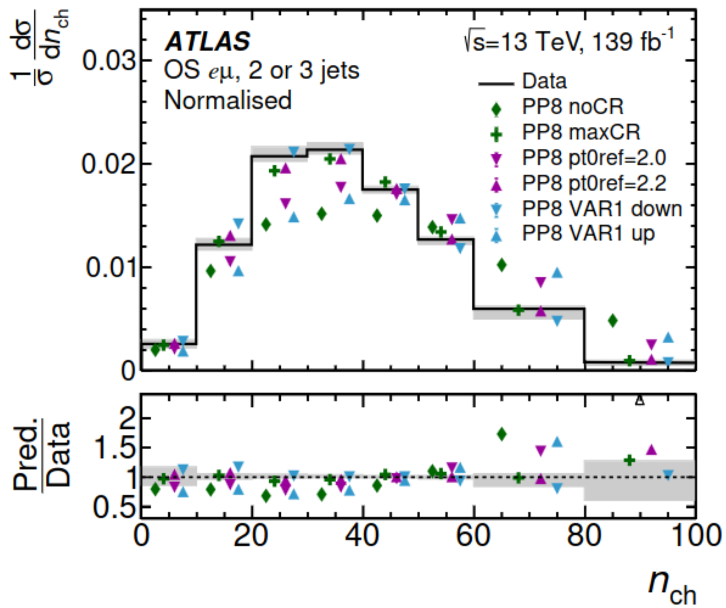
Observables sensitive to CR

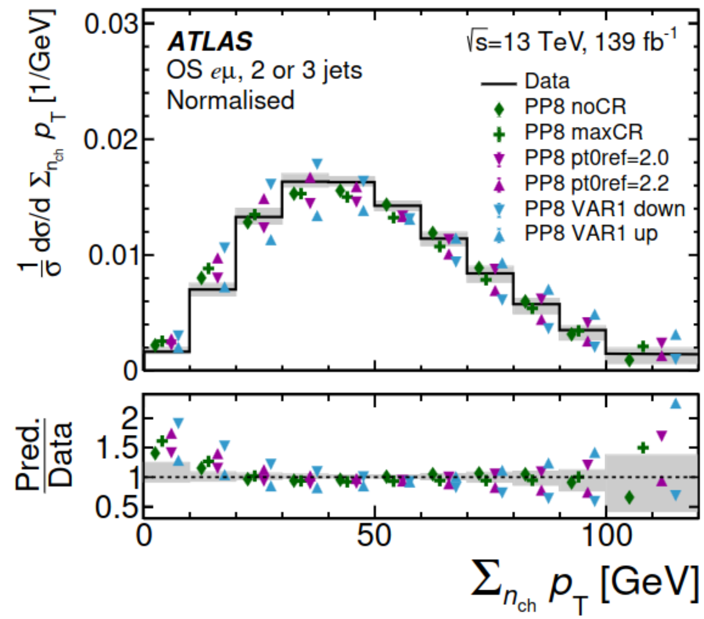
arXiv:2209.07874



Christiansen, J.R. & Skands, P.Z. J. High Energ. Phys. (2015) 2015: 3.

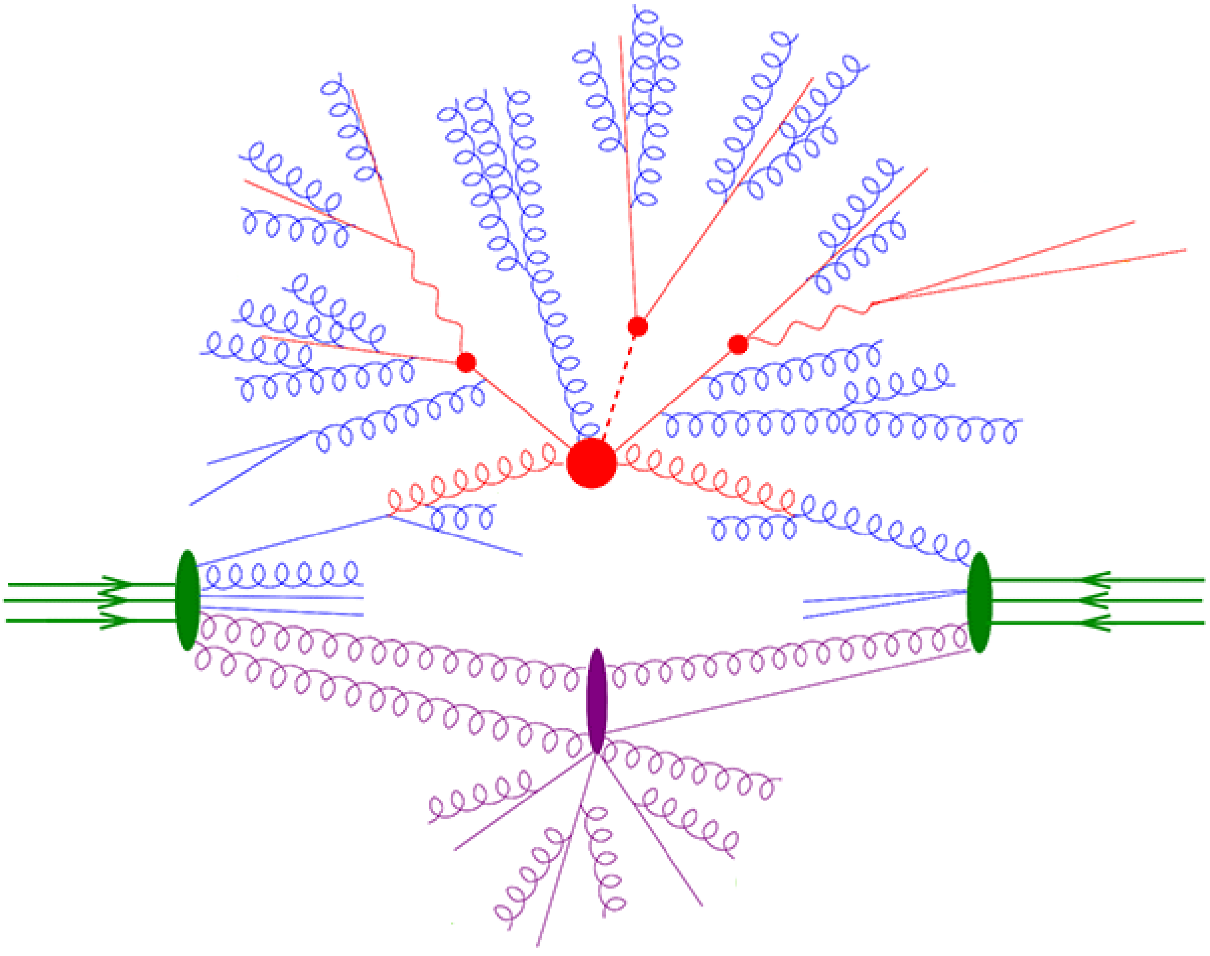




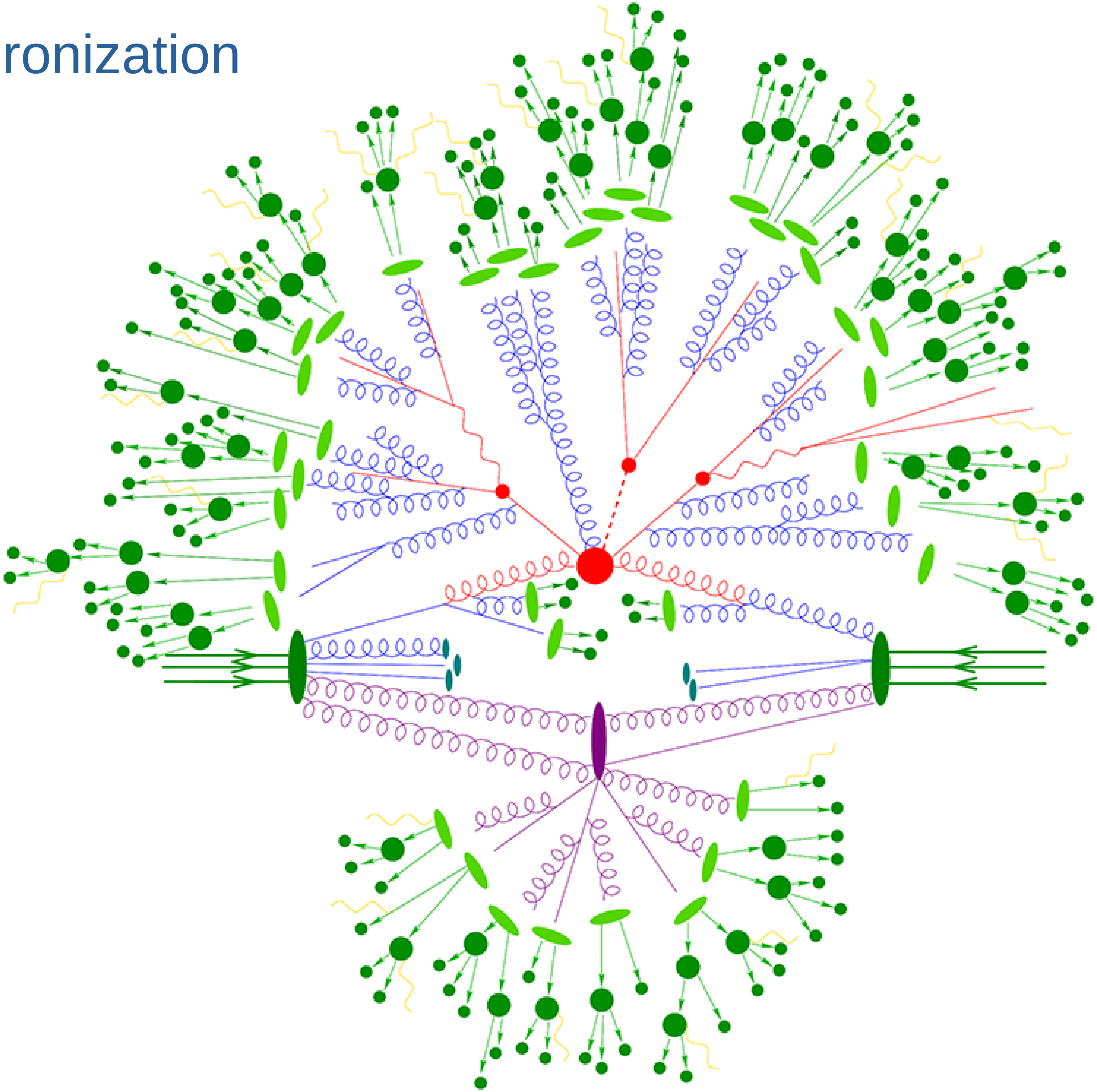


- Considerable freedom in MC generators, systematic source for m_{top}
- ttbar events in the dileptonic channel
- Study of charge multiplicity, and scalar sum of pT of charged particles
- CR is necessary to describe the data
- Interplay between number of MPI and CR
- **Results are valuable input for better tuning of the MC generators**

Hard Process + Parton Shower + MPI

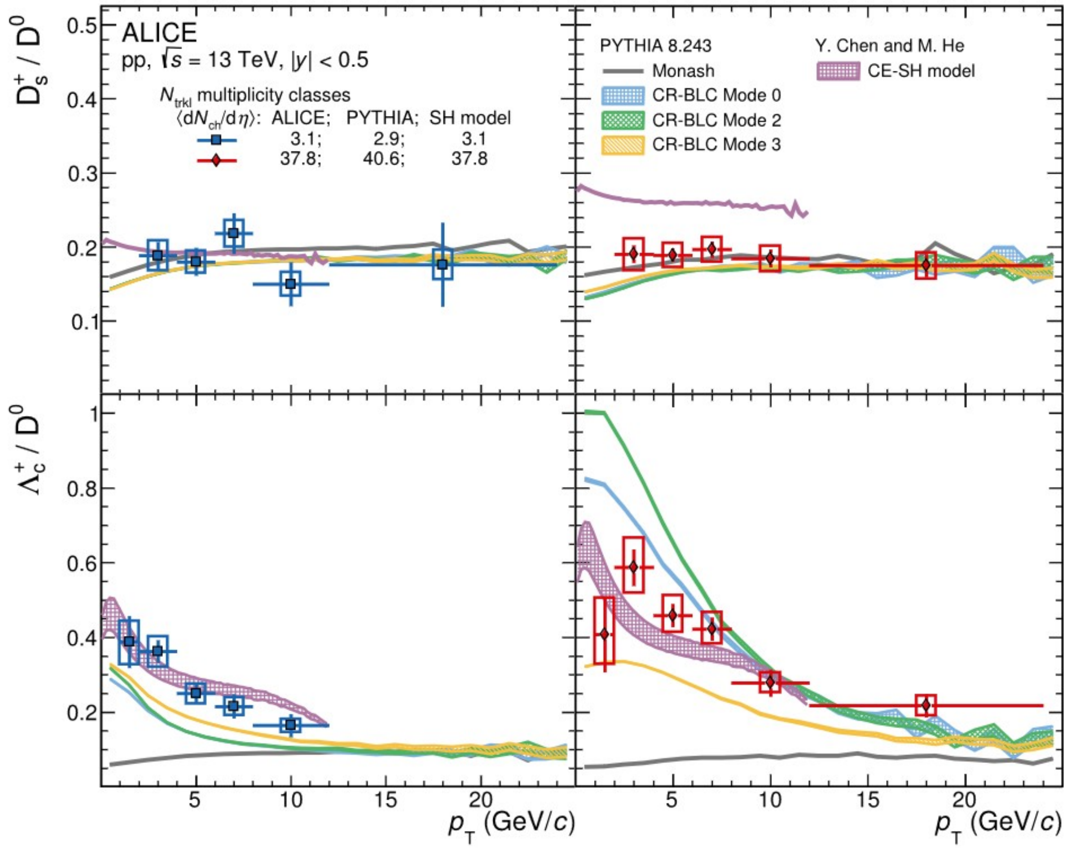


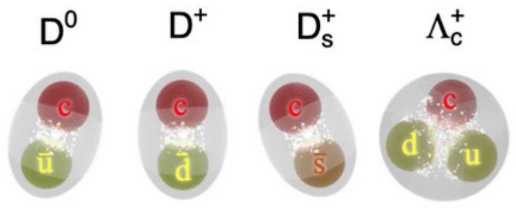
+ Hadronization

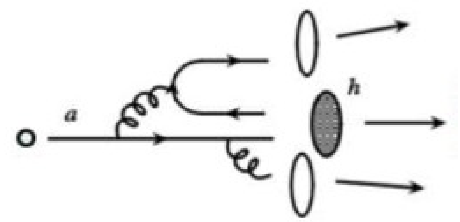


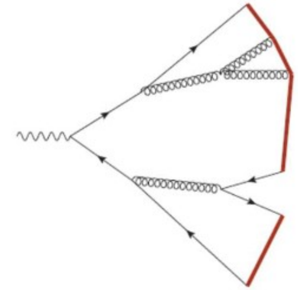
Charm baryon-to-meson ratios

PLB 829 (2022) 137065









- First measurement of D_s^+/D_0 and Λ_c^+/D_0 in pp at 13 TeV
- Study the modification of fragmentation mechanism as environment changes
- D_s^+/D_0 does not dependence on either pT or multiplicity
- Λ_c^+/D_0 larger at high multiplicity
- **Shape described by beyond-leading-color models**
- **Confirms limited validity of universality of fragmentation functions**

Summary

- LHC provides unique environment to test QCD, from soft to very high p_T scales
- ATLAS, LHCb, ALICE and CMS have an innovative program to probe soft and hard QCD effects
- Very valuable input and constraints to theoretical models
- Wide variety of measurements recently made public by the large LHC experiments:

ALICE Public Results

LHCb Public Results

ATLAS Public Results

CMS Public Results

Publicly Available Parton Showers

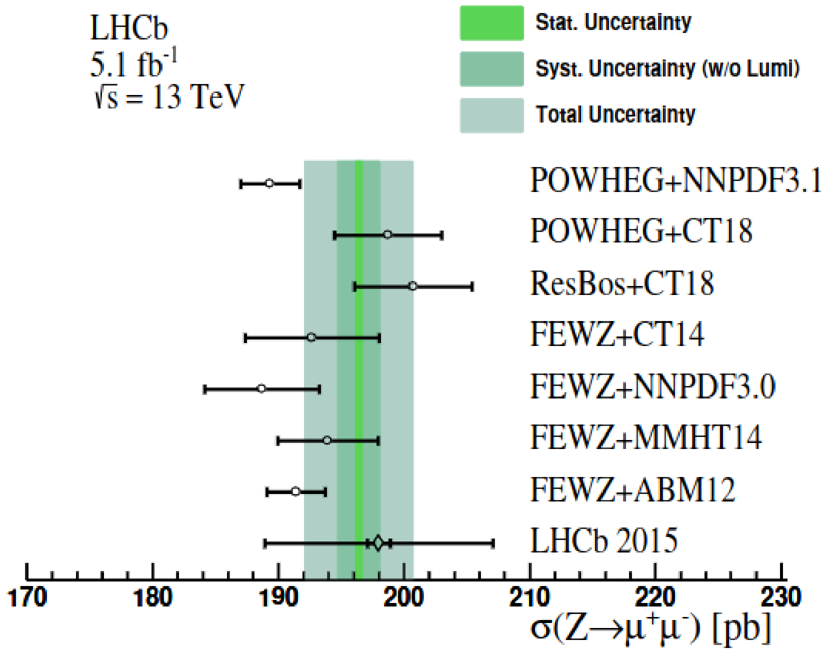
	Evolution variable	Splitting variable	Coherence
Ariadne	dipole $p_\perp^2$	Rapidity	$2 \to 3$ kernel
Herwig	$E^2\theta^2$	Energy fraction	Ang. ord.
Herwig++ / H7	$(t - m^2)/(z(1-z))$	LC mom. frac.	Ang. ord.
	dipole $p_\perp^{2\prime}$	LC mom. frac.	$2 \to 3$ kernel
Pythia 6	t	Energy fraction	Enforced
Pythia 8	$p_\perp^2$	Energy fraction	Enforced
Sherpa 1.1	t	Energy fraction	Enforced
Sherpa $\geq$1.2	dipole-$p_\perp^{2\prime\prime}$	LC mom. frac.	$2 \to 3$ kernel
Vincia	dipole-$p_\perp^{2\prime\prime\prime}$	LC mom. frac.	$2 \to 3$ kernel
Dire	dipole-$p_\perp^{2\prime\prime\prime\prime}$	LC mom. frac.	$2 \to 3$ kernel
...			

https://indico.cern.ch/event/829653/contributions/3568527/attachments/1946887/3230236/ps.pdf

Forward Z boson production

JHEP 07 (2022) 026

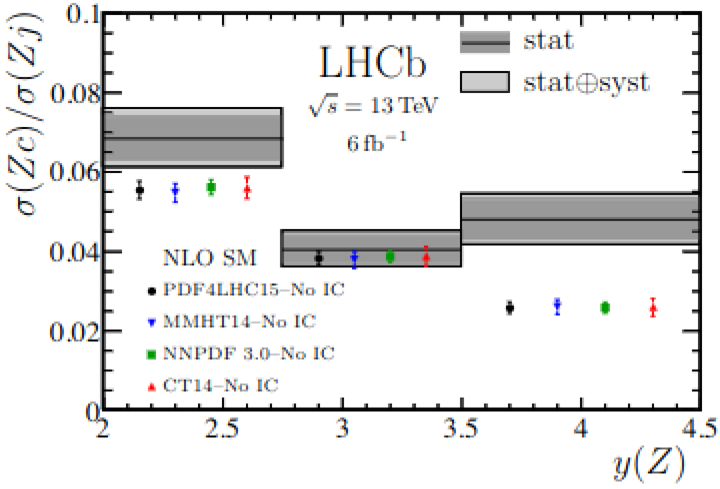
Source	$\Delta\sigma/\sigma$ [%]
Statistical	0.11
Background	0.06
Alignment & calibration	—
Efficiency	0.77
Closure	0.23
FSR	0.15
Total Systematic (excl. lumi.)	0.82
Luminosity	2.00
Total	2.16

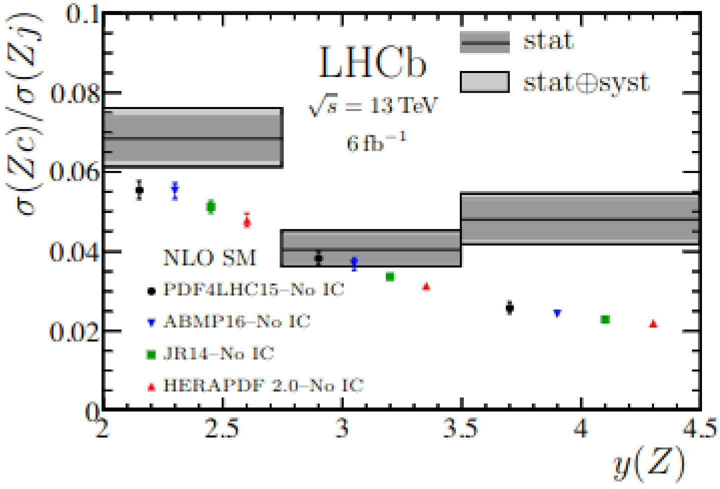


- Systematics dominated by luminosity and efficiency corrections: track reconstruction, PID and trigger
-

Z boson in association with charm

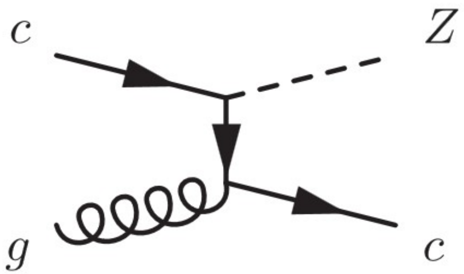
Phys. Rev. Lett. 128 (2022) 082001





- Jet flavor separated with displaced vertex (DV) tagger
- Systematics dominated by c-tagging efficiency

Z bosons	$p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120$ GeV
Jets	$20 < p_T(j) < 100$ GeV, $2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c \text{ hadron}) > 5$ GeV, $\Delta R(j, c \text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$



see talk by D. Zuliani

Transverse energy-energy correlations

arXiv:2301.09351

- transverse energy-weighted distribution of the azimuthal difference between jet pairs

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta\left(\cos\phi - \cos\varphi_{ij}\right)$$

- ATEEC: Difference between forward and backward part of TEEC

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma^{\mathrm{asym}}}{\mathrm{d}\cos\phi} = \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}\cos\phi}\bigg|_{\pi-\phi}$$

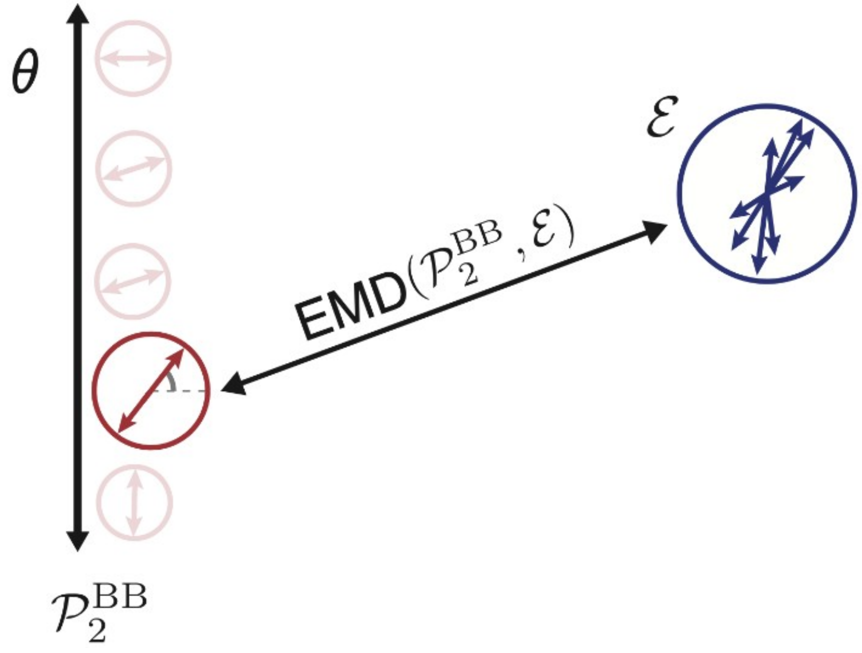
Multi-jet event isotropies

ATLAS-CONF-2022-056

- Event isotropies quantify how far an event E is from a symmetric radiation pattern U
- Energy mover's distance (EMD): minimum amount of work needed to transport one event E into another E' of equal energy

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

$$\sum_{i=1}^{M} f_{ij} = E'_j, \qquad \sum_{j=1}^{M'} f_{ij} = E_i, \qquad \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij} = \sum_{i=1}^{M} E_i = \sum_{j=1}^{M'} E_j = E_{\mathrm{tot}}$$



Charm baryon-to-meson ratios

PLB 829 (2022) 137065

- Mode 0: no time-dilation constraints. m_0 controls the amount of CR (mode 0);
- Mode 2: time dilation using the boost factor obtained from the final-state mass of the dipoles, requiring all dipoles involved in a reconnection to be causally connected (strict);
- Mode 3: time dilation as in Mode 2, but requiring only a single connection to be causally connected (loose).