QCD at the LHC

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The goal is to go from proton-proton (or ion) collisions to the physics of our choosing — whether that be Higgs or Dark Matter or rare decays of heavy flavor hadrons.

But we all need to contend with QCD....
Multiple parton interactions

Underlying event

Hard Scatter/Partonic cross-section

Parton Shower

Higher order processes

Fragmentation & Hadronization

Renormalization Scale

Initial & Final State Radiation

Parton Distribution Functions

Multiple parton interactions

Factorization Scale

fig ref
The QCD @ LHC Lab Tour Itinerary

- Soft and forward physics
- Partonic structure of the proton
- Multi-scale dynamics of jet-based observables
- Measurements Sensitive to pQCD

Highlighting a selection of results from the past year. Please visit the references for more information!
Experimental tools for probing QCD

- Building blocks:
  - Charged hadrons from tracking detectors
  - Calorimeters to capture full hadronic interactions

- Look at event level quantities or build jets:
  - Made out of tracks, calorimeter deposits or combination of both
  - Probe different physics by tweaking algorithmic parameters: effective radius, treatment of soft radiation
  - Build sensitive quantities out of jet constituents

- Correct to particle level quantities by unfolding

- Sometimes use high energy, colorless particles as probes:
  - Photons, Ws, Zs
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- Elastic p-p cross-section @ 2.76 & 13 TeV — TOTEM

- Inclusive single diffractive dissociation — ATLAS
  ATLAS-CONF-2019-012

- Forward energy vs pseudo rapidity & track multiplicity — CMS
  CMS-PAS-FSQ-18-001

- Underlying event in Z boson events — ATLAS
  arXiv:1905.09752

- Particle production vs UE activity — ALICE

- Forward jet cross-sections in p-Pb — CMS
  JHEP 05 (2019) 043

- Dijet production with leading proton — CMS
  CMS-PAS-FSQ-12-033

= result presented here
Forward and Soft QCD

- Realm of non-perturbative or semi-perturbative QCD:
  - Low momentum transfer processes in a strong(er) coupling regime
  - Important for understanding cosmic ray showers, proton structure, has theoretical connections to string theory [ref]

- What’s interesting?
  - Testing models of interactions via colorless exchange
  - Differential distributions of energy and particle multiplicities for generic pp collisions
  - Properties of soft radiation accompanying hard processes (underlying event)
Forward and Soft QCD: Elastic and Diffractive processes

- ~20% of pp collisions are elastic, ~20% are inelastic but involve the exchange of colorless objects: diffractive processes
- Can study through *tagging and measuring* outgoing protons
Forward and Soft QCD: Elastic and Diffractive processes

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- Can study through tagging and measuring outgoing protons

\[ B_{pp} = 16.8 \pm 0.4 \text{ GeV}^{-2} \]
\[ B_{pp} = 19.4 \pm 0.4 \text{ GeV}^{-2} \]
Forward and Soft QCD: Elastic and Diffractive processes

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Difference between D0 and TOTEM is evidence for 3 gluon bound-state
Forward and Soft QCD: Elastic and Diffractive processes

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\[
\begin{align*}
\text{Data} & & \text{Pythia8 A3} & & \text{Pythia8 A2} & & \text{Herwig7} \\
\text{ATLAS Preliminary} & & \text{0.016 < } |t| < 0.43 \text{ GeV}^2 & & -4.0 < \log_{10} \xi < -1.6 \\
\text{Ratio} & & \text{MC/data} & & \\
\end{align*}
\]

**Difference between D0 and TOTEM is evidence for 3 gluon bound-state**

**MC models over predict by 1.5-4x**
Forward and Soft QCD: Forward Energy Density

- Measurements of forward energy flow relatively unexplored, particularly in “soft” phase space
- Inclusive measurements agree well with models but discrepancies exist in single diffractive phase space
- Data support limiting fragmentation hypothesis: forward energy flow independent of $\sqrt{s}$
Forward and Soft QCD: Forward Energy Density

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- Inclusive measurements agree well with models but discrepancies exist in single diffractive phase space.
- Data support limiting fragmentation hypothesis: forward energy flow independent of $\sqrt{s}$. 

Supports limiting fragmentation hypothesis.
Forward and Soft QCD: Underlying Event

- Underlying event measures hadronic activity not related to the primary “hard” scattering process:
  - Important for measurements sensitive to generic hadronic activity: W mass, rapidity gap based selections, etc.

- Main contribution to UE is multiple parton interactions (MPI)
  - \( R_T \) can select hard scatterings with different MPI activity

\[
R_T = \frac{N_{\text{inclusive}}}{\langle N_{\text{inclusive}} \rangle}
\]
Forward and Soft QCD: Underlying Event

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W+charm @ 8 TeV — CMS— CMS-PAS-SMP-18-013
W+charm @ 8 TeV — ATLAS — ATL-PUB-2019-016
W&Z production @ 2.76 TeV — ATLAS arXiv:1907.03567

Evidence for DPS in WW — CMS — CMS-PAS-SMP-18-015

*= result presented here
Partonic Structure of the Proton

- Experimental probes of the dynamics of protons:
  - See into the proton using probes which are unique to the partonic structure
- What’s interesting?
  - Uncertainty in parton distribution functions critical in theory comparison for many cross-section measurements
  - Flavorful content of proton becoming important at LHC energies
  - Multiple simultaneous parton interactions can be perturbative at LHC energies, allowing for precise comparisons with data
Partonic Structure of the Proton: Strange quark content

- W+c production sensitive to strange quark content in proton:
  - Tag with leptonic Ws and D* mesons
  - Can be used to constrain strange quark parton distribution functions

- Previous ATLAS measurements @ 7 TeV showed tension with global PDF fits on strange quark suppression
  - Global fits include neutrino charm production data — neutrino-iron DIS and inclusive charm production measurements
  - 2019 ATLAS update with inclusive W data at 8 TeV maintains tension
Partonic Structure of the Proton: Strange quark content

- **8 TeV CMS measurements:**
  - Cross-section agrees with global PDFs, although high
  - Ratio of $W^+/W^-$ disagrees with global PDFs

- **13 TeV CMS measurements:**
  - Good agreement with PDFs except ATLAS-derived one
  - Note: parameterization uncertainty for ATLAS PDF not used in the comparison, recent paper shows CMS and ATLAS data not in tension*

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Eventshapes — CMS
JHEP 12 (2018) 117
Jet Fragmentation in Z Events — LHCb
arXiv:1904.08878
Jet Fragmentation, Quark Gluon Properties— ATLAS
arXiv:1906.09254
Gluon splitting to b-quarks — ATLAS
Charmed quark jet properties — ALICE
arXiv:1905.02510
Azimuthal separation of 2 & 3-jet events — CMS
arXiv:1902.04374
kT splitting scales — ALICE
ALI-PREL-310018-43
Measurement of Lund Plane—ATLAS
ATLAS-CONF-2019-035
Λ⁺ production — ALICE
JHEP04(2018)108
Ks & Λ₀ production in t-tbar — ATLAS
arXiv:1907.10862
Jet cross-sections versus anti-kT jet size — CMS
CMS-PAS-SMP-19-003
ALICE — ALI-PREL-315682-725
Substructure for Dijet, W and Top jets — ATLAS
arXiv:1903.02942

*= result presented here
Multi-scale dynamics in jet-based observables

- Exploring the evolution of high energy quarks and gluons into hadrons
  - Multi-scale problem which straddles perturbative and non-perturbative effects
  - Good understanding necessary for precise control over observables in many physics analyses

- What’s Interesting?
  - Testing showering and hadronization models against event shape and individual jet observables
  - Measuring how these variables evolve in a wide range of phase-space and with different jet flavors
  - Probing the structure of hadronic resonances
Multiscale Dynamics: Event Shapes

- CMS analysis uses event shape variables calculated using 3-jet events
  - Evaluated versus average of 2 highest $p_T$ jets ($H_{T,2}$) in order to reduce theoretical uncertainties
- Modeling:
  - *Transverse flow* variables well described by all MC models
  - *Total flow* variables best described by Herwig++ (angular ordered parton shower) not well described by Pythia8 ($p_T$ ordered shower). Madgraph (matrix element approach) is more accurate than Pythia
- Distributions (including transverse thrust and jet broadening) in bins of $H_{T,2}$ evaluated in detail in paper!

\[ H_{T,2} = \frac{p_{T1} + p_{T2}}{2} \]
Multiscale Dynamics: Jet Constituent Characteristics

- LHCb analysis uses charged hadron properties of jets in Z+jet events in the forward region:

\[ z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{hadron}}}{|\vec{p}_{\text{jet}}|^2} \]

- Sample is light quark dominated — useful for q/g discrimination studies

\[ \bar{s} = 8 \text{ TeV} \]

\[ 20 < p_T^{\text{jet}} < 30 \text{ GeV} \]

\[ 30 < p_T^{\text{jet}} < 50 \text{ GeV} \]

\[ 50 < p_T^{\text{jet}} < 100 \text{ GeV} \]
LHCb analysis uses charged hadron properties of jets in \(Z+\text{jet}\) events in the forward region:

\[ z = \frac{\vec{p}_{\text{jet}} \cdot \vec{p}_{\text{hadron}}}{|\vec{p}_{\text{jet}}|^2} \]

Sample is light quark dominated — useful for q/g discrimination studies.

Higher \(p_T\) jets have more constituents and populate lower \(z\) values.
Multiscale Dynamics: Jet Constituent Characteristics

- By exploiting the fact that forward jets tend to be quark dominated, can extract *in situ* quark & gluon distributions
  - Utilize ML technique, topic modeling, to extract distributions without dependence on MC models

- Paper has detailed comparisons of jet fragmentation quantities in forward and central regions, compares q/g distributions extracted with MC fractions to N^3LO predictions

![Diagram of jet topics and mixed jet samples](image)

\[ \sqrt{s} = 13 \text{ TeV}, 33 \text{ fb}^{-1} \]
\[ 900 < p_T / \text{GeV} < 1000 \]

\[ \text{Phys. Rev. Lett. 120, 241602 (2018)} \]
Multiscale Dynamics: Jet Constituent Characteristics

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Data topic 2 (gluon-like) matches topic 2 extracted from MC, but not parton matched MC due to some quark contamination


arXiv:1906.09254
Multiscale Dynamics: Gluon splitting

- Select sample rich in $g \to b\bar{b}$ by large radius jet with 2 small radius sub-jets, at least 1 b-tag
  - Probe quantities related to $b\bar{b}$ system

- Data shows significant deviation from models in angle related to gluon polarization (largely unconstrained from prior data)
Multiscale Dynamics: Resummation Effects

- Accurately modeling parton showers requires resummation of soft gluon emission
  - Need measurements sensitive to these effects
- For 2 & 3-jet events, look at $\Delta\phi$ of 2 leading jets in back-to-back topology
  - Cross-section dominated by soft gluon emission in this phasespace
  - Models deviate for $\Delta\phi \gtrapprox 177^{\circ}$
  - Different combinations of $N_{\text{partons}}$ & parton showers describe data best in various jet $p_T$ ranges
Multiscale Dynamics: Resummation

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Multiscale Dynamics: Shower Evolution

- Soft-drop method removes soft radiation not fulfilling minimum $p_T$ requirement ($z_g$) [ref, ref]
  - Relates to parton splitting function
- Sources of $R$-dependence of $z_g$:
  - Perturbative: $\delta p_T \sim \ln(R)$
  - Hadronization: $\delta p_T \sim -1/R$
- ALICE measures cross-section as a function of $k_T$ splitting scale for different cone sizes & $p_T$ to probe these effects
  - more asymmetric splitting for larger $R$ at low $p_T$
  - larger $z_g$ values at low $p_T$ for small $R$

\[ z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \]
Multiscale Dynamics: Lund Plane

- New proposal to represent internal structure of jets*:
  - Lund Plane: \( \ln(1/z) \) vs \( \ln(1/\theta) \)
- Recluster jet using Cambridge/Aachen alg, plot history
- Utilize tracks associated to anti-kT (R = 0.4) jets, recluster with C/A, plot history
- Powerful test of MCs against shower and hadronization history
  - Can distinguish perturbative and non-perturbative effects in same measurement
- Can be used in ML-based jet discriminants

The QCD @ LHC Lab Tour Itinerary

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Inclusive photon production — ATLAS
ATL-PHYS-STDM-2017-29

Differential isolated photon production @ 8 TeV — CMS
arXiv:1907.08155

W&Z cross-sections — CMS
CMS-PAS-SMP-17-010

Z + heavy flavor — CMS
CMS-PAS-SMP-19-004

Inclusive Z cross-sections — ATLAS
arXiv:1907.06728

Photon cross-section ratios at 8/13 TeV — ATLAS
JHEP 04 (2019) 093

* = result presented here
Measurements Sensitive to pQCD

- Comparison of QCD phenomena with precise theoretical calculations
  - Choose hard, colorless probe and measure cross-sections and properties
  - Many searches for new physics (e.g. deviations in Higgs $p_T$ measurements) rely on precise theoretical pQCD calculations

- What’s interesting:
  - Testing state of the art (NLO, NNLO) calculations against data
  - Tests of resummation in parton showers at NNLL

![Diagram showing QCD processes](fig ref)
Measurements Sensitive to pQCD

- ATLAS measurement of inclusive photon production up to $E_{\gamma T} \sim 1$ TeV with < 10% experimental & theoretical uncertainties

- Excellent NLO & NNLO agreement with data; NNLO uncertainties comparable to data uncertainties
Measurements Sensitive to pQCD

• CMS measured W&Z production cross-sections as a function of $p_T$ & $y$.
  • Compare to resumed NNLL at low $p_T$ and NLO, NNLO at high $p_T$
  • Important for W mass measurements
Conclusions

• The LHC is a rich QCD laboratory probing physics at a huge range of energy scales

• Experimental measurements are increasing in precision and informing models of non-perturbative physics as well as providing stringent tests of detailed perturbative calculations

• LHC future is trending towards indirect searches → precise QCD predictions will be critical. Effort needed now to improve our predictions.

• Stay tuned for more Run 2 results!
Jet Energy Scale: ATLAS

Data 2015-2017, $\sqrt{s} = 13$ TeV
anti-$k_t$, $R = 0.4$, EM+JES

$\eta = 0.0$

ATLAS Preliminary

Fractional JES uncertainty

- Total uncertainty
- Absolute in situ JES
- Relative in situ JES
- Flav. composition, inclusive jets
- Flav. response, inclusive jets
- Pile-up, average 2015-2017 conditions
- Punch-through, average 2015-2017 conditions

$\sqrt{s} = 13$ TeV, 36.2 fb$^{-1}$, multijet
Trimmed $R = 1.0$ anti-$k_t$ (LCW+JES+JMS)
Large-$R$ jet $|\eta_{\text{det}}| < 0.8$
Recoil system: anti-$k_t$, $R = 0.4$ EM+JES

Fractional $R_{\text{MB}}$ uncertainty

- Total uncertainty
- Statistical uncertainty
- in-situ $R = 0.4$ EM JES uncertainty
- Single particle uncertainty
- Flavour composition, response
- Pile-up, average 2016 conditions
- MC Modelling
- Event selection criteria

$\sqrt{s} = 13$ TeV, $3\times10^3$ TeV, 36.2 fb$^{-1}$, multijet
Trimmed $R = 1.0$ anti-$k_t$ (LCW+JES+JMS)
Large-$R$ jet $|\eta_{\text{det}}| < 0.8$
Recoil system: anti-$k_t$, $R = 0.4$ EM+JES

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Large-$R$ jet $|\eta_{\text{det}}| < 0.8$
Recoil system: anti-$k_t$, $R = 0.4$ EM+JES
Jet Energy Scale: CMS

Run2016BCDEFGH, 36.5 fb⁻¹ (13 TeV)

CMS Preliminary
R=0.4 PF+CHS
p_T = 30 GeV

Total uncertainty
Excl. flavor, time
Run I
Absolute scale
Relative scale
Pileup (⟨μ⟩=25)
Method & sample
Jet flavor (QCD)
Time stability

CMS Preliminary
R=0.4 PF+CHS
η_{jet} l = 0

Total uncertainty
Excl. flavor, time
Run I
Absolute scale
Relative scale
Pileup (⟨μ⟩=25)
Method & sample
Jet flavor (QCD)
Time stability
Forward and Soft QCD: Forward Energy Density

- When normalizing to the energy flowing events with < 10 central tracks (first bin uncertainties decrease significantly and discrepancies arise
Forward and Soft QCD: Diffractive processes

- ATLAS single diffractive measurement $t$-dependence well described by exponential
  - Slope parameter of $B = 7.60 \pm 0.32 \text{ GeV}^{-2}$
  - Fractional proton dissociation well described by triple pomeron Regge trajectory with slope $\alpha(0) = 1.07 \pm 0.09$
Forward and Soft QCD: Underlying Event

- ALICE: Measure $R_T = \frac{N_{\text{inclusive}}}{<N_{\text{inclusive}}>}$ in transverse region defined by highest $p_T$ track in event [ref]
  - High $R_T$ corresponds to high UE activity
  - Track spectrum harder in higher UE activity events

![Diagram of $R_T$ and $p_T$ distributions](image-url)
Partonic Structure of the Proton: Double Parton Scattering

- Double Parton Scattering: two pairs of partons from one single pp collision interact
  \[ \sigma_{AB}^{DPS} = \frac{k^2}{2} \cdot \frac{\sigma_A \sigma_B}{\sigma_{eff}} \]

- DPS measurements test universality of \( \sigma_{eff} \)

- ATLAS: measure lower limit on \( \sigma_{eff} \) (\( \geq 1 \text{mb} \)) in ZZ events, consistent with DPS interpretation

- CMS: Evidence for DPS in same sign WW production (3.9\( \sigma \)) at 13 TeV

| \( W^\pm W'^\pm \) | \begin{tabular}{c|c|c} \hline
W±W± & \begin{tabular}{c} Pythia 8 \( \sigma(pb) \) \end{tabular} & \begin{tabular}{c} Factorized \( \text{(N)NLO} \) \end{tabular} & \begin{tabular}{c} Measured \end{tabular} \\
\hline
& 1.92 & 0.87 & 1.41 \pm 0.28(\text{stat.}) \pm 0.28(\text{sys.}) \\
Significance & 5.4 & 2.5 & 3.9 \\
\( \sigma_{eff} \) & 20.7 & 12.7^{+5.0}_{-2.9} \\
\hline
\end{tabular} |
Hadronization and Fragmentation: jet flavor

- Select sample rich in c-quarks by tagging track jets with D mesons (ALICE)
- Study cross-sections for fragmentation distributions and overall production; good agreement within uncertainties
- Note: ALICE can access low energy jets and give unique information
Q/G Jet Extraction

- Topics converge to quark/gluon definitions in the case that there are some bins in the dataset which are purely quark or purely gluon
  - Basically true for quarks, not quite true for gluons, but converges at high pT
  - Only true for Nch
- Extraction relying on MC fractions shows good agreement with N3LO at low pT, diverges at high pT
  - Used for Nch & fragmentation variables
ATLAS & CMS PDF Compatibility

- Using ATLAS & CMS inclusive W&Z data
- All datasets have good chi2 w.r.t. fits
- ATLAS data more constraining for s-quark content
- CMS data prefers slightly higher anti-u/d contributions

Table 4: Total and partial \( \chi^2 \) for data sets entering the extended PDF fits of the ATLAS and CMS data to include off-peak Drell-Yan data. Full details are given in the text.
Multi-scale: Jet production

- CMS measures jet cross-sections as a function of anti-kT jet clustering parameter, R, w.r.t. R = 0.4 default
  - Experimental jet corrections extrapolated from R = 0.4
- Compare to MC generators and QCD calculations at different orders
  - Need both higher fixed order and non-perturbative effects to describe data
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Multi-scale: Jet production

- ATLAS selects hadronic top, W and dijet events and compares jet substructure variables for data and standard generators

\[ \frac{\sigma}{dN} \text{ (Nsubjets)} \]

\( \sqrt{s} = 13 \text{ TeV}, 33 \text{ fb}^{-1} \)
- Anti-\(k_t\), \( R=1.0 \) jets
- Soft Drop \( \beta = 0, z_{cut} = 0.1 \)

\( \Delta \)

- W selection
- Top selection
- Dijet selection

Dijet Selection

W Selection

Top Selection

arXiv:1903.02942
Multi-scale: Jet production

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