QCD Measurements in pp collisions

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On behalf of the LHC Collaborations
Outline

- The quark model toward tetraquark and pentaquark
- The strong force: running of $\alpha_S$ and $\nu$ from FASER
- Factorization approach in QCD, measurements of PDFs and TMDs
- Insight on multi-parton scattering with associated production
- Jet fragmentation and substructure
- Hadronization in hadronic environment
QCD measurements in pp collisions

**α_s with multi-jet**

Azimuthal correlations among jets allow to probe $\alpha_s$ running up to 2 TeV

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

### 2-jet topology
- $p_T^1$ and $p_T^2$ with $|\Delta\phi| = \pi$
- Numerator: 2
- Denominator: 2

### 3-jet topology (all jets with $p_T > 100$ GeV)
- Numerator: 1
- Denominator: 3

### Theory at NLO

\[ \alpha_s(Q) \]

**NLO pQCD behaviour confirmed up to 2 TeV**

More from J. Roloff
Thursday 06/06 at 14:18

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Neutrino cross section with FASER & SND

FASER Forward Search Experiment
SND Scattering and Neutrino Detector
480 m from ATLAS IP on both sides

Neutrinos coming from the decay of very forward hadrons
light-flavour and charm

Observation of $\nu_\mu$ interactions the LHC by SND
First neutrino cross-section measurement at a collider, in an unexplored energy regime from FASER
Factorization in QCD

Factorization of the perturbative and non-perturbative component of the interaction

$$f_{a/p}$$
on-perturbative QCD

one-dimensional parton distribution functions (PDFs)

parameterize the longitudinal momentum fraction distributions of partons inside the proton

$$d\sigma^{pp\rightarrow h+X}_{dP_Td\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes \delta_{ab\rightarrow c}(z, \mu) \otimes D_{c}^{h}(z, \mu)$$

hadronization

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Recent results on PDFs

PDF from di-jet cross section

PDF from Z cross section

PDF from $W^\pm$ and Z-bosons Ratio with $t\bar{t}$ pair

More from J. Roloff & Tim Martin
Thursday 06/06
Testing pQCD with jet cross section ratio

Events with multiple jets
Scalar sum of the transverse momenta of the leading two jets

$$H_{T2} = p_{T,1} + p_{T,2}$$

$$H_{T2} \geq 250 \text{ GeV}$$

Proxy for the energy scale of the hard-scattering interaction

NNLO computations better described 3-to-2 cross section ratio, $R_{32}$, than NLO (ratios reduce uncertainties from PDF)

Importance of the higher-order predictions in describing multijet production
Di-J/ψ to access TMDs

Transverse-Momentum Dependent Parton Distribution Functions
3 dimensional imaging of hadrons including transverse momentum and polarization degrees of freedom

Di-J/ψ produced with **one hard process** (Single Parton Scattering) as a **golden channel to probe gluon TMDs** $f_1^g (x, k_T^2, \mu)$

No obvious broadening of the $p_T$ spectrum can be seen in the TMD region
Di-$J/\psi$ to access TMDs

Transverse-Momentum Dependent Parton Distribution Functions
3 dimensional imaging of hadrons including transverse momentum and polarization degrees of freedom

The azimuthal asymmetry of $J/\psi$ pairs is measured to probe the TMD function $h_{1g}^{1g}(x, k_T^2, \mu)$

$$\langle \cos 2\phi_{CS} \rangle = -0.029 \pm 0.050 \text{ (stat)} \pm 0.009 \text{ (syst)} ,$$

$$\langle \cos 4\phi_{CS} \rangle = -0.087 \pm 0.052 \text{ (stat)} \pm 0.013 \text{ (syst)} .$$

Measurement consistent with 0
Presence of an azimuthal asymmetry at a few percent level is allowed

First experimental measurement of linear polarization of gluons inside unpolarized protons

No obvious broadening of the $p_T$ spectrum can be seen in the TMD region
Double parton scattering: $J/\psi + \psi(2S)$ or $\Upsilon(nS)$
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**SPS**

**DPS**

\[
\sigma_{DPS}^A = \frac{m_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}
\]

$m=2$ when $A$ and $B$ are distinguishable

$m=1$ when indistinguishable

Assume PDF factorization

**Expected properties of $\sigma_{eff}$:**
- collision energy independent
- process independent
QCD measurements in pp collisions

Double parton scattering: $J/\psi + \psi(2S)$ or $\Upsilon$(ns)

Assume PDF factorization
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ALICE di-$J/\psi$

$\sigma_{\text{eff}} = 6.7 \pm 1.6\,\text{(stat)} \pm 2.7\,\text{(syst)}\,\text{mb}$


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QCD measurements in pp collisions

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- collision energy independent
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ALICE di-$J/\psi$

$$\sigma_{\text{eff}} = 6.7 \pm 1.6(\text{stat}) \pm 2.7(\text{syst}) \text{mb}$$


Observed properties of $\sigma_{\text{eff}}$
- Process dependent
- Kinematic dependent
- Energy dependent

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QCD measurements in pp collisions

Next orders: tri-J/ψ in pp and di-J/ψ in p-Pb

Confirm the dependence of the effective DPS cross section on the relevant parton species and $x$ fractions probed

Also extracted from p-Pb collisions
Jet Fragmentation Function of charged hadrons

Extraction of the double differential JFFs in $j_T$ and $z$, in 3 jet $p_T$ intervals for unidentified charged hadrons

Probe the longitudinal and transverse profiles of identified charged pions, kaons, and protons inside predominantly light-quark-initiated jets

Probe the 3D picture of FF in the collinear and transverse dimension with respect to the jet axis

$z$ longitudinal momentum fraction of the jet carried by the hadron

$f_T$ transverse component of the hadron momentum with respect to the jet axis

More from S. Caletti & T. Martin
Thursday 06/06
Lund sub-jet multiplicities

Two-dimensional representation of the phase space of emissions inside a jet ...

... Allow to probe different mechanisms depending on kinematic
Lund sub-jet multiplicities

Two-dimensional representation of the phase space of emissions inside a jet ...

Running of $\alpha_s$ in the jet shower

- dominant mechanism responsible for the rise of the LJP density at low $k_T$
- ($k_T$ characteristic energy scale in $\alpha_s$ evolution)

... Allow to probe different mechanisms depending on kinematic

Testing QCD with jet substructure
Two-dimensional representation of the phase space of emissions inside a jet ...

... Allow to probe different mechanisms depending on kinematic

Running of $\alpha_s$ in the jet shower dominant mechanism responsible for the rise of the LJP density at low $k_T$ ($k_T$ characteristic energy scale in $\alpha_s$ evolution)

Measurement of average number of Lund subject multiplicities to constrained models

Testing QCD with jet substructure
QCD measurements in pp collisions

Substructure of $D_0$ tagged jets

Direct experimental constraint of the splitting function of heavy-flavour quarks
Charm quarks $R_g$ distribution: reduction at large-angles. Inclusive sample with larger-angle perturbative emissions (gluon)

Direct experimental constraint of the splitting function of heavy-flavour quarks
Charm quarks $R_g$ distribution: reduction at large-angles. Inclusive sample with larger-angle perturbative emissions (gluon)

$n_{SD}$ distribution (number of emissions of the charm quark satisfying the Soft Drop condition): shift to smaller values for the charm-tagged jets. Charm quarks on average emit fewer gluons. Consistent with dead cone effect for charm quark.

Different characteristics of heavy-quark emissions vs. light quarks and gluons: constrain the roles of quark mass and Casimir colour factors in the parton shower.

Direct experimental constraint of the splitting function of heavy-flavour quarks
$\Lambda_c^+$-baryon yields much higher than predicted

(general-mass variable-flavor-number scheme with FF from OPAL and Belle fits)

Breakdown of the universality of charm quark fragmentation functions

Charm hadronization is different in hadronic environment and in $e^+e^-$
Charm fragmentation at LHC

$\Lambda_c^+$-baryon yields much higher than predicted
(general-mass variable-flavor-number scheme with FF from OPAL and Belle fits)

Breakdown of the universality of charm quark fragmentation functions

ALICE measured several charm hadron species
Prompt $\Lambda_c^+$-baryon fragmentation fraction in pp is $\sim 3x$ larger than in $e^+e^-$ and $ep$

Imply an overall reduction of the relative D-meson abundance
(charm fragmentation function sum up to 1)

Charm hadronization is different in hadronic environment and in $e^+e^-$

More from V. Feuillard & P. Das
Wednesday 05/06 & Thursday 06/06

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**Charm fragmentation at LHC**

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[charts and graphs]

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Wednesday 05/06 & Thursday 06/06

Charm hadronization is different in hadronic environment and in e^+ e^-
Charm fragmentation at LHC

- First measurement of the $\Sigma_{c}^{0,++}(2520)$ relative production at the LHC
- ALICE measurement in $p_T$ range 6-14 GeV/c compatible with $e^+e^-$ $p_T$ integrated within uncertainties
- SHMc reproduces the ratio $p_T$ integrated
- PYTHIA 8 (Monash + Mode 0/2/3) and Statistical Hadronization Model + RQM do not describe the data (feed-down from higher states under discussion)

ALICE Preliminary
$\Sigma_{c}^{0,++}(2520)/\Sigma_{c}^{0,++}(2454)$
$|y| < 0.5$

- Data
- PYTHIA 8
- Monash
- Mode0
- Mode2
- Mode3

SHMc GSI-Heidelberg
$\Sigma_{c}^{0,++}(2520)/\Sigma_{c}^{0,++}(2454)$
$T_H = 170$ MeV

Belle (PRD 97, 072005)
$e^+e^-, \sqrt{s} = 10.52$ GeV
- Prompt
- Direct

Charm abundance in pp under study

More from V. Feuillard
Wednesday 05/06 at 14:18

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Beauty fragmentation at LHC

Beauty, charm, and strange hadrons show a similar trend as a function of $p_T$


ALICE, $|y| < 0.5$

PP, $s = 13$ TeV

PYTHIA 8 Monash

LHCb, $2.0 < y < 4.5$

AL-I-DE-563938

Beauty hadronization is different in hadronic environment and in $e^+e^-$

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**Beauty hadronization is different in hadronic environment and in $e^+ e^-$**
Beauty fragmentation at LHC

Beauty, charm, and strange hadrons show a similar trend as a function of $p_T$

Lowest multiplicity bins: pp data $\sim e^+e^-$ data at LEP
$\Rightarrow$ fragmentation in vacuum

Beauty hadronization is different in hadronic environment and in $e^+e^-$
QCD measurements in pp collisions

Beauty fragmentation at LHC

Beauty, charm, and strange hadrons show a similar trend as a function of $p_T$

Rise of the baryon fraction with multiplicity, plateaus for collisions $> 2x$ average number of VELO tracks

Beauty hadronization is different in hadronic environment and in $e^+e^-$

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Hadronization in and out of jets

Strange baryon-to-meson and baryon-to baryon ratios suppressed by a factor ~ 2 in jets w.r.t inclusive measurements

Hadronic environment (in jet vs. out of jet) impact hadronization
Hadronization in and out of jets

Strange baryon-to-meson and baryon-to baryon ratios suppressed by a factor ~ 2 in jets
w.r.t inclusive measurements

Deuteron coalescence probability in jets x 10 vs. underlying event
Nucleons have a smaller average phase-space distance

Hadronic environment (in jet vs. out of jet) impact hadronization

More from P. Das
Thursday 06/06 at 15:12
QCD measurements in pp collisions

Underlying event study with strangeness production

- Phase space divided in 3 regions
  - Toward the leading jet: dominated by jet fragmentation
  - Away from the leading jet (back-to-back)
  - Transverse region: dominated by underlying event, MPI and soft processes

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ATLAS arXiv:2405.05048
**Underlying event study with strangeness production**

- Phase space divided in 3 regions
  - Toward the leading jet: dominated by jet fragmentation
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Δ and $K_S^0$ production in 3 regions allow to understand **modelling of underlying event** from event generators

None tested can reproduce all aspects

Strangeness production to study underlying event dynamic
Event shape modeling to understand strangeness production in pp collisions

Strangeness production

Suppressed in events with jet-like topologies
Slightly enhanced in softer, isotropic event topologies

\[ S_0 = \frac{\pi^2}{4} \min_{(n_x, n_y, 0)} \left( \sum_i |p_{T_i} \times \hat{n}| \right)^2 \]
\[ S_0 = \begin{cases} 0 & \text{“jetty” limit (hard events)} \\ 1 & \text{“isotropic” limit (soft events)} \end{cases} \]

\[ \sqrt{s} = 13 \text{ TeV}, \ N_{|\eta| < 0.8}^{\text{tracks}} (I), \ |\eta| < 0.8, \ N_{\text{ch}} \geq 10 \]

ALICE JHEP05(2024)184 arXiv:2310.10236

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**Event shape modeling**

The tensor $S$

$$S^\alpha\beta = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2}$$

$\alpha, \beta \in \{x, y, z\}$ cartesian coordinates

$i$ is the index for the final-state charged particles that passed the selections based on the detector acceptance

Sphericity $S$ from the two eigenvalues

Data more isotropic than the modeling in event generators
QCD measurements in pp collisions

Conclusions

- The strong force: running of $\alpha_s$ and $\nu$ from FASER
  - Running of $\alpha_s$ up to 2 TeV
  - First $\nu$ cross section at collider

- Factorization approach in QCD, measurements of PDFs and TMDs
  - Precision measurement with electroweak bosons
  - Jet cross section ration highlight the importance of NNLO computations
  - Accessing the transverse-Momentum Dependent Parton Distribution Function

- Insight on multi-parton scattering with associated production
  - DPS with charm and beauty show non universal $\sigma_{eff}$
  - Next orders: Tri-$J/\psi$ in pp and di-$J/\psi$ in p-Pb

- Jet fragmentation and substructure
  - Direct experimental constraint of the splitting function of heavy-flavour quarks
  - Testing QCD with jet substructure

- Hadronization in hadronic environment
  - Charm and beauty hadronization are different in hadronic environment and in $e^+e^-$
  - Hadronic environment (in jet vs. out of jet) impact hadronization
  - Underlying event dynamic and event shape modeling under study

More in QCD, Flavor Physics & Heavy Ion parallel sessions

To be continued with A. Dobrin
Friday 07/06 at 09:00

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Backup
QCD measurements in pp collisions

Exploring the strong interaction of 3-body systems

Measuring correlation functions of 3-body systems with femtosopic techniques in high multiplicity pp collisions at 13 TeV

Proton-deuteron correlations
Distance comparable to the proton radius

\[ p - p - p/\bar{p} \] and \( p - p - \Lambda \)

Only a full 3-body calculation that accounts for the internal structure of the deuteron can explain the data (Av18+UIX full)

Non zero 3-particle cumulant hints for 3-body forces

More from D.L. Mihaylov Friday 07/06 at 14:18
**Exploring the strong interaction of 3-body systems**

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New ALICE RUN 3 results

More from D.L. Mihaylov Friday 07/06 at 14:18
Testing L-QCD with strangeness

- Measurement of two-particle correlations as a function of the relative momentum to test the strong interaction among hadrons with strange quarks
- Comparisons with theoretical models:
  - including leading-order and next-to-leading-order chiral Effective Field Theory calculations
  - a meson exchange model
  - Lattice QCD calculations close to the physical point for systems rich in strangeness

Data more compatible with predictions of small scattering parameters and hence a weak $\Lambda - \Xi^{-}$ interaction

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Tetraquark with di-$J/\psi$ spectrum

- Tetraquark candidate $X(6900)$ first observed by LHCb in 2020 [Sci. Bull. 65, 1983 (2020)]
- $X(6900)$ confirmed by CMS and ATLAS in channel $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi J/\psi$ and $T_{cc\bar{c}\bar{c}} \rightarrow J/\psi\psi(2s)$
- Structure observed by CMS in $J/\psi J/\psi$ spectrum, hint for $X(6600)$ and $X(7100)$

Presented by P. Gandini
Monday 03/06 at 17:36

New charmed Tetraquark candidates
sarah.porteboeuf@clermont.in2p3.fr
$f_0(980)$ : hint at a 2-quark structure with p-Pb collisions

- Is the $f_0(980)$ a $q\bar{q}$ meson, a tetraquark state, a $K\bar{K}$ molecule or a $q\bar{q}$-gluon hybrid state?
- Study of $f_0(980)$ production and dynamic in p-Pb collisions

Clear suppression of $f_0$ nuclear modification factor production suggests impact of final state scattering and meson like structure.

CMS Submitted to Nature Physics arXiv:2312.17092v1

$f_0(980)$ is found to be a $q\bar{q}$ meson (number-of-constituent-quarks scaling hypothesis)
Other hypothesis ruled out
Search for Pentaquark

- First observation of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$
- First observation of $\Lambda_b^0 \rightarrow J / \psi \Xi^- K^+$

Opens the possibility to search for doubly-strange hidden-charm pentaquarks
J/ψ & ψ(2S) (non-)prompt production cross section

- Cross sections measured up to 100 GeV
- Similar $p_T$-dependences for the prompt and non-prompt differential cross-sections
- Non-prompt fractions nearly constant for both J/ψ and ψ(2S) states

Charmonia cross sections up to 100 GeV

More from V. Feuillard
Wednesday 05/06 at 14:18

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Charm fragmentation is different in hadronic environment and in $e^+e^-$