

QCD measurement at low scales

Weijie Jin

QCD@LHC 2026

Outline

Challenges in soft (low-scale) QCD theory:

- Non-perturbative, hard to quantify from the first principle
- Phenomenological models with large flexibility and uncertainty
→ **Rely on experimental** inputs to constrain the models

Collide hadrons as **composite particles**

→ rich environment to test different aspects in soft QCD:

Hadron structure, inter-parton correlation inside hadrons, parton shower and hadronization, mutual impacts of hard scattering and hadronic environment...

Soft QCD measurements at the LHC target different parts of theoretical models

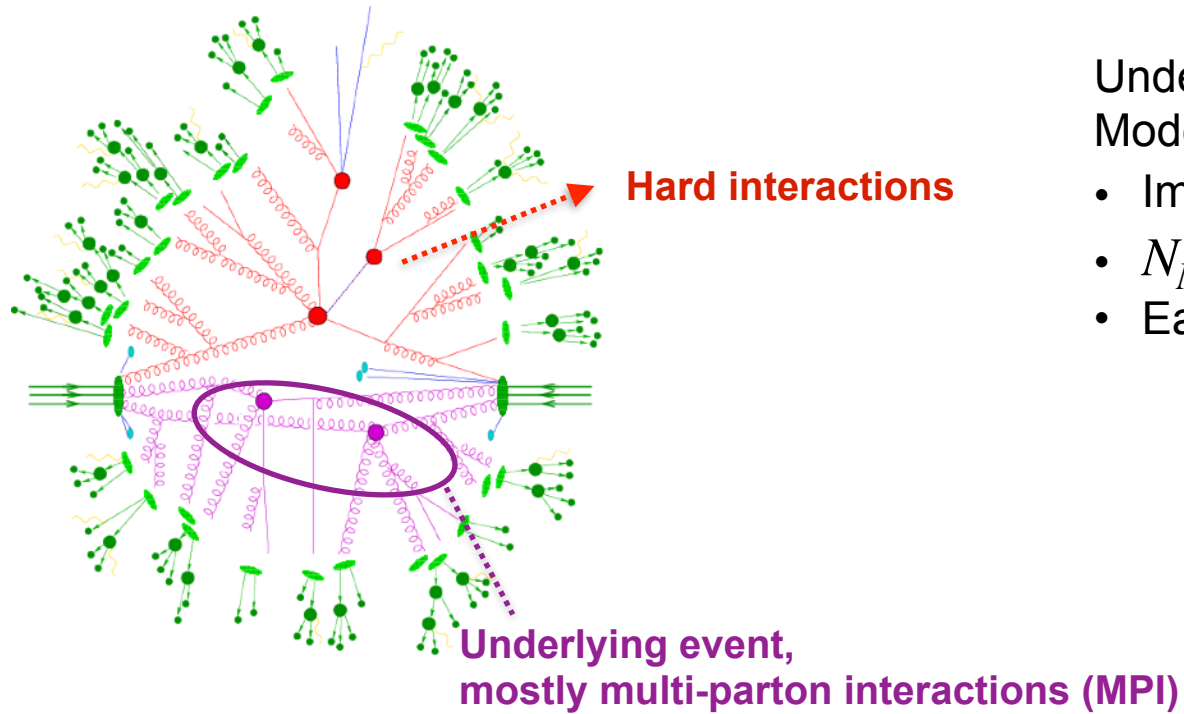
- Underlying-event (UE) measurements with tagged hard scatters
- Measurements of identified hadrons in UE
- Overall event shape measurements in hadron collisions
- Double parton scattering measurements (DPS)
(Multiple hard scatters in one collision)

Topics (partially) covered in this talk
Focus on **underlying event & multi-parton scattering**

Thorough experimental tests → improved model of hadron collisions in a consistent framework

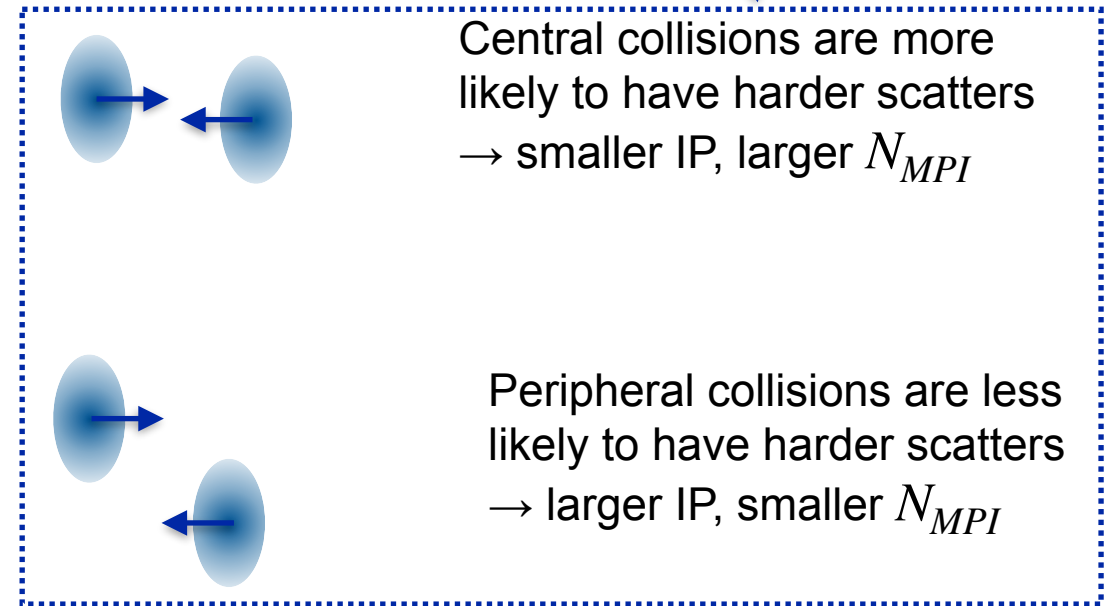
Underlying event measurement with hard-scatter tagging

Underlying event (UE) model

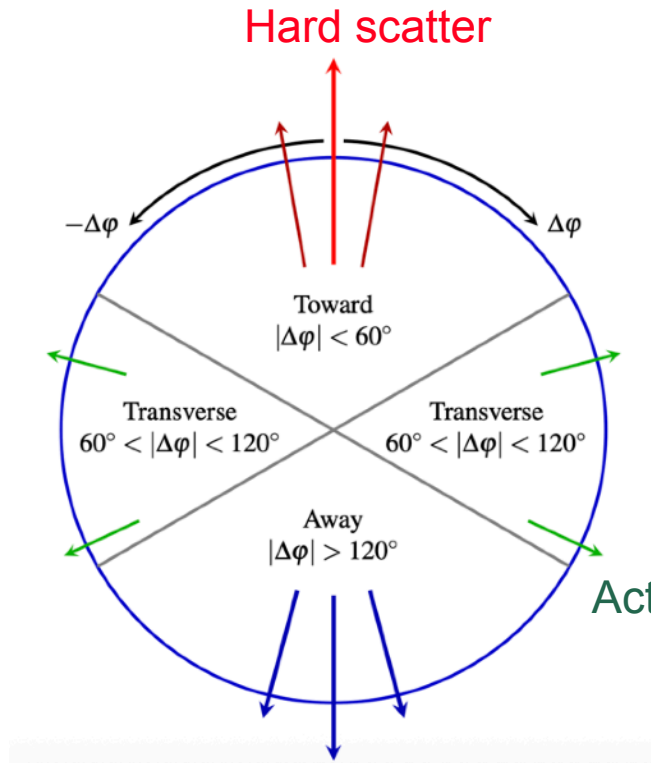


Underlying event: rest of interactions except the hard process
Modeled by MPI or QCD scatterings

- Impact parameter (IP) sampled depending on p_T^{hard}
- N_{MPI} affected by impact parameter
- Each of MPI: 2→2 parton scattering

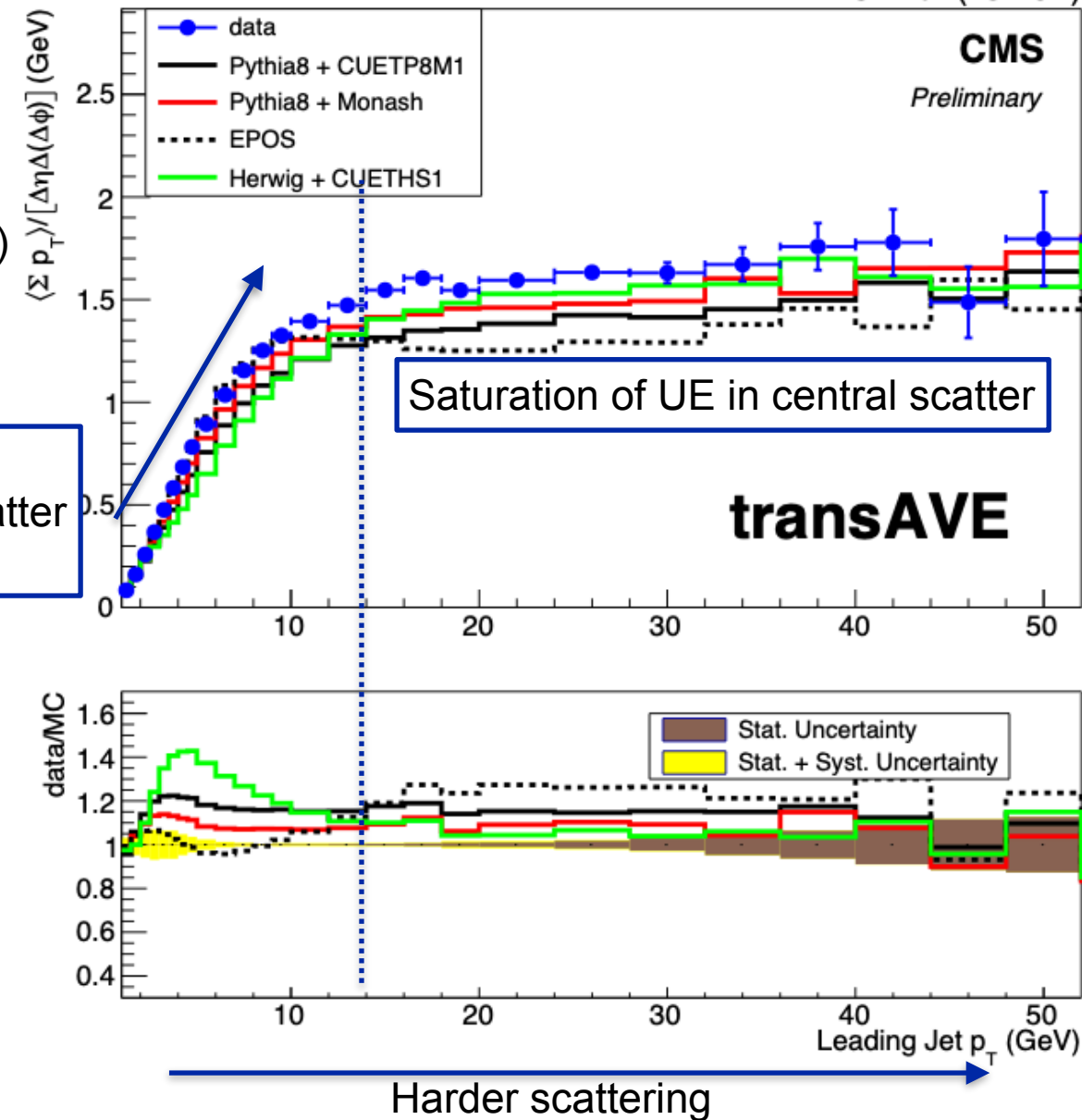


Underlying event measurement: Standard procedure



UE activity $\sim$
 p_T/N_{ch} density in $(\Delta\eta, \Delta\phi)$

Decreasing IP
More central scatter
Increasing UE



Biasing the event selection to central
collisions with smaller IP

Azimuthal plane to beam

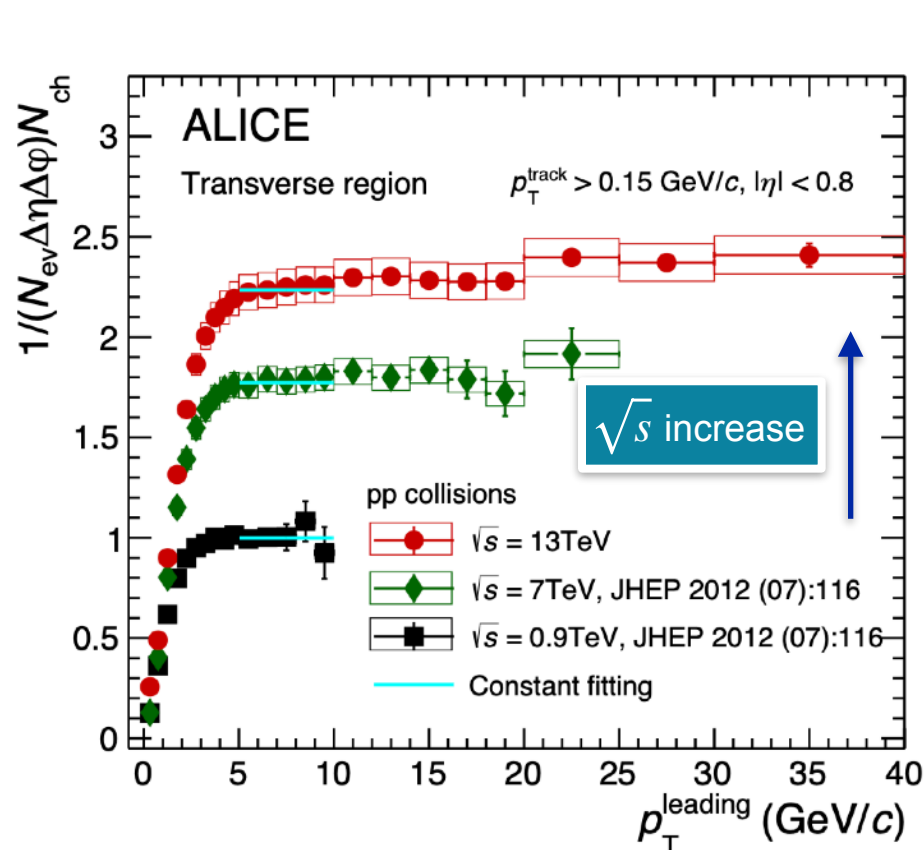
<https://arxiv.org/pdf/1910.14400>

Hard scatter tagged by charged particles/jets

Variation of hard scatters targeting UE in different perspectives

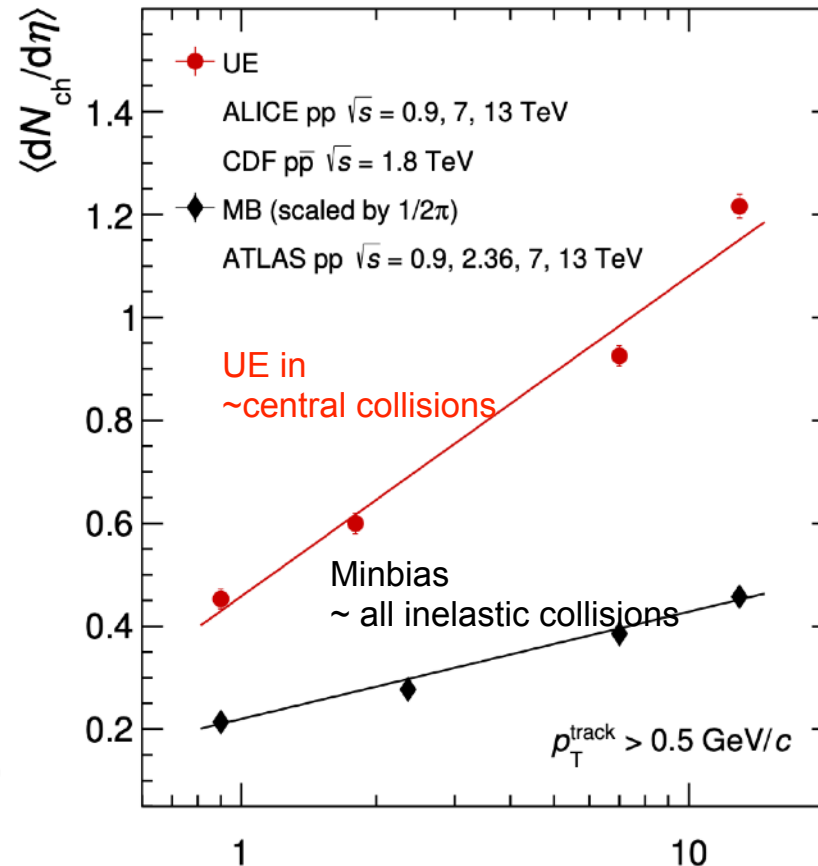
Hard scatter tagged by charged particles/jets → relatively low p_T^{hard}

Study the UE turn on w.r.t. p_T^{hard}



Increase of UE w.r.t. $\sqrt{s}$ on the plateau

<https://arxiv.org/pdf/1910.14400>



UE activity $\sim \ln(\sqrt{s}) \sqrt{s} \text{ (TeV)}$

<https://arxiv.org/pdf/1910.14400>

Future prospects:

- UE measurement at 13.6 TeV

→ Cross check with $\sqrt{s} \leq 13 \text{ TeV}$ results

- Extended CMS & ATLAS tracker coverage from $|\eta| \sim 2.5$ to 4 in HL-LHC

- ➔ More UE measurements in $|\eta| > 2$

- ➔ Quantify and control the QCD background for hard processes

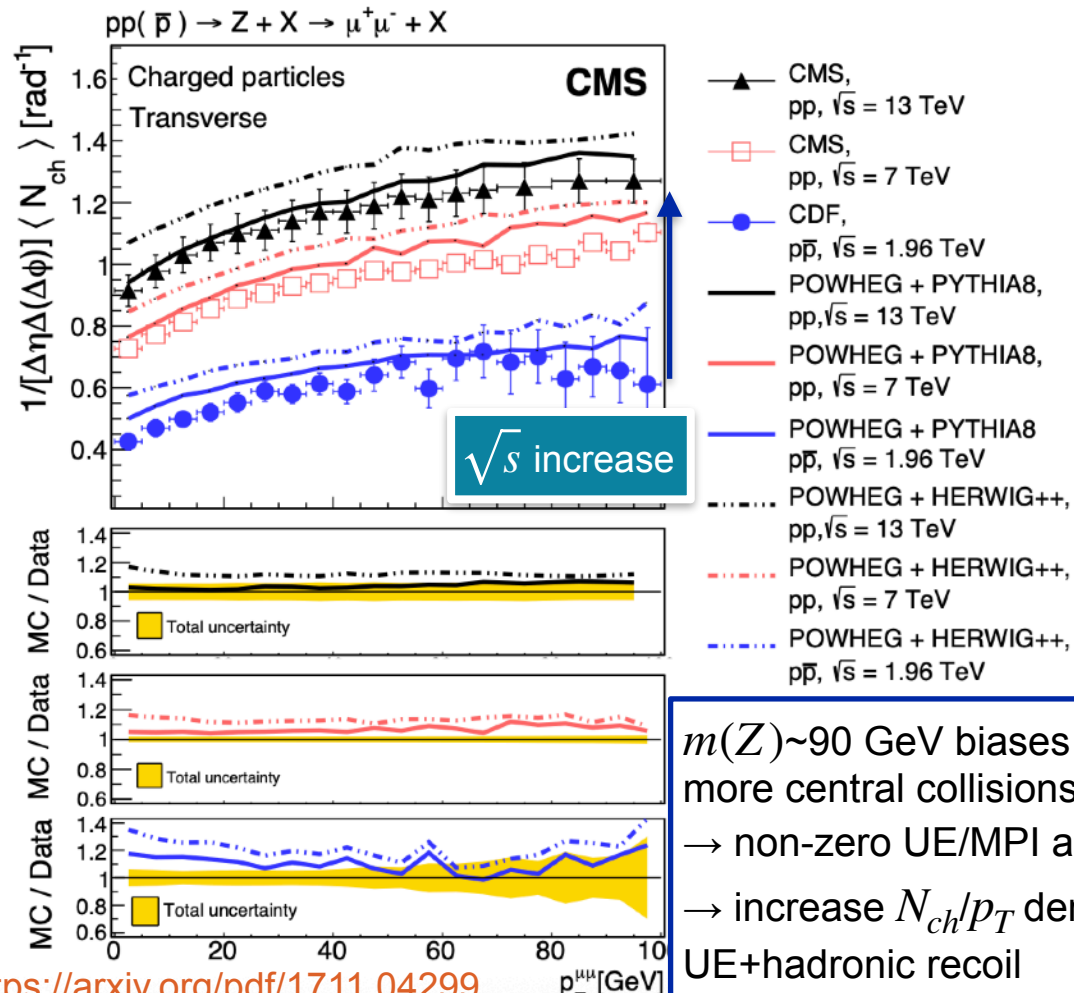
- ➔ Inputs for theoretical models & generator tuning

Hard scatter tagged by Drell-Yan

Variation of hard scatters targeting UE in different perspectives

Hard scatter tagged by **Drell-Yan**

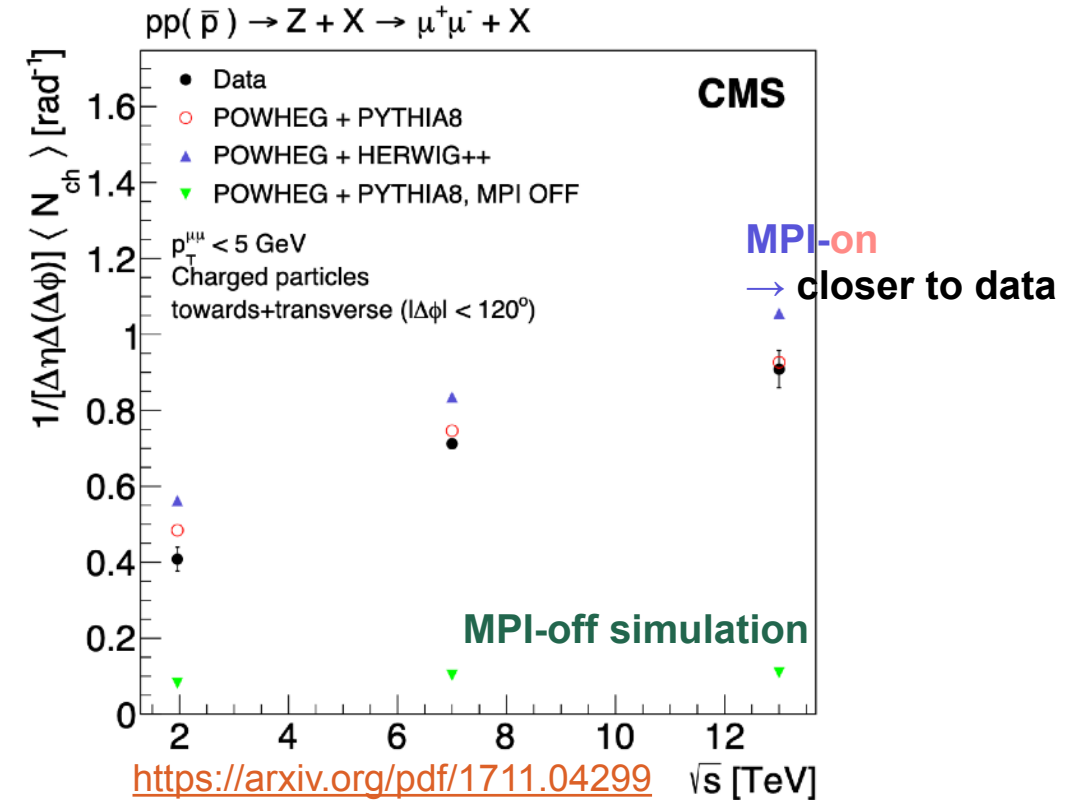
→ clean color-neutral final state, no FSR contamination to UE, no color reconnection between hard scatter and UE



$m(Z) \sim 90$ GeV biases the events towards more central collisions

→ non-zero UE/MPI at $p_T^{\mu\mu} \rightarrow 0$

→ increase N_{ch}/p_T density versus $p_T^{\mu\mu}$ from UE+hadronic recoil



Cut on $p_T^{\mu\mu} < 5$ GeV

→ suppress hadronic recoils to DY

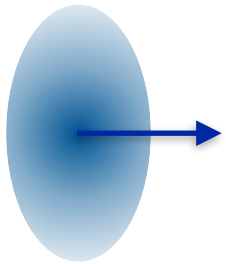
→ purer MPI contributions

Hard scatter tagged by Drell-Yan: future prospects

Variation of hard scatters targeting UE in different perspectives

Future prospects for **DY-associated UE** measurement

Probe proton structures and MPI with Drell-Yan



Simplified parton transverse distribution in protons (Pythia, Herwig, Sherpa)

- Single/double Gaussian or power law w.r.t. IP
- MPI scales with $\sqrt{s}$

MPI independent of the hard process

→ Proton profile independent of parton momentum, flavor, spin, color

→ to be tested and improved with experimental inputs

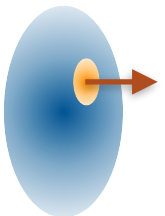
More flexible models?

e.g. x-dependence of proton profile

(x: momentum fraction of a hard-scattering parton in proton)

proton width $\sim \ln(1/x)$

(Pythia option <https://arxiv.org/pdf/1101.5953>)



small x
larger proton size



large x
smaller proton size

Experimental probe:

Differential UE measurement w.r.t. m_{l+l-} , y_{l+l-} , p_T^l

$(m_{l+l-}, y_{l+l-}) \rightarrow (x_1, x_2)$

Check prediction with measurement; model tuning

Hard scatter tagged by $t\bar{t}$

Variation of hard scatters targeting UE in different perspectives

Hard scatter tagged by $t\bar{t}$

→ test UE models at higher energy scale

→ color-reconnection is required between hard scatter and UE

→ tests the color-reconnection (CR) models (affects m_t modeling)

Future prospects:

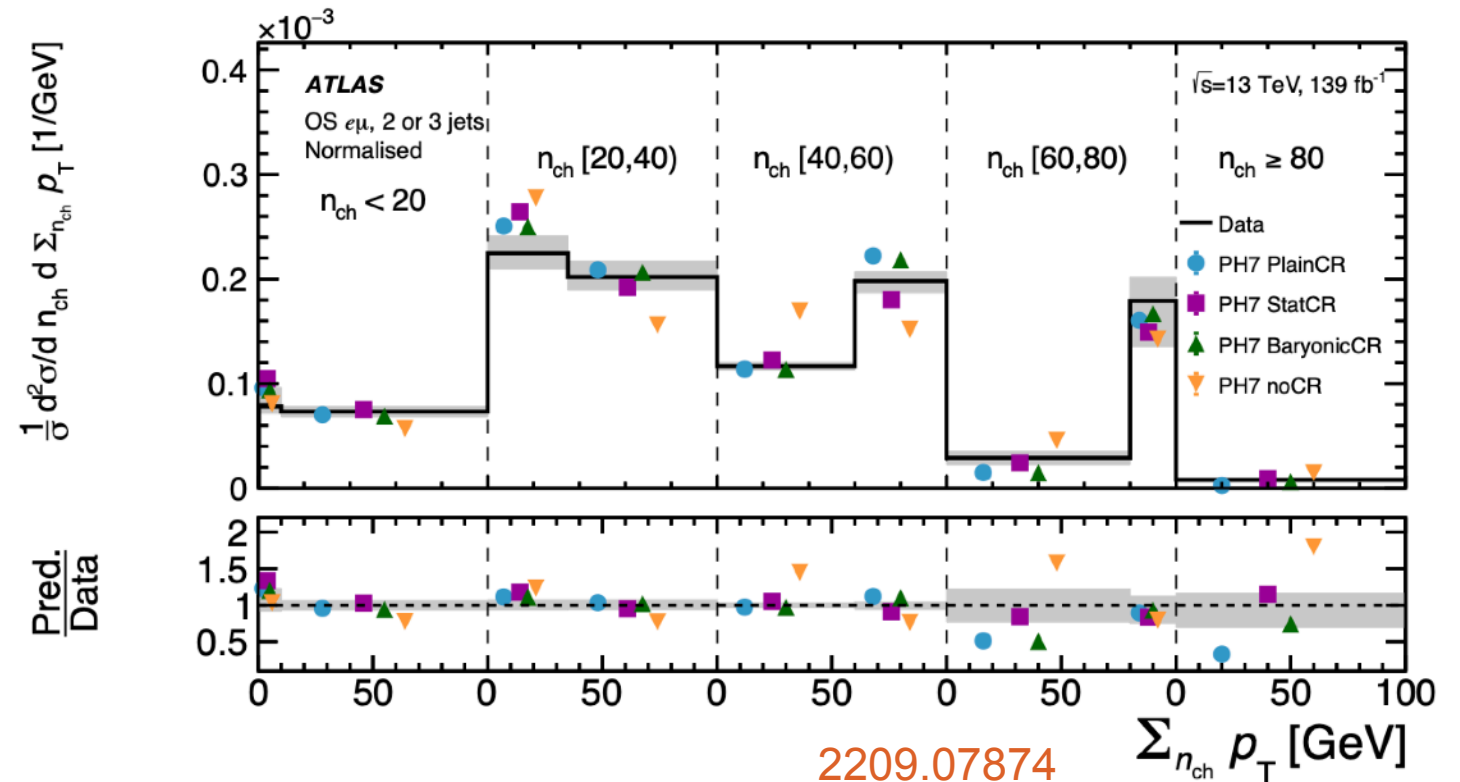
- CR-model development and fit to UE, $t\bar{t}$ jet-pull variables, jet shape measurements

([1807.02810](#) [1805.02935](#) [2209.07874](#) [2202.13901](#))

- Select high-purity $t\bar{t}$ in $(e\nu b)(\mu\nu b)$ channel
- Measure charged particles not matched to $e/\mu/b$ -jets: $N_{ch}, \sum |p_T|, \bar{p}_T$
- Systematic comparison of CR & UE models to measurement

→ **no-CR models are disfavored**
→ **some CR models are ruled out**

→ CR-tunes were performed
([2205.02905](#))



Identified hadrons in underlying events

UE measurement for specific particle species

Hadron flavors are sensitive to **hadronization models**

— non-perturbative, phenomenological, depend on experimental inputs

Experimental handles:

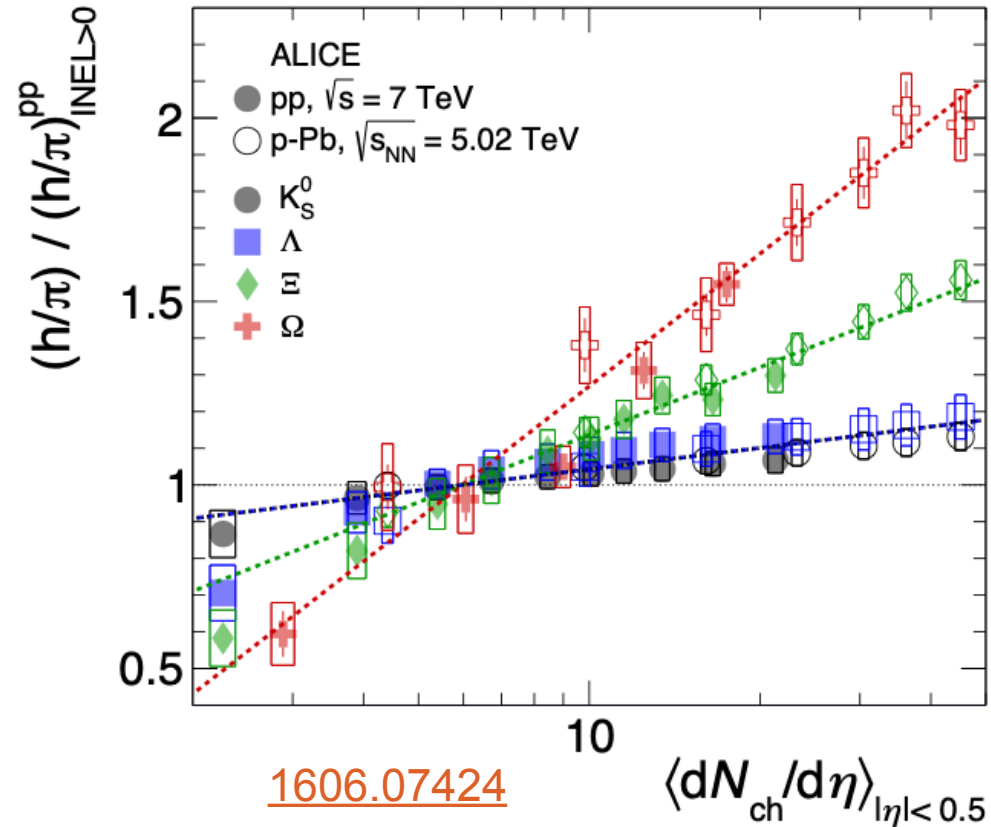
- Ratio of strange hadrons to all charged hadrons K_S^0/N_{ch} , Λ/N_{ch}
- Charm multiplicity and fractions
- Meson to baryon ratios
- Identified particle multiplicity differential to p_T
- Comparison in UE and jet-enriched (hard-scattering) regions
- Comparison in different collisions systems (p-p, p-Pb, Pb-Pb)



Test

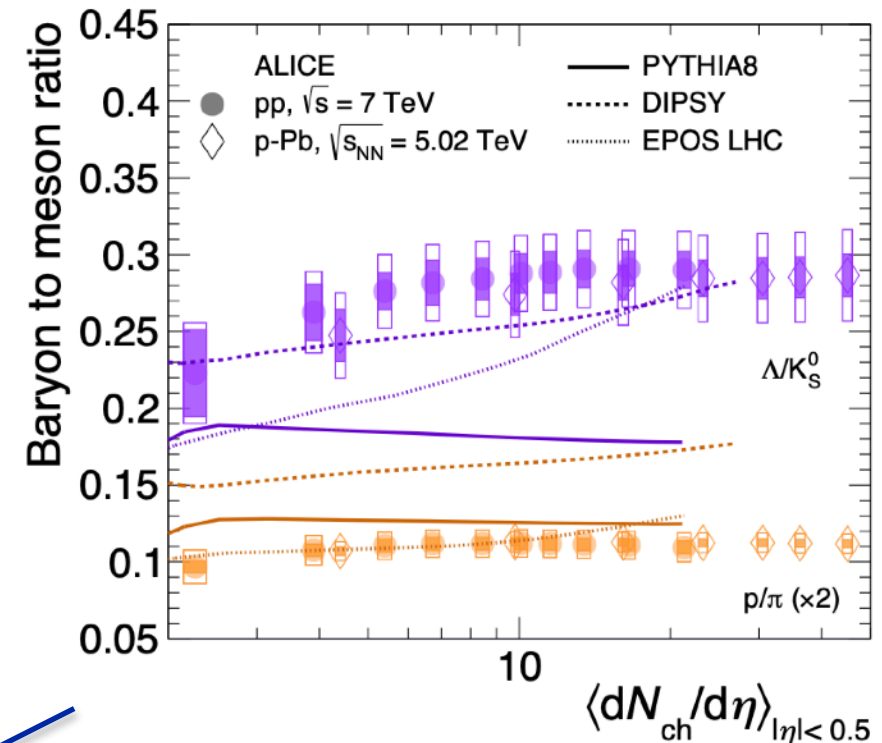
Different hadronization models: string breaking, color reconnection, rope, string shoving, cluster hadronization, thermal hadronization ...
Quark-gluon-plasma(QGP)-related models
Hadron production models for UE and jets...

UE measurement: overall strangeness enhancement



Strangeness-enhancement as a QGP signature

- Reported in heavy-ion experiment but also observed in small systems (pp)
- Collective behaviors were also observed in pp collisions ([1606.06198](#), [1009.4122](#))



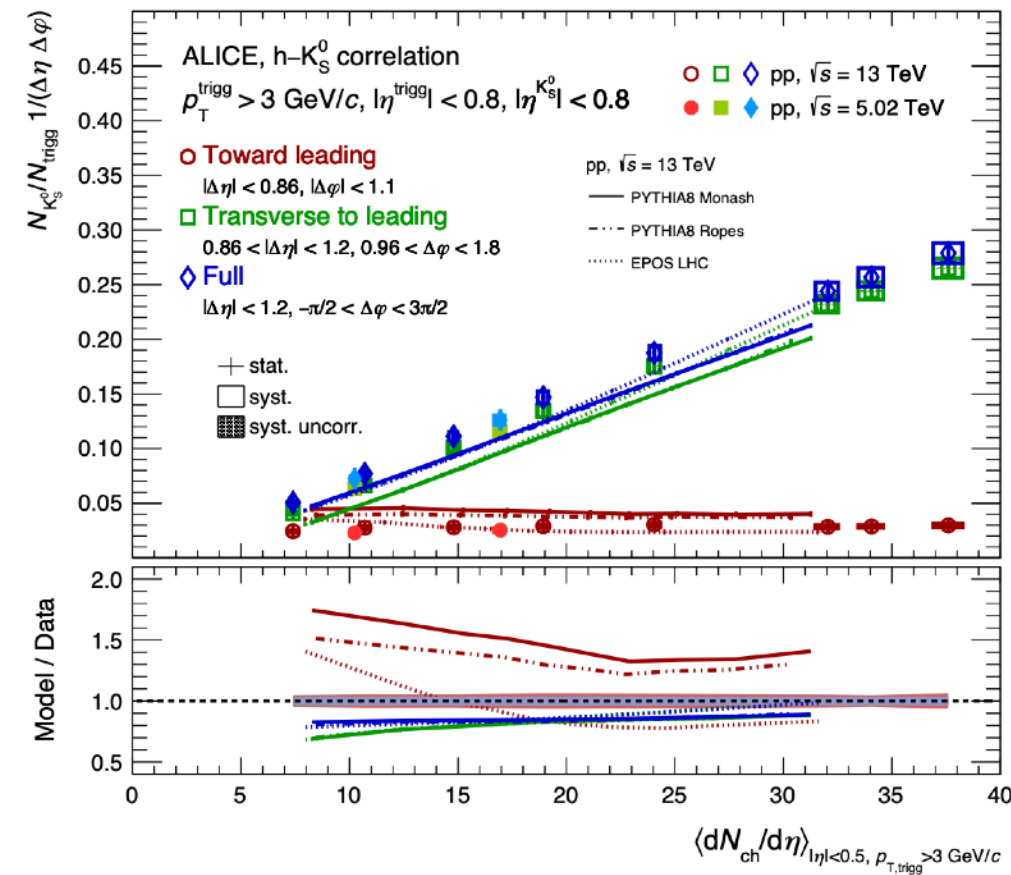
Ratios of yields: strange hadron to π , increases with multiplicity

- Consistent trends in pp, p-Pb, Pb-Pb collisions
- Consistent across different $\sqrt{s}$
- Enhancement grows with #s: $\Omega(sss) > \Xi(dss) > \Lambda(uds) \sim K_S^0$
- Strangeness enhancement is not attributed to mass differences

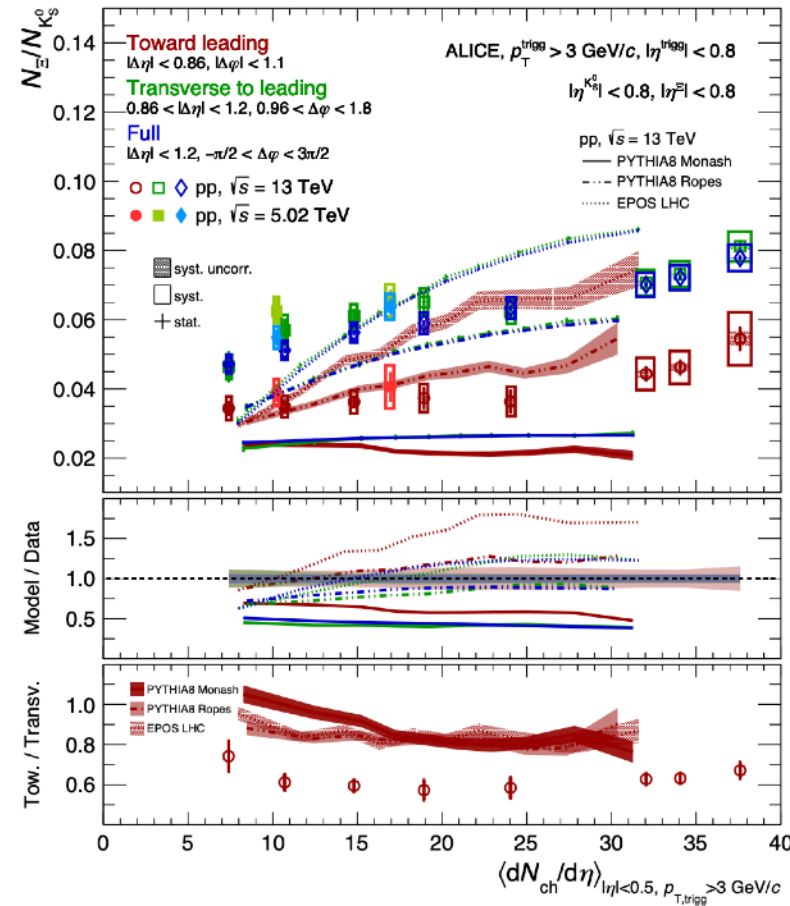
Baryon/meson ratios are not enhanced with multiplicity

1606.07424

More strangeness enhancement in UE than hard-scattering jets



K_S^0 density versus multiplicity



$\Xi(|S|=2)/K_S^0(|S=1|)$ versus multiplicity

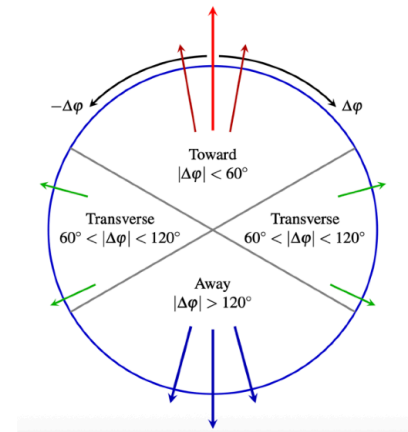
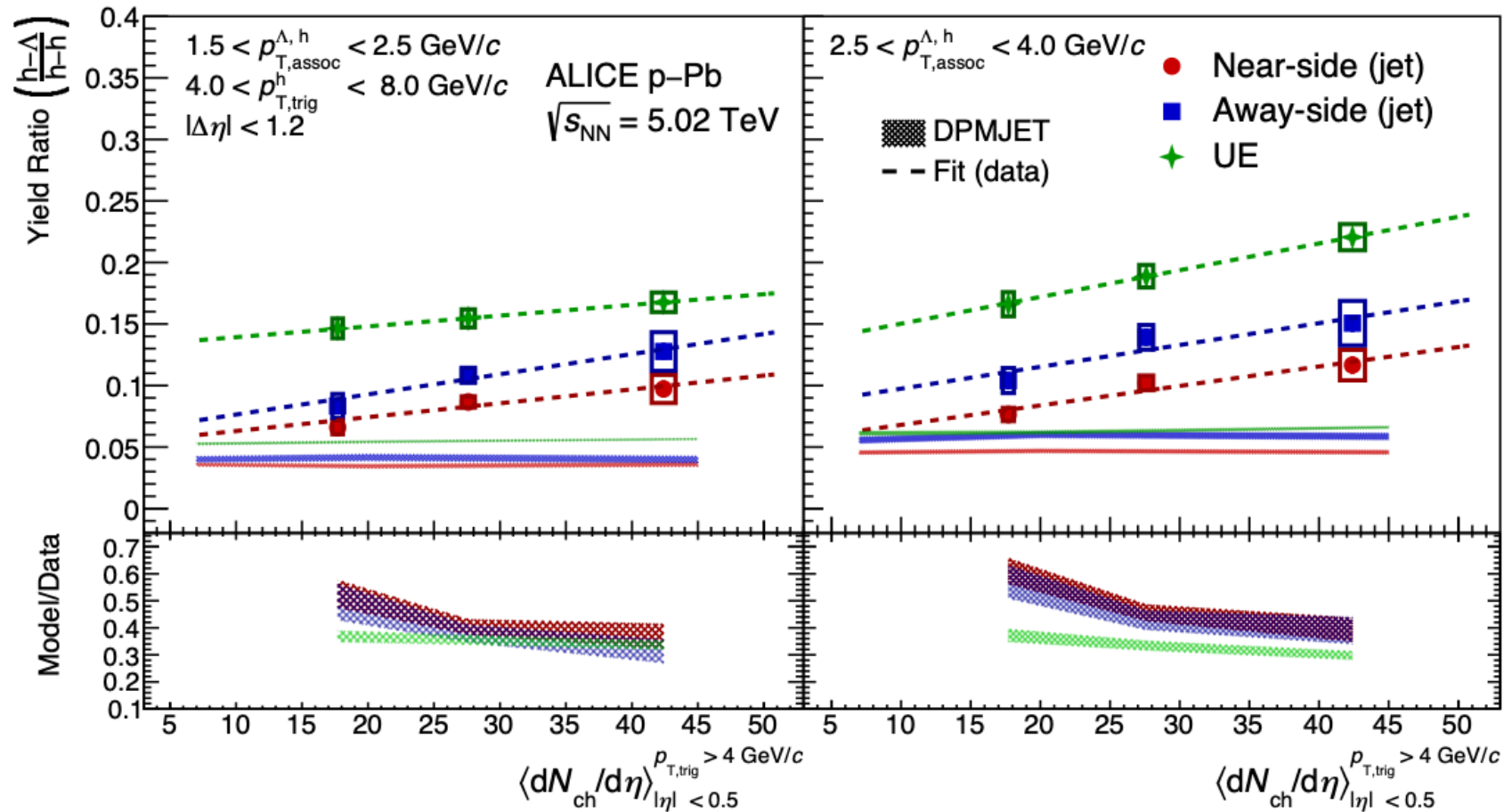
Strange density in **UE-enriched** region
 Transverse to the leading track

Strange density in hard scattering **jet region**
 Aligned with the leading track

Strangeness enhancement is more pronounced in UE than jet

[2405.14511](https://arxiv.org/abs/2405.14511)

More strangeness enhancement in UE than jets



Strangeness enhancement
 UE
 > away side (~ recoils to jet)
 > near side (~ jet)

Strange quark production
 in away side might be
 influenced by UE

[2405.19855](https://arxiv.org/abs/2405.19855)

Prospects: strangeness in diffractive events

Strange particle measurements in **systems smaller than p-Pb or pp collisions**

Use large rapidity gaps, forward energy flow, forward proton tagging

→ Diffractive, photon-induced, pomeron-induced systems

CMS measurement [2606.00171](#): no two-particle azimuthal correlations (collectivity signature of QGP) observed in diffractive-enhanced p-Pb collisions

→ what about strangeness enhancement effects?

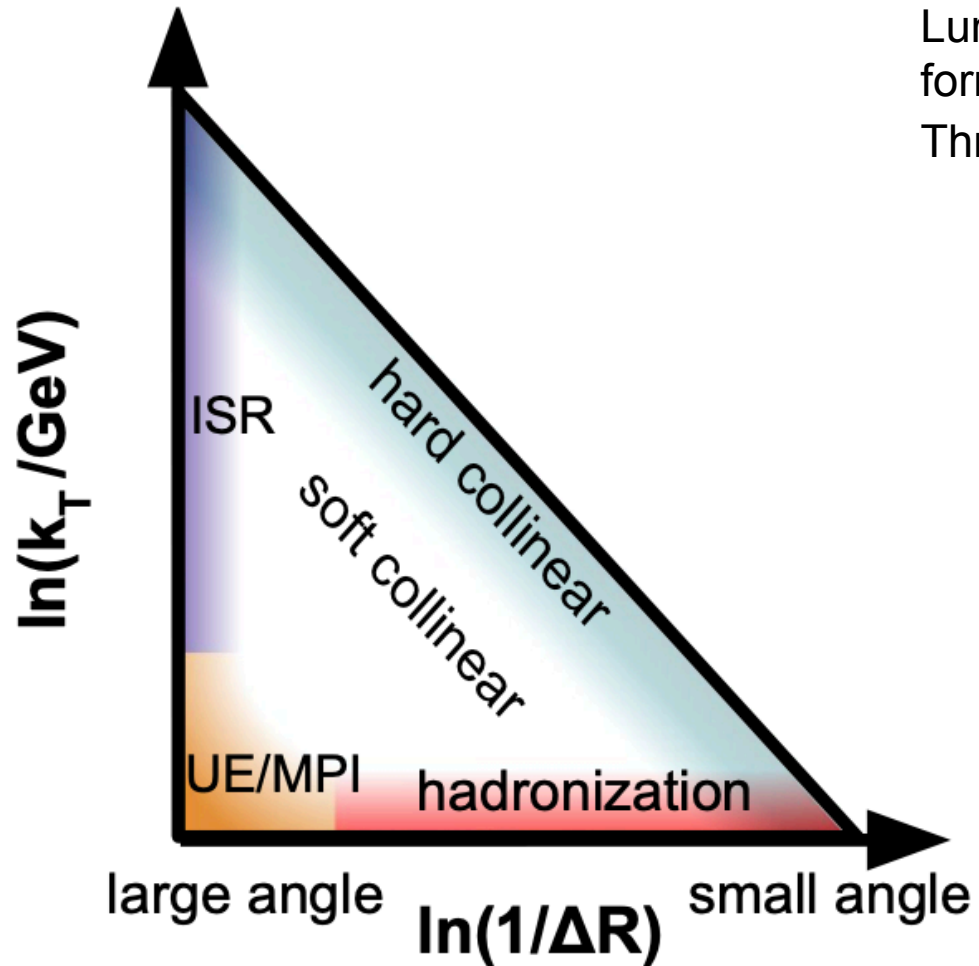
ATLAS measurement [2503.08181](#): strange hadrons in photo-nuclear Pb-Pb & p-Pb collisions

→ all generator models fail to describe the measurements

Future prospects:

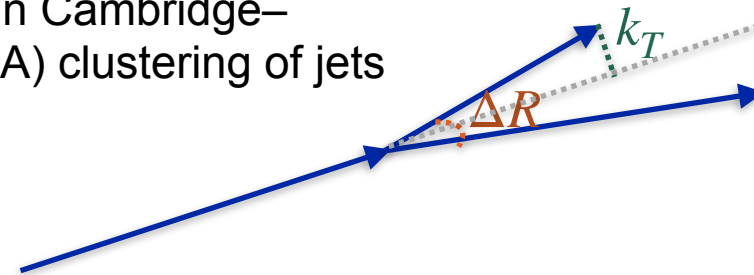
- Strangeness measurements in diffractive / pomeron-induced systems
- Systematic model comparisons to measurements, fitting and improvements
- UE contamination to jets in strange hadron components?
 - Impacts on new physics search & jet-flavor tagging?
 - Strangeness in archived e⁺e⁻ LEP data?

Prospects: identified hadrons in Lund jet plane



Lund jet plane as a powerful tool to separate different stages of jet formation & phenomenological models
Through angle (ΔR) and transverse momentum (k_T) of $1 \rightarrow 2$ splittings

A splitting in Cambridge–Aachen (CA) clustering of jets

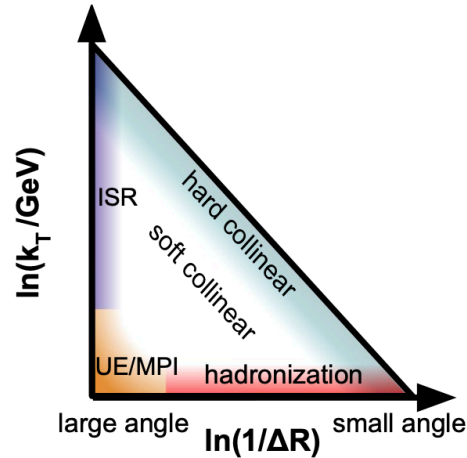


Find all $1 \rightarrow 2$ splittings (“emissions”) in CA-clustered jets

Measure:

$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{\text{jets}}} \frac{d^2 N_{\text{emissions}}}{d \ln(k_T / \text{GeV}) d \ln(R / \Delta R)}$$

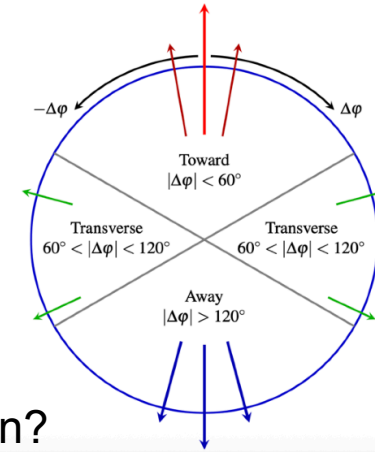
Prospects: identified hadrons in Lund jet plane



Measure **where the identified hadrons land** in the Lund-jet plane

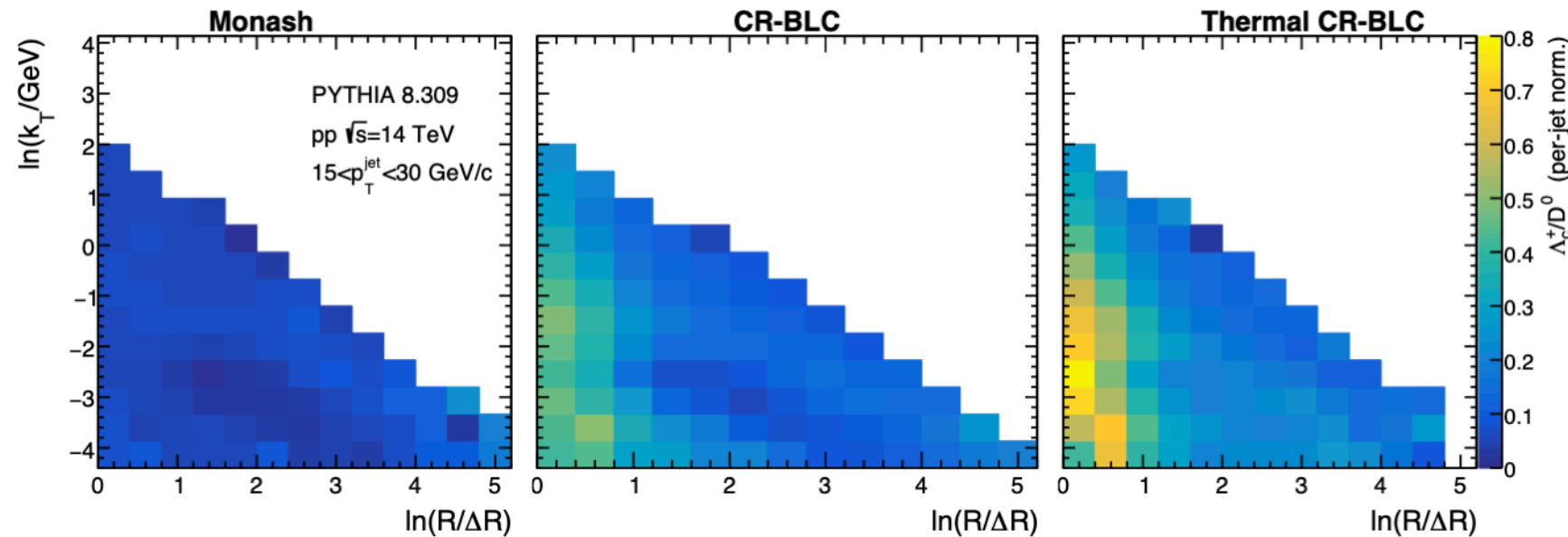
- **Disentangle UE/MPI contaminations in jets**

→ are certain types of hadrons produced more in UE contaminations
 → cross check with measurements in **toward/away/transverse** region of the azimuthal plane defined by hard scatter



- Identified hadrons in different stage of jet fragmentation

→ Hard scatter in initial state radiation (ISR)? Parton shower? Hadronization?
 → Sensitive to models of parton shower, color reconnection, hadronization



Baryon/meson ratios
in Lund-jet plane

- Three hadronization models give very different predictions
- Proposed identified hadron measurements in Lund-jet plane at LHC [2609.18693](#)
- Similar identified hadron measurements with energy-correlator variables?

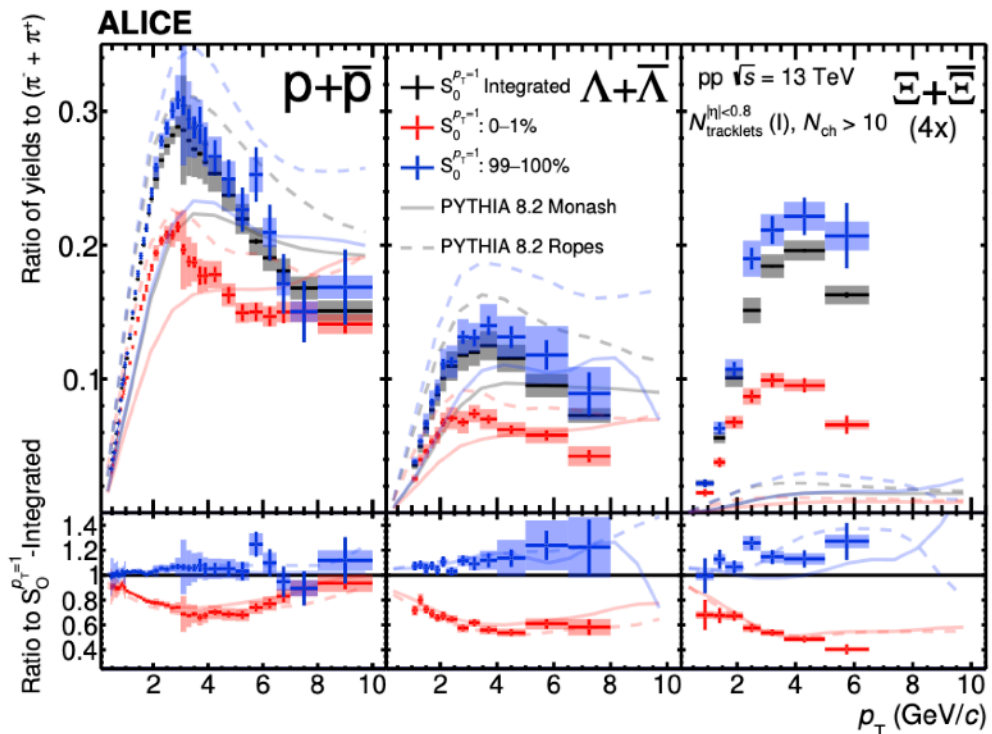
Probing overall hadron collision shapes: Event shape variable measurements

UE measurement: overall event shape variables

Variables beyond the multiplicity, momentum and identity
→ **event shape variables** e.g. transverse sphericity

$$p_T \text{ weighted} \quad S_0 = \frac{\pi^2}{4} \min_{\vec{n}=(n_x, n_y, 0)} \left(\frac{\sum_i |\vec{p}_{Ti} \times \vec{n}|}{\sum_i p_{Ti}} \right)^2$$

$$\text{Unweighted} \quad S_O^{p_T=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\sum_i |p_{T,i} \times \hat{n}|}{N_{\text{trks}}} \right)^2$$



Use transverse sphericity to classify events:

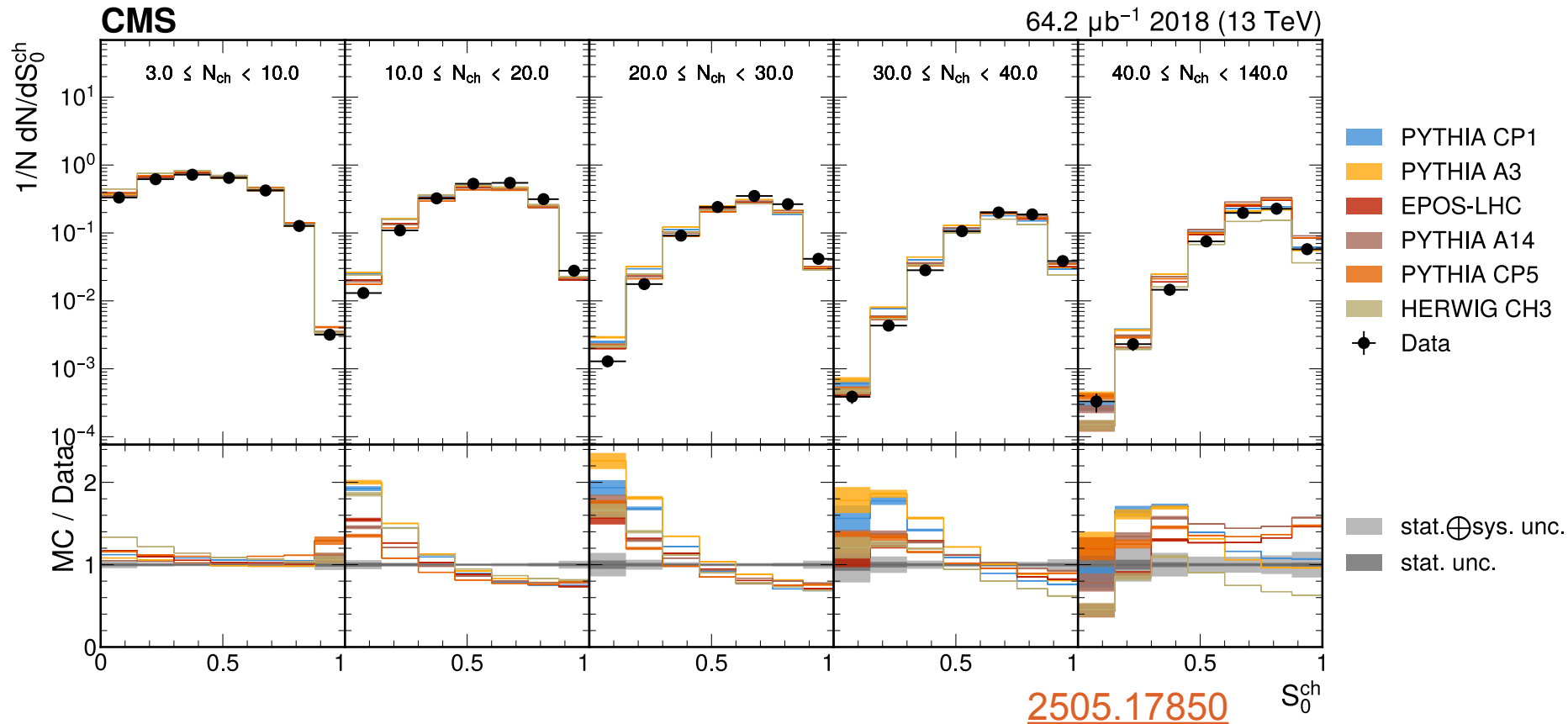
High-sphericity — high MPI soft interaction

Low-sphericity — jet-like events

Disentangle the two classes with event shapes
(mixed in N_{ch} classifications)

→ test the strange particle multiplicity

UE measurement: overall event shape variables



Multi-dimensional event shape variable measurement in minimum bias pp events

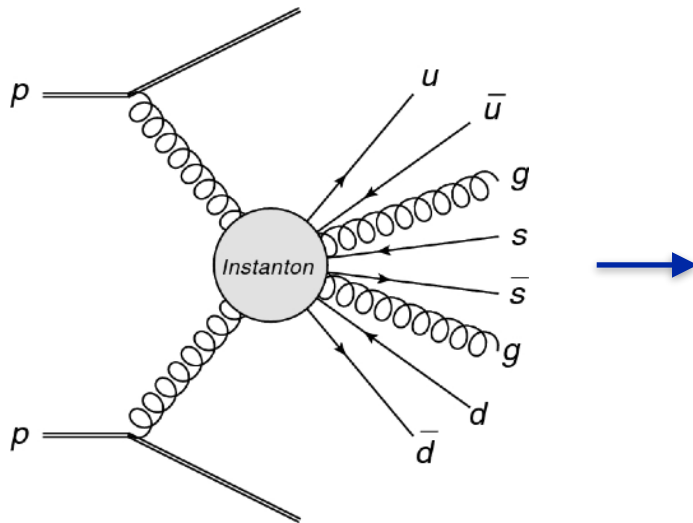
- Event shapes differential in multiplicity ($\sim$ UE activity, MPI, centrality)
- All generator models underestimate the transverse sphericity (data is more isotropic than predicted)

UE measurement: overall event shape variables

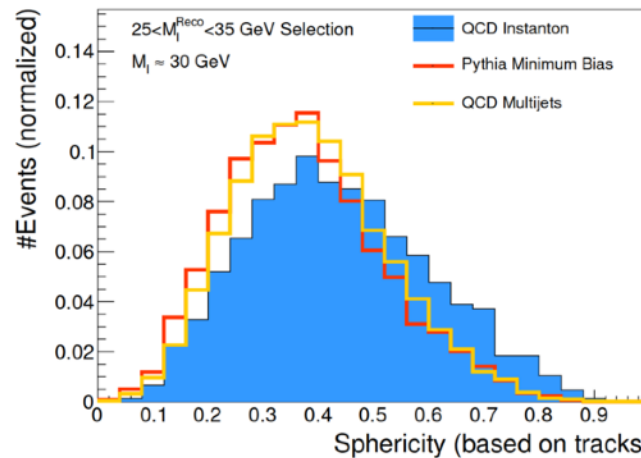
Overall event-shape variables are sensitive to topological effects of QCD

QCD instantons:

- Predicted to be abundant in LHC pp collisions ([1911.09726](#))
- Multi-particle production from a vertex → **isotropic shape**
- A pair of $q\bar{q}$ for each accessible flavor → potential contribution to strange & charm productions in UE
→ alternative explanation to strangeness enhancement in small systems?



Instanton predictions



More isotropic shapes

Experimental handles:

- Event shape measurement
- Strange/charm hadrons in UE

Ongoing efforts in CMS & ATLAS in instanton searches

Future prospects in event shape measurements

Event shape measurements in **diffractive** pp collisions

Forward intact proton $\rightarrow$ pomeron-induced hard diffraction
 $\rightarrow$ characterize event shapes of pomeron-proton scattering
+ identified particle multiplicities
Opportunities from the recent low pileup run in CMS

Instanton-related measurements

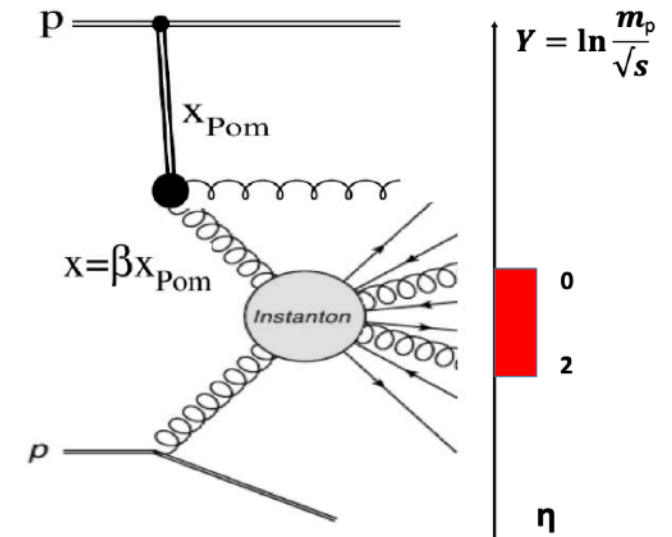
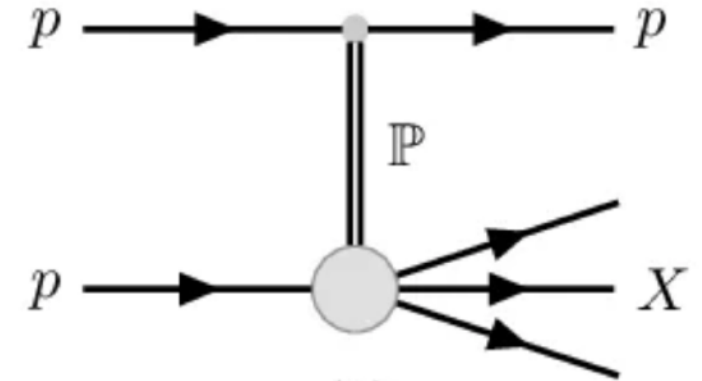
- Instanton production from pomeron-proton interaction

[2104.01861](#)

$\rightarrow$ disentangled from MPI
 $\rightarrow$ probed by event shapes in diffractive events
(Large rapidity gaps, forward proton tagging)

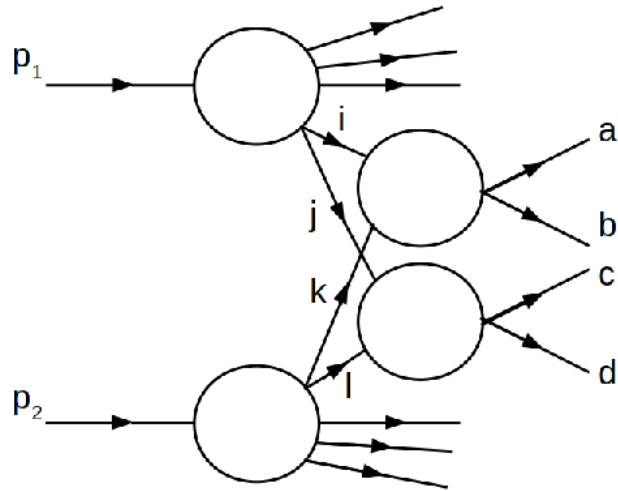
- Instanton production from non-diffractive pp collisions
 $\rightarrow$ Understand the MPI background
 $\rightarrow$ Understand the impacts of parton shower and hadronization models to event shapes
 $\rightarrow$ UE measurement and generator tuning
 $\rightarrow$ High-mass instanton searches?

- Model improvements for cross section prediction, instanton in MPI ...



Multiple hard scatters in one collision: Double parton scattering measurement

Double parton scattering measurements



Double parton scattering (DPS):
~ Special MPI with two hard scattering

Probe the transverse parton distribution via σ_{eff}

σ_{eff} in various processes

- Same-sign WW ([2206.02681](#), [2505.08313](#))
- Jet pairs ([2109.13822](#), [1608.01857](#))
- W+jets ([1312.5729](#), [1301.6872](#))
- Quarkoniums ([2311.14085](#), [2305.15580](#), [1612.07451](#), [1610.07095](#))

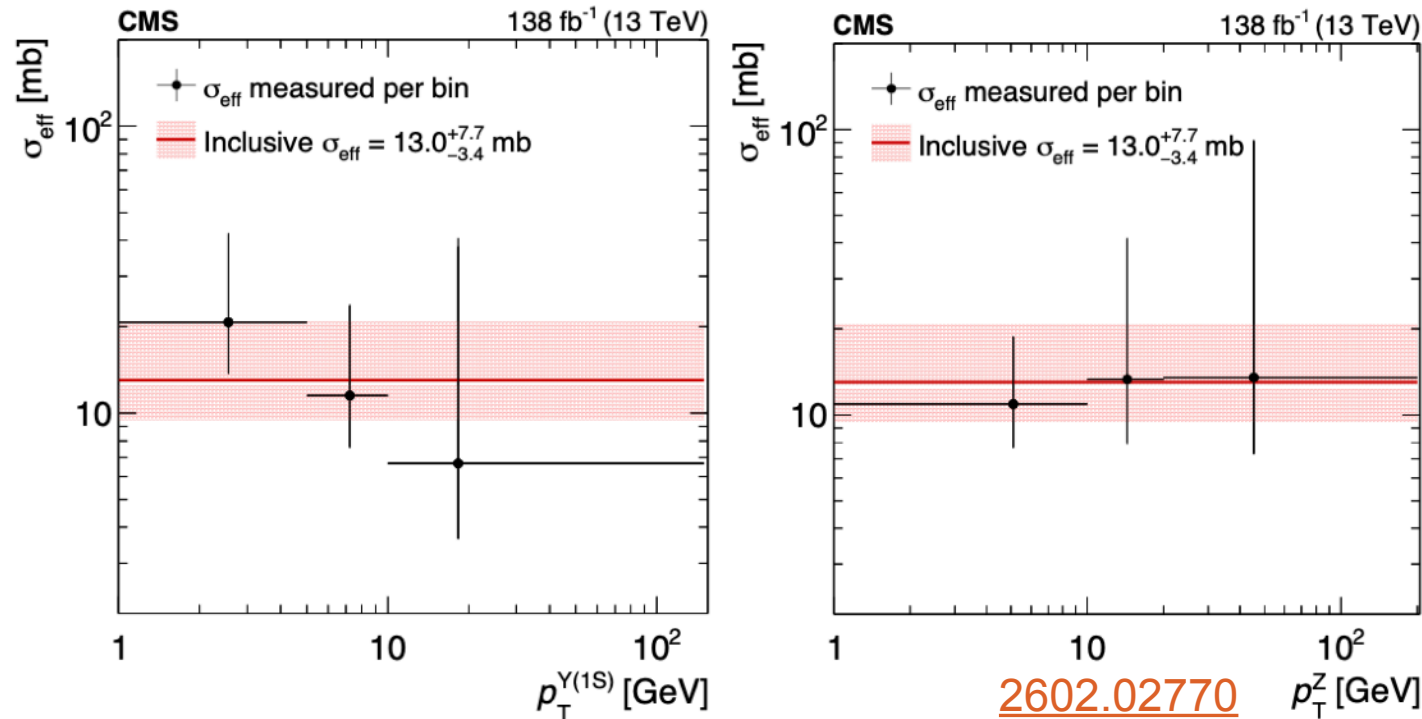
Dependence of σ_{eff} on process

→ transverse parton distribution affected by flavor & momentum of partons

$$\sigma_{DPS}^{AB} = \frac{m}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}, m = 1(2) \text{ if } A=B \text{ (otherwise)}$$

Prospects of double parton scattering

Y(1S)+Z from DPS measurement



Differential σ_{eff} in $p_T^{Y(1S)}$ and p_T^Z

→ scale-dependent transverse parton distribution

More differential σ_{eff} to come (more data, more final states)

σ_{eff} versus hard scatter mass, rapidity, p_T

→ quantify the x-dependence of transverse parton distribution

Prospects of double parton scattering

Probe the spin correlation of partons in protons with DPS

→ Use same-sign WW in leptonic channels

→ lepton-pair η -asymmetry reflects the spin correlation of partons

[2003.03347](#)

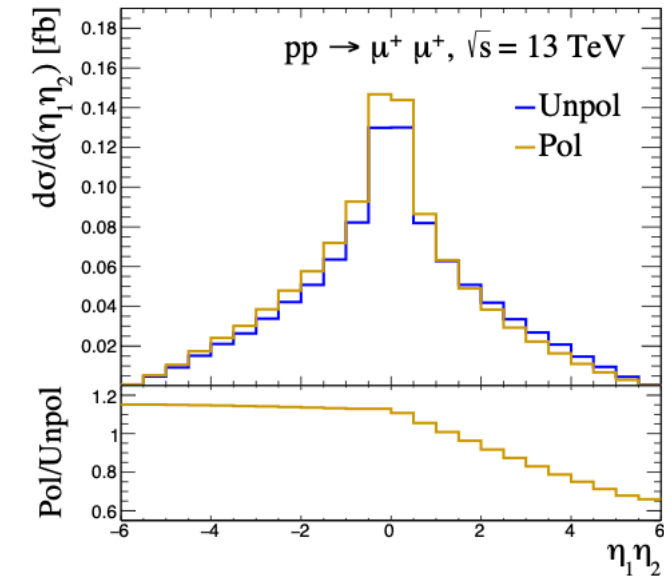
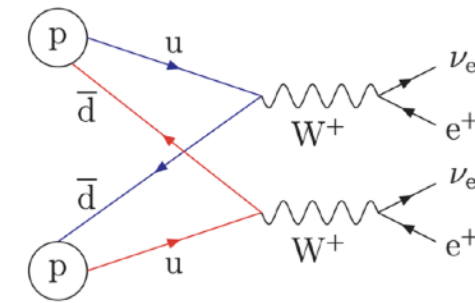
$$A = \frac{\sigma(\eta_1 \eta_2 < 0) - \sigma(\eta_1 \eta_2 > 0)}{\sigma(\eta_1 \eta_2 < 0) + \sigma(\eta_1 \eta_2 > 0)}$$

Sensitivity expected with HL-LHC luminosity

Probe different quark components

→ W^+W^+ , W^-W^- asymmetry in DPS [1003.3953](#)

Test u/d ratio correlation in DPS



Summary

Existing/future **measurements targeting different characteristics of soft QCD** in UE/MPI

- Underlying-event (UE) measurements with tagged hard scatters
- Measurements of identified hadrons in UE
- Overall event shape measurements
- Double parton scattering measurements

→ multiplicity, momentum, flavor, shape, correlations of particles from UE/MPI

→ probing physics in proton structure, hadronization, parton shower, QCD topological effects

Future prospects:

- Differential UE measurements
- New variables sensitive to modeling variations
- Soft QCD in diffractive collisions