QCD AND HEAVY ION MEASUREMENTS AT CMS AND ATLAS

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on behalf of the CMS and ATLAS collaborations

La Thuile 2021
March 11, 2021

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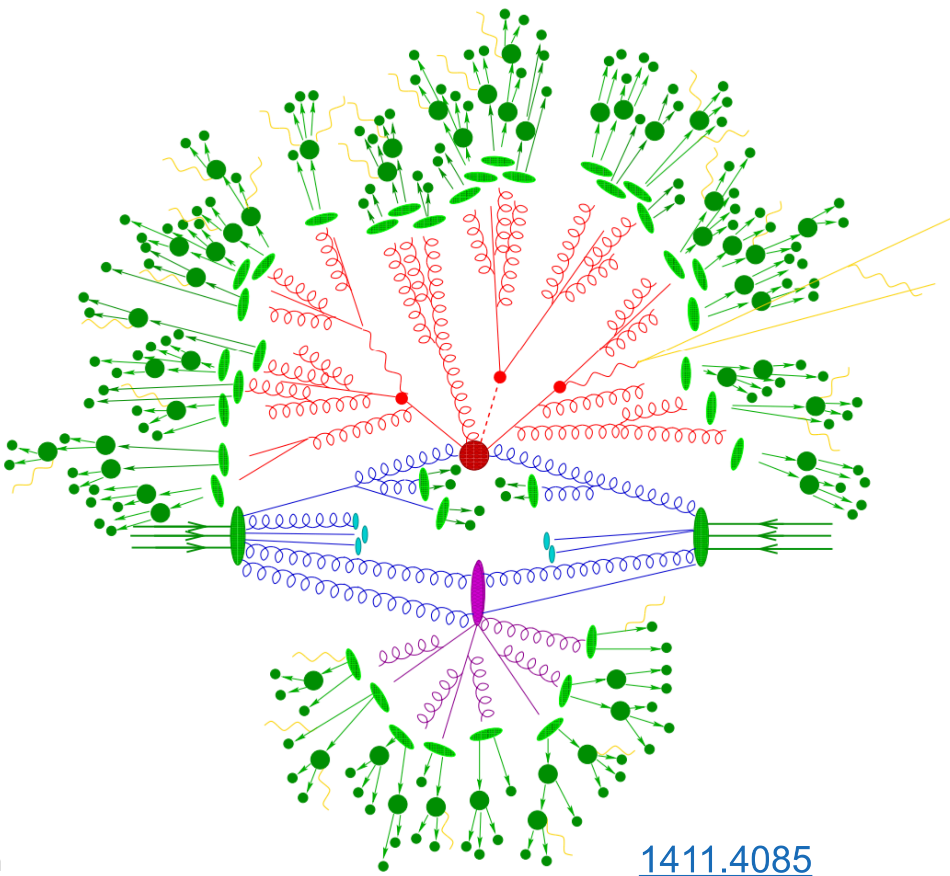
QCD

Probing the strong force at high energies

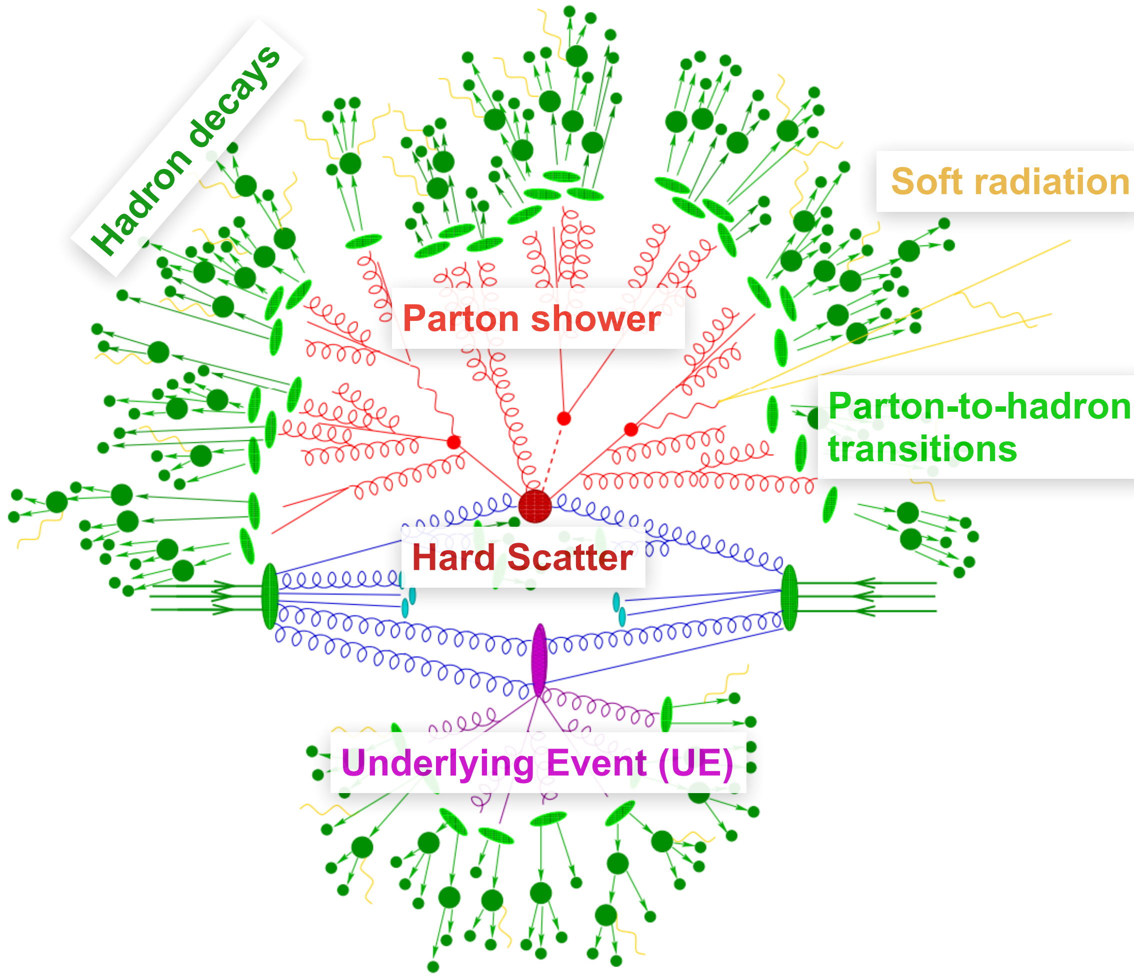


1411.4085

QCD is complex and abundant

1411.4085

- **Observed in our detector as jets**
- **Important source of background for searches**
- **Not well modeled in simulation**
  - Parton shower uncertainties dominate ML tagger systematics
- **Can be probed by a multitude of measurements!**

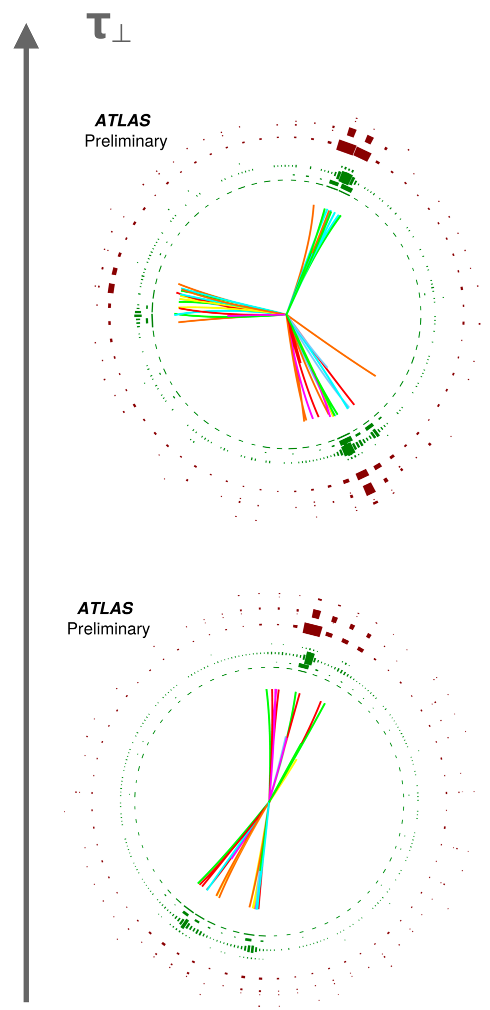


EVENT SHAPE VARIABLES

Measuring hadronic energy flow

Event Shape Variables

ESVs sensitive to flow of energy in hadronic states



Transverse thrust

$$T_\perp \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}$$

Complement to $T_\perp$

$$\tau_\perp \equiv 1 - T_\perp$$

sensitive to hard-scattering

Jet broadening

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$

Sensitive to hadronization, NP effects

JHEP 12 (2018) 117
ATLAS-CONF-2020-011

Event Shape Variables

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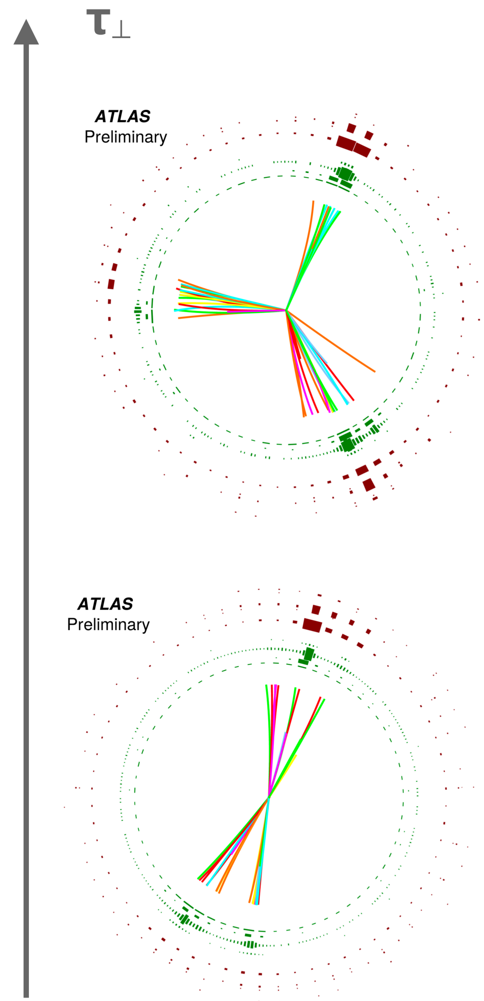


CMS

- Multijet events at 13 TeV
- Differential measurement of ESVs

ATLAS

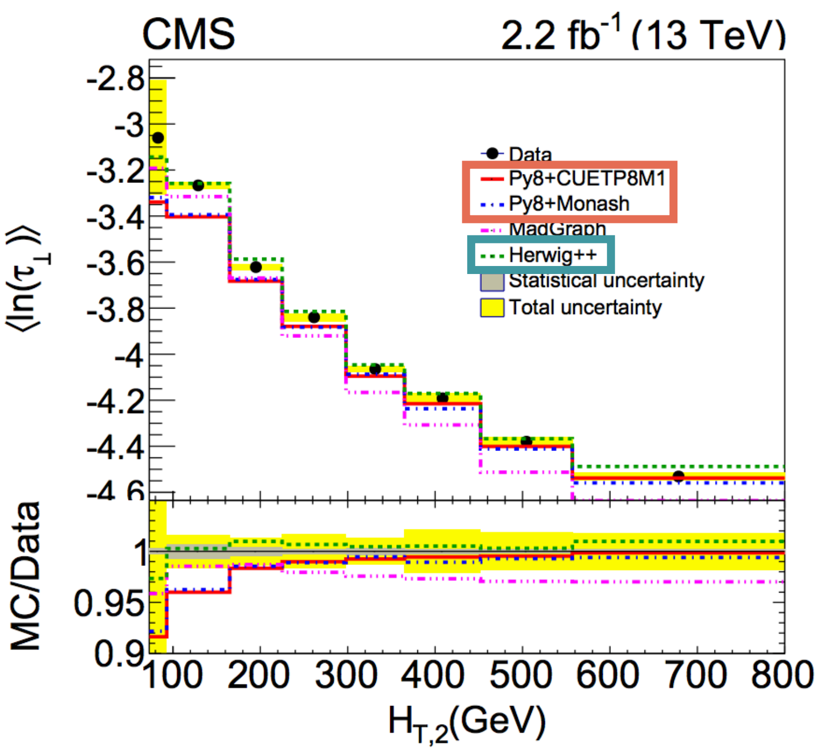
- 13 TeV
- Multijet events
- Triple-differential measurement of ESVs, HT, & jet multiplicity

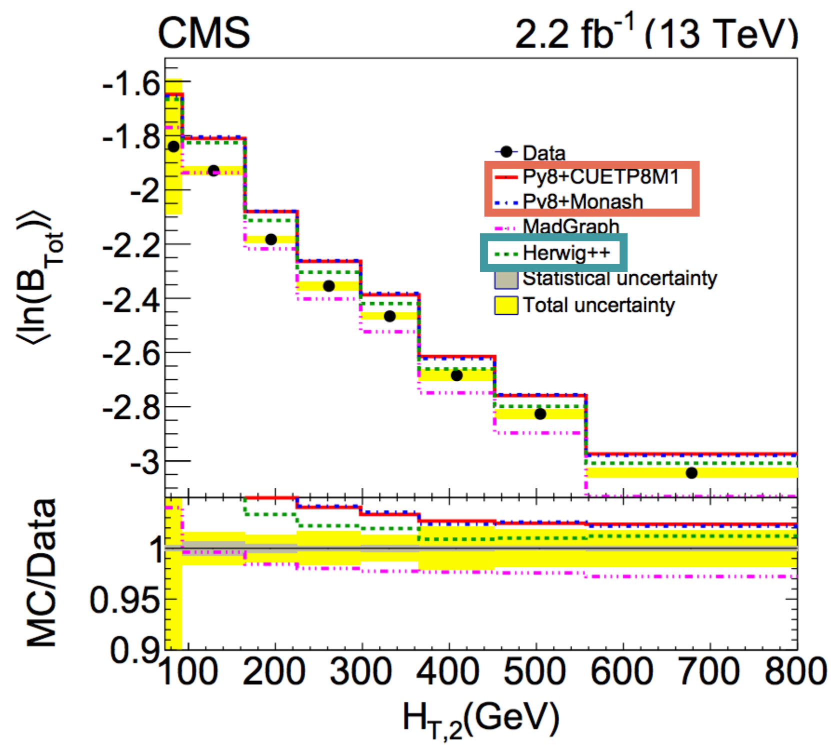
NP effects

JHEP 12 (2018) 117

ESVs in CMS

- **Best ESV data/MC agreement at higher energy**
  - Partons more boosted, less spherical events
  - α_s decreases, less hard gluon emission

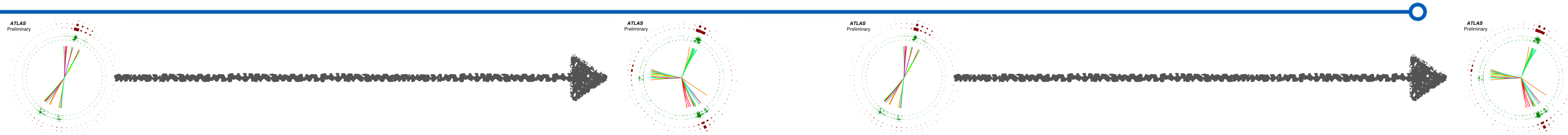


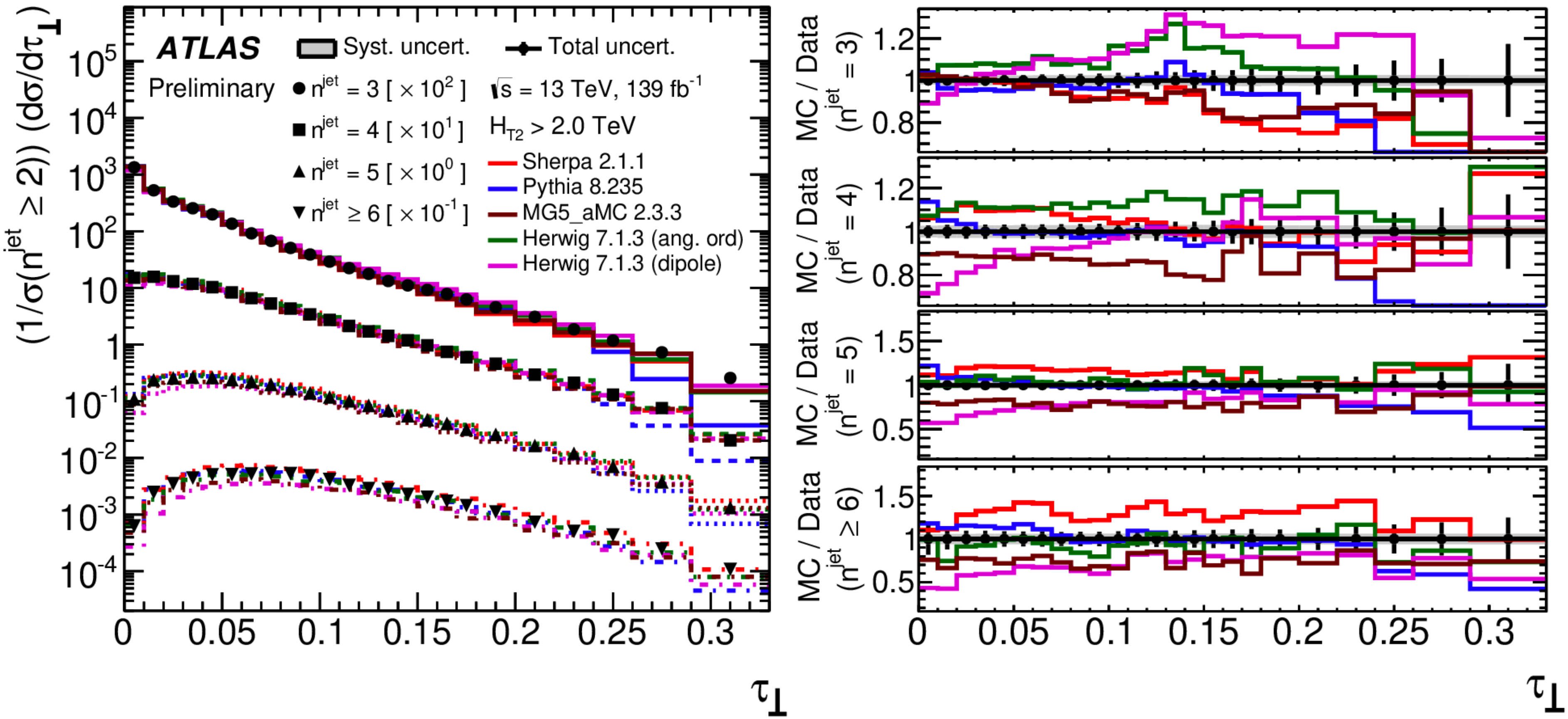


Pythia8 models energy flow in plane transverse to the beam well
(string fragmentation + p_T-ordered shower)

Herwig++ performs well
(cluster fragmentation
+ angular-ordered shower)

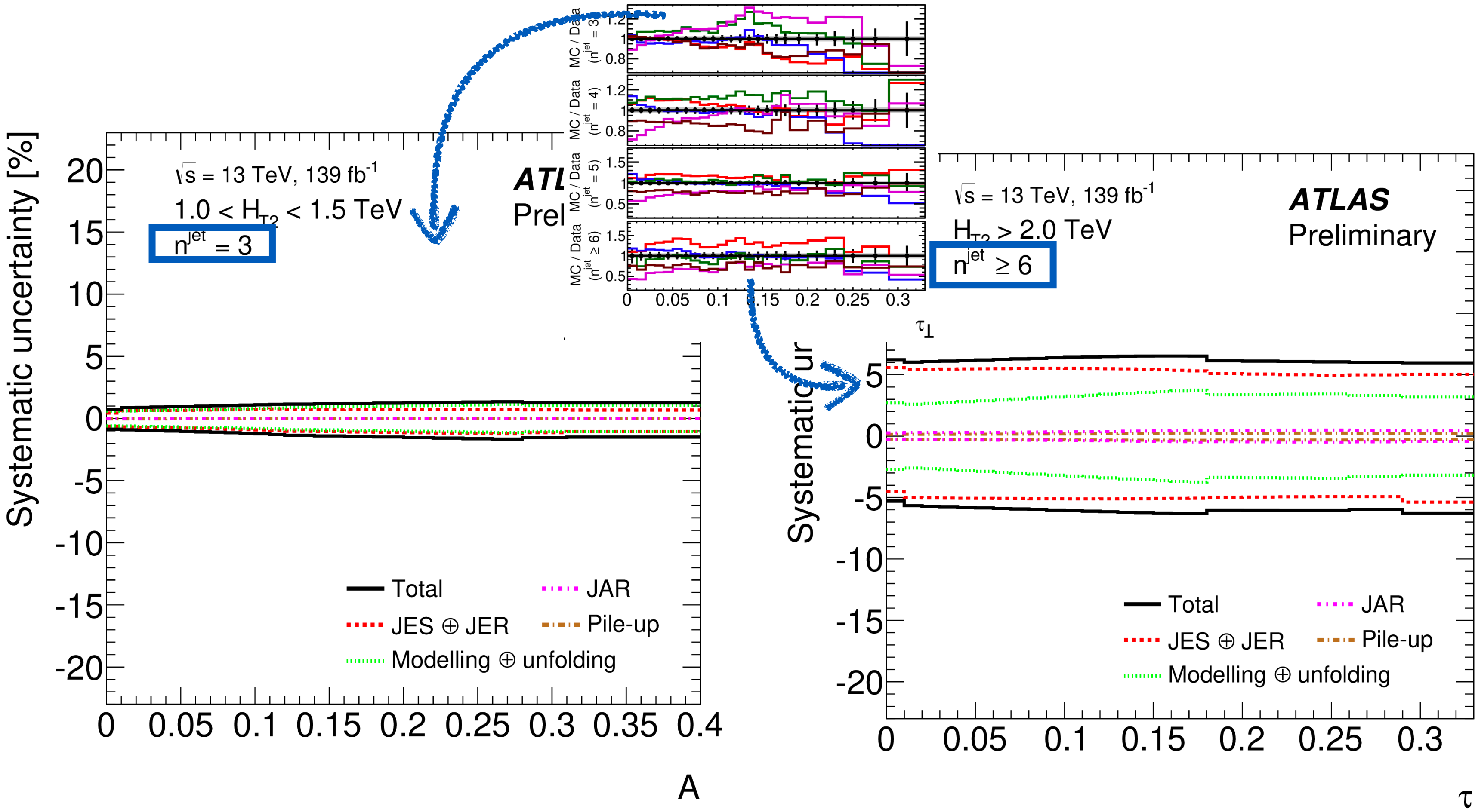
ESVs in ATLAS





Good **Pythia8**/data agreement in more dijet-like events. Some sensitivity to H7 PS algorithm (dipole, ang. ord). Sherpa under (over) predicts at low (high) jet multiplicity, while H7 does the opposite.

ESVs in ATLAS



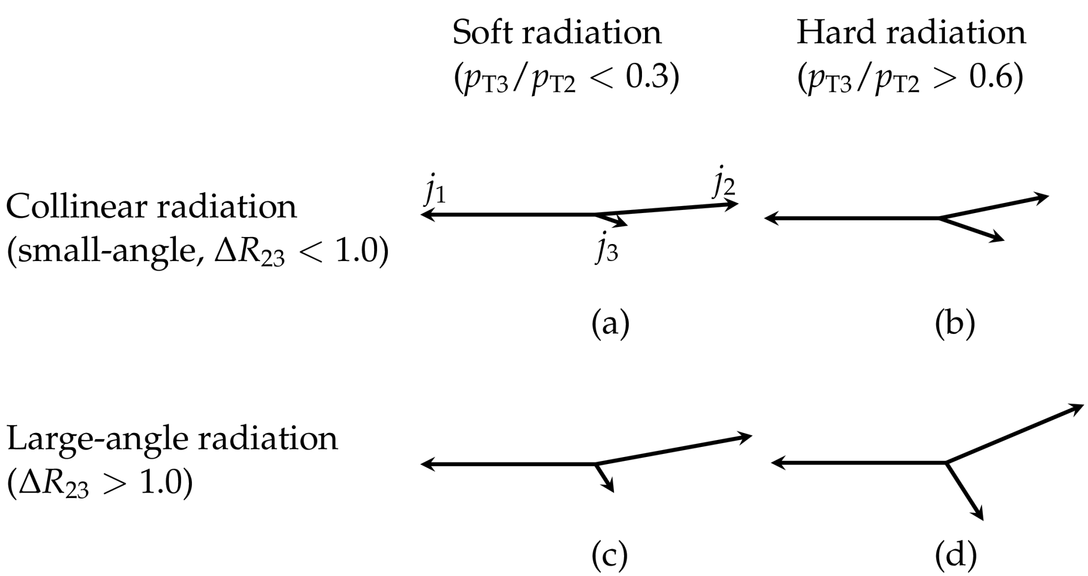
Modeling uncertainty dominates at low jet multiplicity and H_{T2}.
JES/JER dominate at high multiplicity and energy.

MULTI-JET CORRELATIONS

Multi-jet Correlations in CMS

- **Goal: understand multi-jet modeling**
- **Approach**
  - Use **3-jet events** (8 & 13 TeV) & **Z + 2-jet events** (8 TeV)
  - Measure two observables (of sub-leading jets):
    - Transverse momentum ratio: p_{T3}/p_{T2}
    - Angular separation: $\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\phi_3 - \phi_2)^2}$
  - Split events into categories of interest:

j_1, j_2, j_3: p_T-ordered jets (Z boson is j_1)



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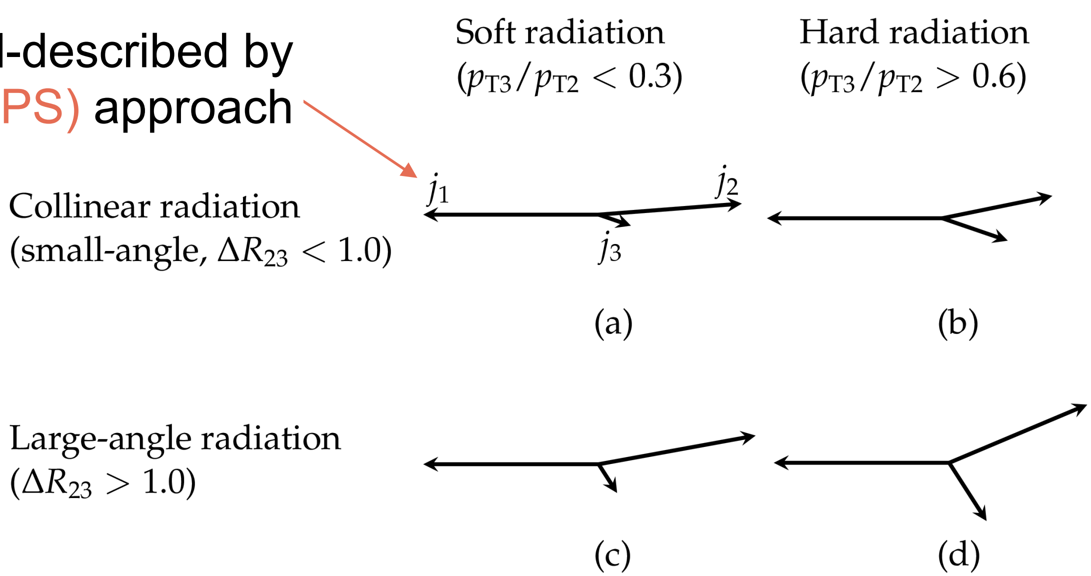
Should be well-described by
Parton Shower (PS) approach



Multi-jet Correlations in CMS

arXiv:2102.08816

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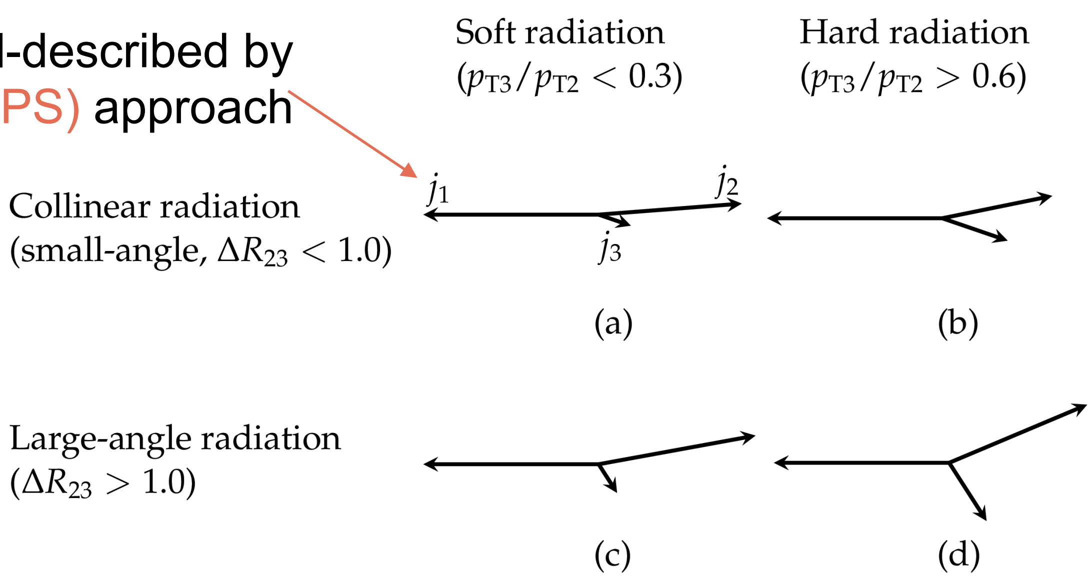
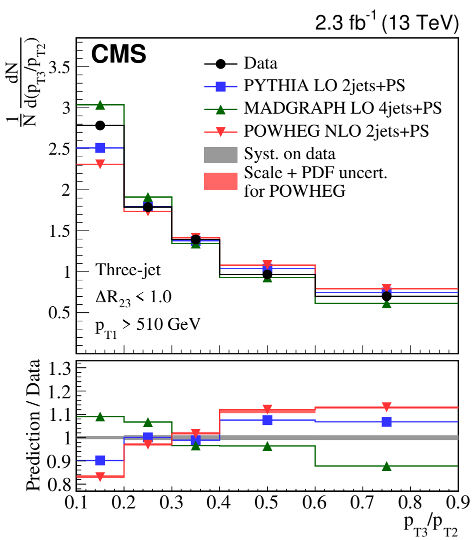


Should be well-described by Matrix Element (ME) calculations

Multi-jet Correlations in CMS

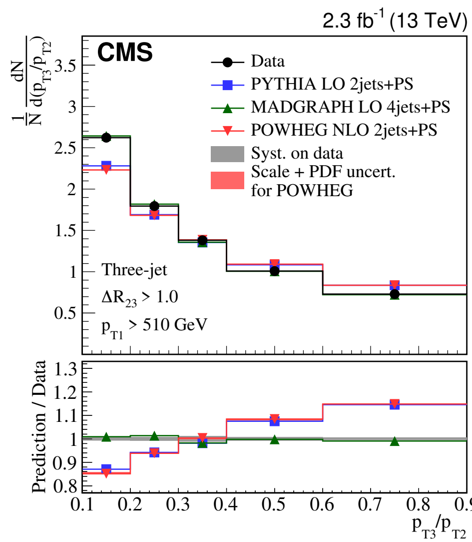
Full phase space not yet well-described by a single ME + PS merging scheme!

Soft ⟷ Hard



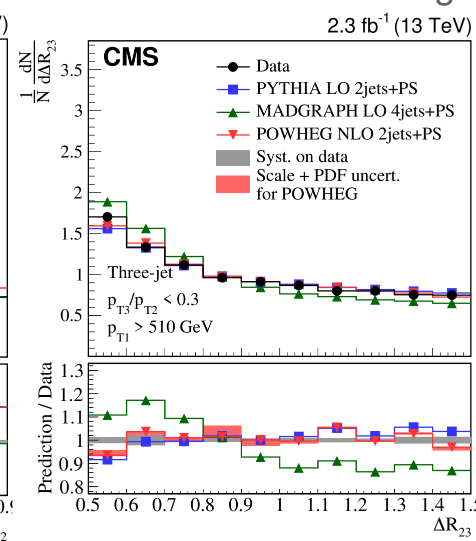
Collinear radiation

Soft ⟷ Hard



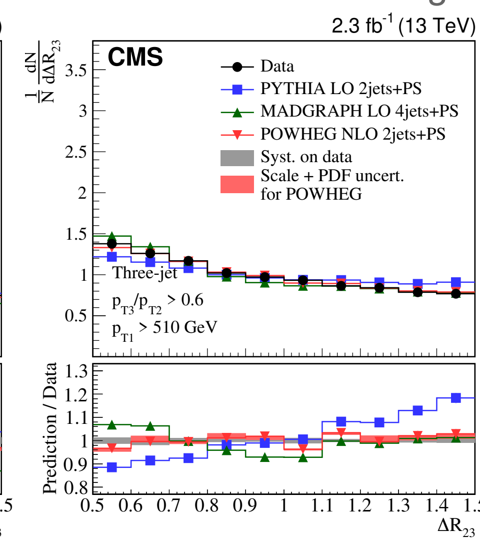
Large-angle radiation

Collinear ⟷ Large angle



Soft radiation

Collinear ⟷ Large angle



Hard radiation

Large-angle and hard radiation well described by ME (LO 4j+PS). Soft region well described by PS approach (LO 2j+PS and NLO 2j+PS). Collinear region not well described by either.

Z+JETS MEASUREMENTS

Testing perturbative QCD

Z+jets at 13 TeV

CMS

Z/γ + jets

- Differential cross sections & ratio
  - Presented vs p_T and $\Delta R_{Z,jet}$
- First measurement of collinear emission of a Z + high p_T jet!
- Precision test of pQCD & EW calculations

arXiv:2102.02238

ATLAS

Z+b

- Total & differential cross sections
- Z + $\geq$ 1 b:
  - Presented vs $|y|_b$, $p_{T,b}$, $|y|_Z$, $p_{T,Z}$, $\Delta\phi_{Zb}$, Δy_{Zb}, ΔR_{Zb}
- Z + $\geq$ 2 b:
  - Presented vs $p_{T,Z}$, $p_{T,bb}$, m_{bb}, $p_{T,bb}/m_{bb}$, $\Delta\phi_{bb}$, Δy_{bb}, ΔR_{bb}
- Precision test of pQCD and MC simulation

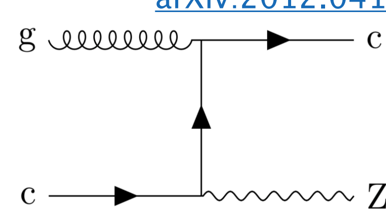
10.1007/JHEP07(2020)044

CMS

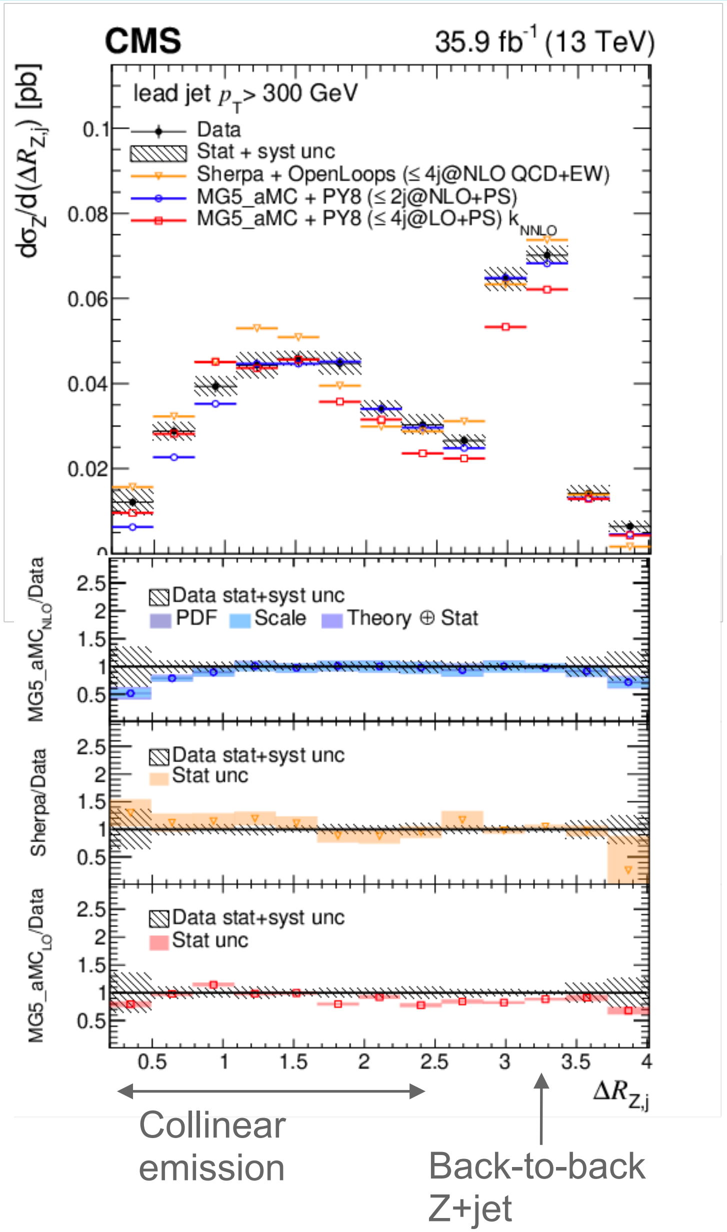
Z+c

- Total & differential cross sections
  - Presented vs $p_{T,Z}$ and $p_{T,c}$
- New: use charm tagging!
- Test QCD models and probe charm quark PDF

arXiv:2012.04119



CMS Z/γ+jets



Madgraph LO underpredicts data for $\Delta R_{Z,jet} > 1.8$.

Madgraph NLO agrees well with data, some discrepancy for very collinear emission ($\Delta R_{Z,jet} < 0.8$).

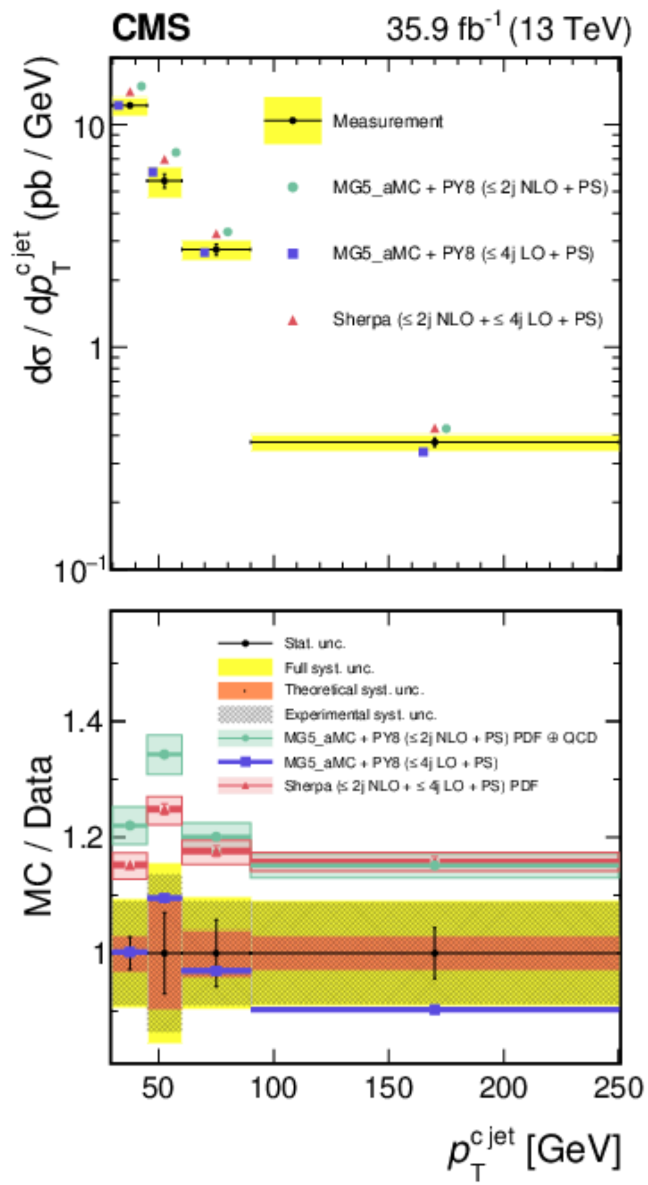
Sherpa (NLO) overestimates data for $\Delta R_{Z,jet} < 1.8$ but is within uncertainties. **Better overall agreement with NLO predictions.**

CMS Z+c

arXiv:2012.04119

Sherpa (NLO) and Madgraph NLO overestimate the data. Madgraph LO agrees well with within uncertainties.

We saw inclusive Z+jets agrees better with NLO - PDFs may overestimate charm quark content in the proton.



10.1007/JHEP07(2020)044

ATLAS Z+b

In general,
5-flavour number schemes (5FNS) at NLO agree with data; 4FNS at LO (Alpgen) shows discrepancies

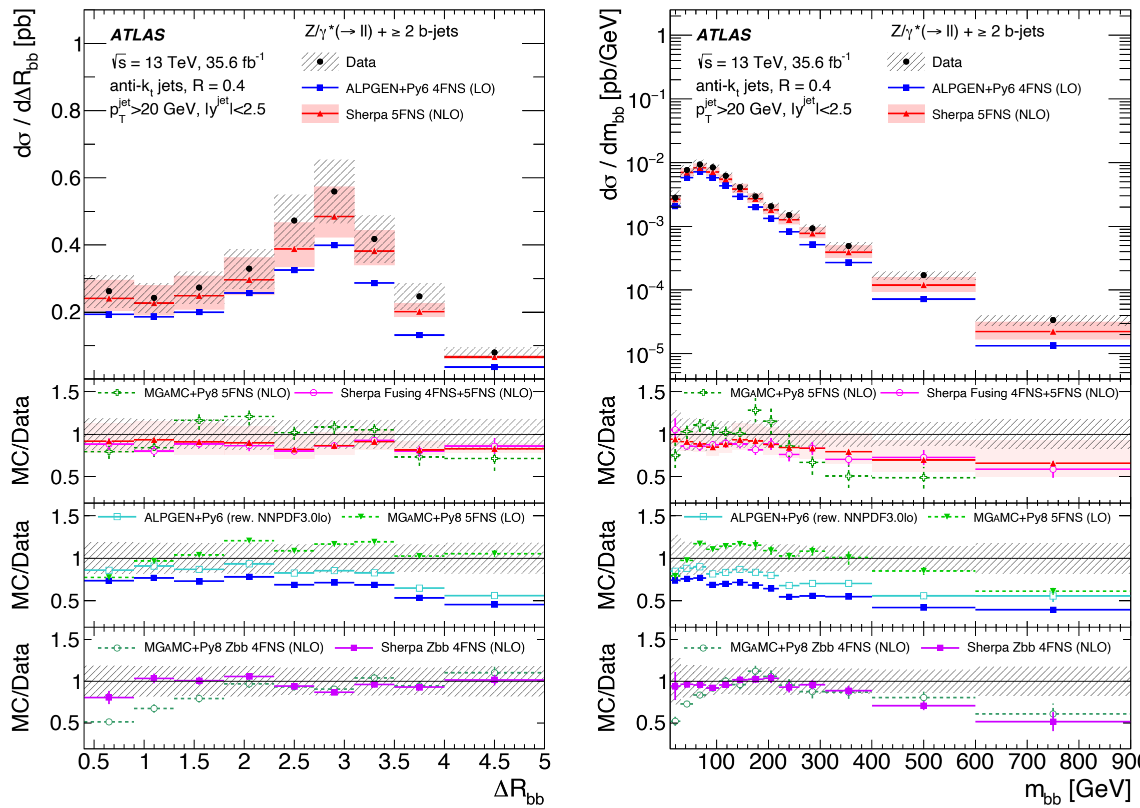
Sherpa 5FNS predicts data well within uncertainties. **Novel** Sherpa Fusing 4FNS+5FNS (NLO) also does well.

Often, MGaMC + Py8 5FNS (LO) does better than MGaMC + Py8 5FNS (NLO). Indicates importance of simulation with multiple partons in matrix element.

Pure Zbb (4FNS at NLO) show shape discrepancies

Z+b

Discrepancies at high m_{bb}!



Much crucial input for Z+b theory predictions and MC generators!

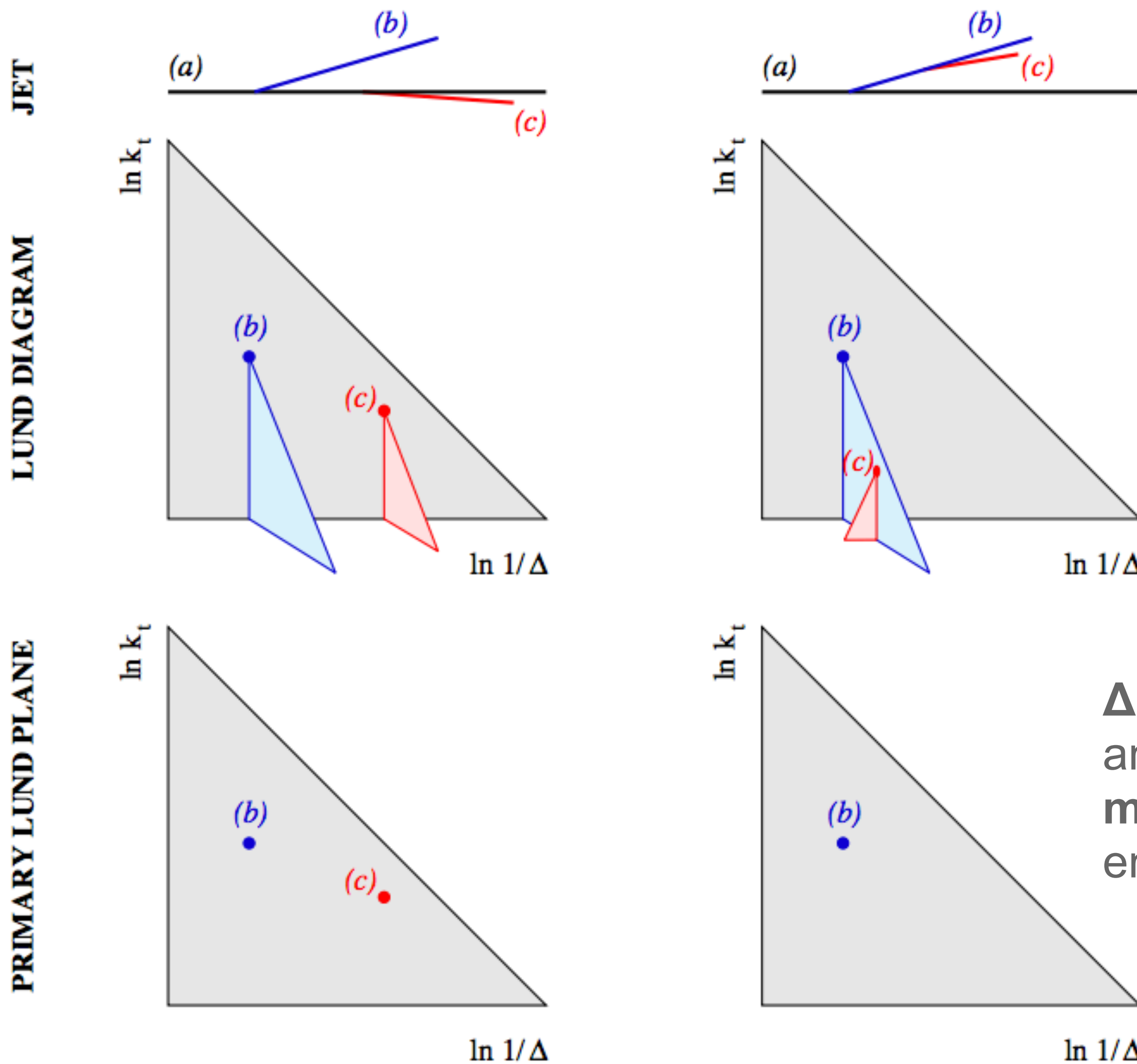
BEYOND SINGLE VARIABLES: THE LUND PLANE

Parameterizing jet emissions

The Lund Jet Plane

1807.04758

Inside jet: particles b and c emitted from particle a

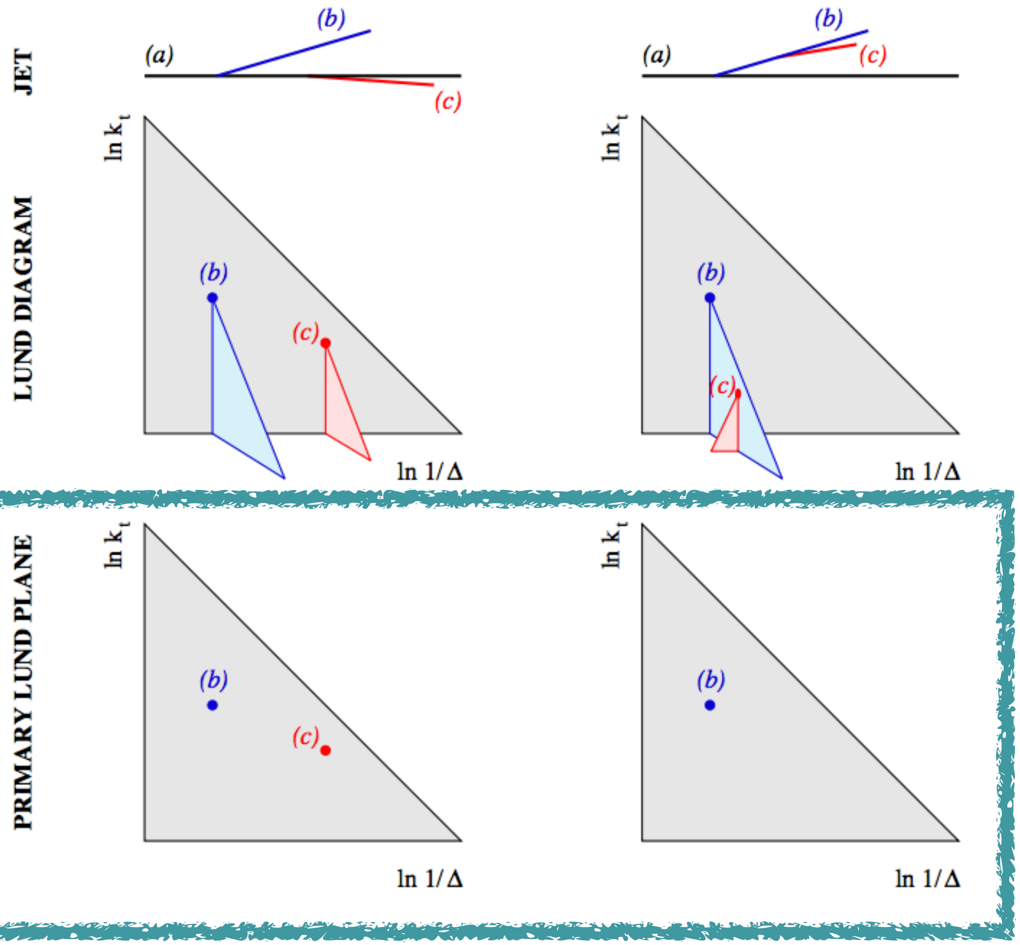


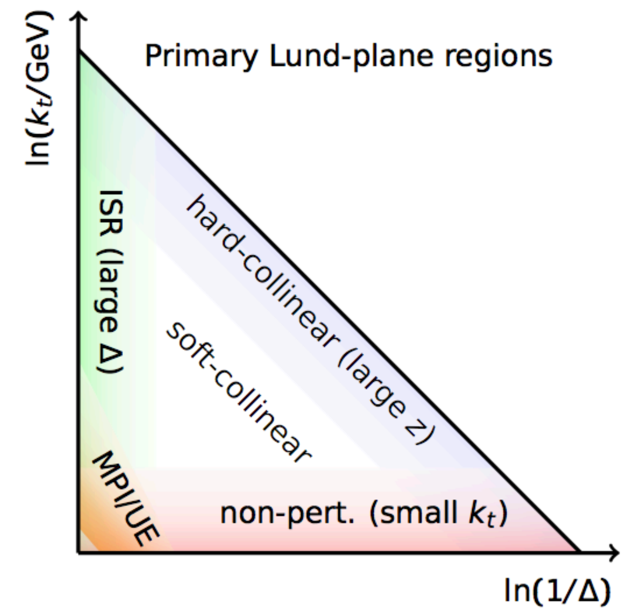
Δ, k_t: relative angle and **transverse momentum** of an emission

The Lund Jet Plane

1807.04758

Inside jet: particles b and c emitted from particle a





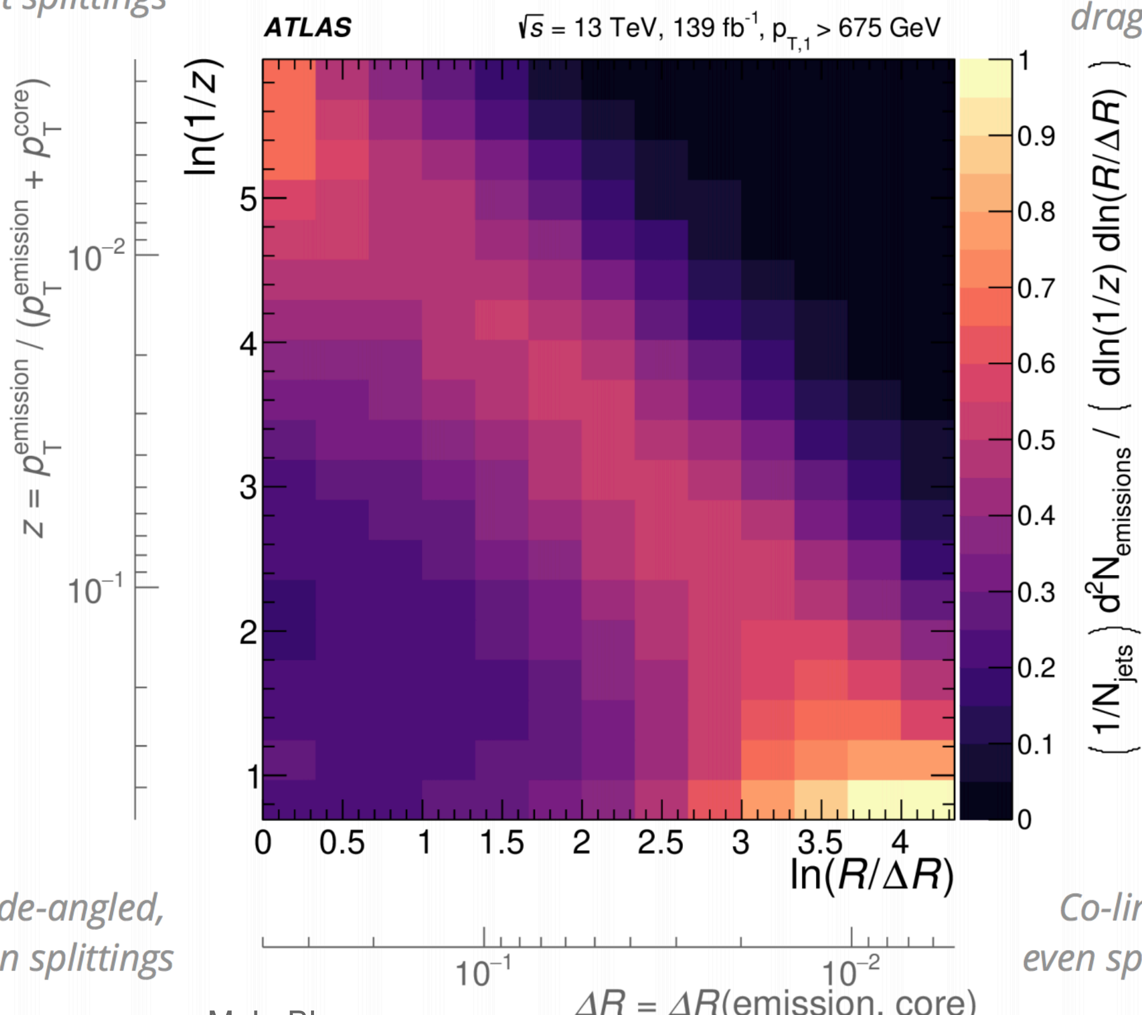
Lund plane gives us a handle on many aspects of QCD

ATLAS Lund Plane in Dijets

2004.03540

Wide-angled, soft splittings

Here there be (non-perturbative) dragons

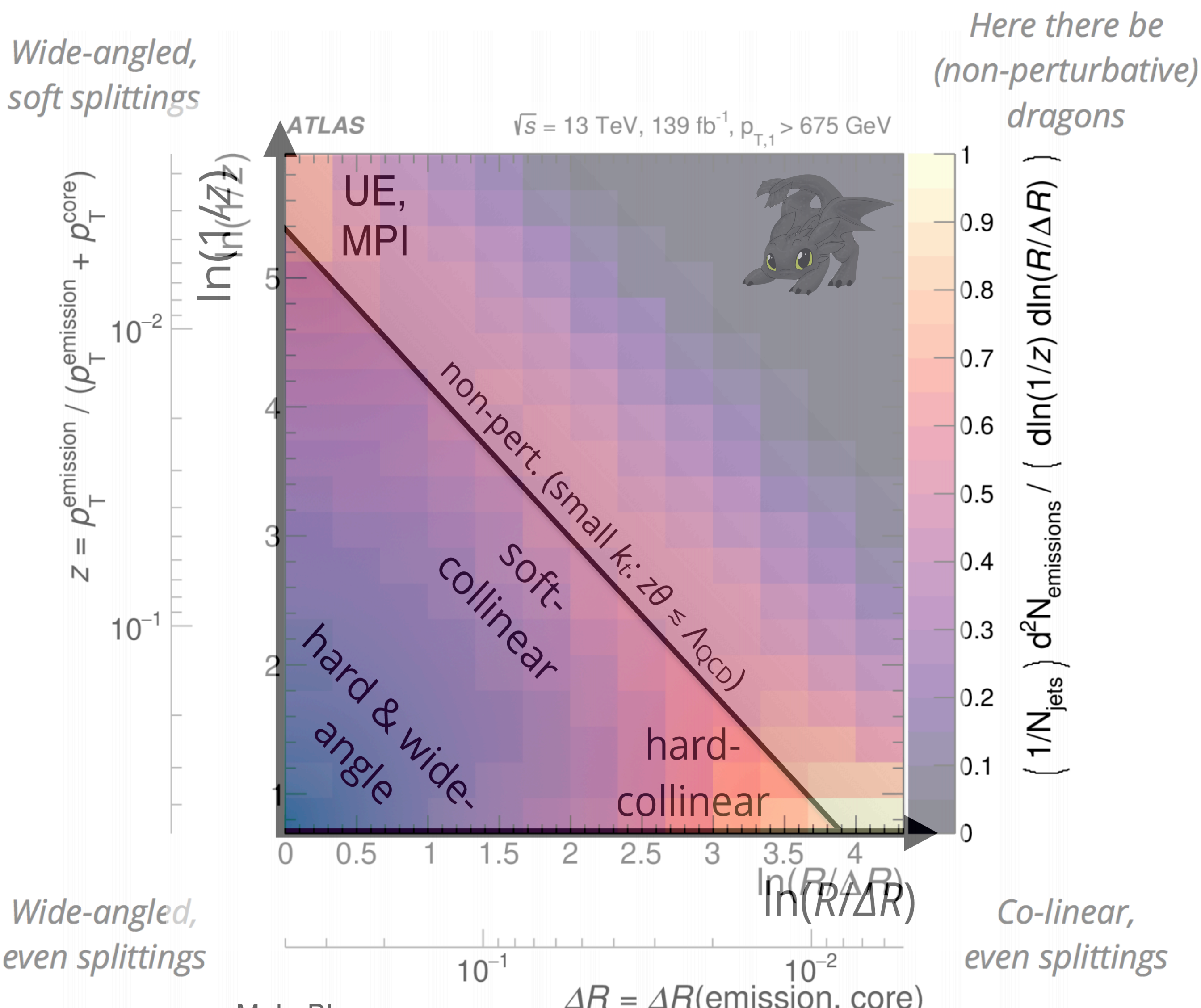


Wide-angled, even splittings

Co-linear, even splittings

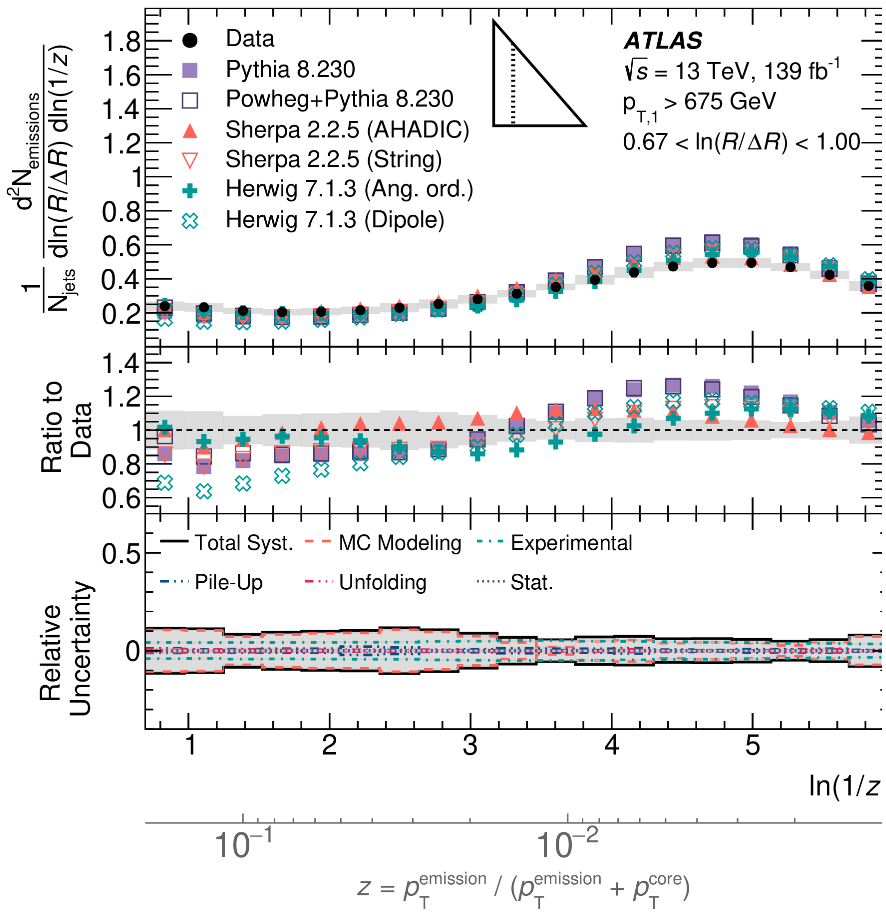
ATLAS Lund Plane in Dijets

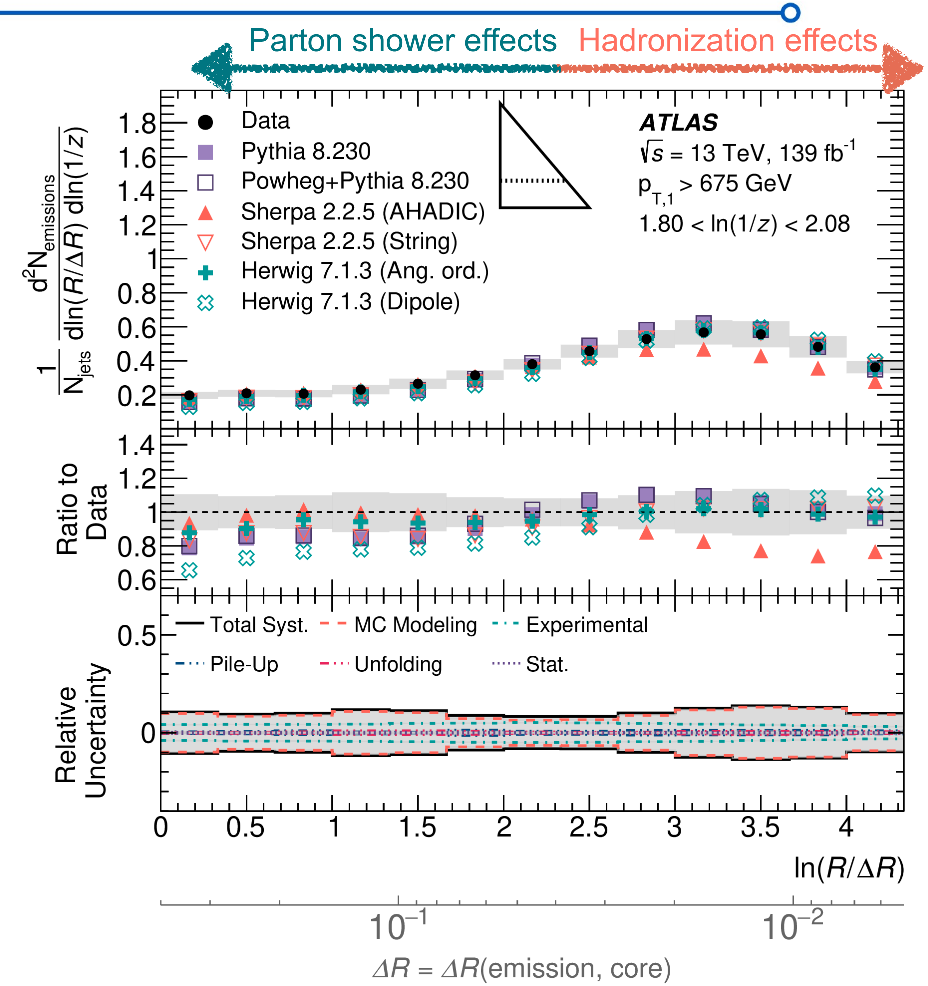
2004.03540



ATLAS Lund Plane Slices

2004.03540

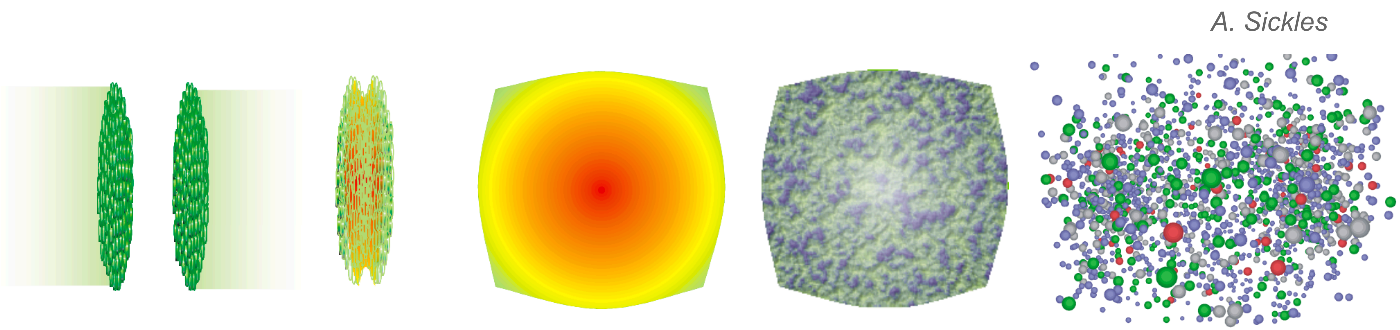




Modeling uncertainties dominate.
No one model describes data best - effects of hadronization and parton showering can be seen in separate regions of the plots

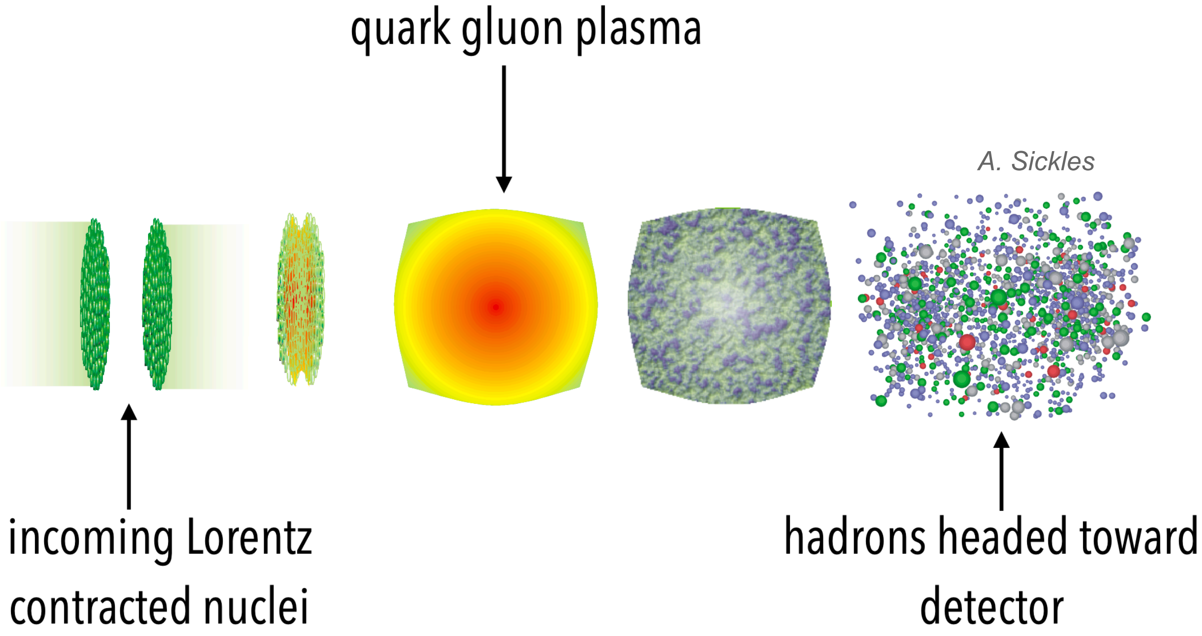
HEAVY IONS

QCD at high temperatures



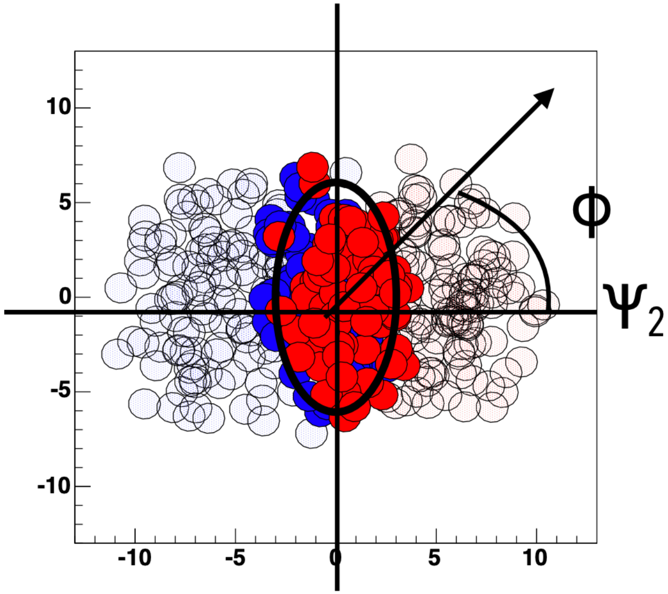
Heavy Ions

- **QGP in HI collisions**
  - Hot, dense, short-lived, equilibrium state, nearly perfect fluid, seems to have quark and gluon degrees of freedom
  - **Can't be measured directly!**
    - We use hard particles as probes

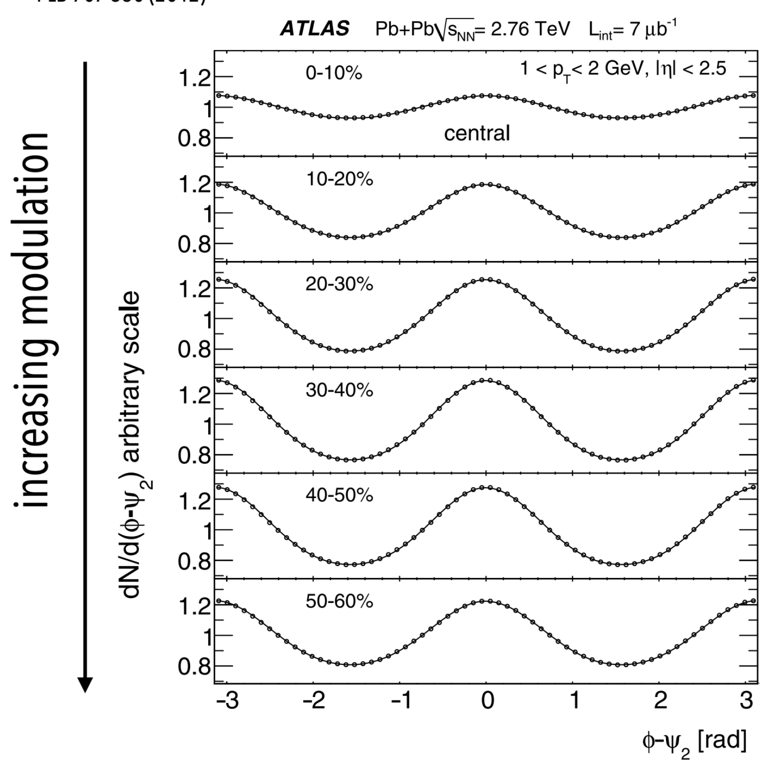


Heavy Ion Collision Geometry

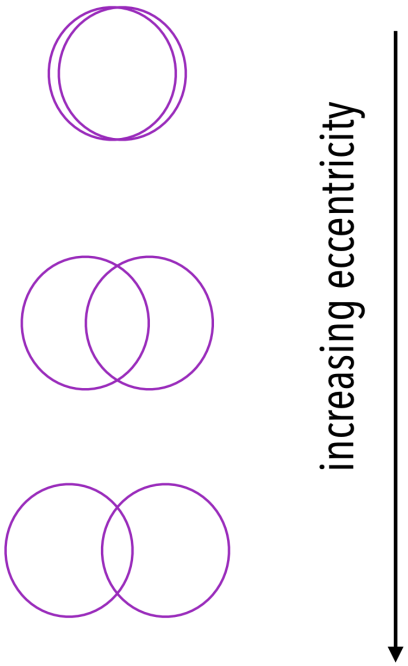
Interaction plane of nuclei



Distribution of particles



Central

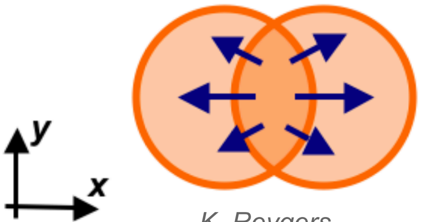


Peripheral

Probing Charm Quark Dynamics in QGP

- **Measure v_2 (elliptic flow) to probe initial collision geometry and corresponding fluctuations**

Elliptic Flow



K. Reygers

v_2: 2nd harmonic Fourier coefficient in $dN/d\varphi$ with respect to the reaction plane

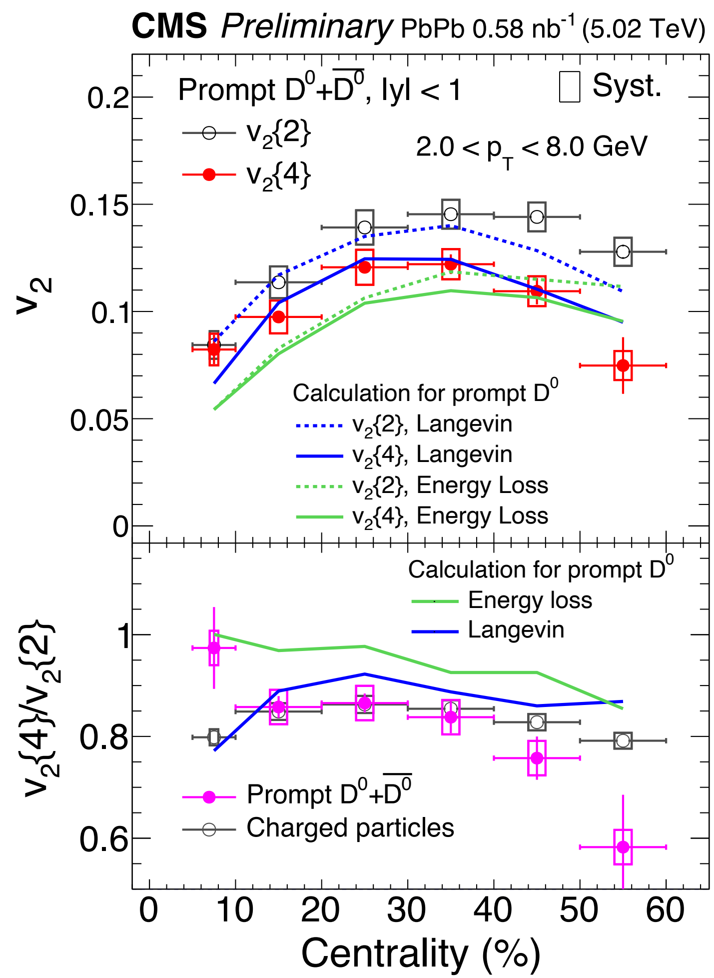
- **Previous measurements of D^0 suggest low p_T charm quarks strongly coupled to QGP**
  - Measure $v_2\{2\}$, two-particle correlation
- **This analysis: first D^0 measurement with four-particle correlations $v_2\{4\}$ (and $v_2\{4\}/v_2\{2\}$)**
  - Probes magnitude of event-by-event fluctuations of flow harmonics from heavy-flavor quarks
  - Use PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Probing Charm Quark Dynamics in QGP

In general, v2{4} values lower than v2{2} - indicates event-by-event fluctuations in flow signal

Similar trends in D^0 mesons & light flavor hadrons indicate contributions from fluctuations of initial geometric conditions dominate

Divergent behavior in most central and peripheral regions indicate influence of energy loss fluctuation

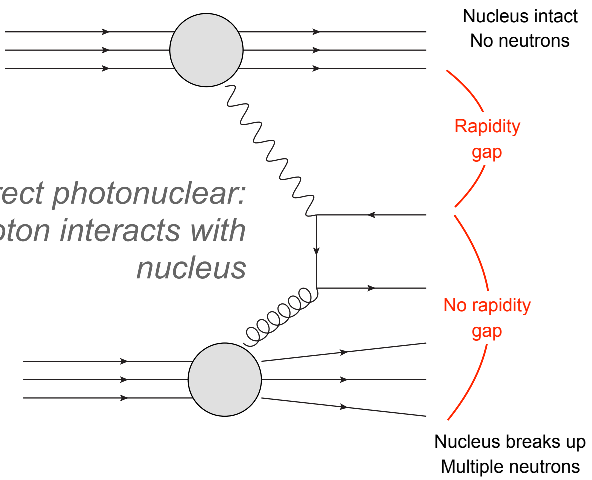


ULTRAPERIPHERAL MEASUREMENTS

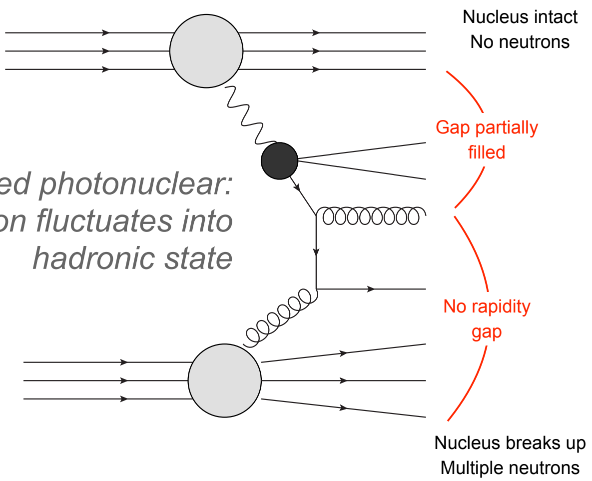
Two-particle correlations in photonuclear ultraperipheral PbPb collisions

- **Ultraperipheral collisions (UPC): interactions at very large impact parameters**
  - No hadronic interaction occurs
  - Caused by the strong EM fields of fully ionized nuclei
  - Include photon-photon ($\gamma\gamma$) and photonuclear ($\gamma + A$) interactions
- **Measure two-particle correlations in photonuclear collisions**
  - New way to probe origin of collective signatures previously observed only in hadronic collisions!

Direct photonuclear: photon interacts with nucleus



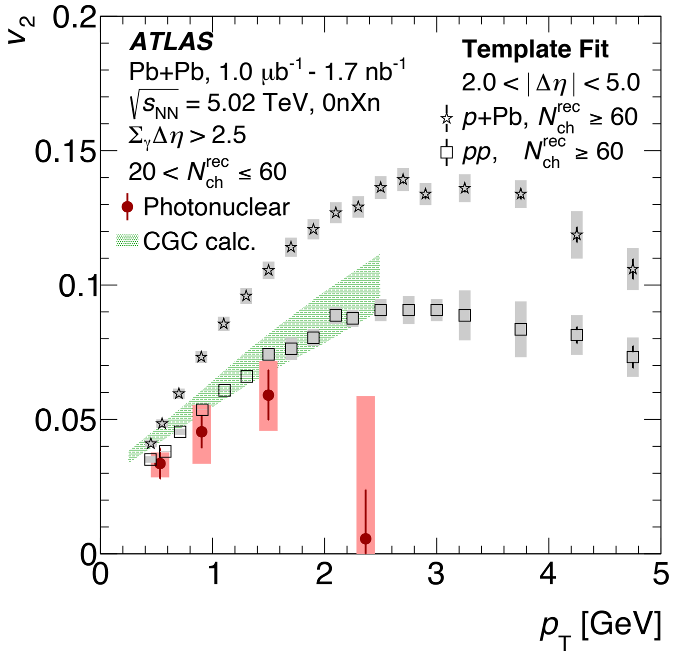
Resolved photonuclear: photon fluctuates into hadronic state

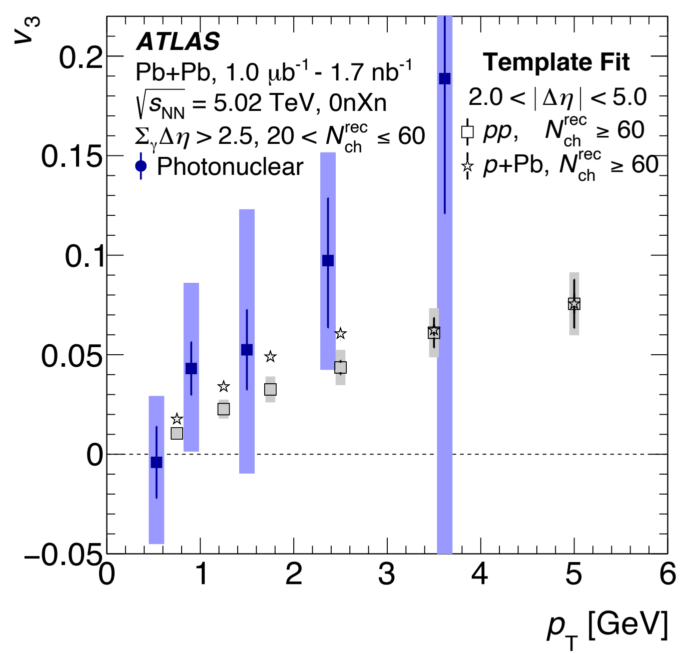


Two-particle correlations in photonuclear ultraperipheral PbPb collisions

Significant, nonzero v_2, **v_3 values** - indicate that particles produced in photonuclear events participate in azimuthally dependent, collective motion

v_2 values smaller than those in pp and p+Pb collisions at similar particle multiplicities

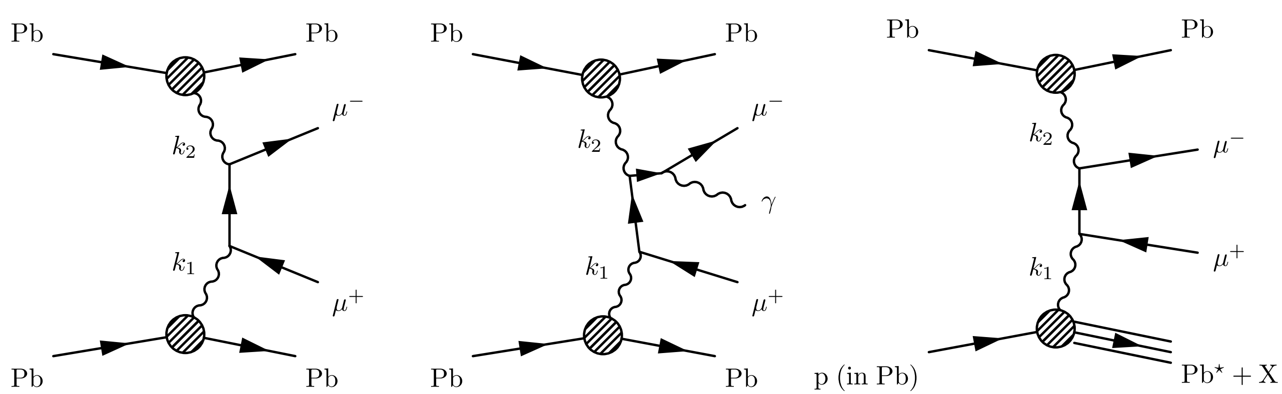




New information about long-range collective behavior in an exotic collision system!

Exclusive dimuon production in ultraperipheral Pb+Pb collisions

- **Measure the total and differential cross sections of UPC dimuon pairs**
  - Presented vs $m_{\mu\mu}$, $|y_{\mu\mu}|$, and the scattering angle in the dimuon rest frame $|cos\vartheta^{*}_{\mu\mu}|$
- **Main UPC dimuon (aka Breit-Wheeler process) production mechanisms:**
  - Resonant diffractive photon–pomeron scattering - produces a vector meson that decays muonically
  - Nonresonant exclusive two-photon scattering
- **Measuring UPC dimuons useful for**
  - Precise measurements of the incoming photon fluxes to calibrate rates of other hard processes involving UPC
  - Improving predictions for purely EM processes such as light-by-light scattering
  - Understanding UPC dimuons as a non-negligible background for vector-boson production in peripheral heavy-ion collisions



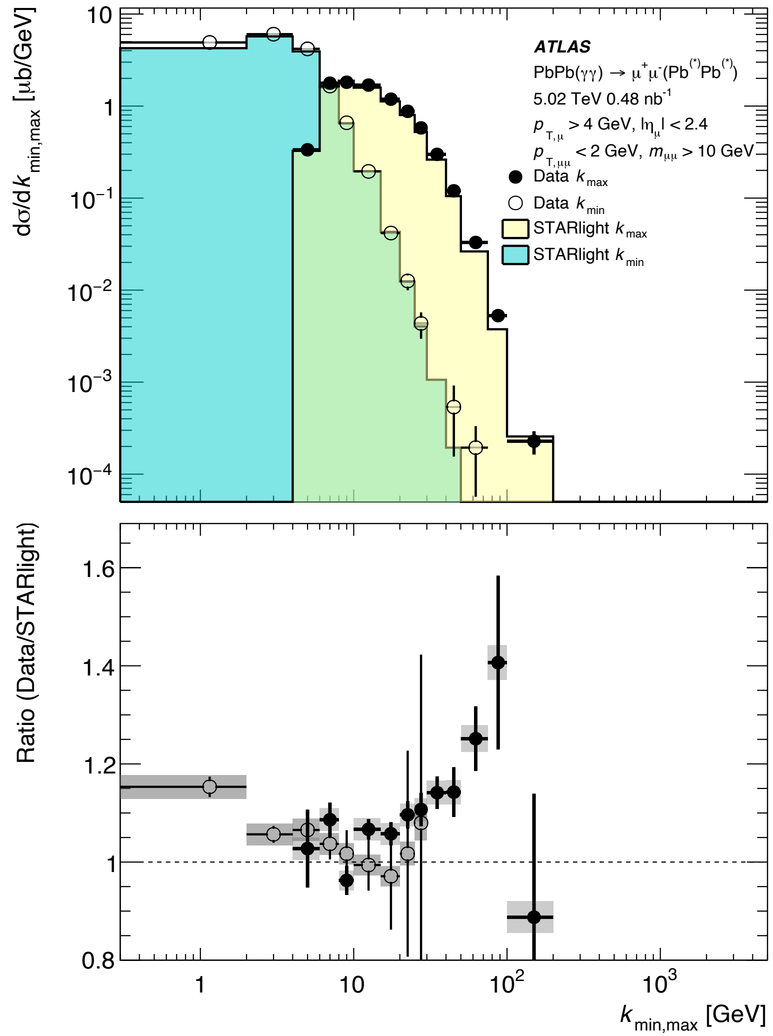
Exclusive dimuon production in ultraperipheral Pb+Pb collisions

Generally, good agreement found with STARlight 2.0 model.

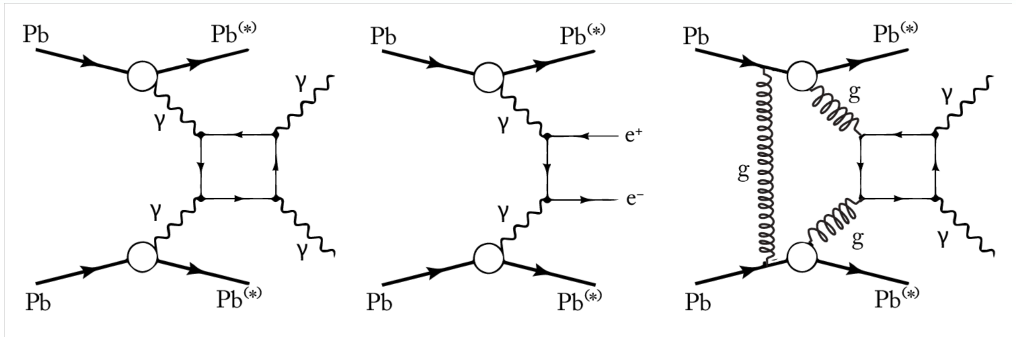
Differences seen may indicate deficiencies in modeling incoming photon flux

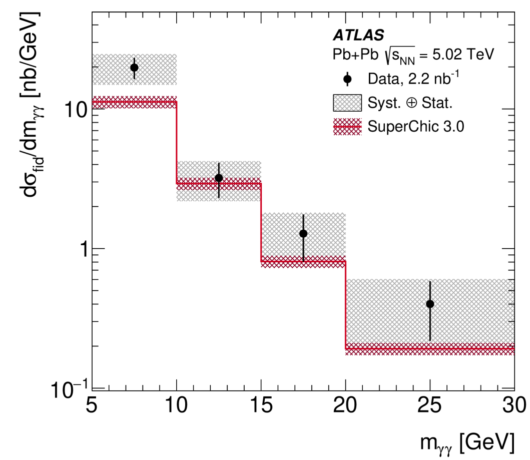
Allowing dilepton pairs to be produced deeper within the nuclear skin may explain the observed differences

These results will be important in reducing uncertainties in the photon fluxes, needed. for precision studies of QED and QCD in nuclear collisions, as well as to probe BSM physics



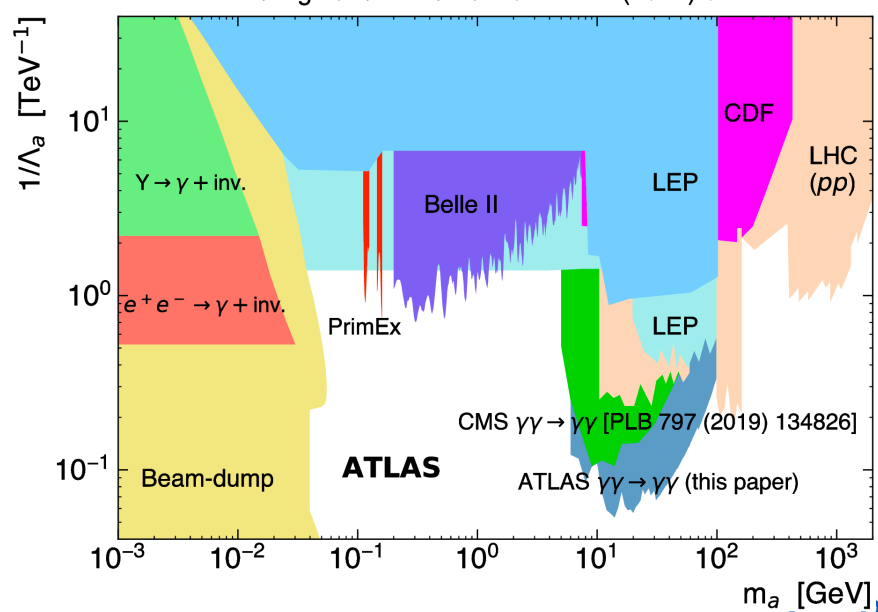
Light-by-light scattering at 5.02 TeV





- Pure quantum mechanical process
- **First evidence seen at CMS at 3.7 σ and measurement from ATLAS!**
- Both experiments place limits on axion-like particles

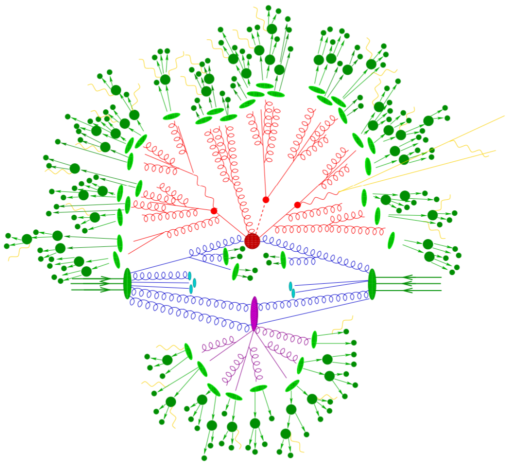
Existing constraints from JHEP 12 (2017) 044



10.1016/j.physletb.2019.134826 2008.05355

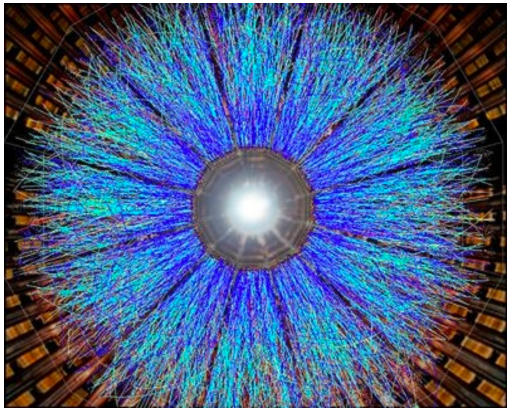
Conclusions

Many interesting new results in QCD and heavy ions!



QCD

- ESVs measure hadronic energy flow
- Multijet correlations investigate modeling of soft, collinear, hard, and large-angle QCD phase space
- Z/gamma + jets and Z+b probe perturbative QCD
    - NLO modeling doing well
- Z+c measurement shows PDFs may overestimate charm content
- Lund plane measurement uses jet substructure to probe many aspects of QCD



Heavy Ions

- Measuring four-part correlations of D^0 mesons shows large contribution of indicates event-by-event fluctuations in flow signal of charm quarks
- Evidence seen that particles produced in photonuclear events participate in azimuthally dependent, collective motion
- UPC dimuon measurements indicate deficiencies in modeling incoming photon flux
- First observation and measurement of light-by-light scattering!
    - Used to set limits on axion-like particles

New measurements of these complex systems will help improve modeling for future precision measurements and BSM searches to come!