Observation of QCD collectivity inside high-multiplicity jets in pp collisions with the CMS experiment

Parker Gardner on behalf of the CMS collaboration

Rice University. Houston, TX.

Forward Physics and QCD at the LHC and EIC

23-27 Oct 2023, Bad Honnef

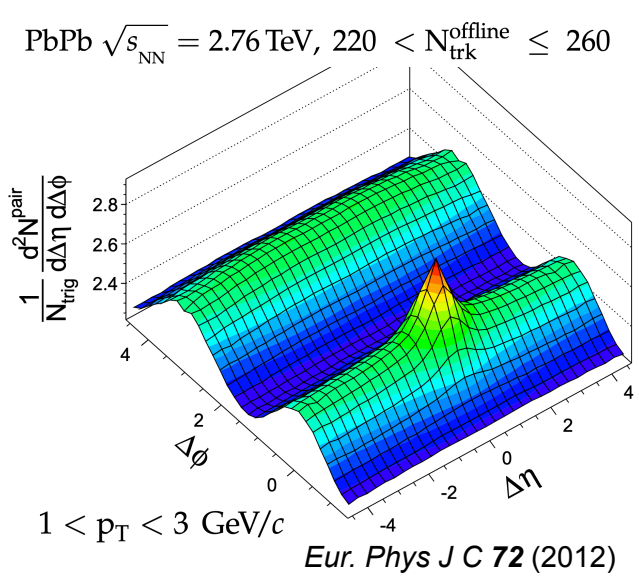
CMS-PAS-HIN-21-013 link

RICE

CMS

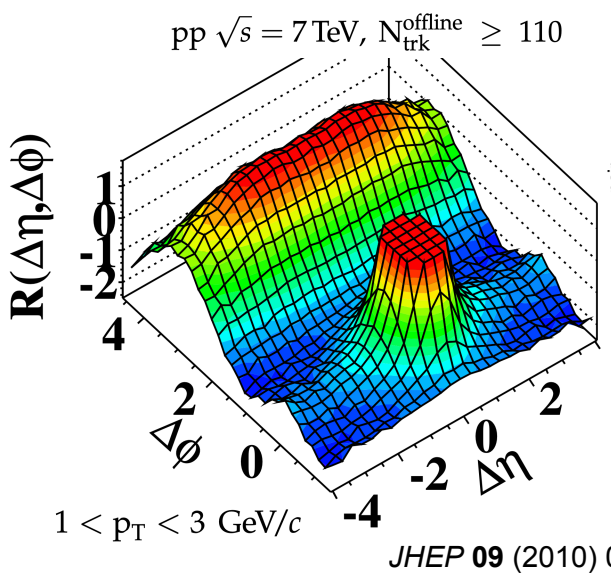
Background: from AA to pp

QGP-like signals from PbPb also found in high energy, high multiplicity pp and pPb! Collectivity in small systems?



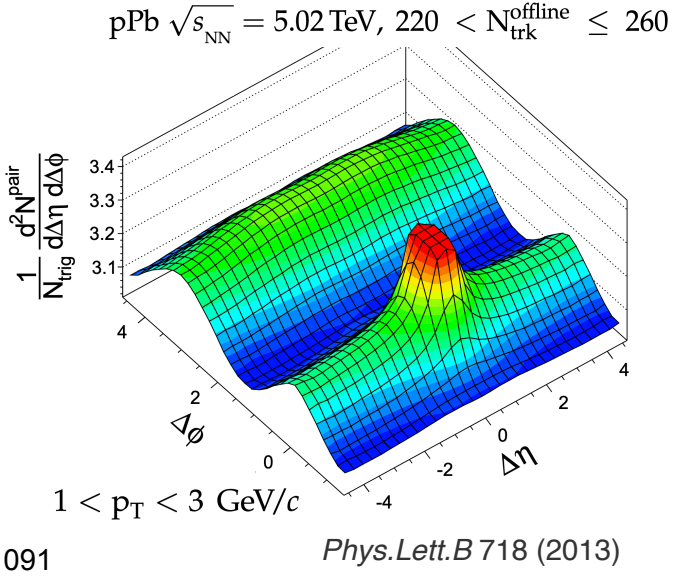
Eur. Phys J C **72** (2012)

Unexpected



JHEP **09** (2010) 091

Unexpected

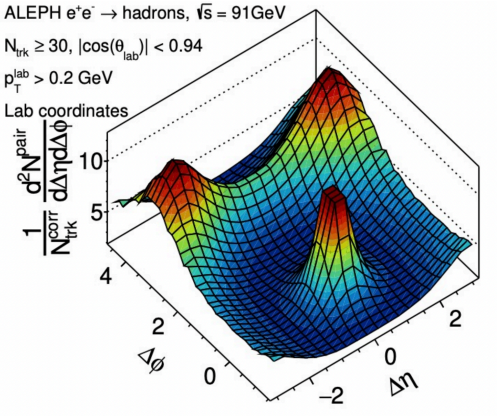


Phys.Lett.B 718 (2013)

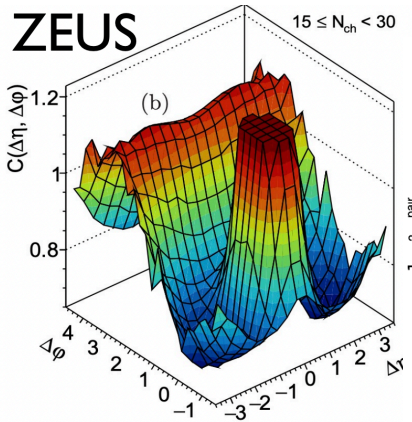
Background: Important questions arise

- From how small of a system can partonic collectivity emerge?
- True surprise or consequence of strongly coupled QCD?
- Can hydrodynamics be generalized for non perturbative QCD processes?

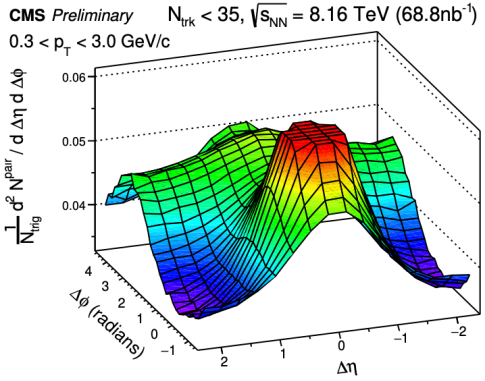
e^+e^- (~30) ep (~30) γp (~20) γPb (~40)



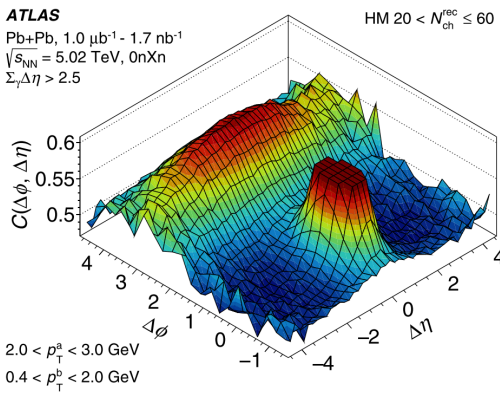
PRL 123, 212002 (2019)



JHEP 04 (2020) 070



arxiv: 2204.13486



PRC 104 014903 (2021)

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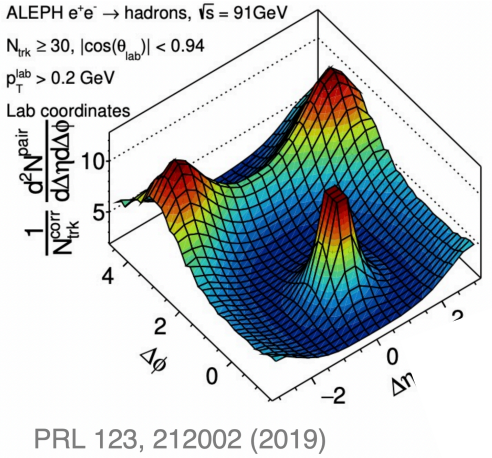

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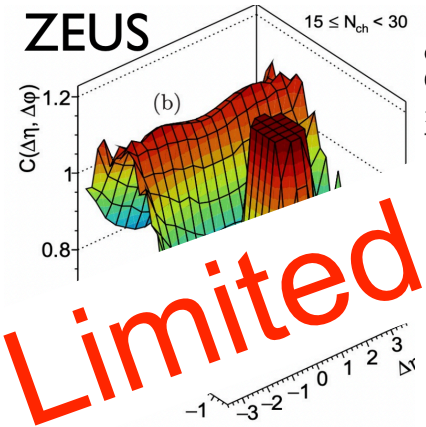
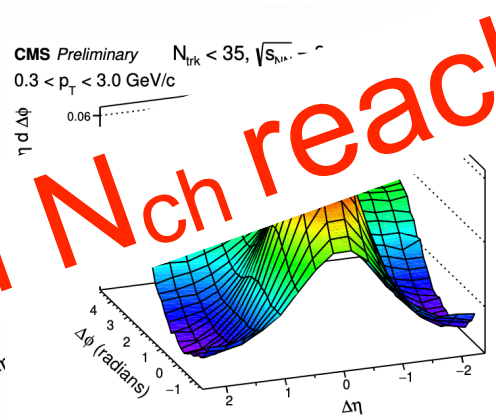


JHEP 04 (2020) 070



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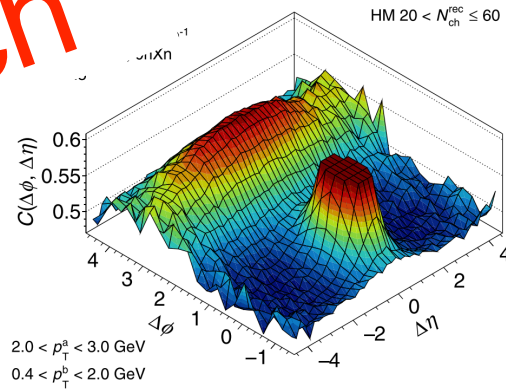
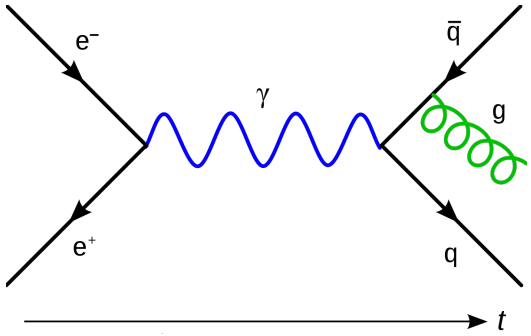
Limited N_{ch} reach



PRC 104 014903 (2021)

Background: Puzzles in e^+e^-

- Hadron production in elementary collisions well described by thermal gas approach. Entanglement or MPI?
- 2D correlation studies in e+e- *arxiv.org/pdf/1906.00489*

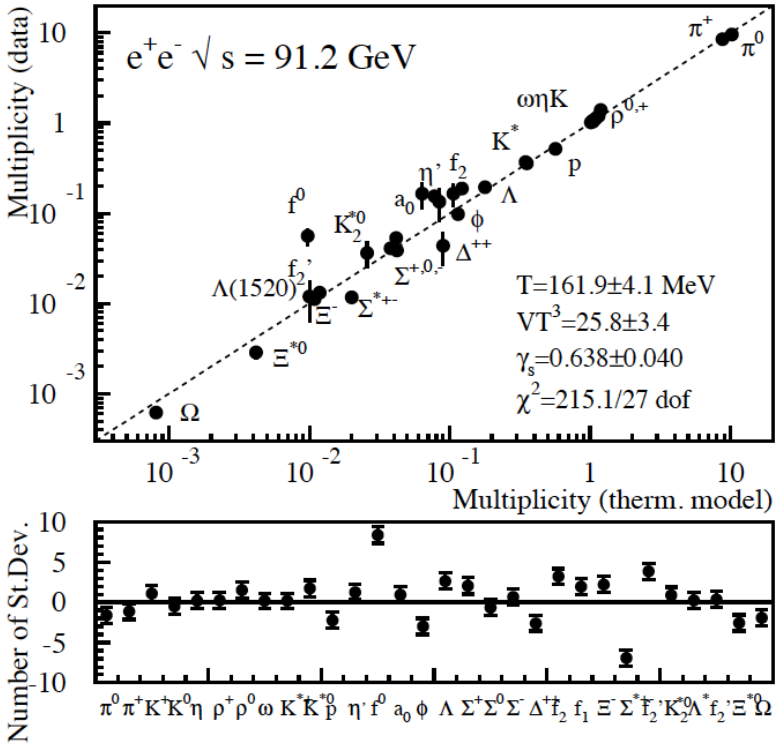


A thermodynamical approach to hadron production in e^+e^- collisions

F. Becattini

Università di Firenze and INFN Sezione di Firenze, Largo E. Fermi 2, I-50125 Firenze, Italy (e-mail: becattini@vaxfi.fi.infn.it)

Received: 17 May 1995



F. Becattini et. al., EPJC (2010) 66, 377

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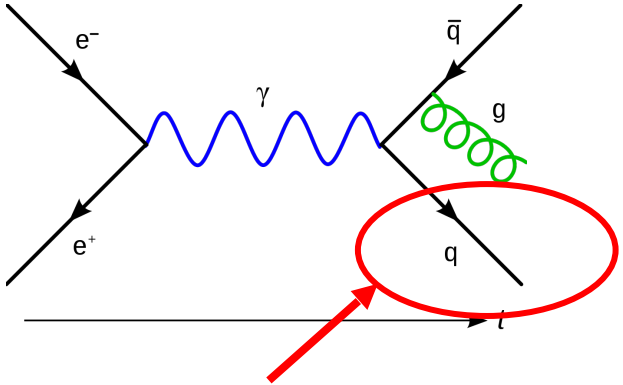
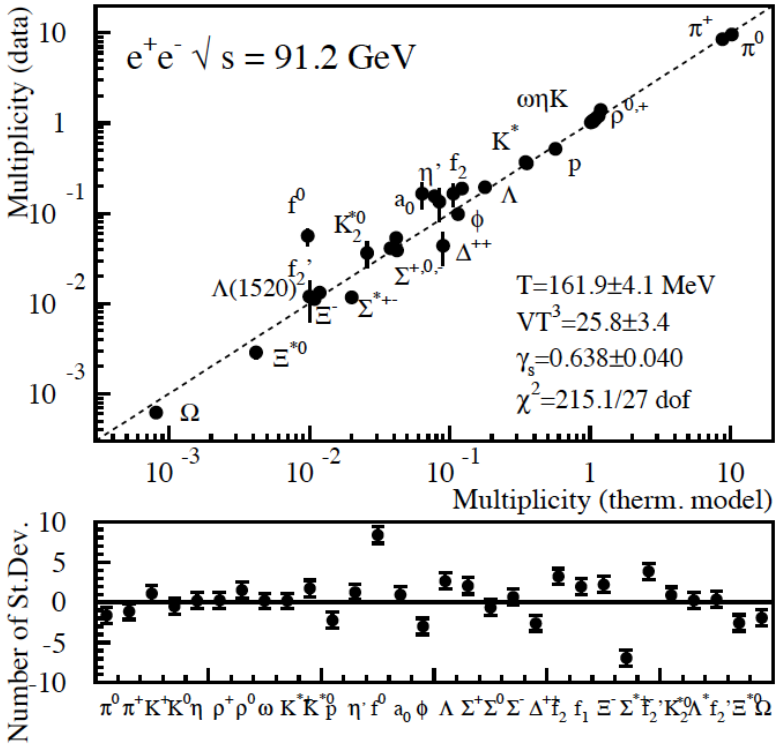


Study single jets fragmenting to high multiplicity final state!



F. Becattini et. al., EPJC (2010) 66, 377

Postulate:

Strongly interacting QGP-like state can be formed by systems initiated by single quark or gluon propagating through QCD vacuum.

A. Baty, P. Gardner, W. Li, PhysRevC.107.064908,

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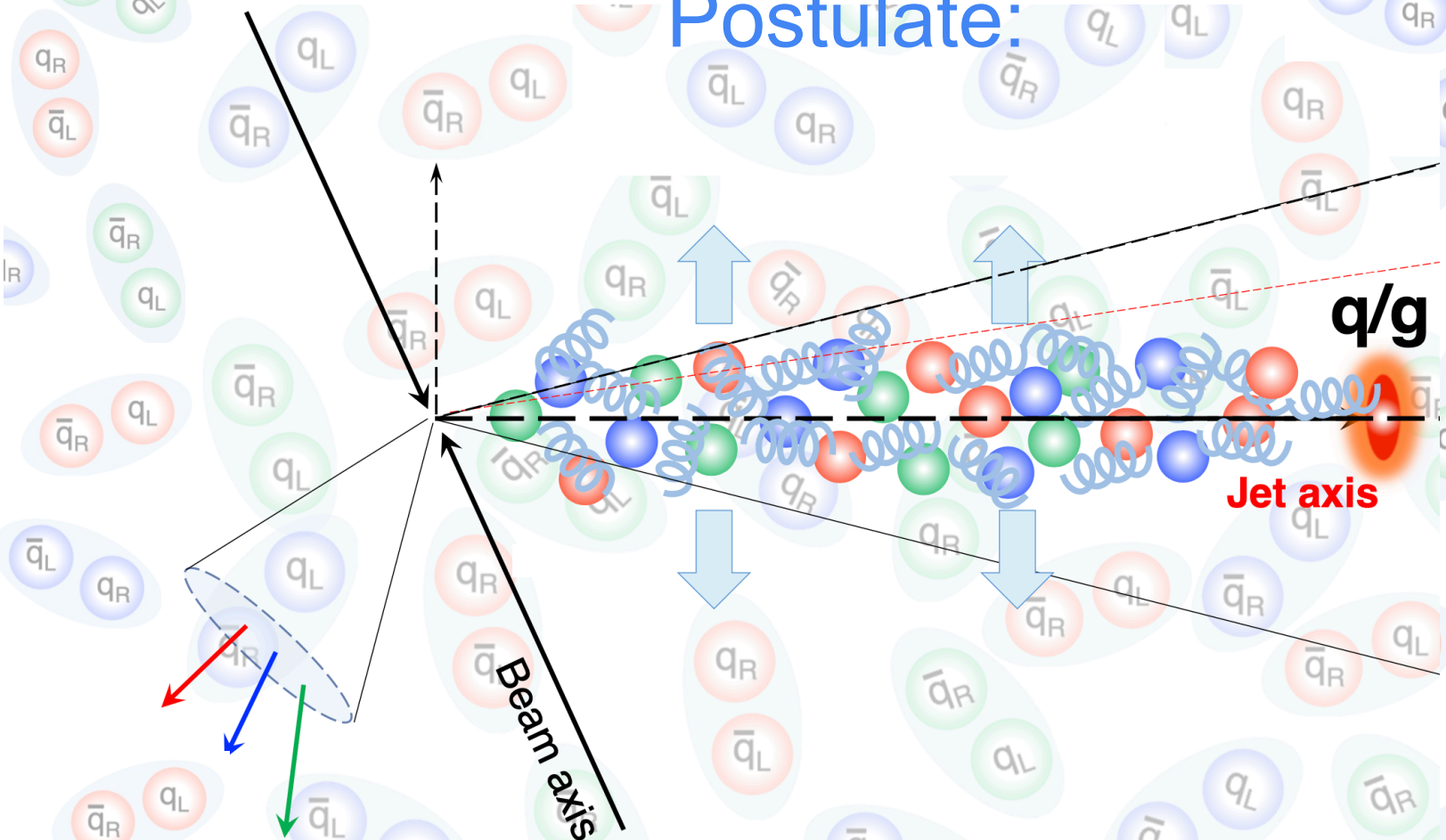

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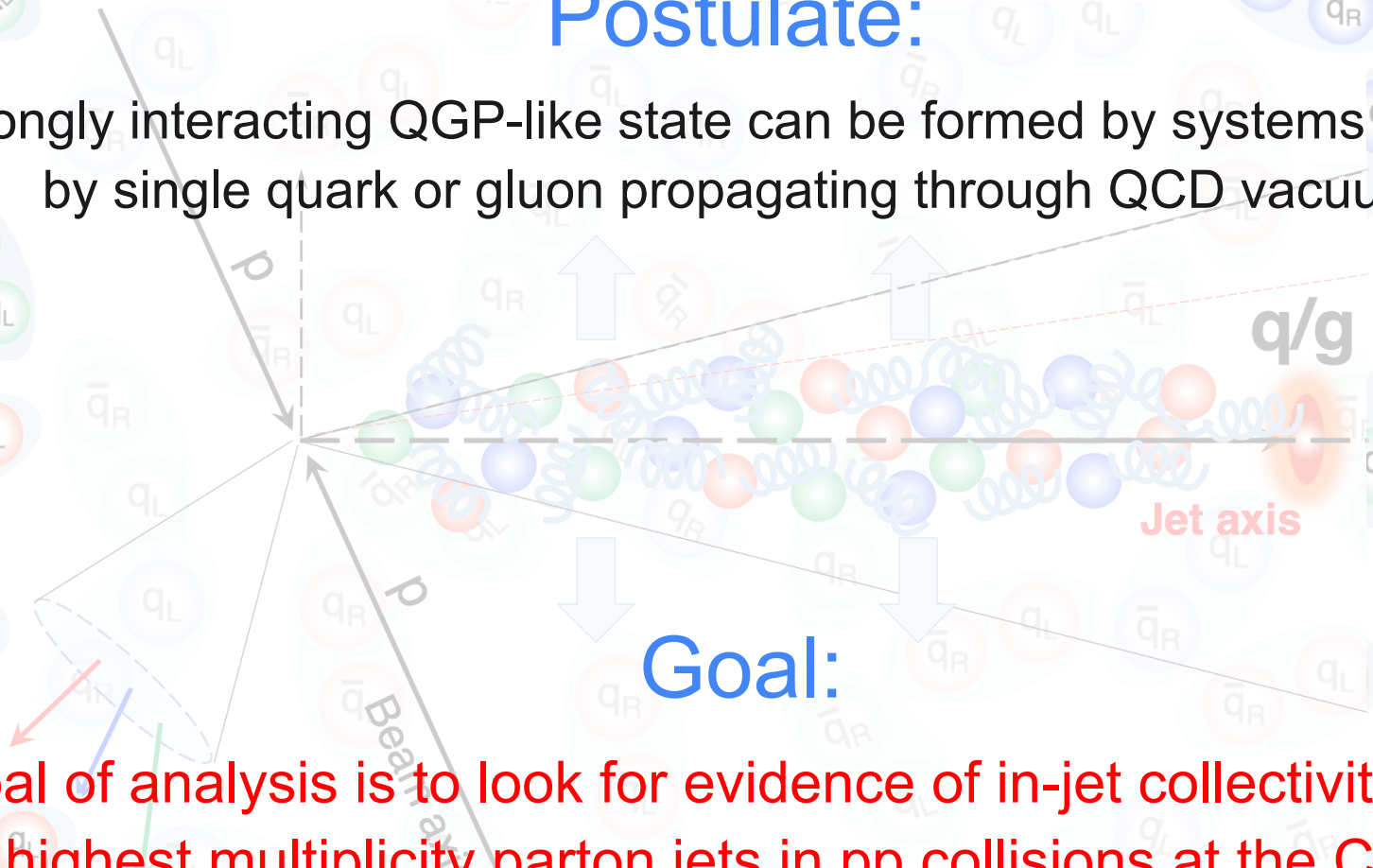
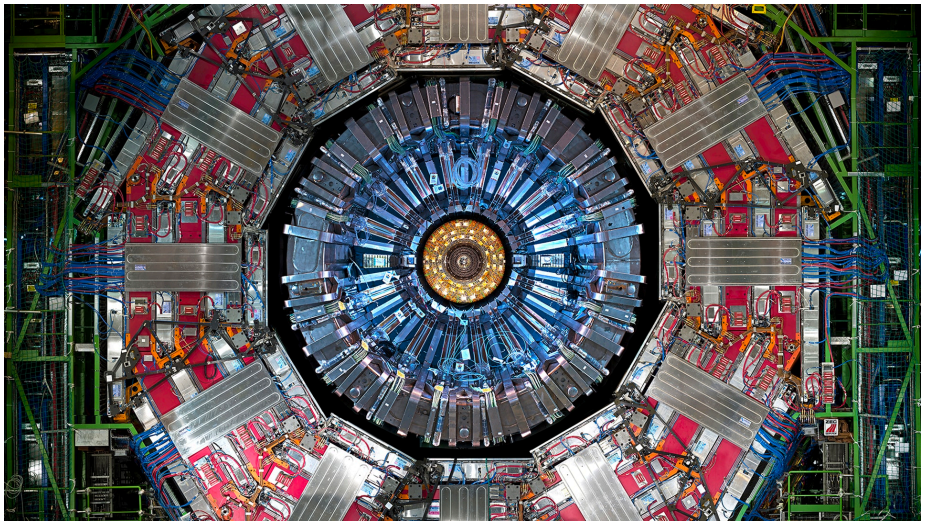


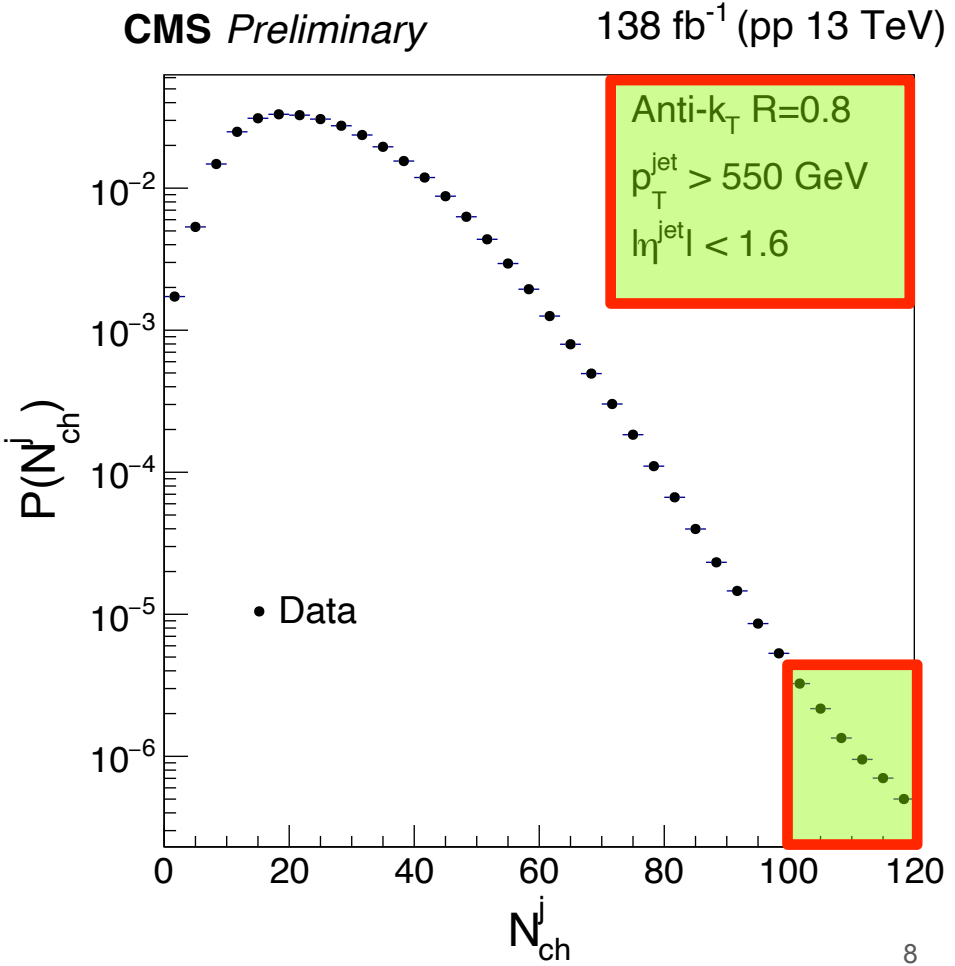
Goal:

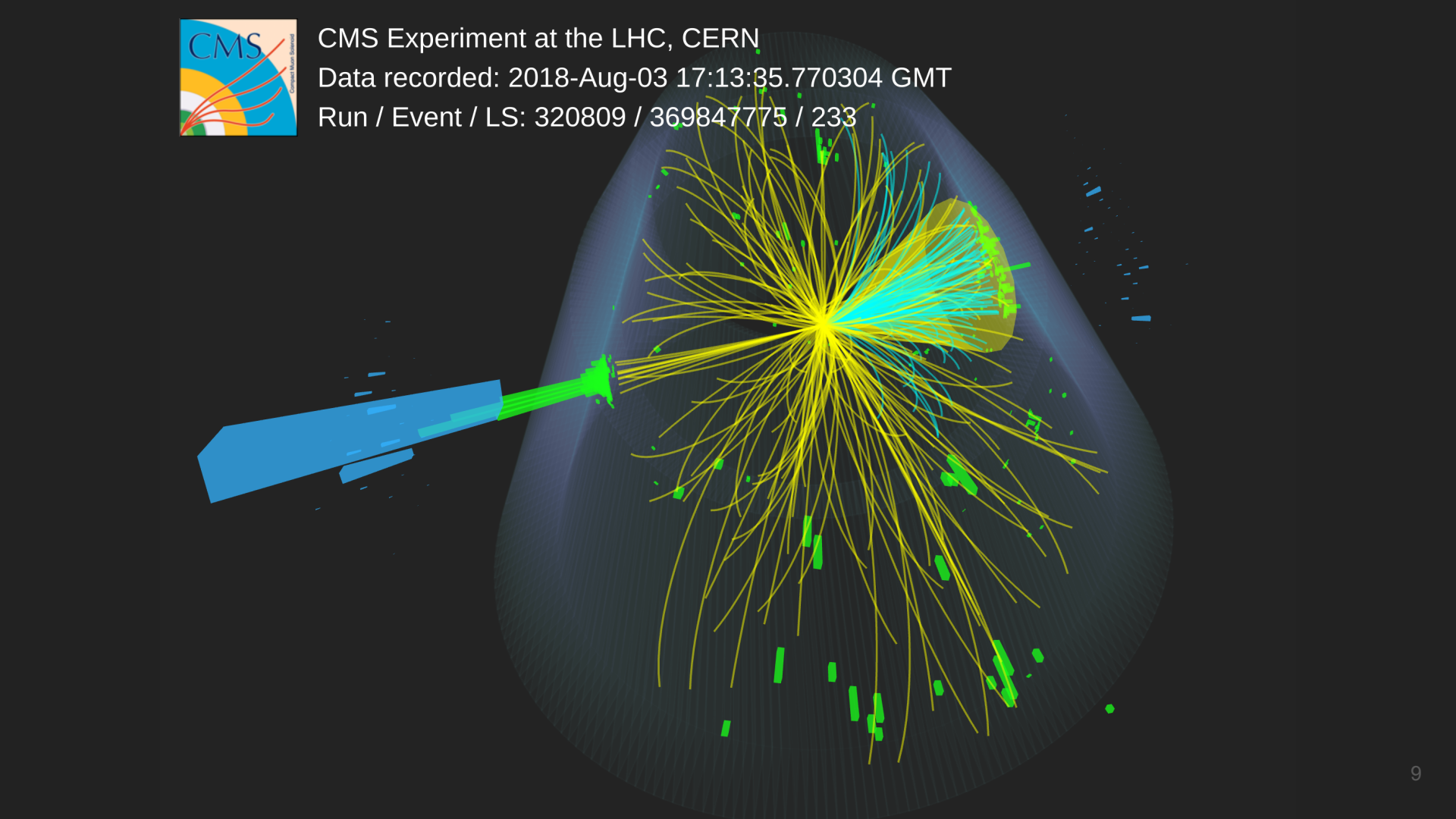
Goal of analysis is to look for evidence of in-jet collectivity using highest multiplicity parton jets in pp collisions at the CMS.

Rare Jets from the LHC

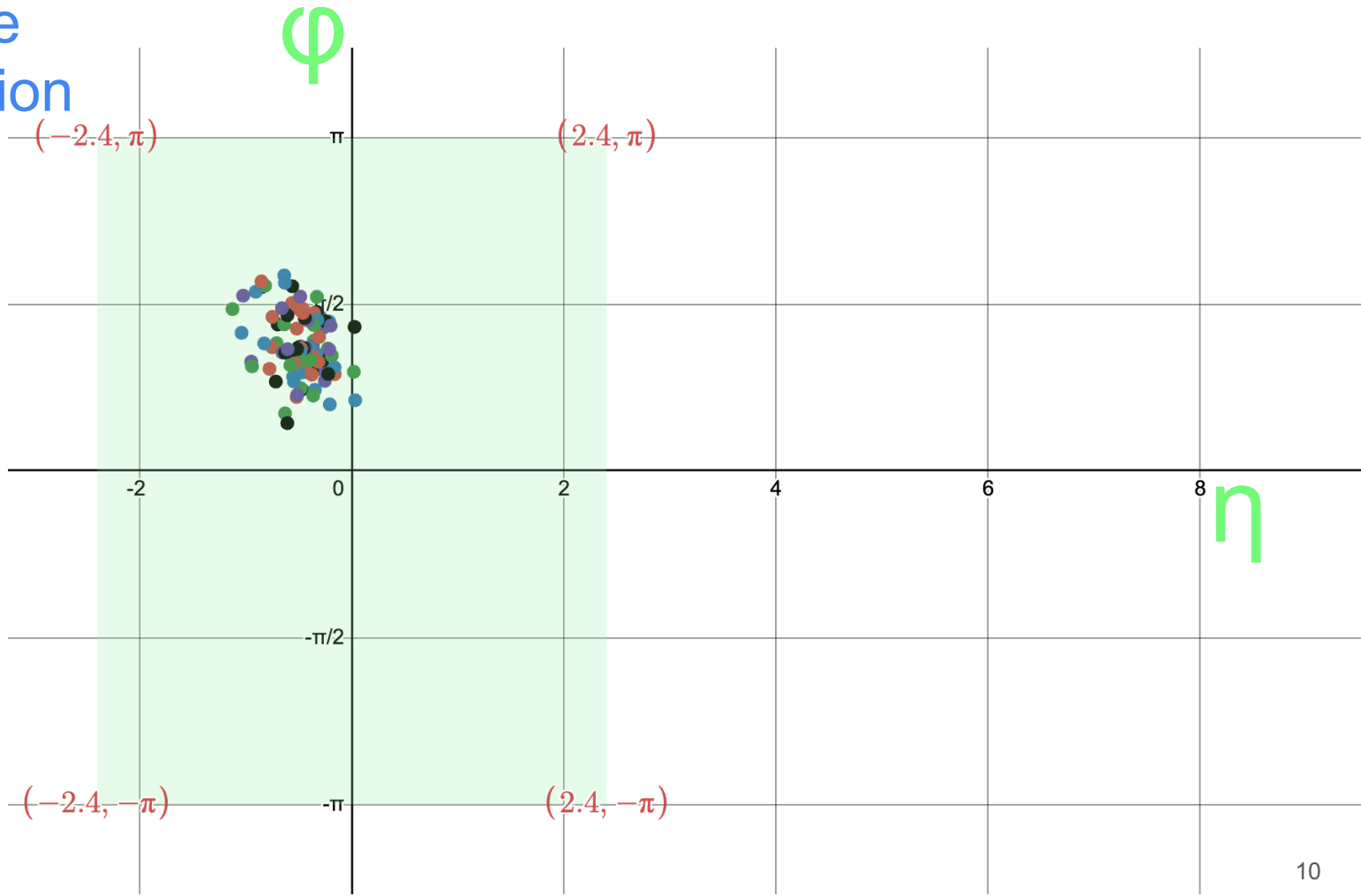
- Full 13 TeV pp dataset from LHC Run II
- >100 million jets analyzed
- A few thousand jets at highest multiplicities






CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-03 17:13:35.770304 GMT
Run / Event / LS: 320809 / 369847775 / 233

Coordinate Transformation

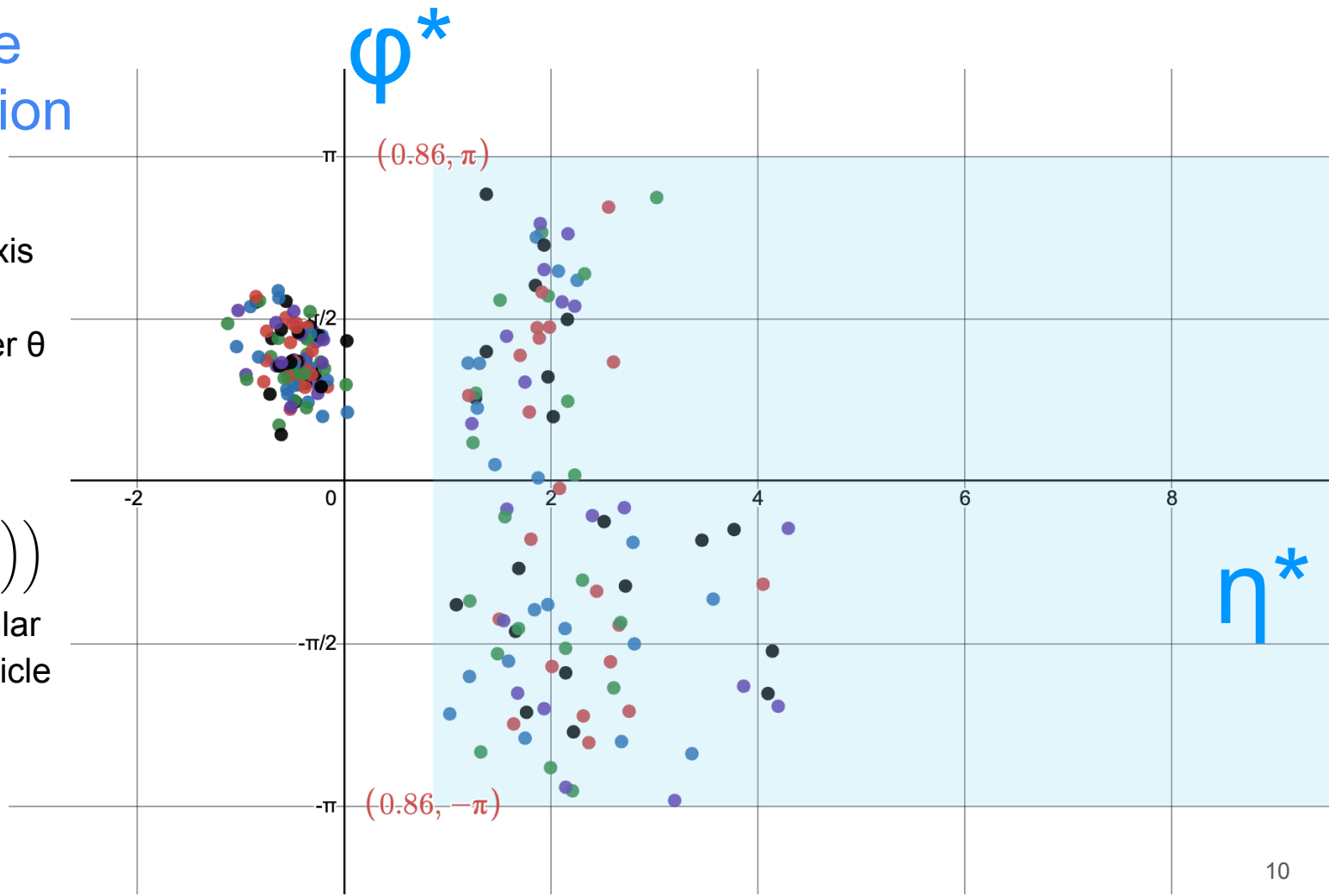


Coordinate Transformation

- Reconstruct Jet Axis
- Calculate Daughter θ with respect to jet
- Daughter

$$\eta^* = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

- j_T from perpendicular component of particle ***p*** to jet ***p***



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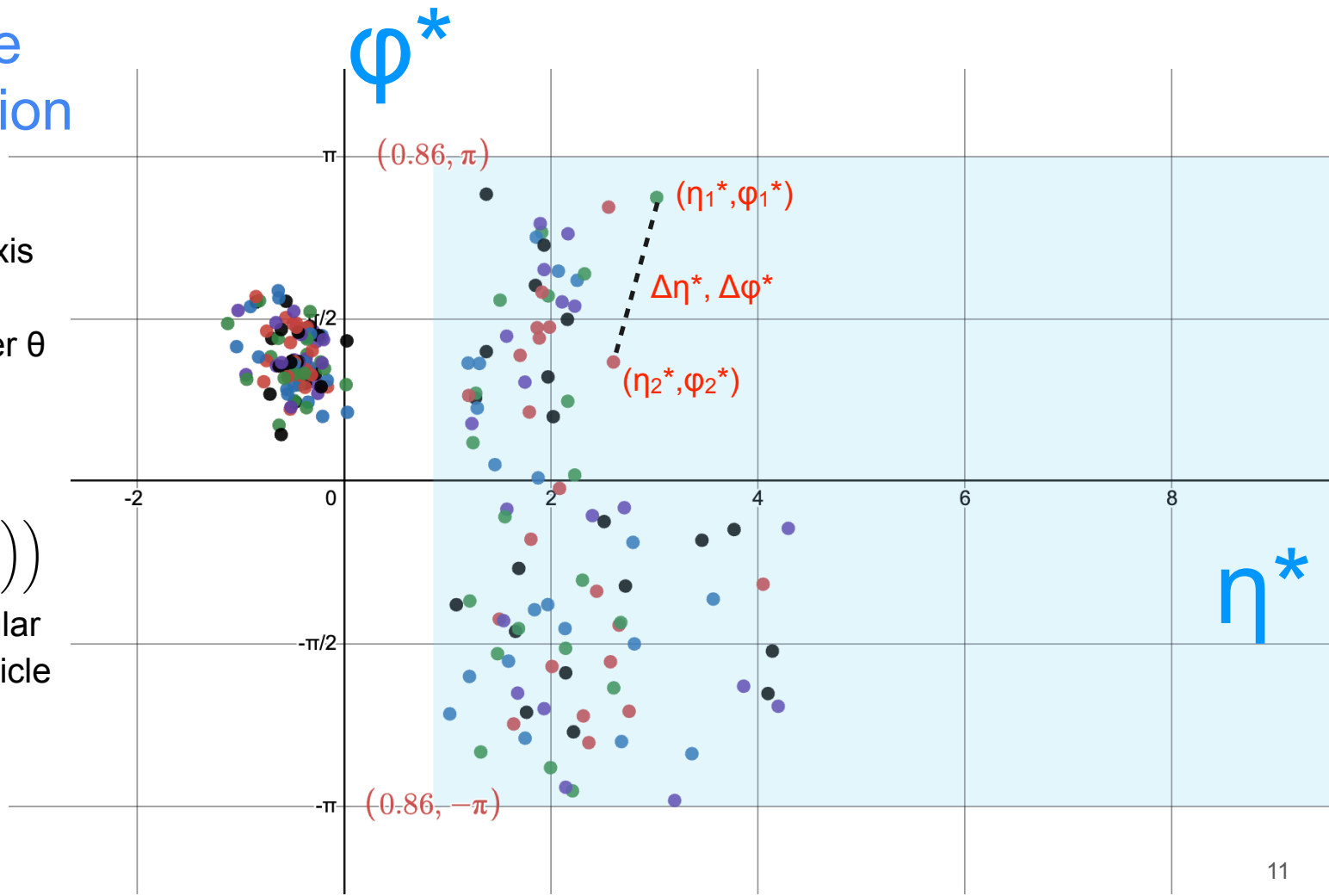
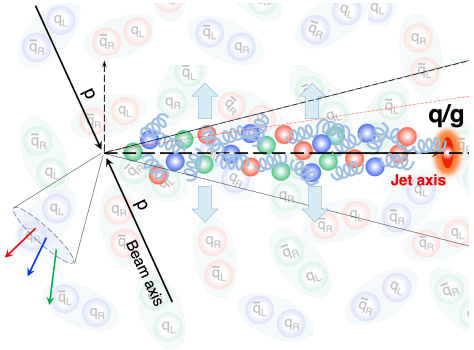


Particle Correlation in 2D

CMS *preliminary*

138 fb^{-1} (pp 13 TeV)

- Particle production dynamics seem similar to MinBias collisions in beam axis.
- Away side enhancement at Δφ*=π
- Peak at (0,0)



$\langle N_{ch}^{j} \rangle = 26$

All Jets Multiplicities Inclusive

Anti-k_TR=0.8

$p_T^{jet} > 550$

$|\eta^{jet}| < 1.6$

$\frac{1}{N_{trg}} \frac{d^2N^{pair}}{d\Delta\phi^* d\Delta\eta^*}$

$0.3 < j_T < 3.0$ GeV

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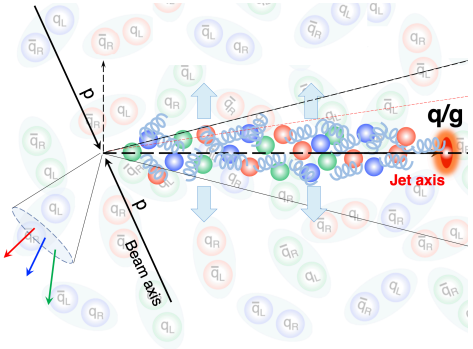
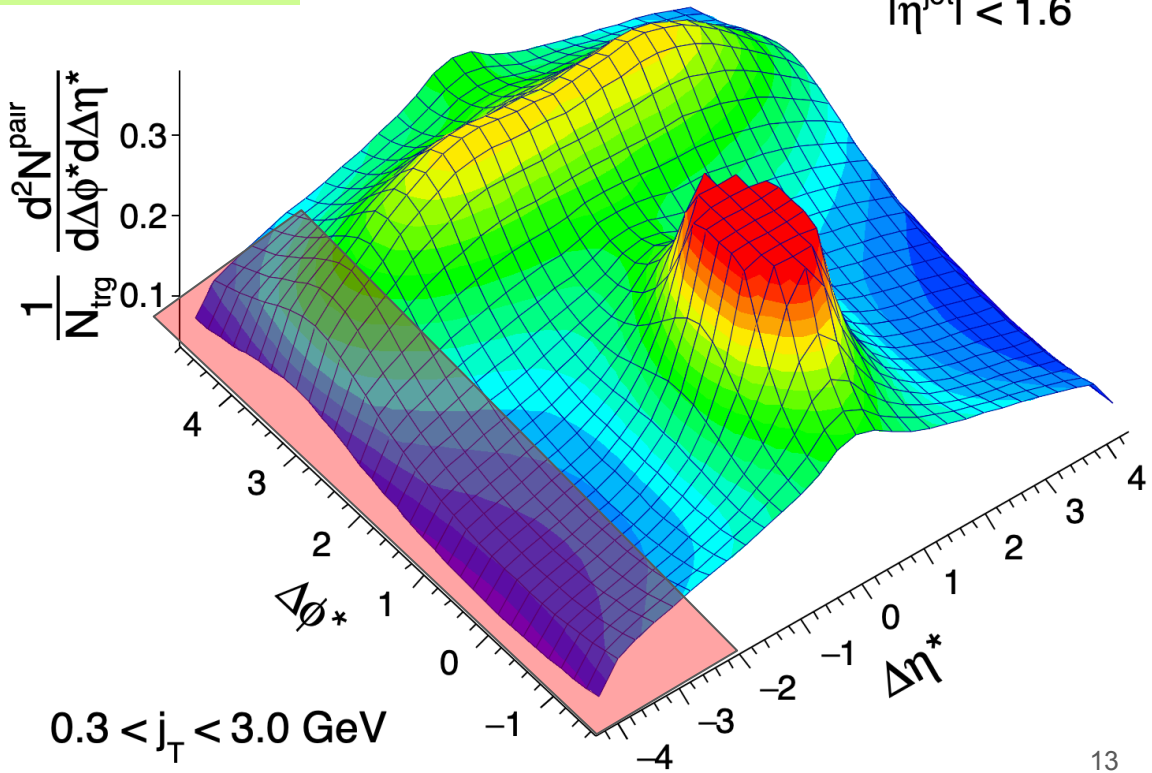
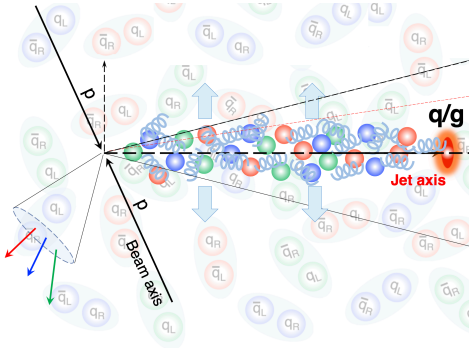
- Large Δη* pairs correspond to earliest moments after collision
- Study long range Δη* projection in Δφ*

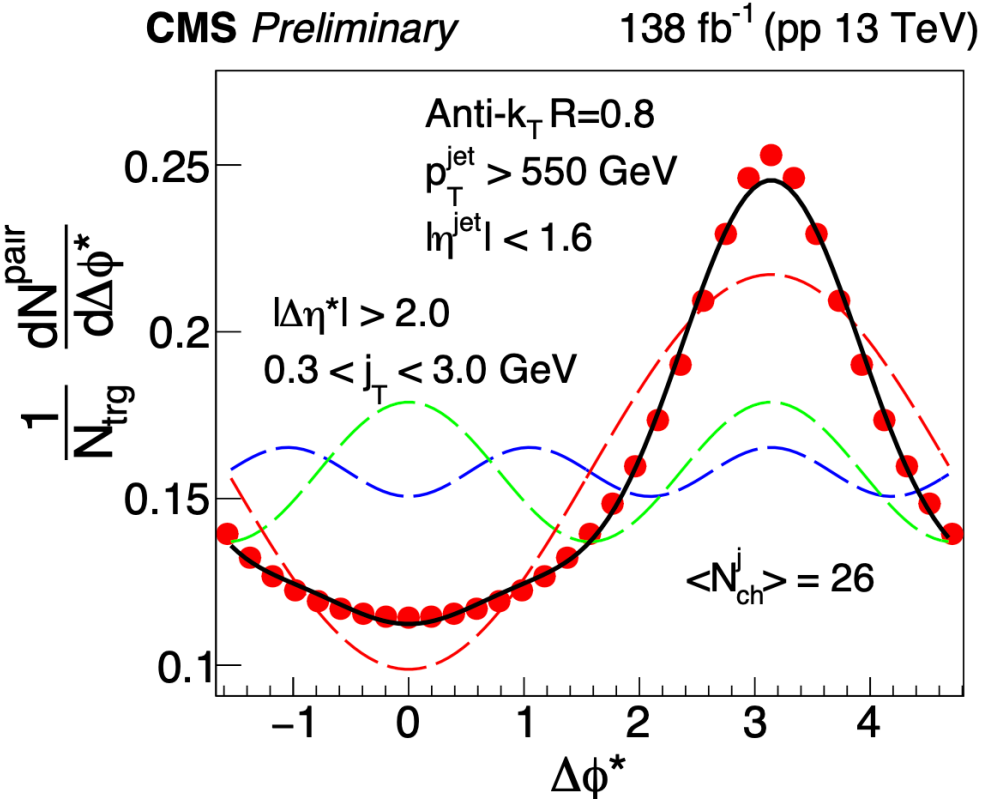




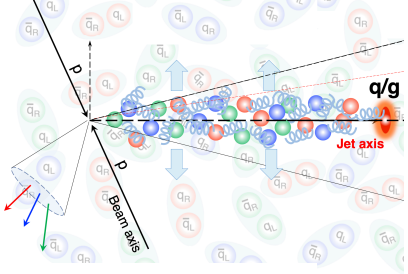
Long range Δφ* projection

$$\frac{1}{N_{\mathrm{ch}}^{j}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi^{*}} \propto \sum_{n=1}^{\infty} V_{\mathrm{n}\Delta}\cos(\mathrm{n}\Delta\phi^{*})$$





2D and long range Δφ* projection: Monte Carlo



CMS *Simulation Preliminary*

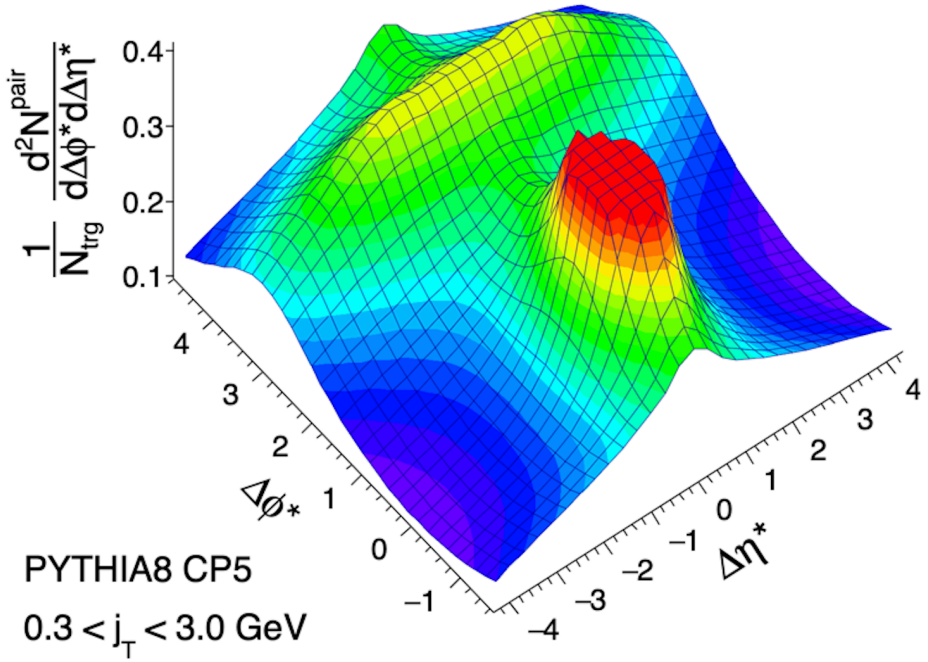
$\langle N_{ch}^{j} \rangle = 28$

Inclusive Jets Multiplicity

Anti-k_T R=0.8

$p_T^{jet} > 550$

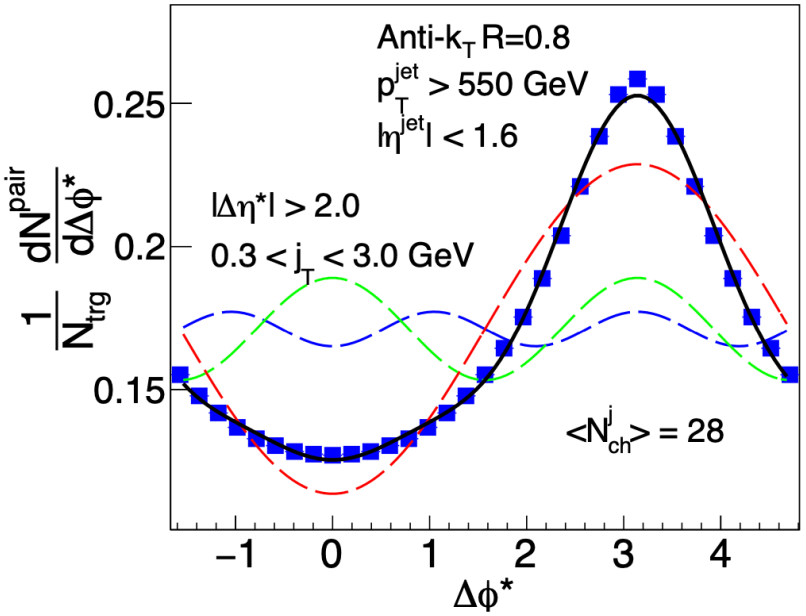
$|\eta^{jet}| < 1.6$



PYTHIA8 CP5

$0.3 < j_T < 3.0$ GeV

CMS *Simulation Preliminary* PYTHIA8



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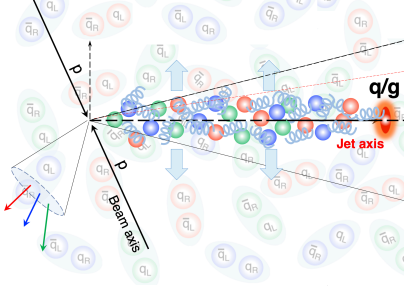
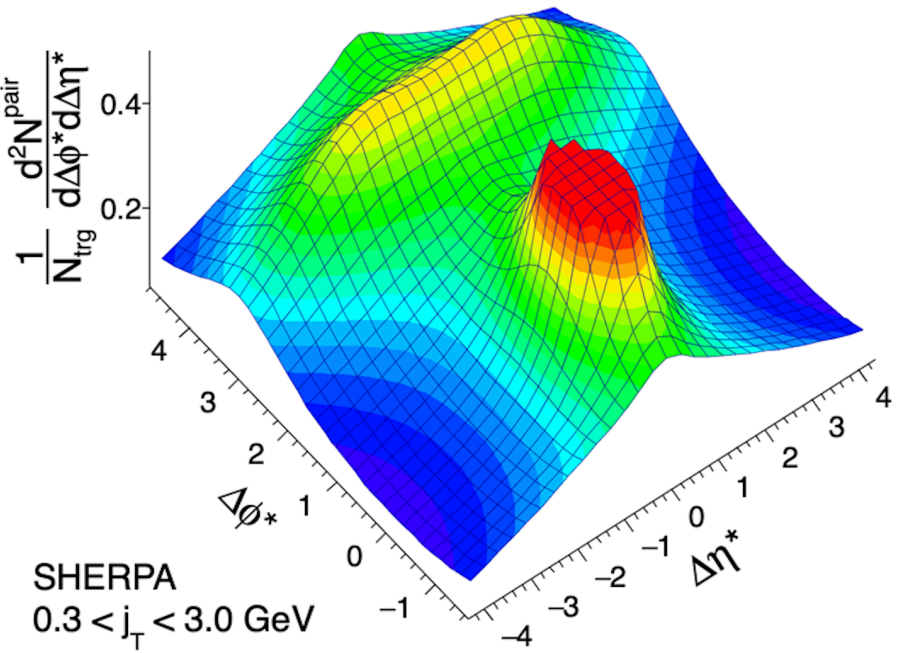


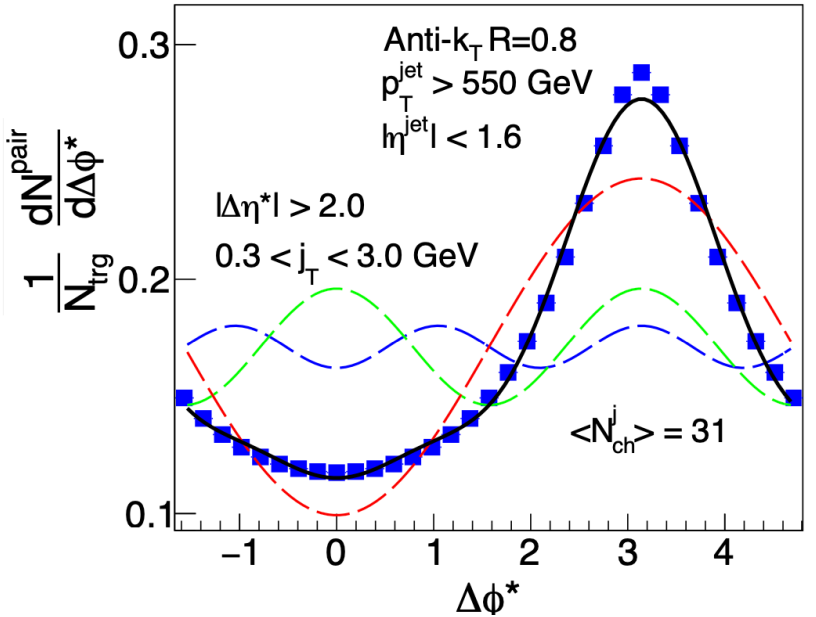
CMS *Simulation Preliminary*

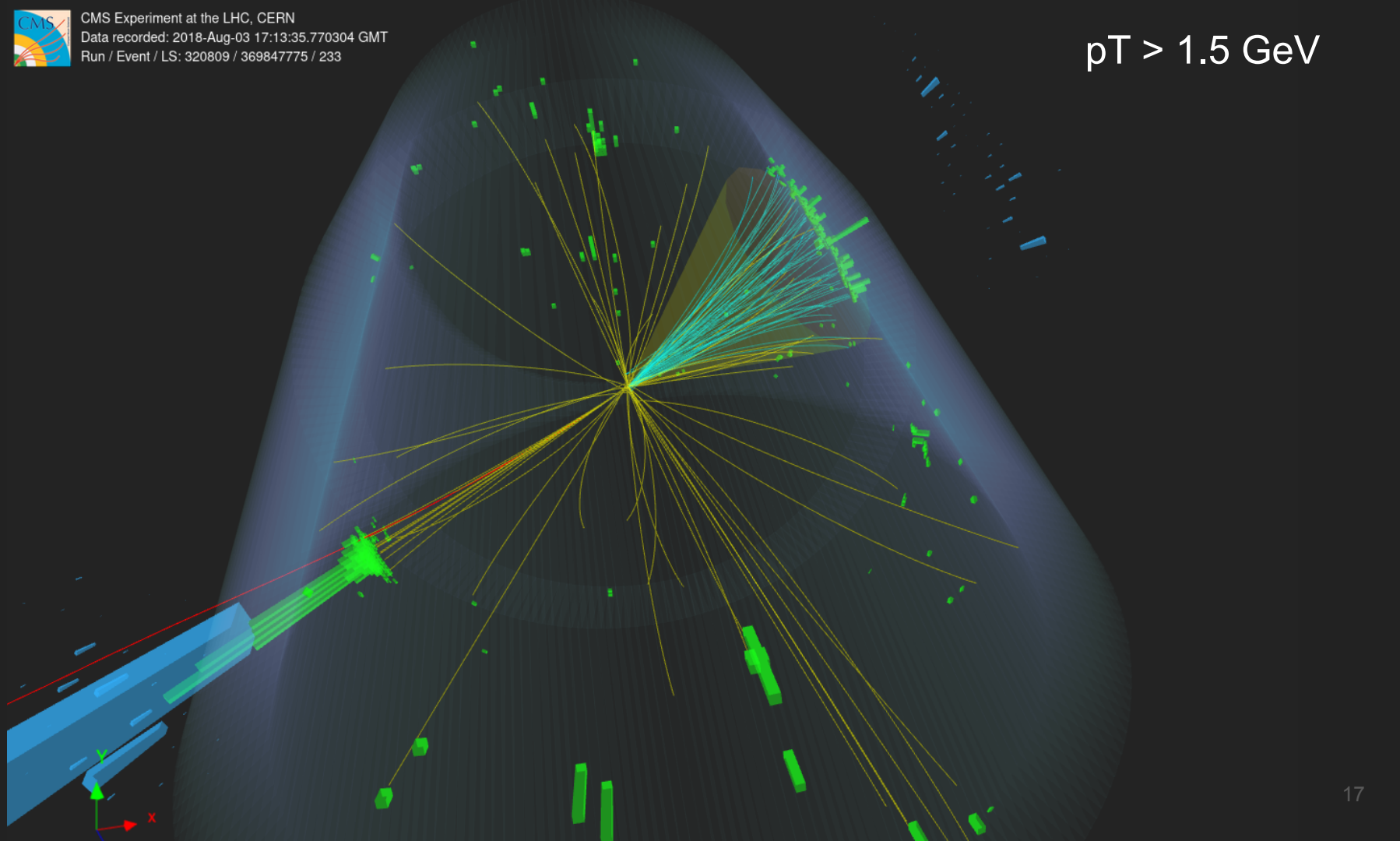
$\langle N_{ch}^{j} \rangle = 31$
Inclusive Jets Multiplicity

Anti-k_T R=0.8
$p_T^{jet} > 550$
$|\eta^{jet}| < 1.6$



CMS *Simulation Preliminary* SHERPA

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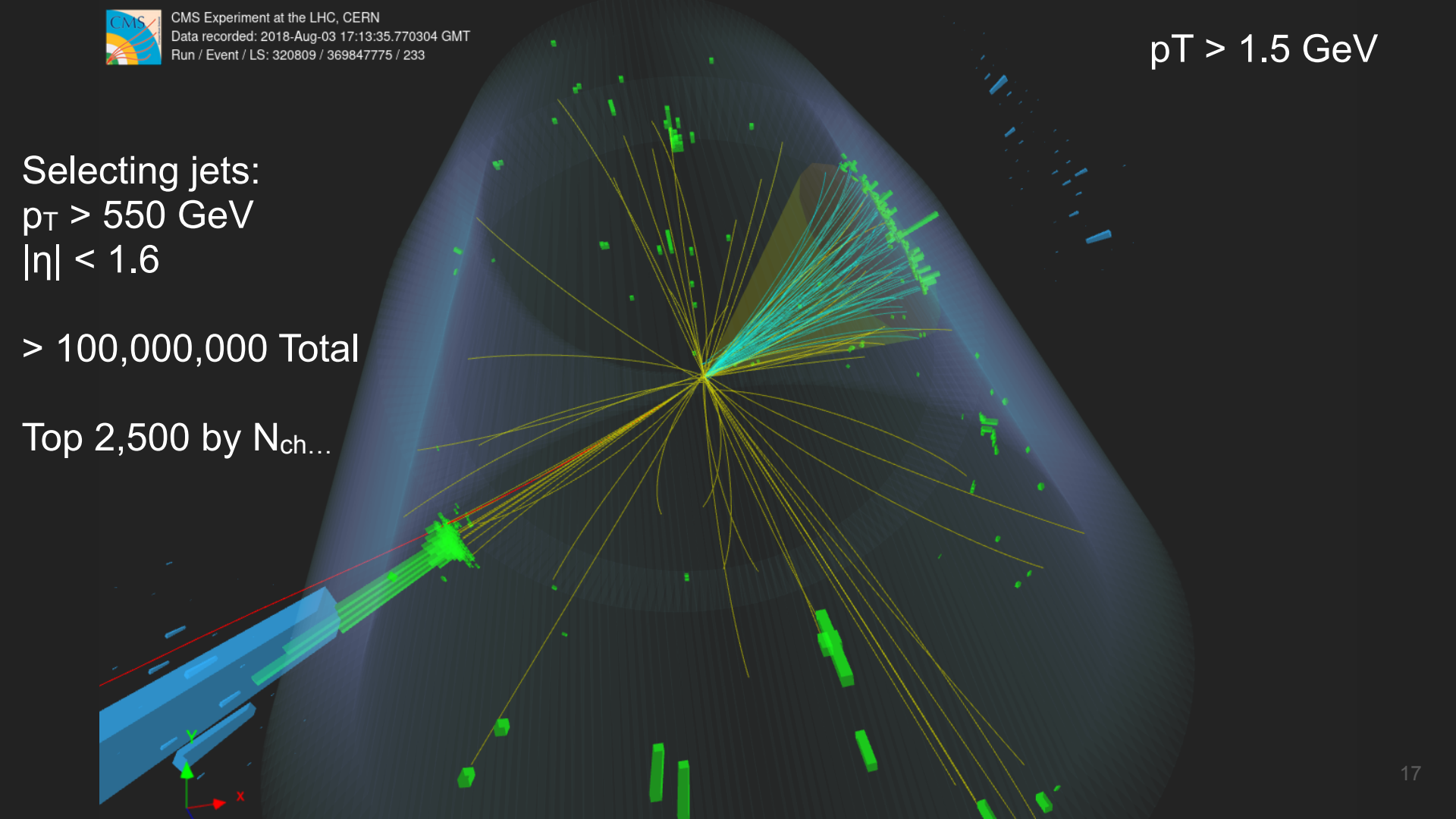
Run / Event / LS: 320809 / 369847775 / 233
pT > 1.5 GeV
Y
X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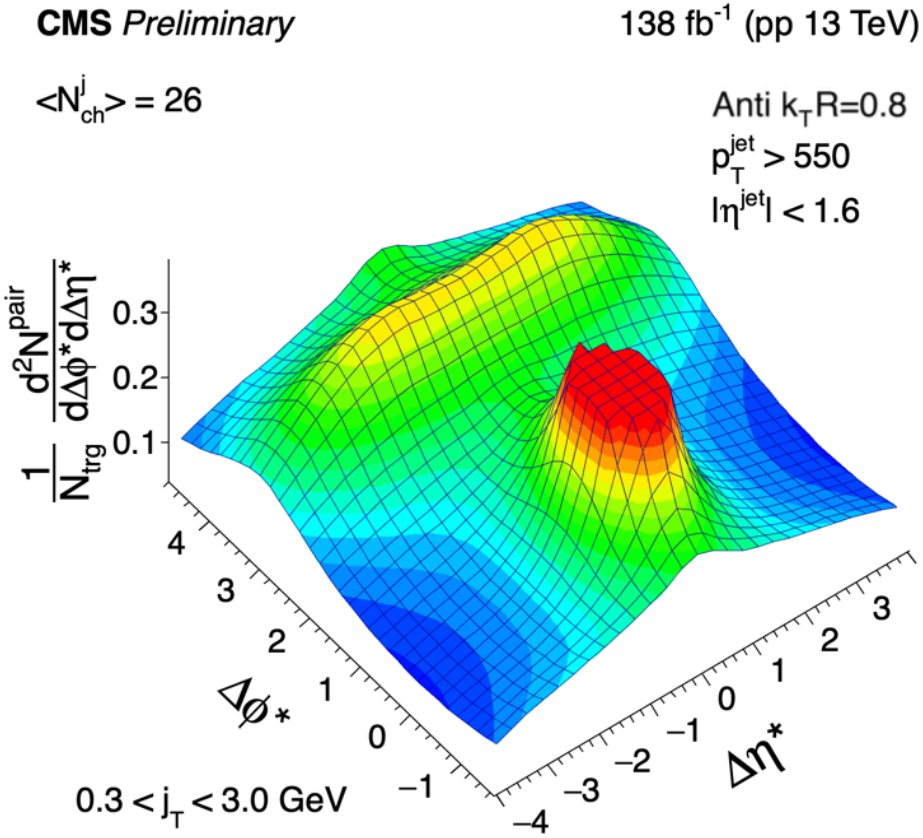
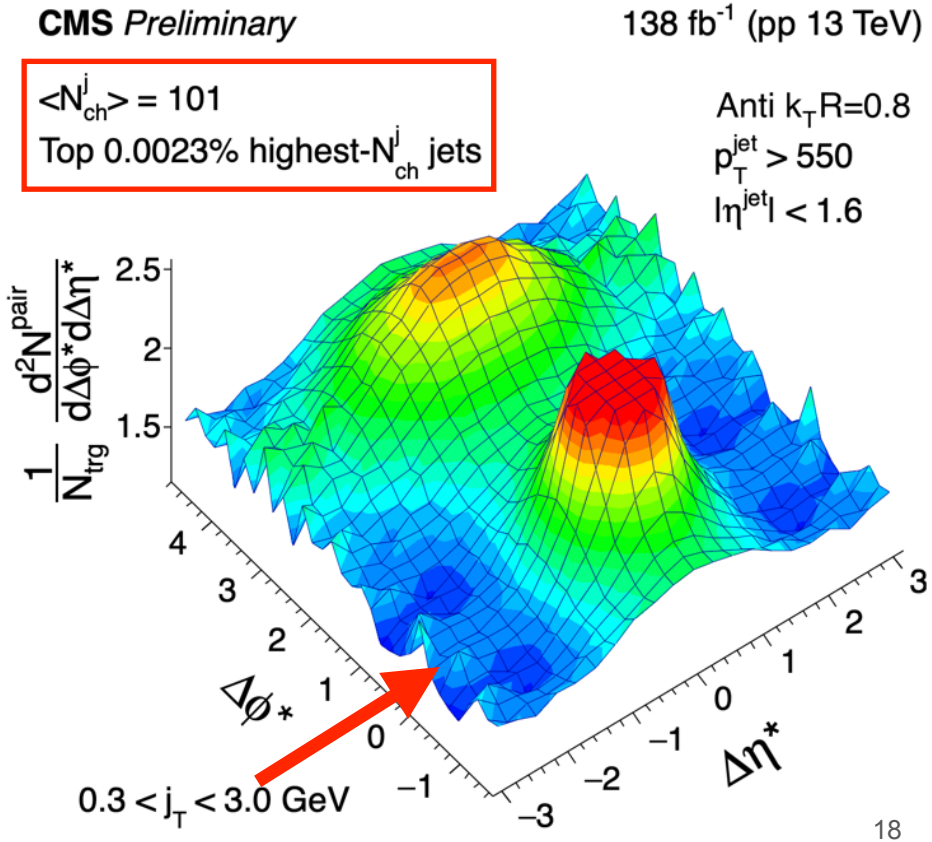
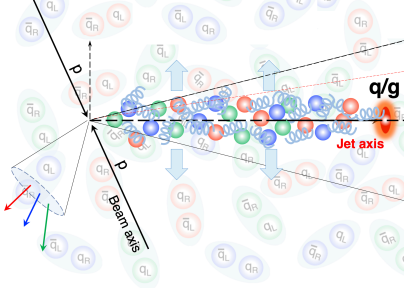
Data recorded: 2018-Aug-03 17:13:35.770304 GMT
Run / Event / LS: 320809 / 369847775 / 233
pT > 1.5 GeV
Selecting jets:
pT > 550 GeV
|η| < 1.6
> 100,000,000 Total
Top 2,500 by Nch...
Y
X

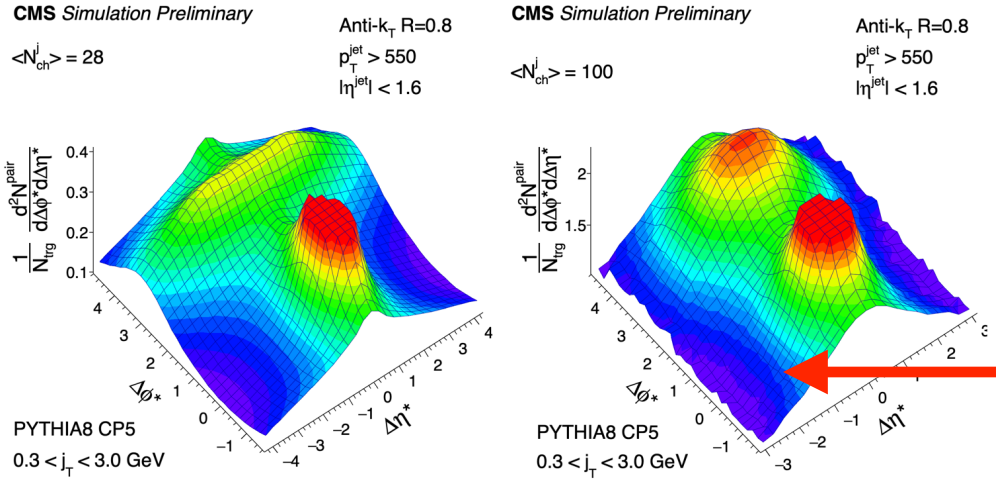
Results: 2D Correlations in Data



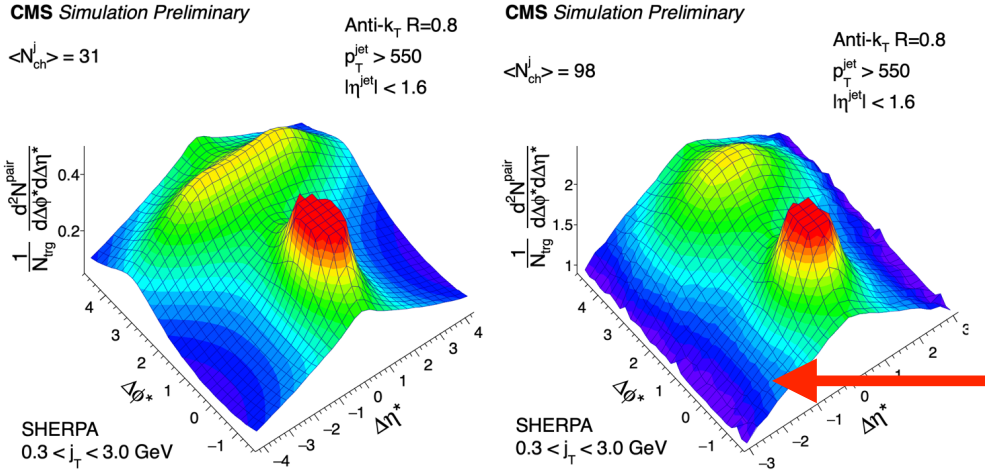


Results: 2D Correlations in MC



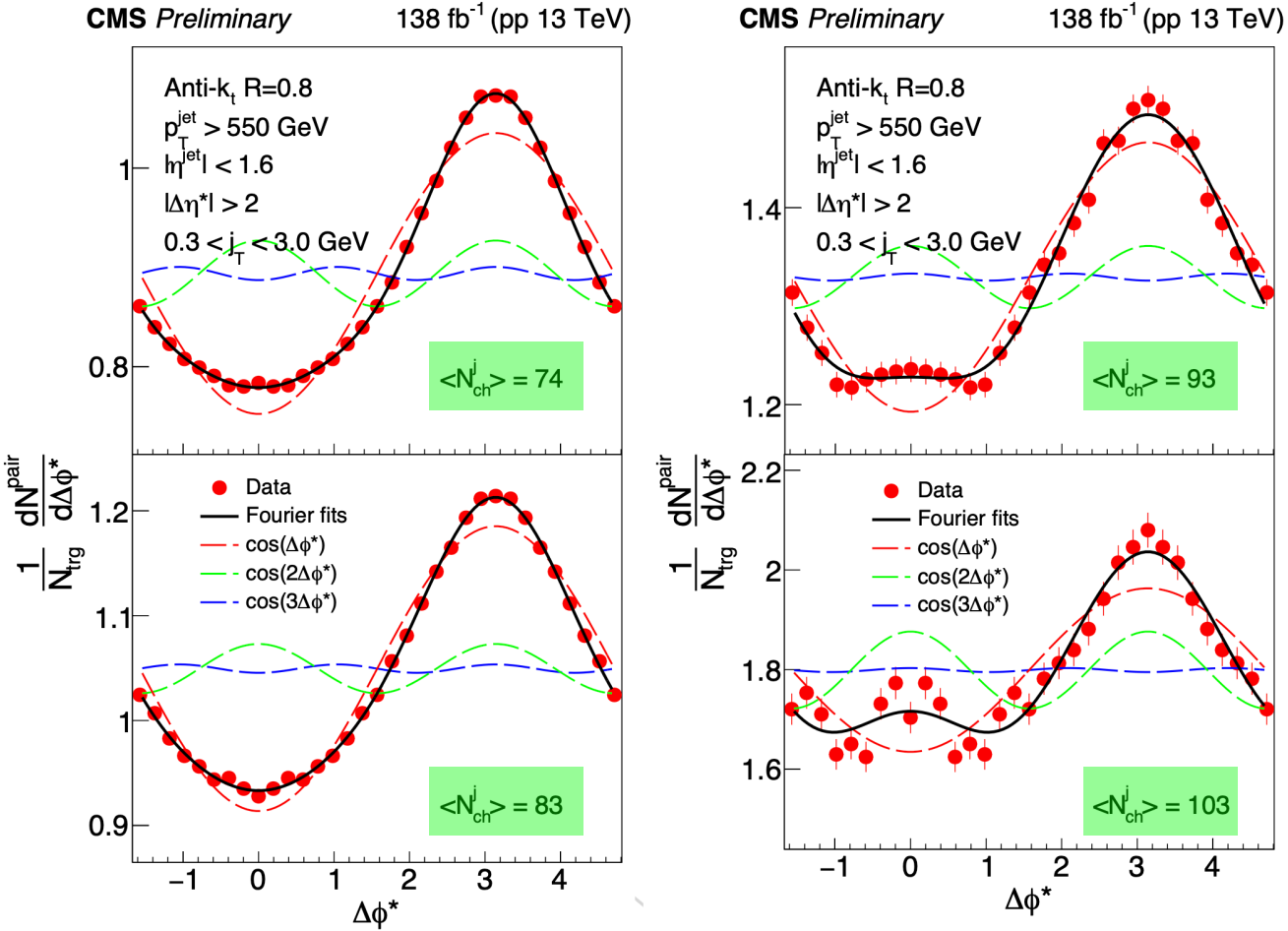


No such feature in high-mult PYTHIA8

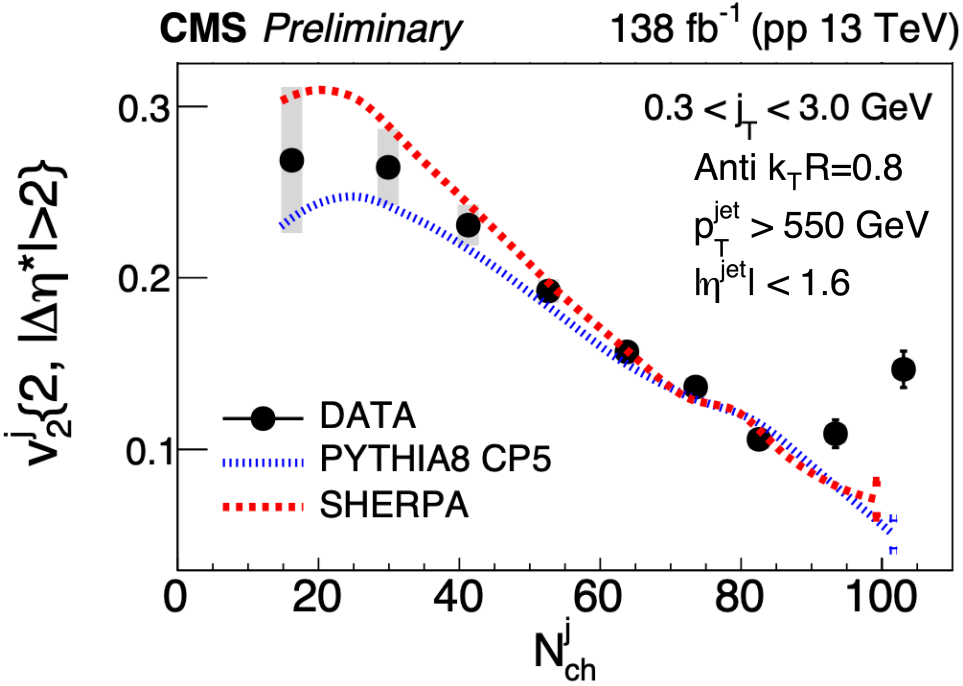


No such feature in high-mult Sherpa

Results: Evolution of $v_2\{2\}$, 1D Fits

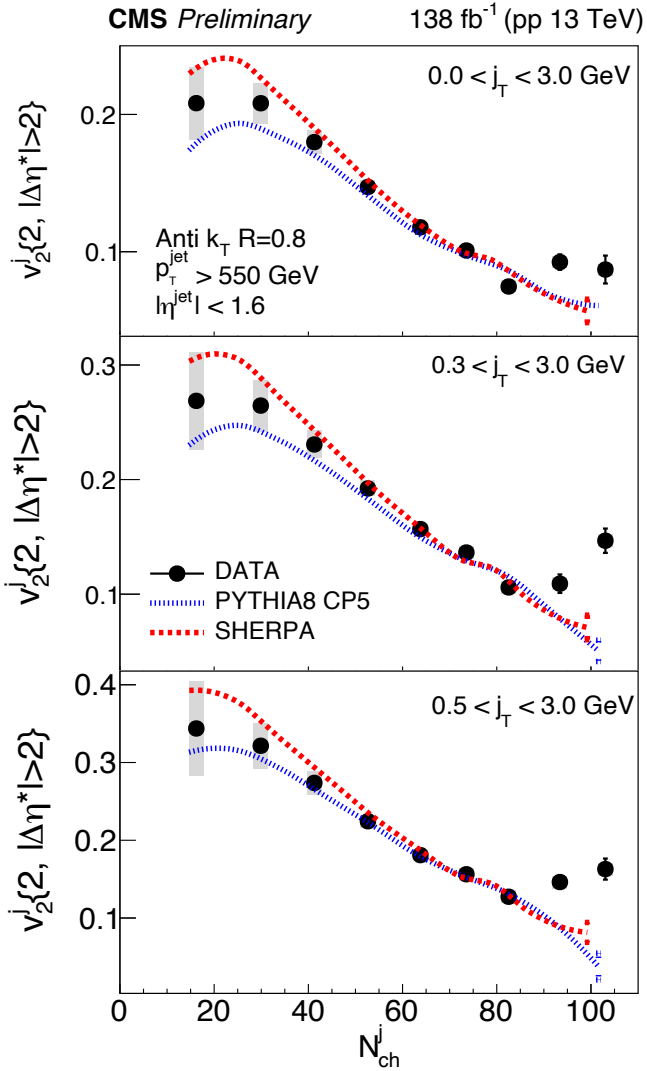


Results: Evolution of $v_2\{2\}$



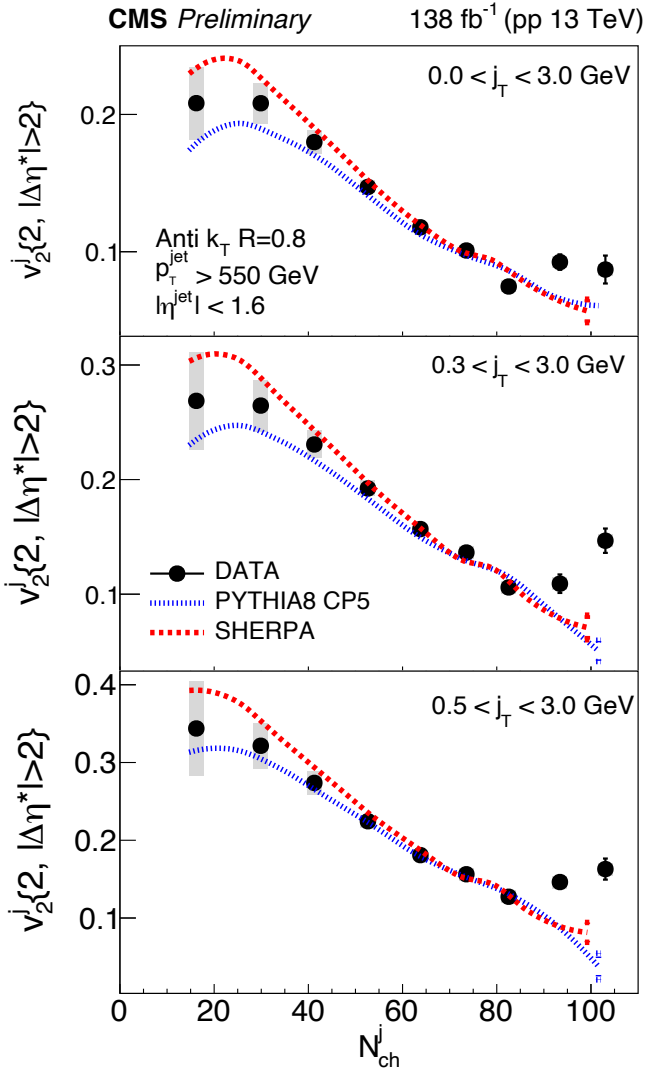
- $v_2\{2\} = (V_{2\Delta}\{2\})^{1/2}$
- Good agreement between data, PYTHIA8, and Sherpa up to N_{ch}~80
- *Data: increasing $v_2\{2\}$ with N_{ch}>80, onset of collective effects?*
- No such trend in PYTHIA8 or Sherpa …
- …. even with underlying event injection.

Results: Evolution of $v_2\{2\}$



- Linear fit for last 3 points in MC and Data, slope extracted
- Significance > *5σ* comparing Data to Sherpa, PYTHIA8 in 0.3-3.0 & 0.5-3.0 GeV j_T

Results: Evolution of $v_2\{2\}$



Above N^{j}_{ch}~80

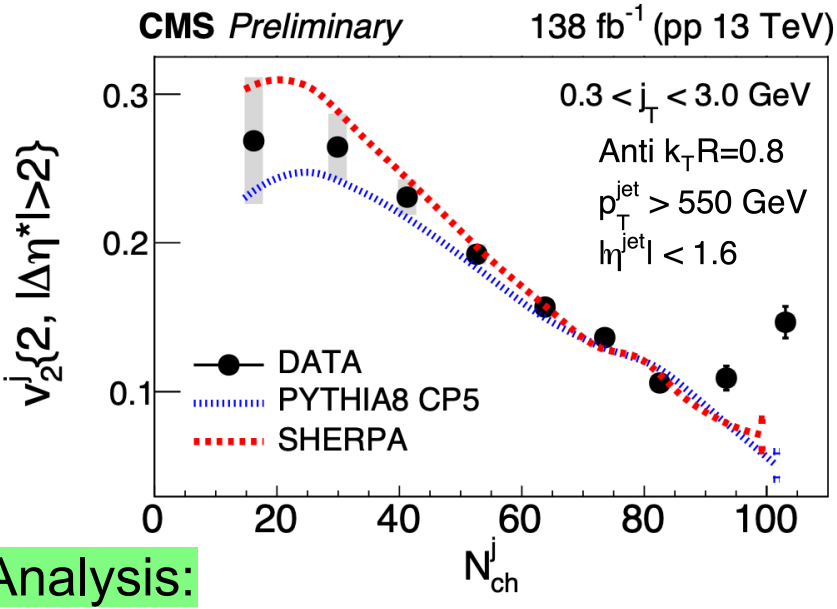
in-jet $v_2\{2\}$ *w.r.t* to the jet axis

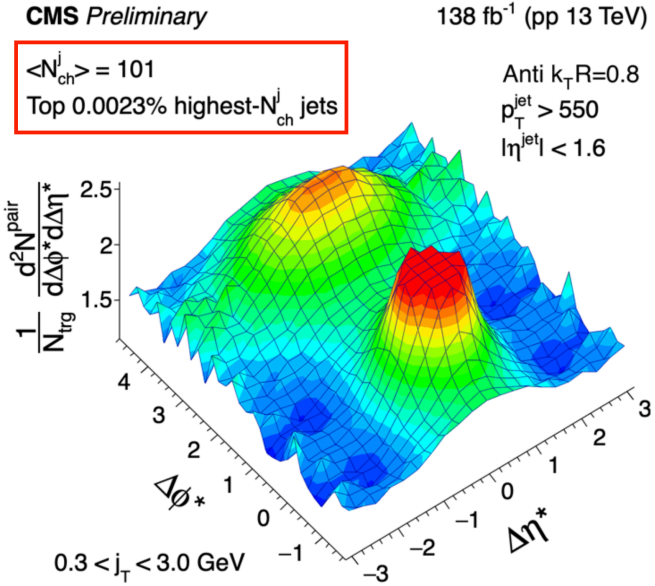
increases across 3 j_T ranges in *Data*

decreases in *Sherpa* and *PYTHIA8*

Summary:

In-jet $v_2\{2\}$ w.r.t to the jet axis *increases* across 3 j_T ranges in *Data* and *decreases* in *Sherpa* and *PYTHIA8*



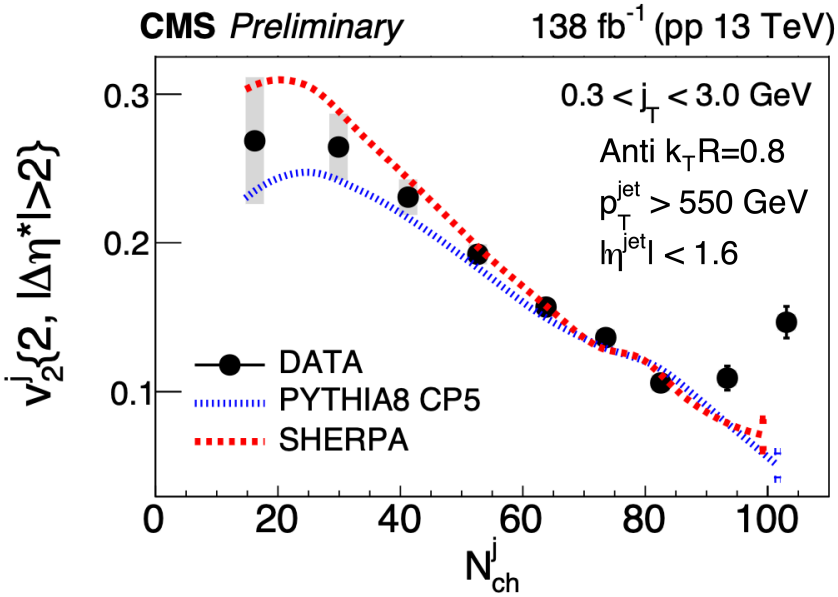


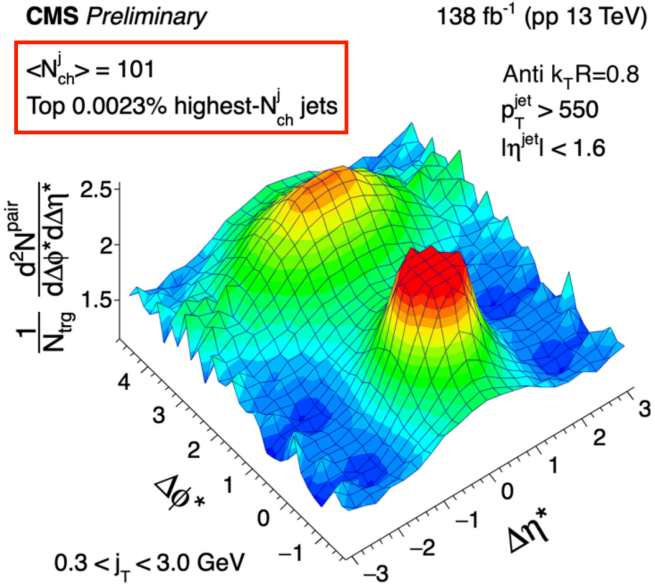
This Analysis:

- … sees possible collectivity in single parton jets during fragmentation
- … raises profound questions about the nature of QCD in nonperturbative regime
- … seeks to stimulate theoretical discussion and interpretations
- … uses a small fraction of the eventual data from the LHC, just the beginning!

Summary:

In-jet $v_2\{2\}$ w.r.t to the jet axis *increases* across 3 j_T ranges in *Data* and *decreases* in *Sherpa* and *PYTHIA8*





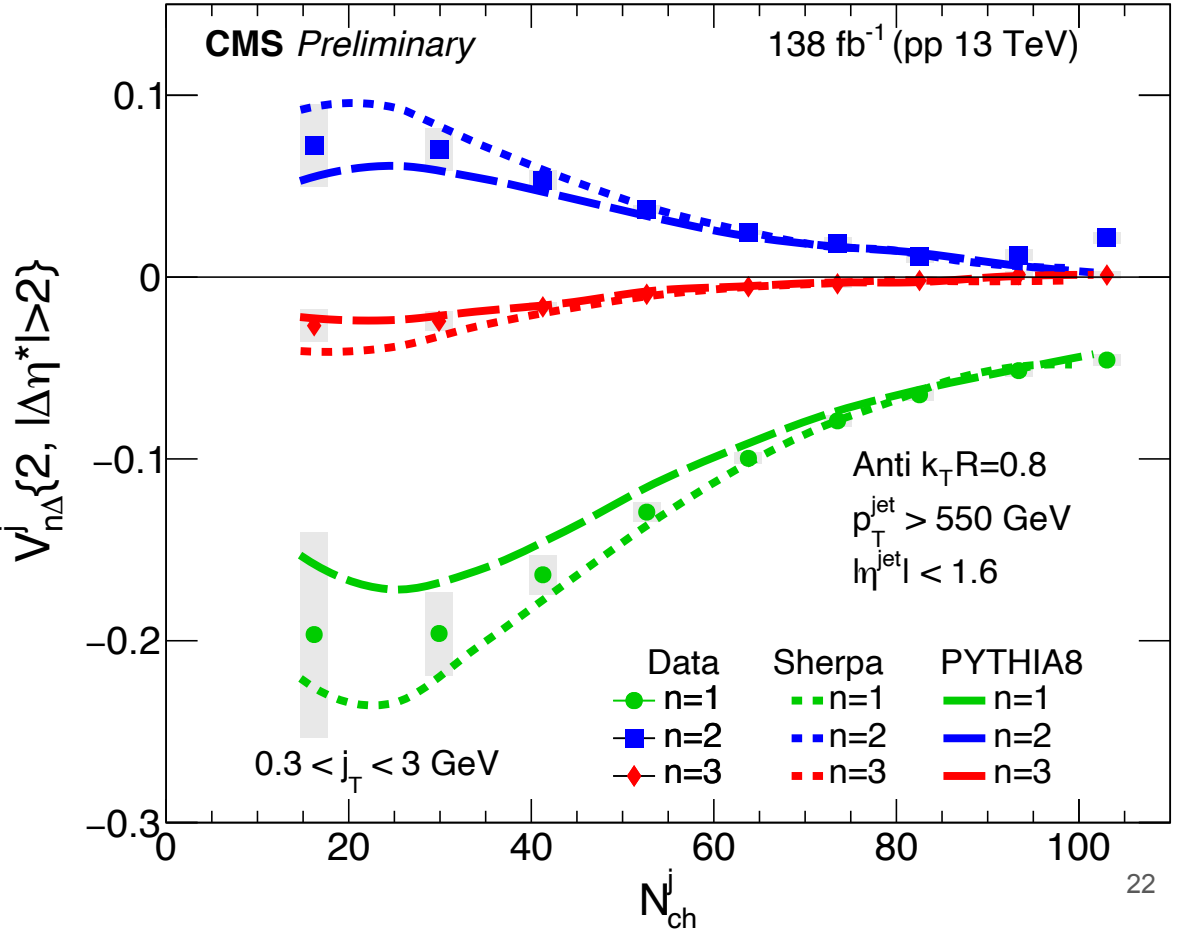
Thank You!

Please find the CMS-PAS-HIN-21-013 link

Back Up

Results: Evolution of Fourier Harmonics with N^{j}_{ch}

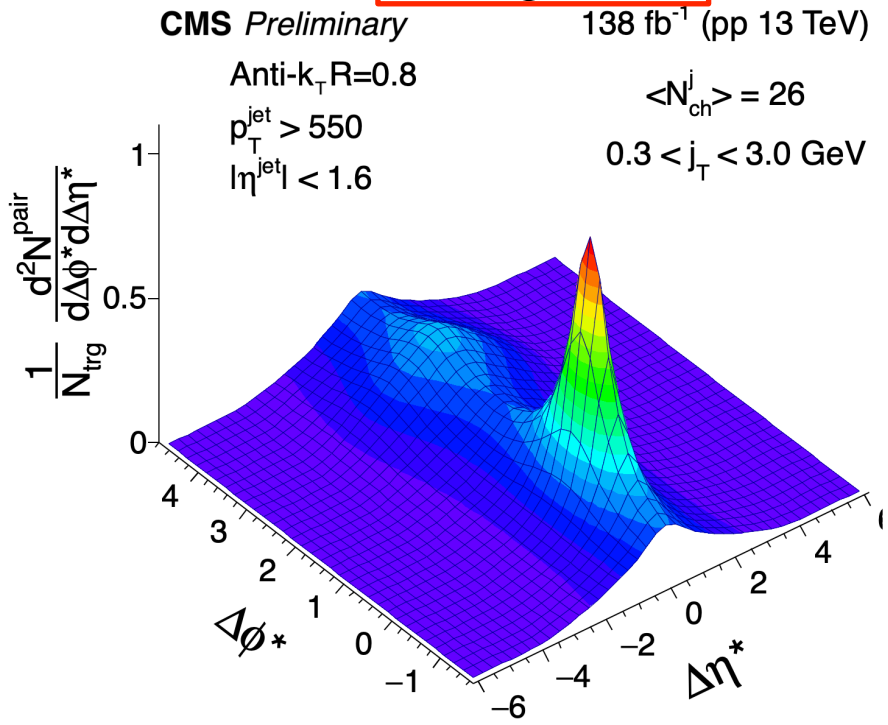
- $V_{n\Delta}$ results extracted from 1D projections
- Negative odd Fourier components, positive even components.
- Decreasing magnitude of $V_{n\Delta}$ for multiplicities up to ~80.
- Good agreement between data and MC for $N_{ch} < 80$



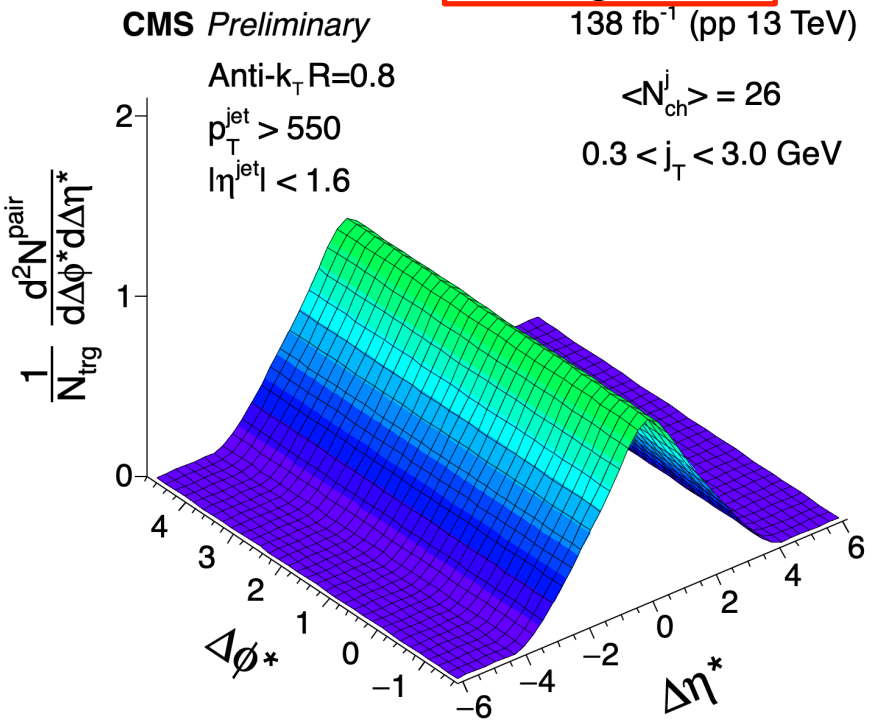
Particle Correlation in 2D

$$\frac{1}{N_{\mathrm{ch}}^{\mathrm{trg}}}\frac{\mathrm{d}^2N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta^*\mathrm{d}\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$

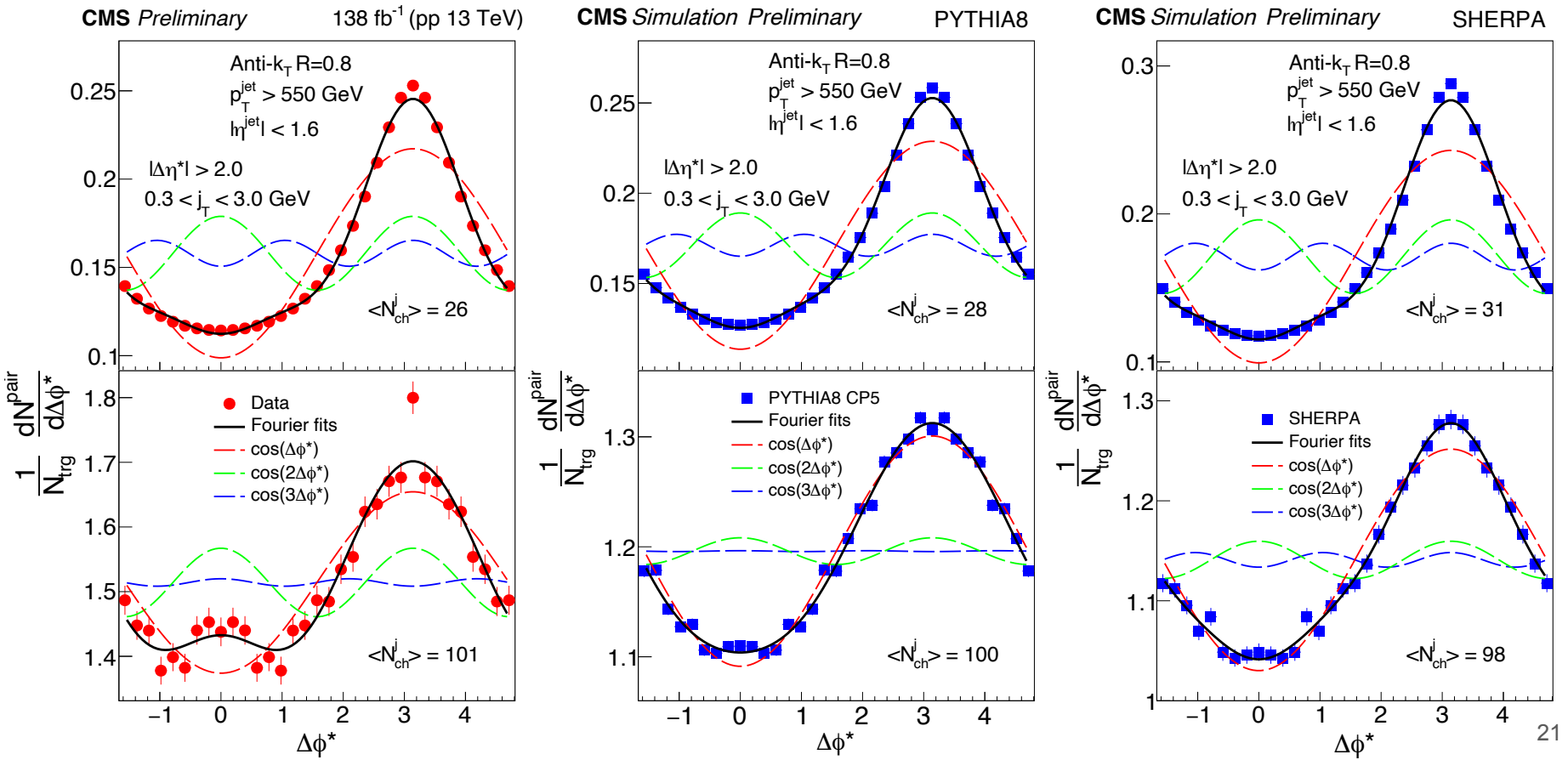
Signal



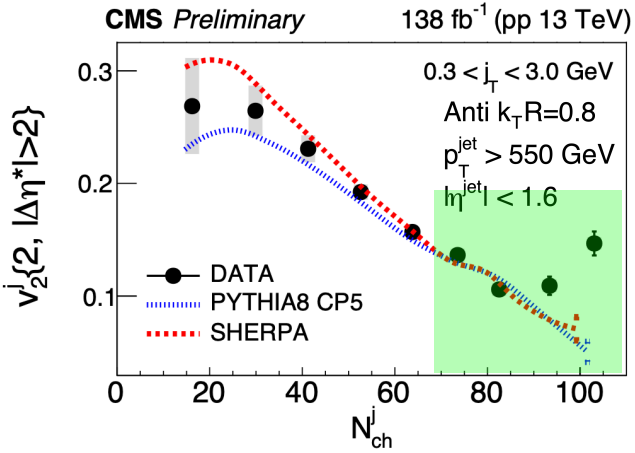
Background



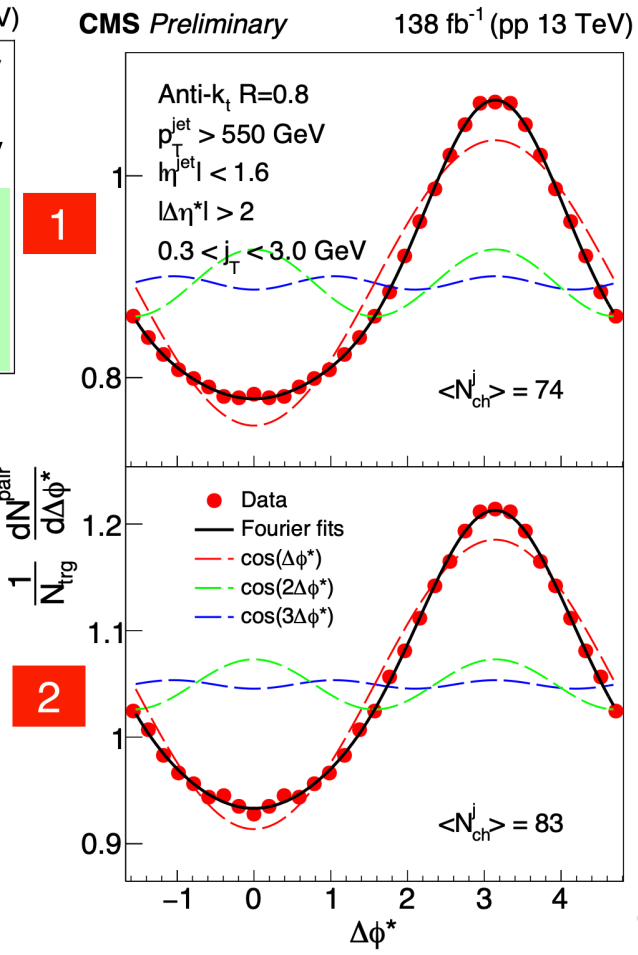
Results: (|Δη*| > 2) Correlations: 1D Δφ*

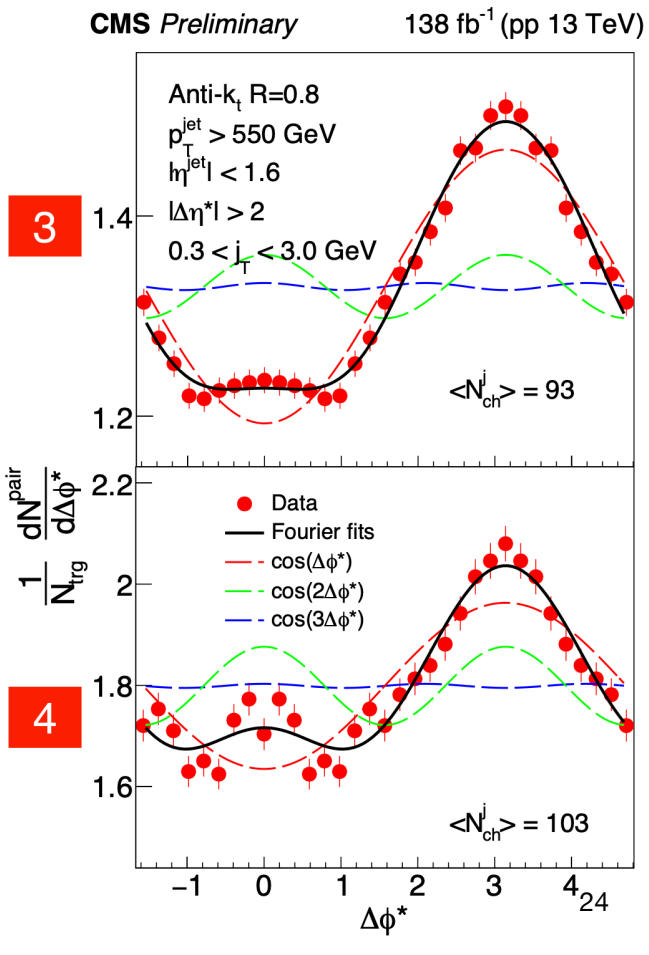


Results: Evolution of $v_2\{2\}$, 1D Fits

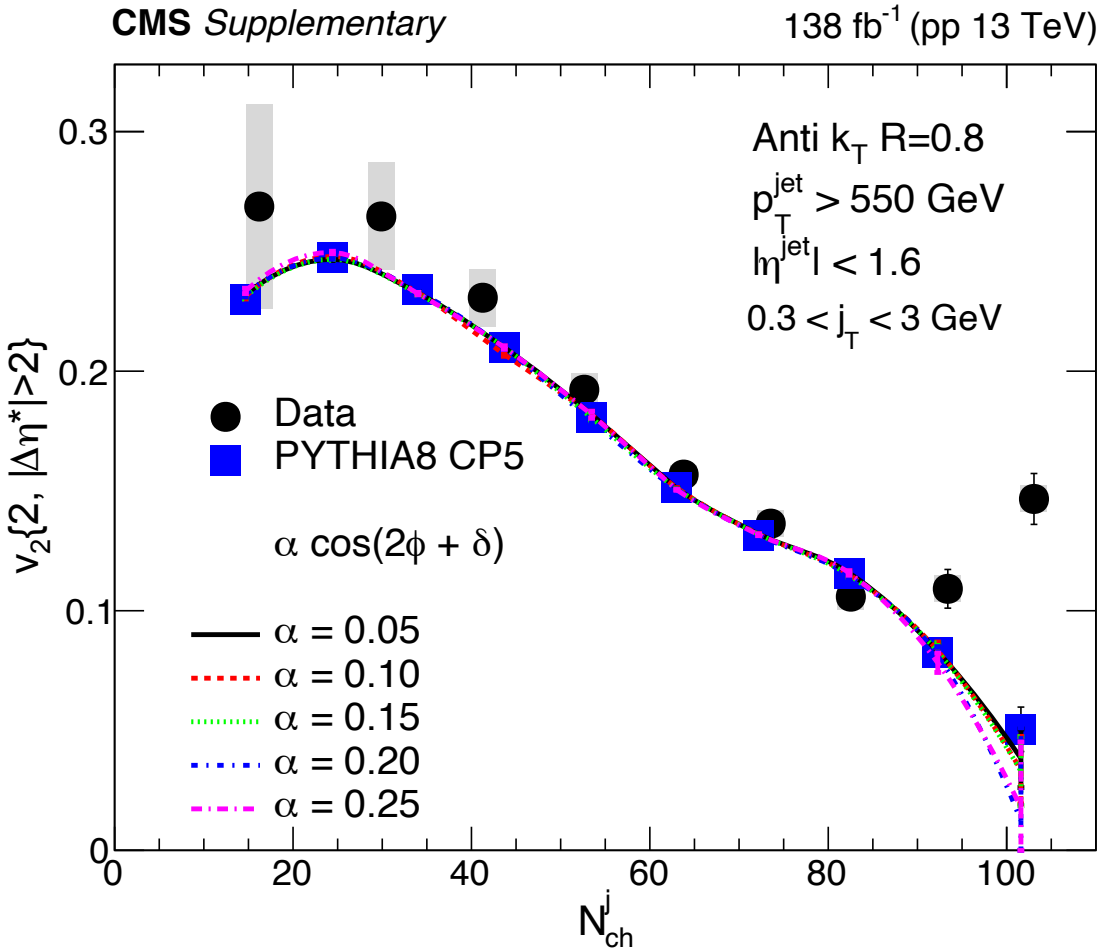


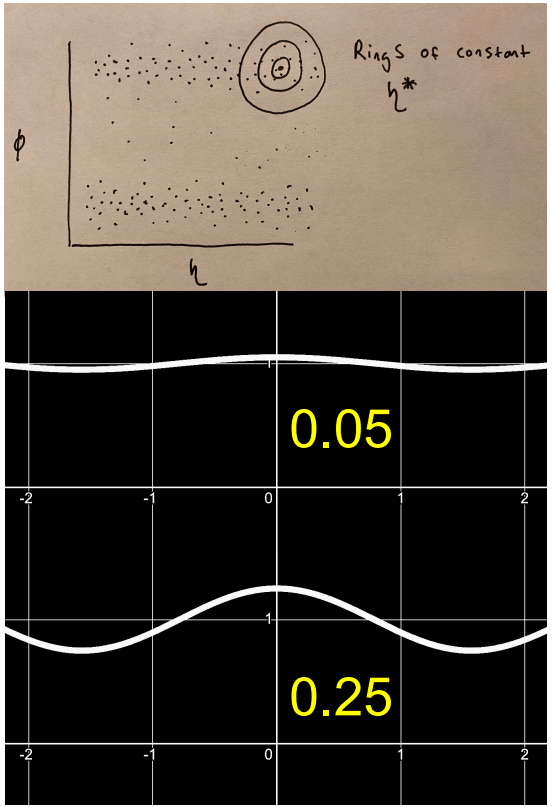
Highlighted Point	$\langle N^j_{ch} \rangle$	χ^2 / ndf
1	74	1.09
2	83	0.73
3	93	0.81
4	103	1.41



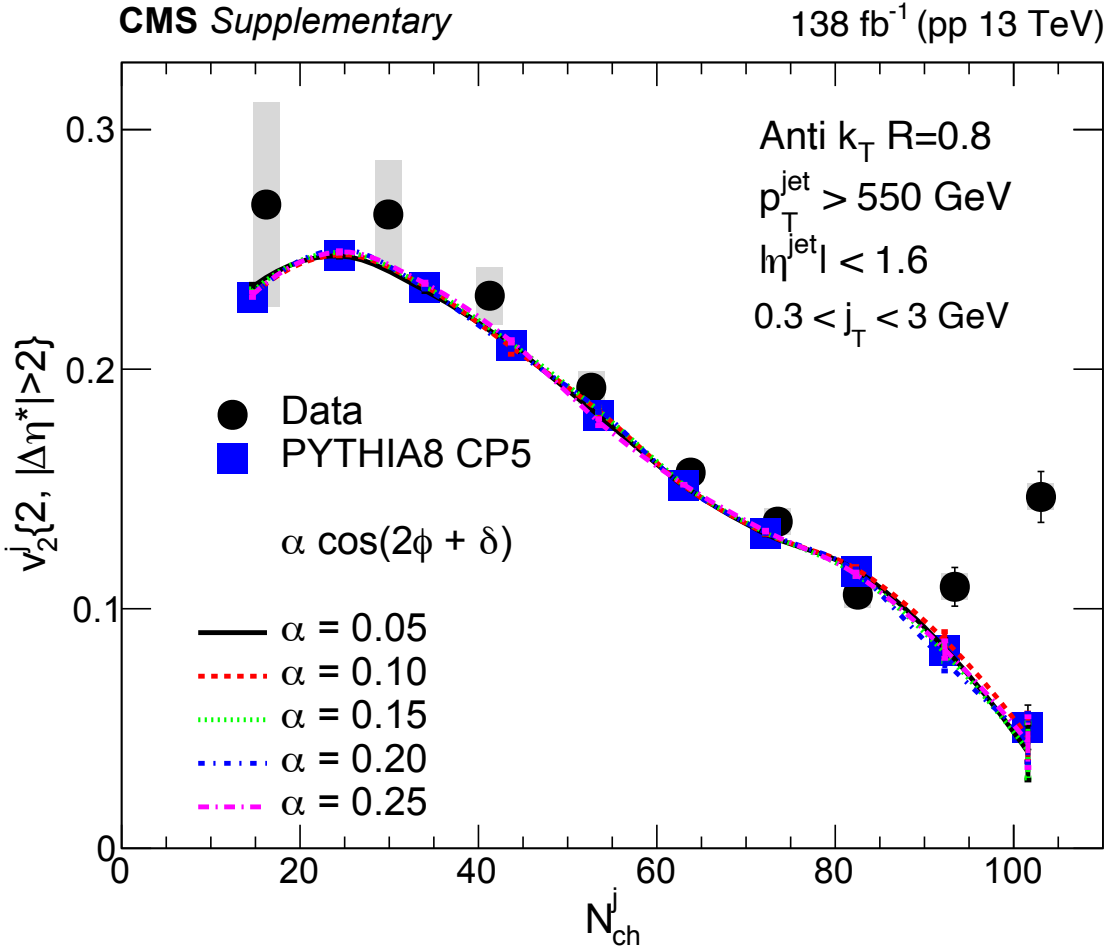


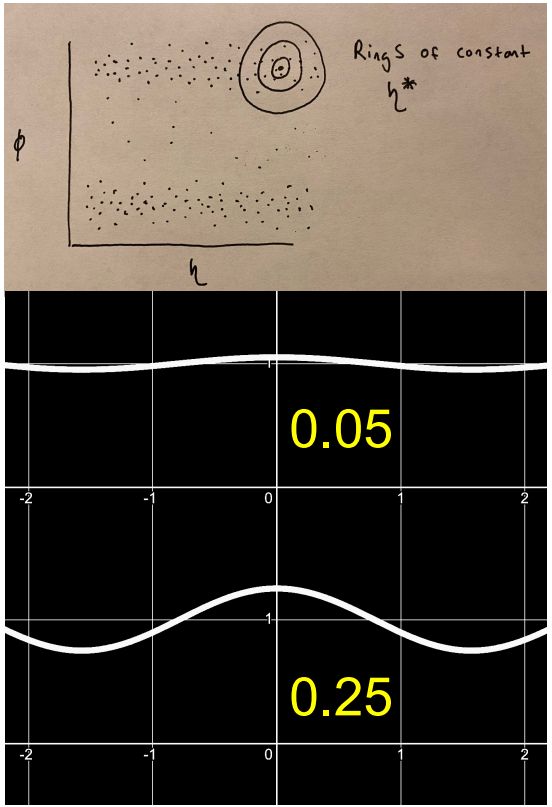
Underlying Event Injection: Random Phase



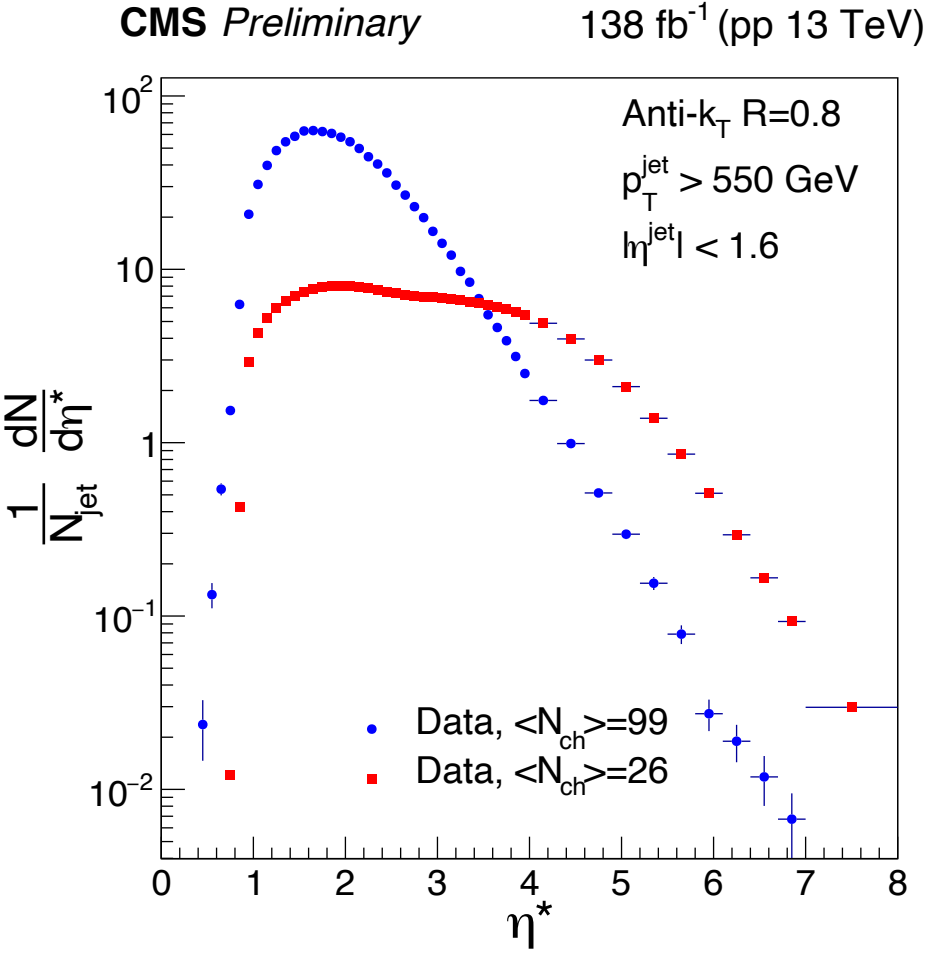


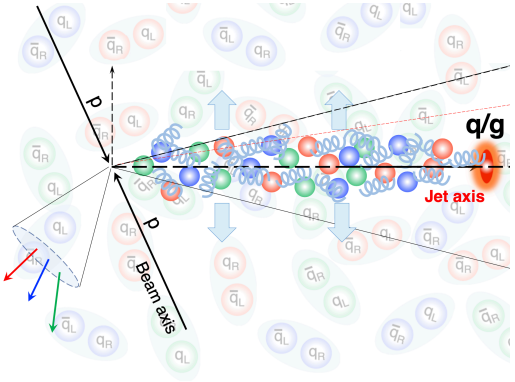
Underlying Event Injection: Phase locked with Jet





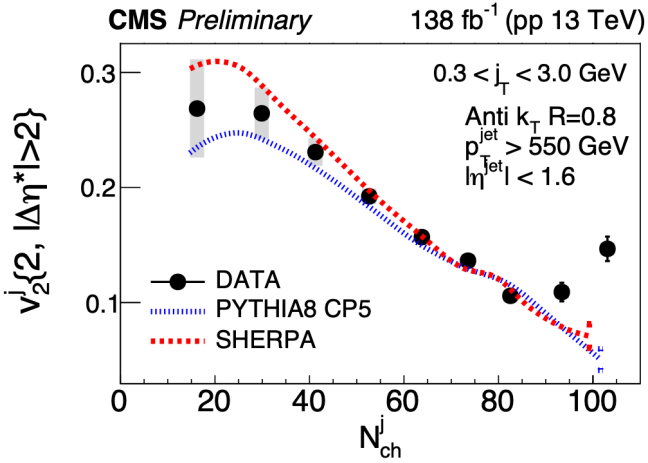
Basic properties of jets and daughters in new frame

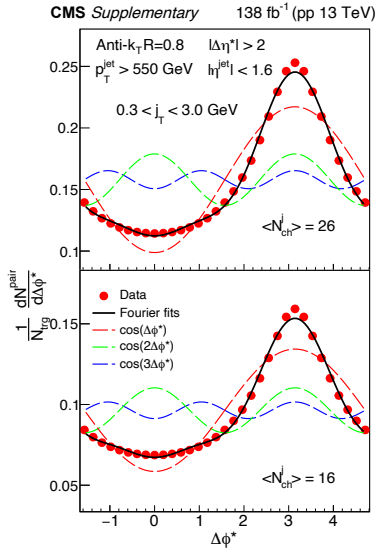


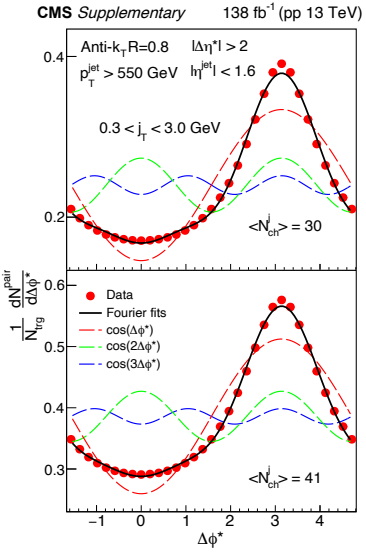


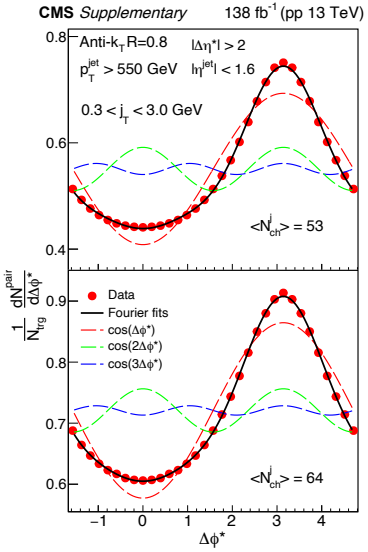
- Narrower distribution in high multiplicity jets
- dN/dη* in jet can approach that of peripheral AA

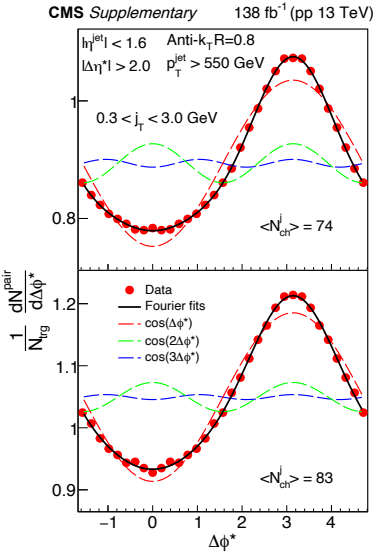
All Fits:

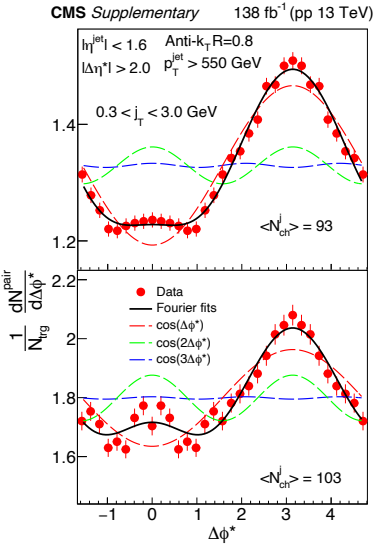

CMS Preliminary
138 fb-1 (pp 13 TeV)
0.3 < jT < 3.0 GeV
Anti kT R=0.8
pjet T > 550 GeV
|ηjet T| < 1.6
DATA
PYTHIA8 CP5
SHERPA
v2j{2, |Δη*|>2}
Nj ch


CMS Supplementary
138 fb-1 (pp 13 TeV)
Anti-kTR=0.8 |Δη*| > 2
pjet T > 550 GeV |ηjet| < 1.6
0.3 < jT < 3.0 GeV
<Nj ch> = 26
<Nj ch> = 16
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
Δφ*


CMS Supplementary
138 fb-1 (pp 13 TeV)
Anti-kTR=0.8 |Δη*| > 2
pjet T > 550 GeV |ηjet| < 1.6
0.3 < jT < 3.0 GeV
<Nj ch> = 30
<Nj ch> = 41
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
Δφ*

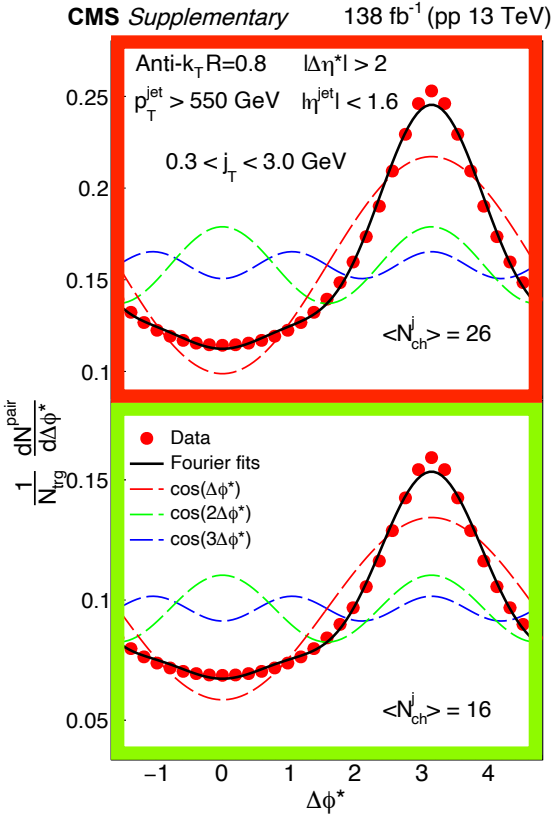

CMS Supplementary
138 fb-1 (pp 13 TeV)
Anti-kTR=0.8 |Δη*| > 2
pjet T > 550 GeV |ηjet| < 1.6
0.3 < jT < 3.0 GeV
<Nj ch> = 53
<Nj ch> = 64
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
Δφ*

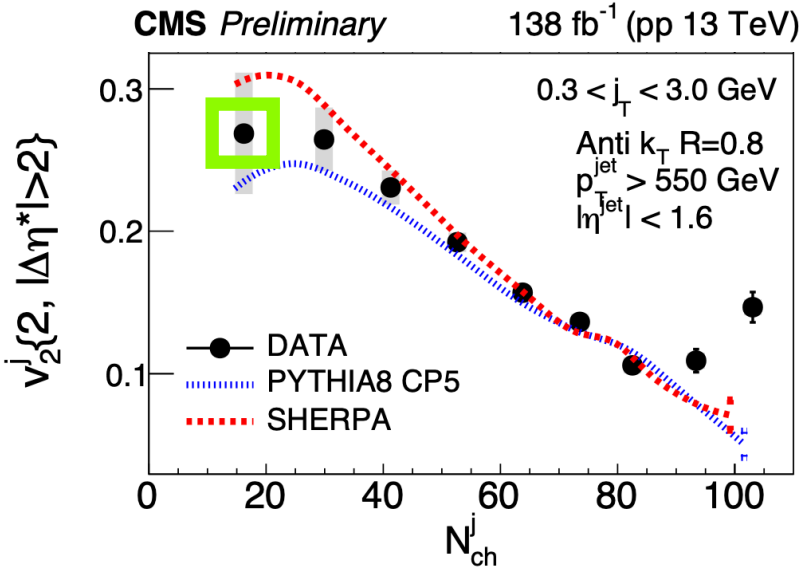

CMS Supplementary
138 fb-1 (pp 13 TeV)
|ηjet| < 1.6 Anti-kTR=0.8
|Δη*| > 2.0 pjet T > 550 GeV
0.3 < jT < 3.0 GeV
<Nj ch> = 74
<Nj ch> = 83
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
Δφ*


CMS Supplementary
138 fb-1 (pp 13 TeV)
|ηjet| < 1.6 Anti-kTR=0.8
|Δη*| > 2.0 pjet T > 550 GeV
0.3 < jT < 3.0 GeV
<Nj ch> = 93
<Nj ch> = 103
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
Δφ*

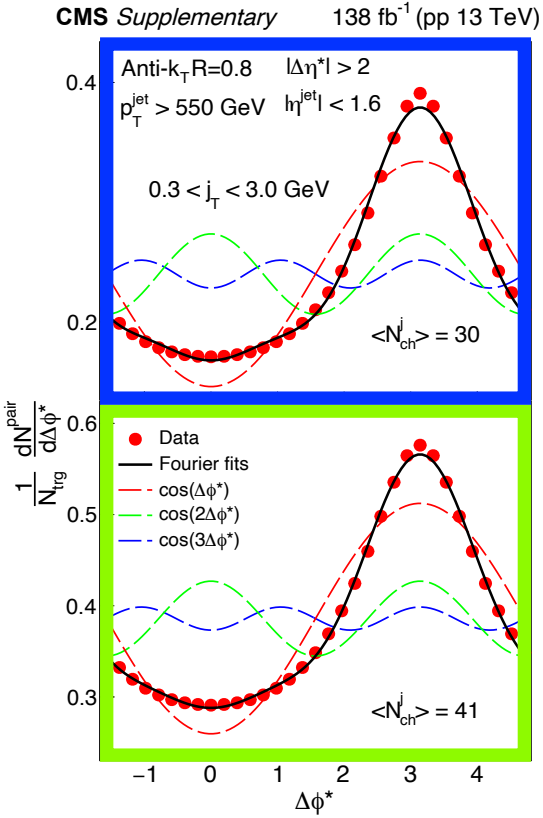
All Fits:

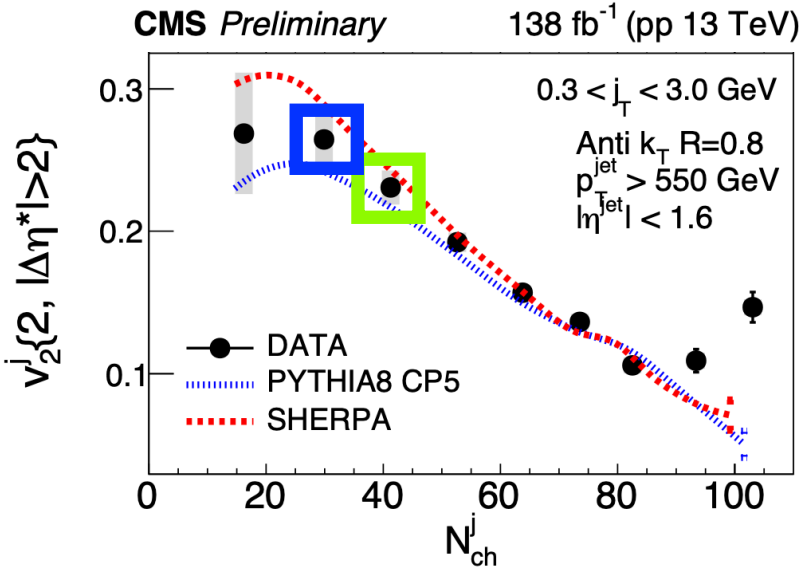
Inclusive N_{ch}



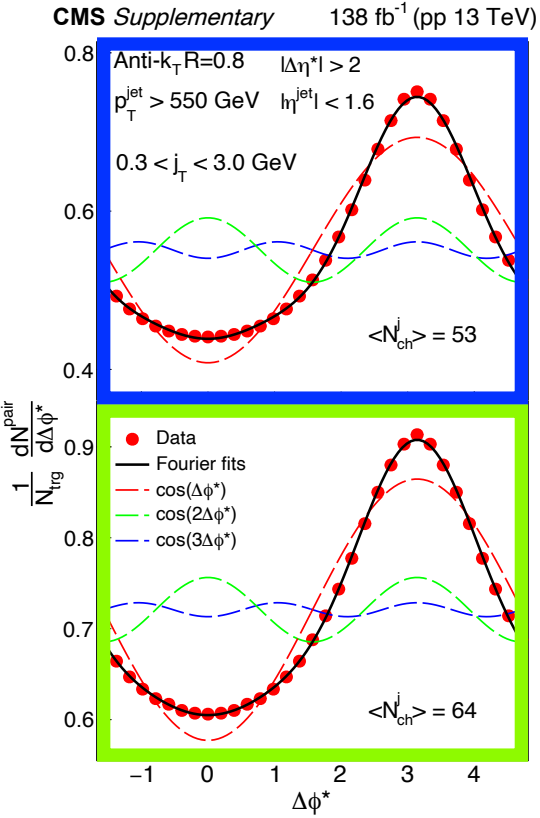


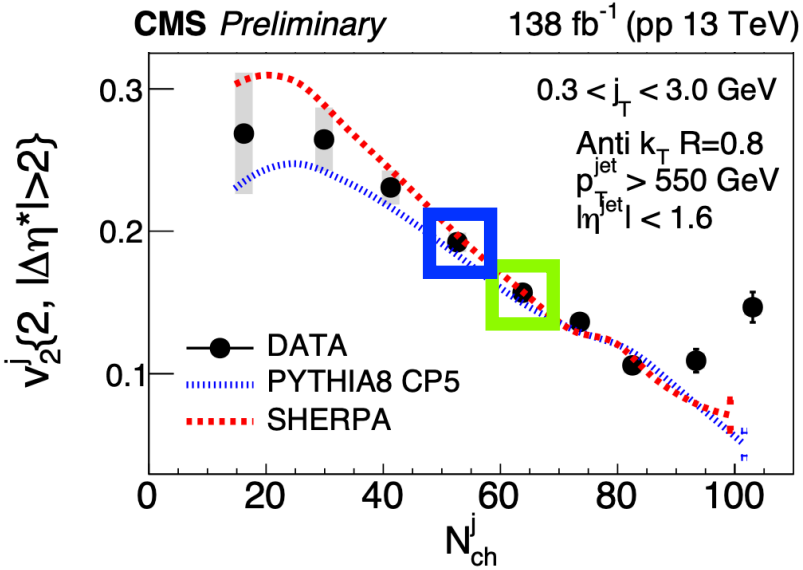
All Fits:


CMS Supplementary
138 fb-1 (pp 13 TeV)
Anti-kTR=0.8
|Δη*| > 2
pjetT > 550 GeV
|ηjet| < 1.6
0.3 < jT < 3.0 GeV
<Nj ch> = 30
<Nj ch> = 41
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
1/Ntrg dNpair/dΔφ*
Δφ*

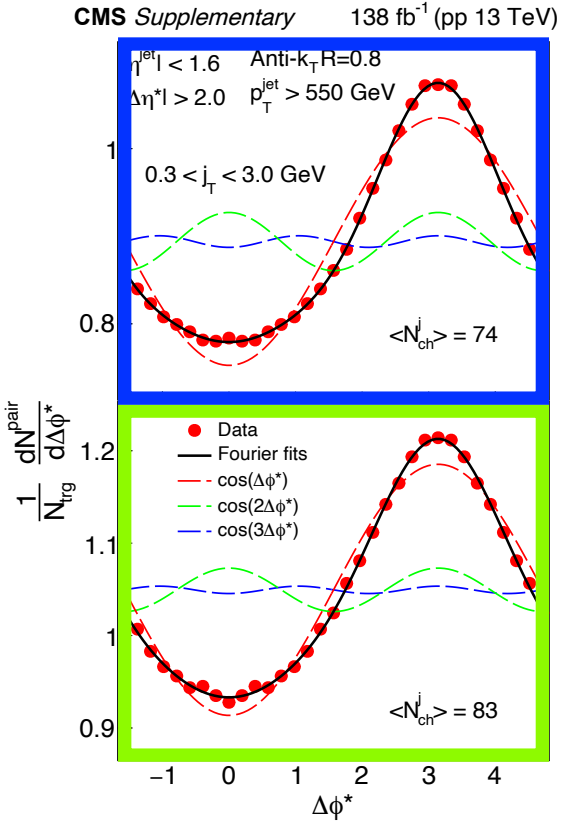

CMS Preliminary
138 fb-1 (pp 13 TeV)
0.3 < jT < 3.0 GeV
Anti kT R=0.8
pjetT > 550 GeV
|ηjet| < 1.6
DATA
PYTHIA8 CP5
SHERPA
vj2{2, |Δη*|>2}
Nj ch

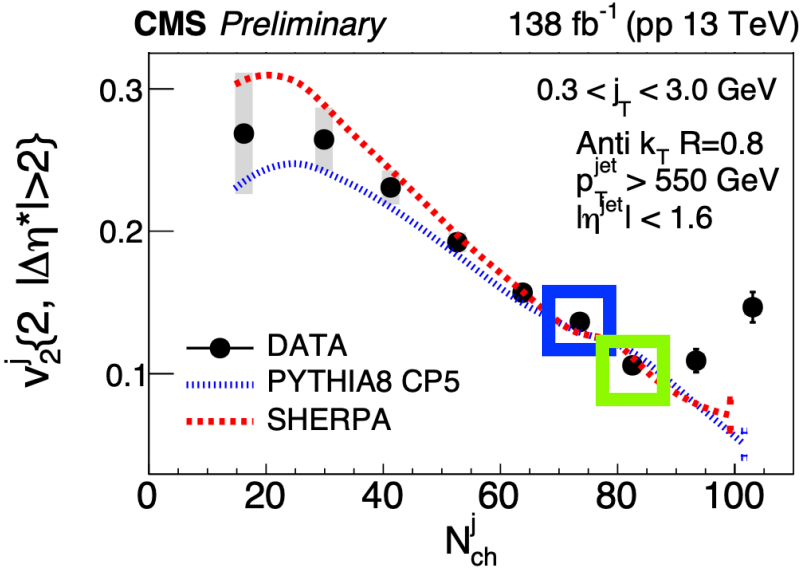
All Fits:


CMS Supplementary
138 fb-1 (pp 13 TeV)
Anti-kT R=0.8
|Δη*| > 2
pTjet > 550 GeV
|ηjet| < 1.6
0.3 < jT < 3.0 GeV
<Nchj> = 53
<Nchj> = 64
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
1/Ntrg dNpair/dΔφ*
Δφ*

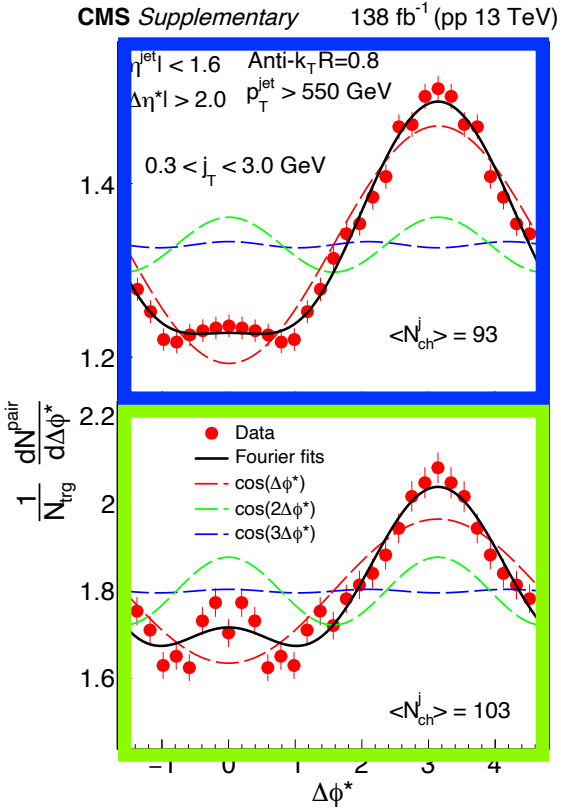

CMS Preliminary
138 fb-1 (pp 13 TeV)
0.3 < jT < 3.0 GeV
Anti kT R=0.8
pTjet > 550 GeV
|ηjet| < 1.6
DATA
PYTHIA8 CP5
SHERPA
vj2{2, |Δη*|>2}
Nchj

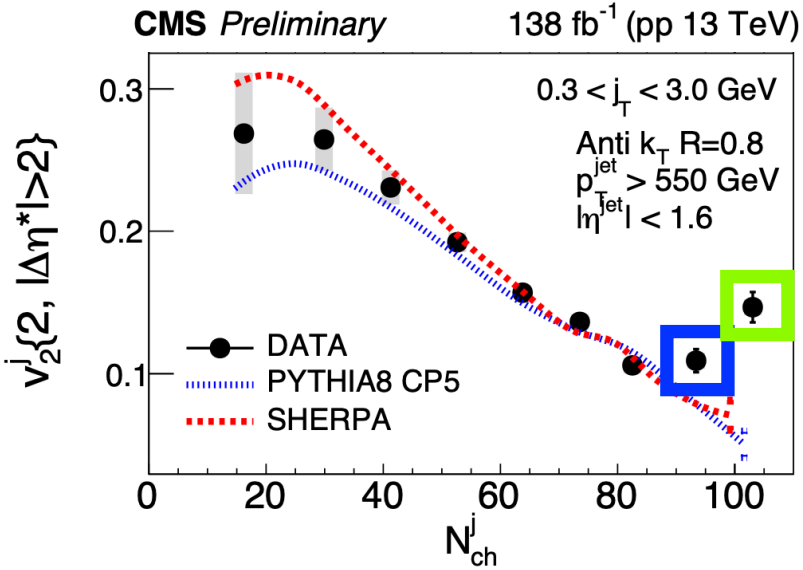
All Fits:


CMS Supplementary
138 fb-1 (pp 13 TeV)
|η^jet| < 1.6
Anti-kT R=0.8
|Δη*| > 2.0
p_T^jet > 550 GeV
0.3 < j_T < 3.0 GeV
<N_ch^j> = 74
<N_ch^j> = 83
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
1/N_trg dN^pair/dΔφ*
Δφ*


CMS Preliminary
138 fb-1 (pp 13 TeV)
0.3 < j_T < 3.0 GeV
Anti k_T R=0.8
p_T^jet > 550 GeV
|η^jet| < 1.6
DATA
PYTHIA8 CP5
SHERPA
v_2^j{2, |Δη*|>2}
N_ch^j

All Fits:


CMS Supplementary
138 fb-1 (pp 13 TeV)
|η^jet| < 1.6
Anti-k_T R=0.8
|Δη*| > 2.0
p_T^jet > 550 GeV
0.3 < j_T < 3.0 GeV
<N_ch^j> = 93
<N_ch^j> = 103
Data
Fourier fits
cos(Δφ*)
cos(2Δφ*)
cos(3Δφ*)
1/N_trg dN^pair/dΔφ*
Δφ*


CMS Preliminary
138 fb-1 (pp 13 TeV)
0.3 < j_T < 3.0 GeV
Anti k_T R=0.8
p_T^jet > 550 GeV
|η^jet| < 1.6
DATA
PYTHIA8 CP5
SHERPA
v_2^j{2, |Δη*|>2}
N_ch^j

PileUp

From HLT_AK8PFJet500 events:

PUPPI algorithm
simplified

- PUPPI mitigates PU by applying weights to tracks
- w = 1 from primary Vtx
- w = 0 from PU Vtx
- Caveats for 2 closest Vtx and unassociated hard tracks

CP5, CP2, and Ropewalk

PYTHIA8 parameter	CP2
PDF Set	NNPDF3.1 LO
$\alpha_S(m_Z)$	0.130
SpaceShower:rapidityOrder	off
MultipartonInteractions:EcmRef [GeV]	7000
$\alpha_S^{\mathrm{ISR}}(m_Z)$ value/order	0.130/LO
$\alpha_S^{\mathrm{FSR}}(m_Z)$ value/order	0.130/LO
$\alpha_S^{\mathrm{MPI}}(m_Z)$ value/order	0.130/LO
$\alpha_S^{\mathrm{ME}}(m_Z)$ value/order	0.130/LO
MultipartonInteractions:pT0Ref [GeV]	2.3
MultipartonInteractions:ecmPow	0.14
MultipartonInteractions:coreRadius	0.38
MultipartonInteractions:coreFraction	0.33
ColorReconnection:range	2.32

PYTHIA8 parameter	CP5
PDF Set	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118
SpaceShower:rapidityOrder	on
MultipartonInteractions:EcmRef [GeV]	7000
$\alpha_S^{\mathrm{ISR}}(m_Z)$ value/order	0.118/NLO
$\alpha_S^{\mathrm{FSR}}(m_Z)$ value/order	0.118/NLO
$\alpha_S^{\mathrm{MPI}}(m_Z)$ value/order	0.118/NLO
$\alpha_S^{\mathrm{ME}}(m_Z)$ value/order	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	1.41
MultipartonInteractions:ecmPow	0.03
MultipartonInteractions:coreRadius	0.76
MultipartonInteractions:coreFraction	0.63
ColorReconnection:range	5.18