Underlying event and correlation results from CMS

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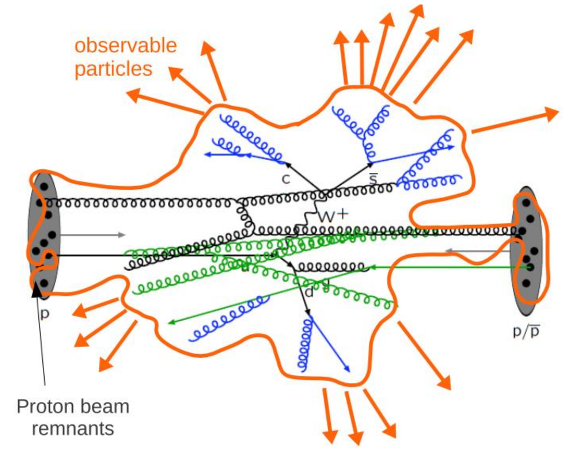
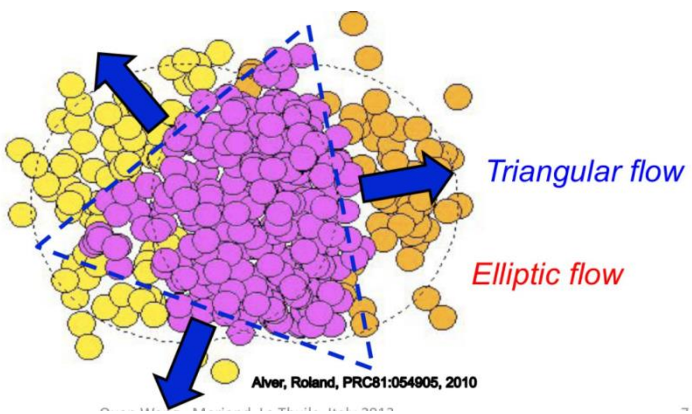
Outline

1. Underlying event
   i. Data/MC samples
   ii. Underlying event Results
2. 2-particle correlations
   i. 2-particle correlation results in pp collisions



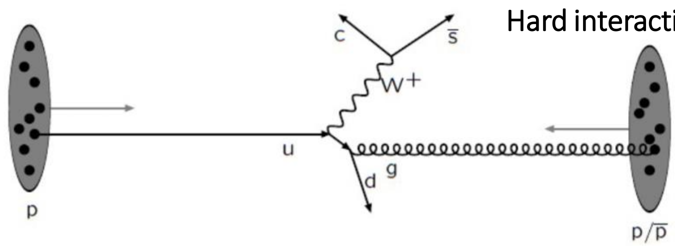


Underlying Event

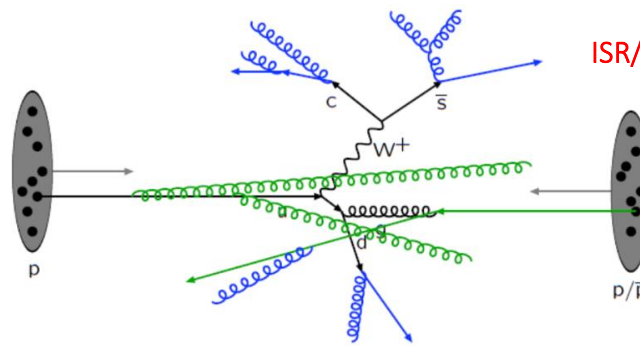
The underlying event:

- Additional activity on top of the hard scattering component of the collision

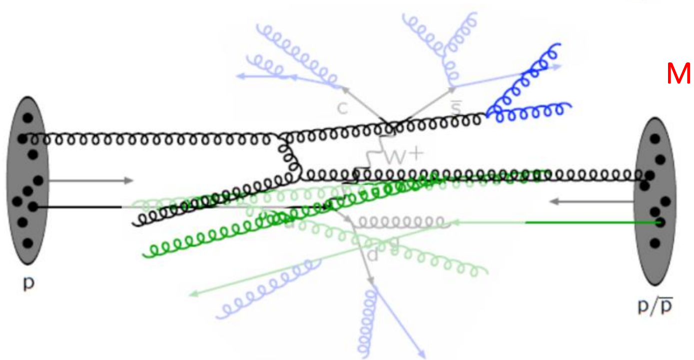
Hard interaction



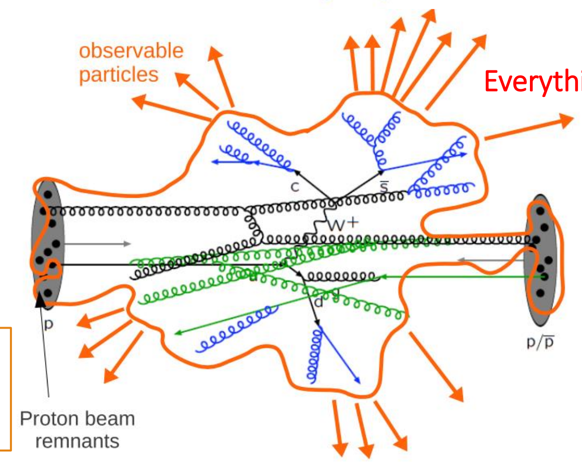
ISR/FSR



MPI



Everything + hadronisation

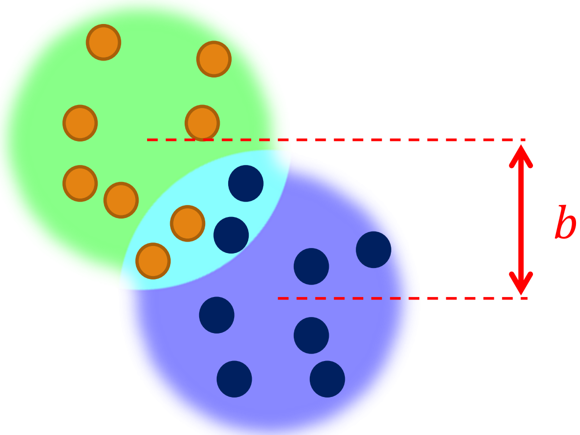


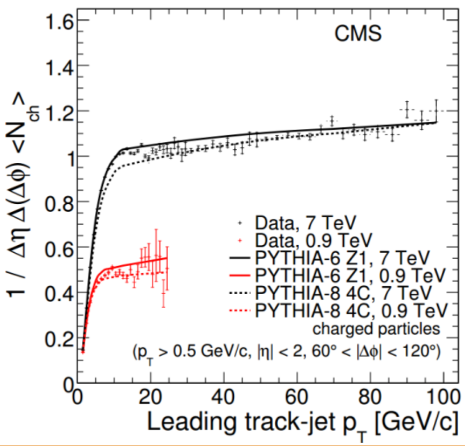
MPI, ISR/FSR, hadronisation, colour reconnections, beam remnants, soft rescattering of beam remnants etc…

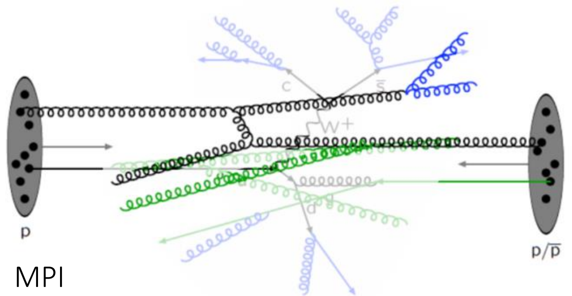
Underlying Event

Multi-parton Interactions (MPI):

- Not just a pair of partons interacting
- $N(b) \sim Poisson(b)$
  - Number of MPI assumed to be Poissonian, with an impact parameter dependence
- Smaller impact parameter $\Rightarrow$ higher probability of MPI + bias towards harder interactions and thus jets, and vice versa
  - Jets serve as good probes of MPI and thus UE
- In collisions with the smallest impact parameters, the number of MPIs saturate







doi:10.1140/epjc/s10052-010-1453-9
doi:10.1007/JHEP09(2011)109

Underlying Event

Towards region: $|\Delta\phi| < 60°$

Away region: $|\Delta\phi| > 120°$

Transverse region: $60° < |\Delta\phi| < 120°$

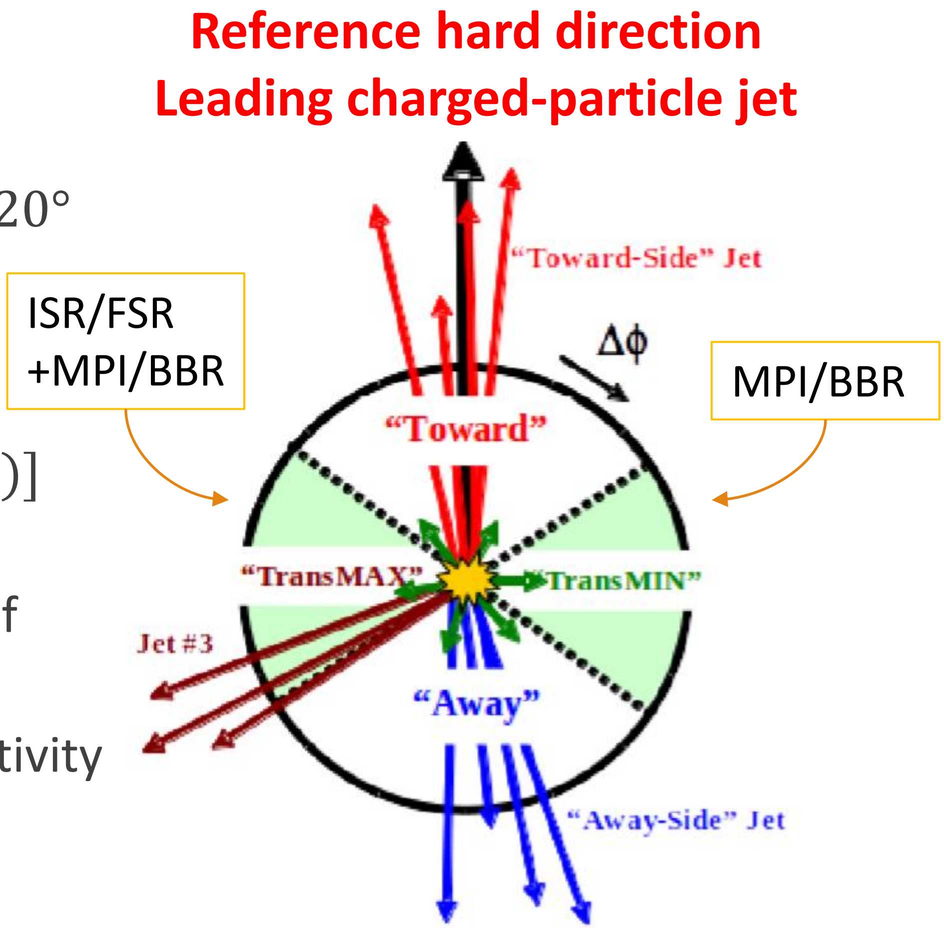
UE observable:

$\langle N_{ch} \rangle / [\Delta\eta\Delta(\Delta\phi)]$, $\langle \Sigma p_T \rangle / [\Delta\eta\Delta(\Delta\phi)]$

TransMAX(TransMIN): activity in maximum(minimum) activity side of transverse region

TransDIF: (*TransMAX-TransMIN)* activity

- Sensitive to ISR/FSR



Data samples

Measured at 0.9, 7 TeV, and recently at 2.76 TeV:

- doi:10.1007/JHEP09(2015)137
- http://arxiv.org/abs/1507.07229

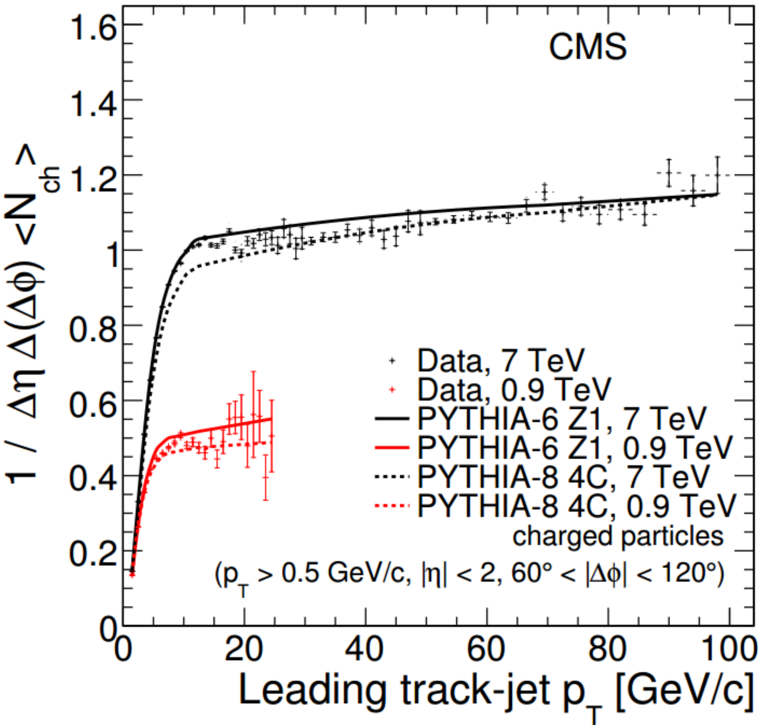
Data samples @ 2.76 TeV:

- Dedicated run of a few days in March 2011 (0.3 nb^{-1})
- Low pile-up run especially suited for studying UE

3 different triggered samples

- Minimum bias
- Jet20 (1 jet with $p_T > 20$ GeV)
- Jet40 (1 jet with $p_T > 40$ GeV)

Transverse density



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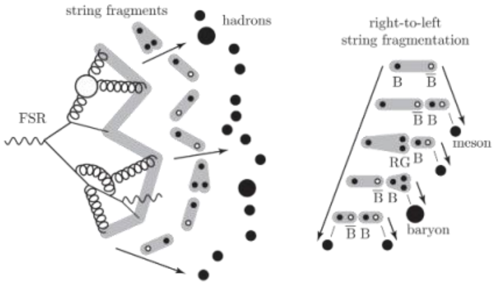
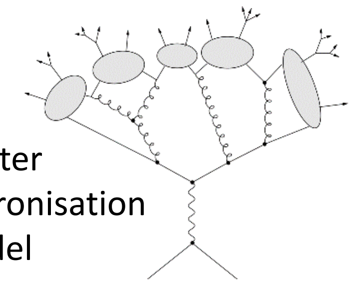
Monte Carlo samples

Monte Carlo samples:
- Validation and correction:
  - PYTHIA 6 Z2
- Model dependent systematic:
  - PYTHIA 8 4C
- comparison with data:
  - **PYTHIA 6 (version 6.426):** Z2*, CUETP6S1
  - **PYTHIA 8 (version 8.175):** 4C, CUETP8S1, Monash, CUETP8M1
  - **HERWIG++ (version 2.7.0):** UE-EE-5C

String hadronisation model

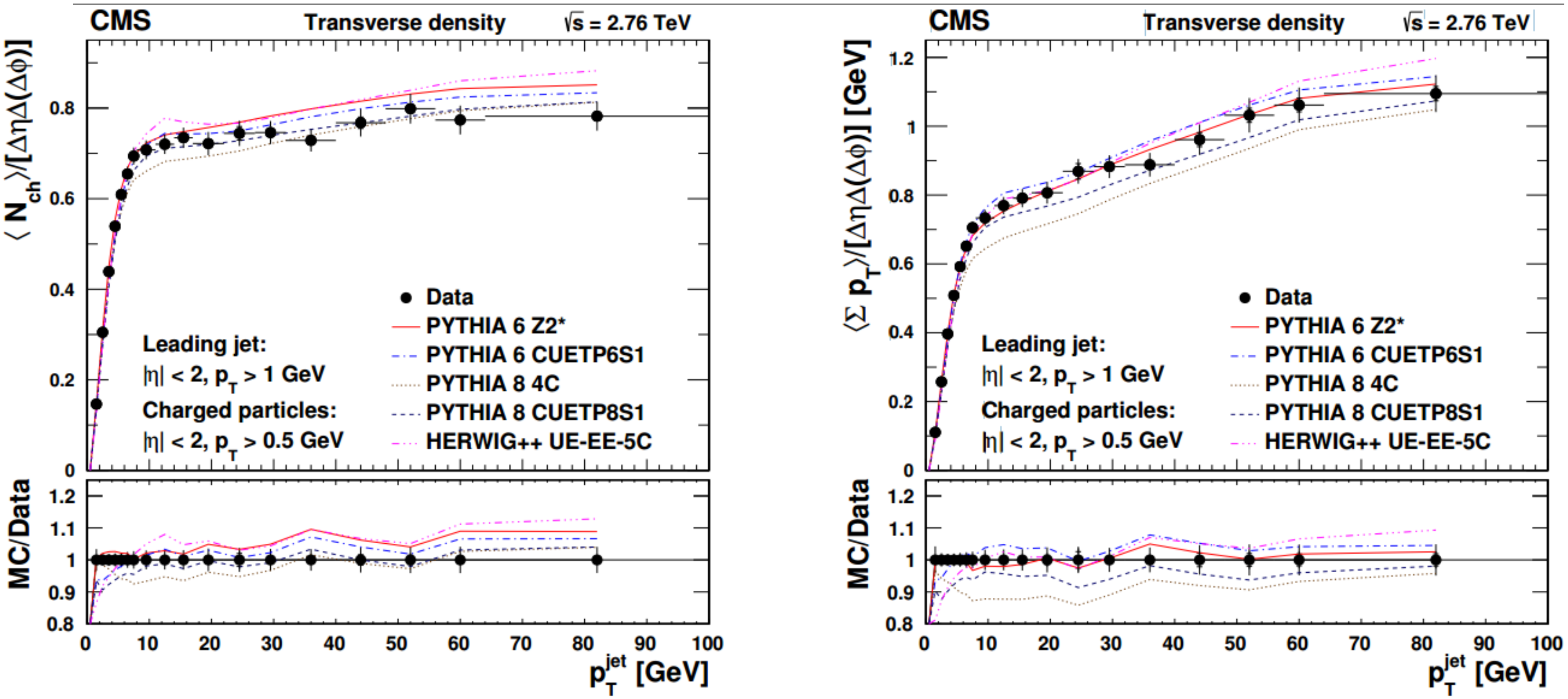


Cluster hadronisation model



PYTHIA/HERWIG differences (same parton density function, CTEQ6L1):
- Details of interleaving between ISR/FSR/MPI
- p_T-ordered/angular-ordered evolution
- Lund string/cluster hadronisation
- Tunable parameters in all MC are optimised with different datasets

Transverse densities



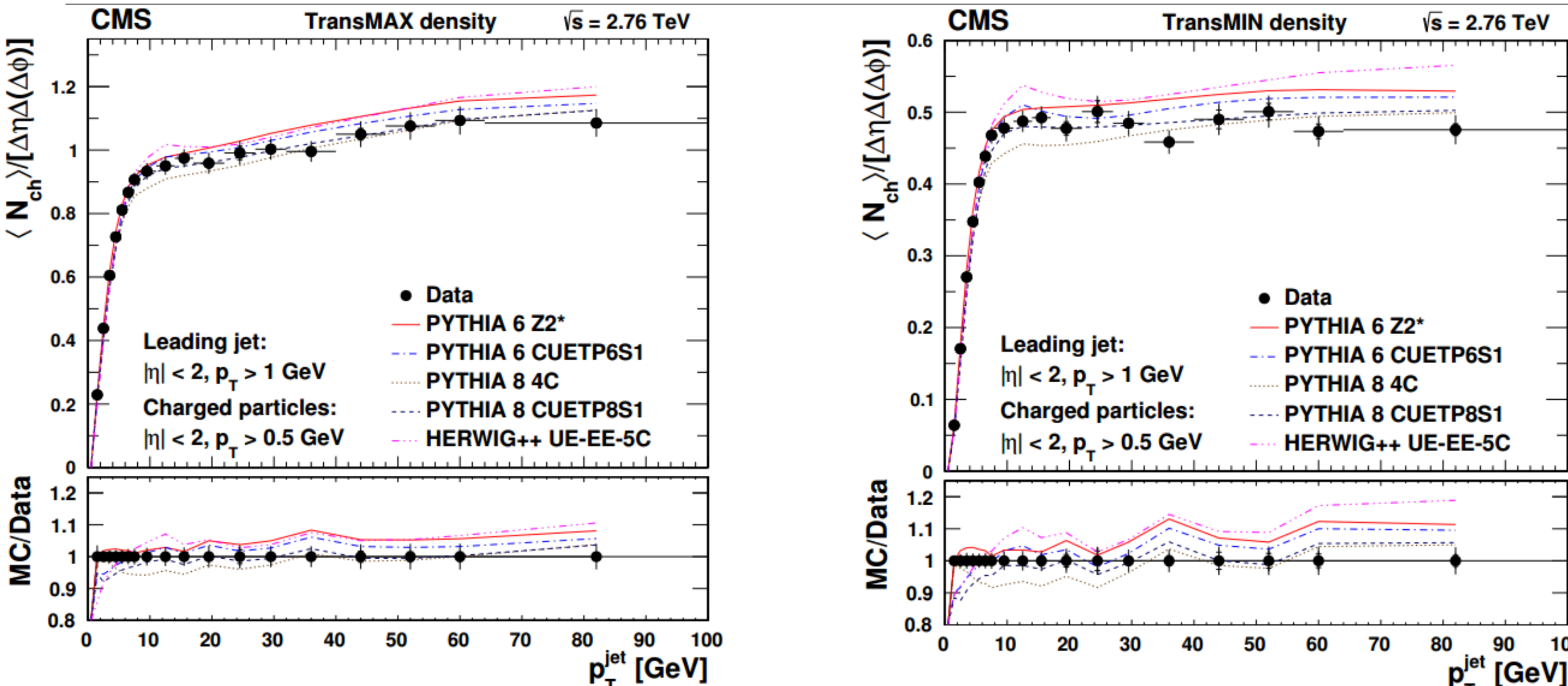
Clear transition between a rising and a plateau region.

Comparison with PYTHIA6 (Z2*, CUETP6S1), PYTHIA8 (4C, CUETP8S1), HERWIG++ (UE-EE-5C).

Best performing: Z2*, CUETP6S1, CUETP8S1, (UE-EE-5C performing pretty well, but slightly overestimating the transverse densities).

doi:10.1007/JHEP09(2015)137

TransMAX/MIN particle densities

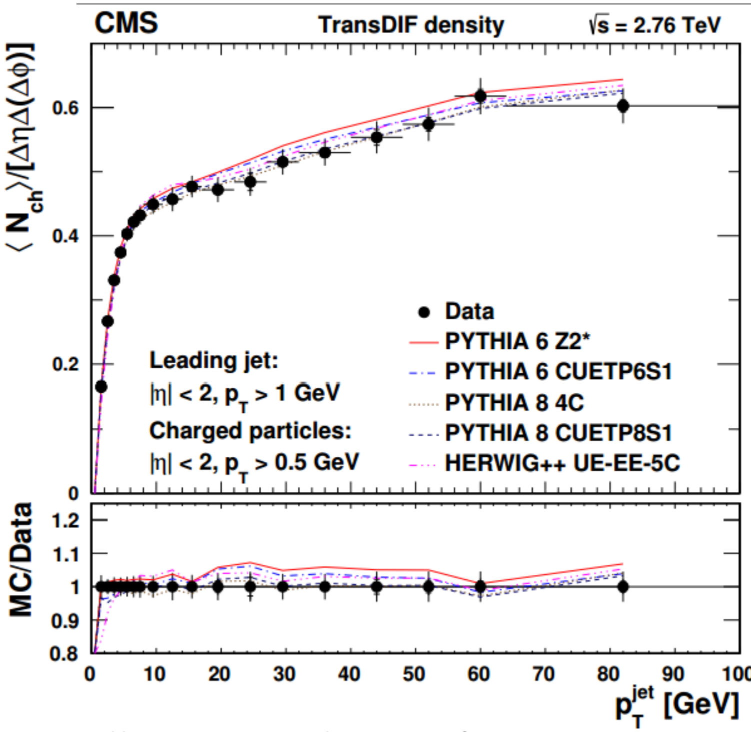


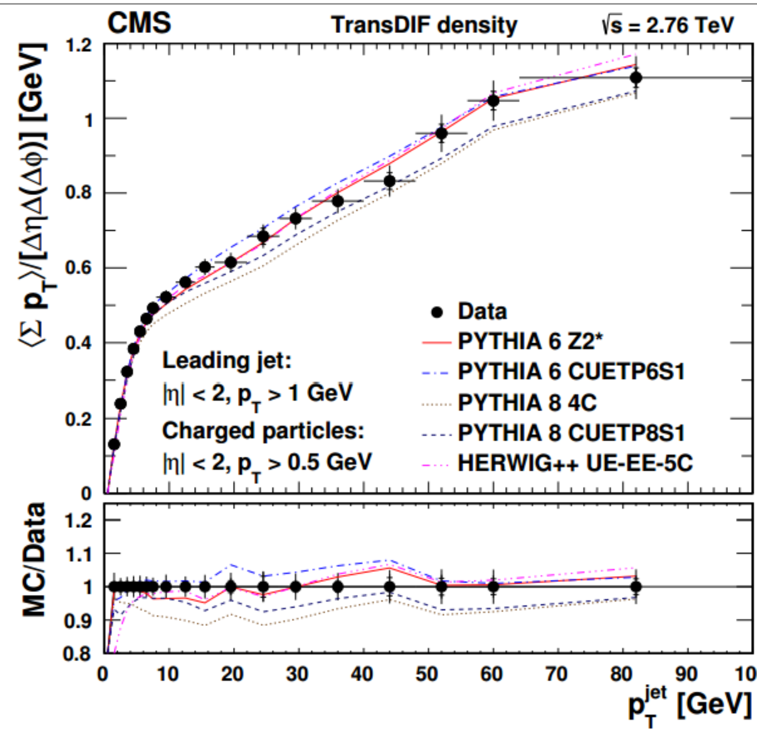
More distinct transition from rising to plateau region in transMIN particle density supporting hypothesis that the activity is dominated by MPI/BBR. TransMAX shows a slow rise.
All tunes perform reasonably well for transMAX particle density. CUET tunes perform the best in both transMAX and transMIN densities.

Energy densities in appendix

doi:10.1007/JHEP09(2015)137

TransDIF densities





All tunes do better for *transDIF* densities.
CUET tunes are performing best overall, Z2* describes Σp_T density well.
Herwig++ describing the densities well, especially Σp_T density.
TransDIF activity rising faster in “plateau” region due to sensitivity to ISR/FSR.

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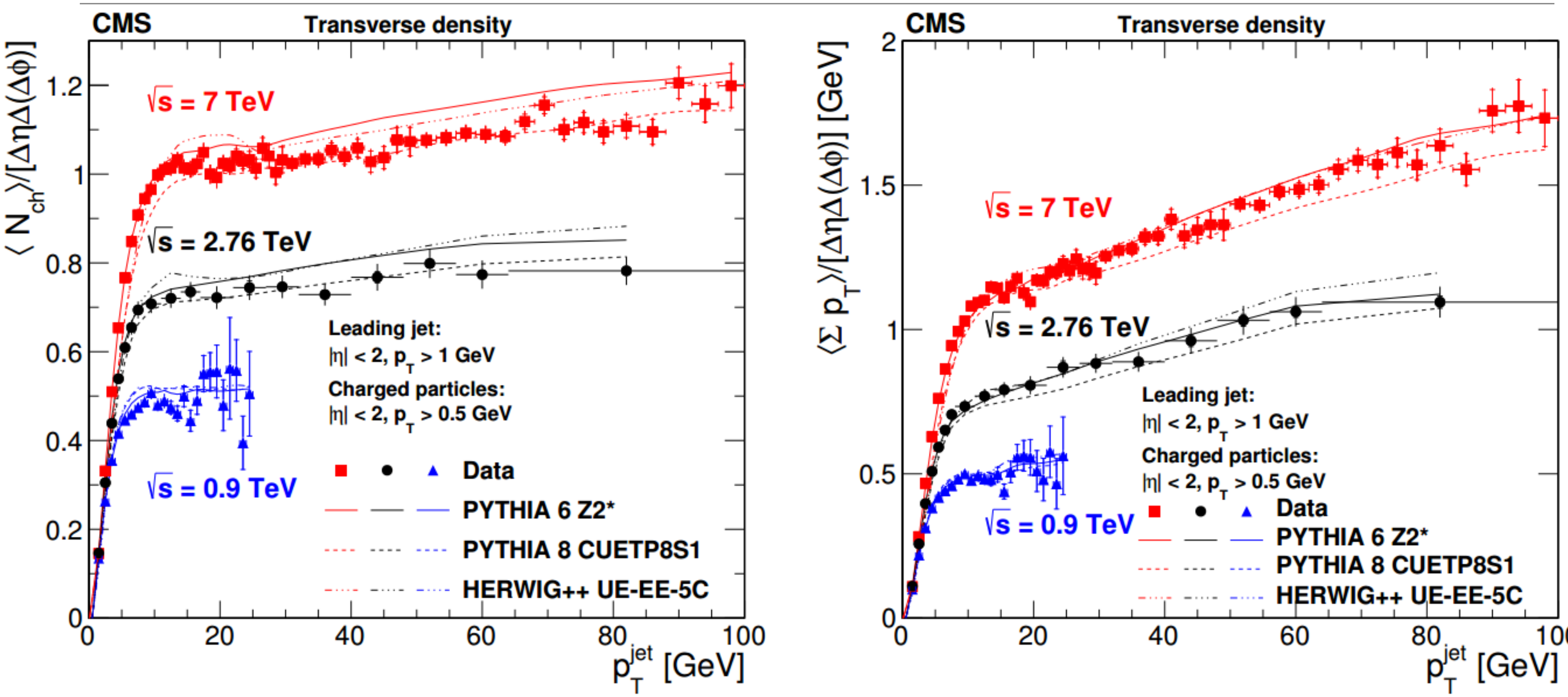
Energy dependence



Center-of-mass energy dependence compared with Z2*, CUETP8S1 and UE-EE-5C.

Strong growth of UE activity at similar values of leading jet p_T.

All tunes predict the center-of-mass energy dependence well.

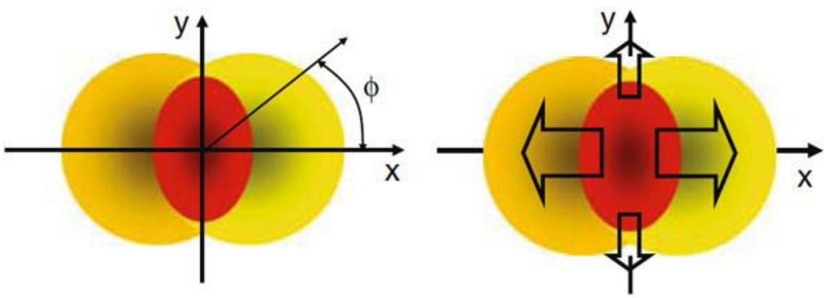
doi:10.1007/JHEP09(2015)137

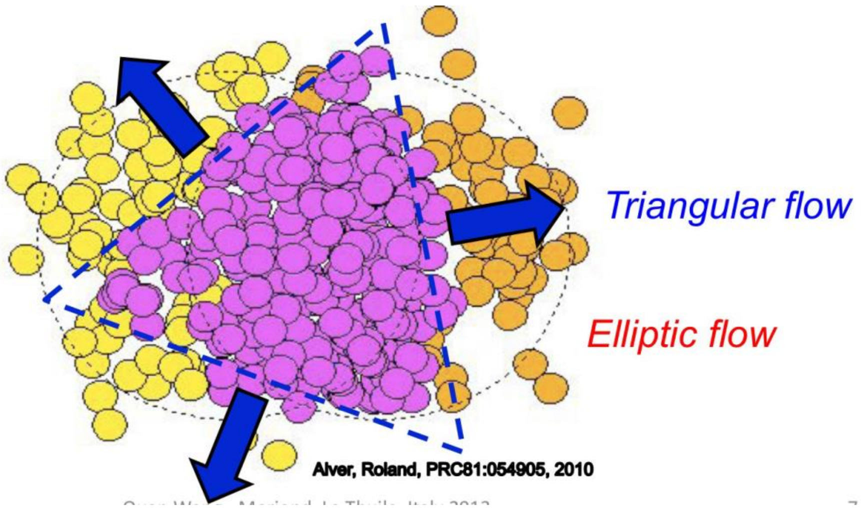
2-particle correlations

Originally used to probe for hydrodynamics in heavy ion collisions

Non-uniform emisison of particles

- Different initial collision geometry give rise to different flow effects





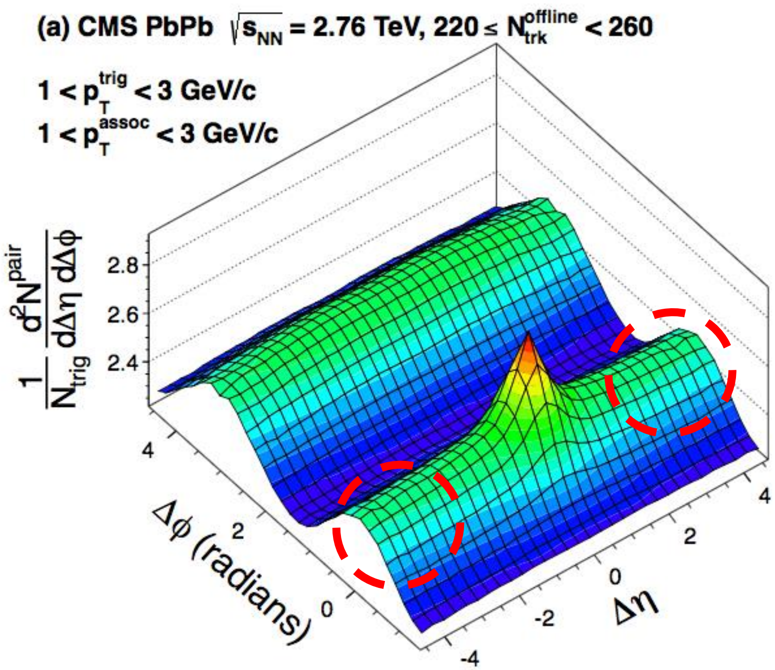
2-particle correlations

Interested in ridge structure in $(\Delta\eta, \Delta\phi)$

- Mostly in the long range $(|\Delta\eta| > 2)$, near side $(\Delta\phi \approx 0)$ region

2D correlation functions reveal information on the origins of the correlation:

- **Jets**:
  - peak around $(0, 0)$
- **Back-to-back jet + hydrodynamic flow**:
  - Ridge structures around $\Delta\phi = 0$ and $\Delta\phi = \pi$



doi:10.1016/j.physletb.2013.06.028

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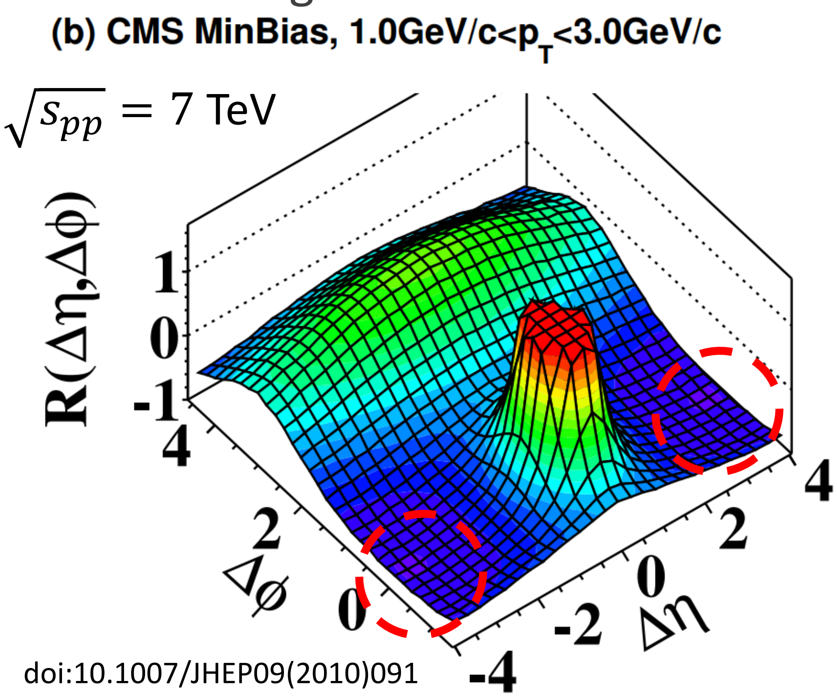
- Long range near side structures not seen in low multiplicity pp collisions



doi:10.1007/JHEP09(2010)091

2-particle correlations

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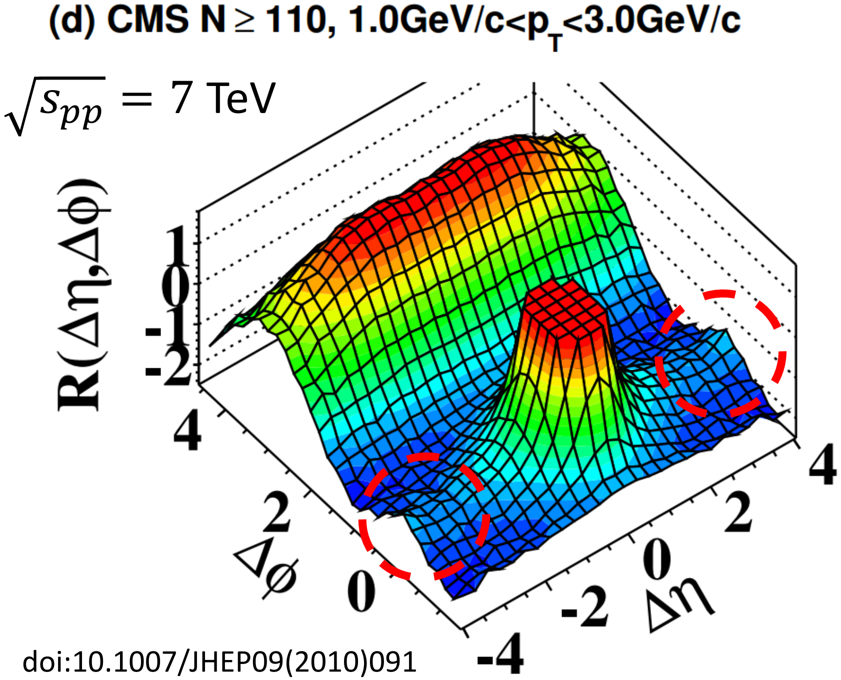
- Mostly in the long range $(\Delta\eta > 2)$, near side $(\Delta\phi \approx 0)$ region

Structure of 2D correlation function reflect information on the origins of the correlation:

- **Jets**:
  - peak around $(0, 0)$
- **Back-to-back jet + hydrodynamic flow**:
  - Ridge structures around $\Delta\phi = 0$ and $\Delta\phi = \pi$
- Long range near side structures not seen in low multiplicity pp collisions
- Origins of the ridge in high multiplicity pp collisions remains unknown



doi:10.1007/JHEP09(2010)091

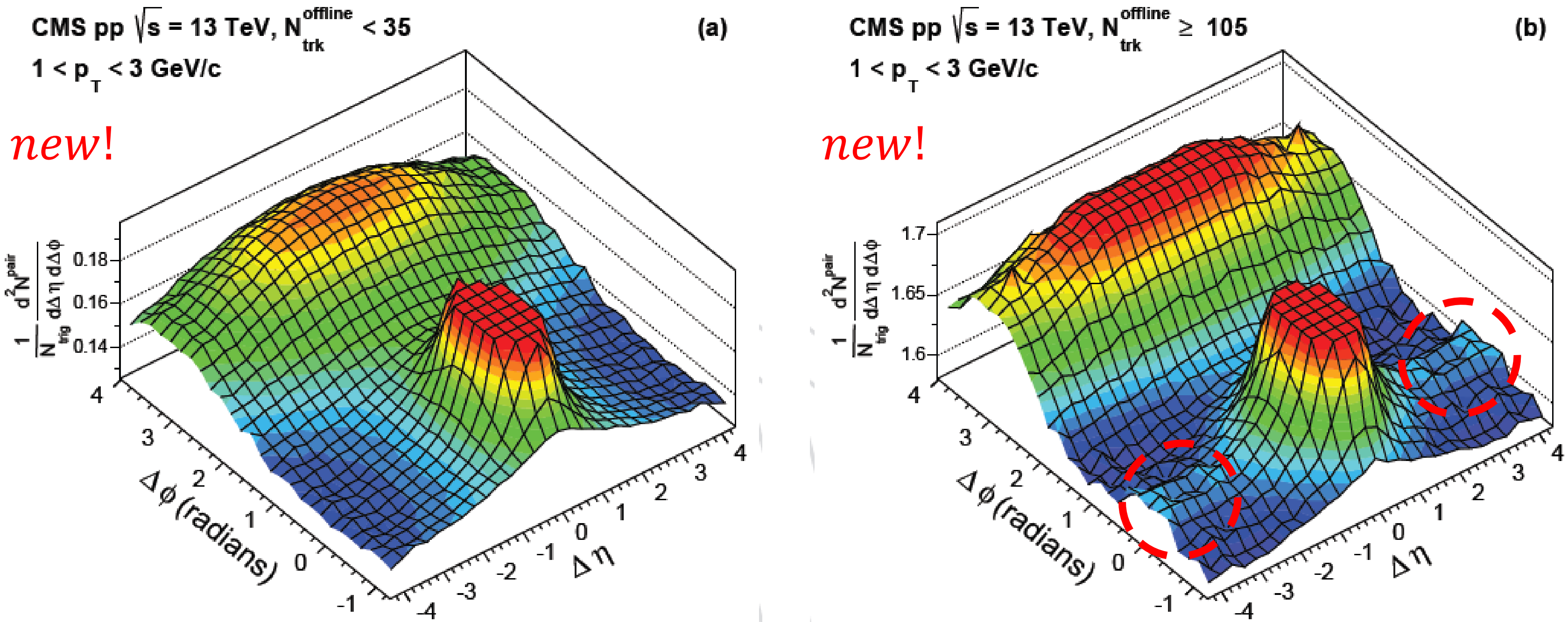
Hydrodynamic flow? Colour glass condensate glasma?

Results

Long range near side ridge in high multiplicity ($N_{trk}^{offline} \geq 105$) events

Early run 2 data: $\sqrt{s_{pp}} = 13$ TeV, $L \sim 270$ nb^{-1}

CMS-FSQ-15-002

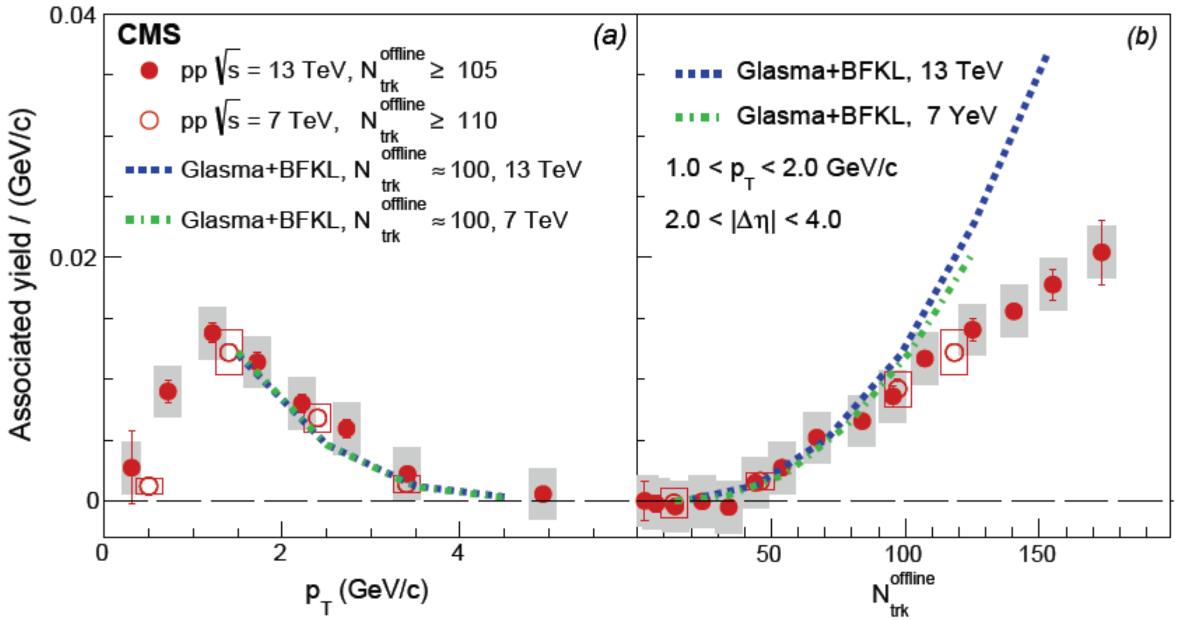


Results

Long range near side correlation yields become significant at a multiplicity ~ 40

Nearly linear increase above 40

No centre-of-mass energy dependence



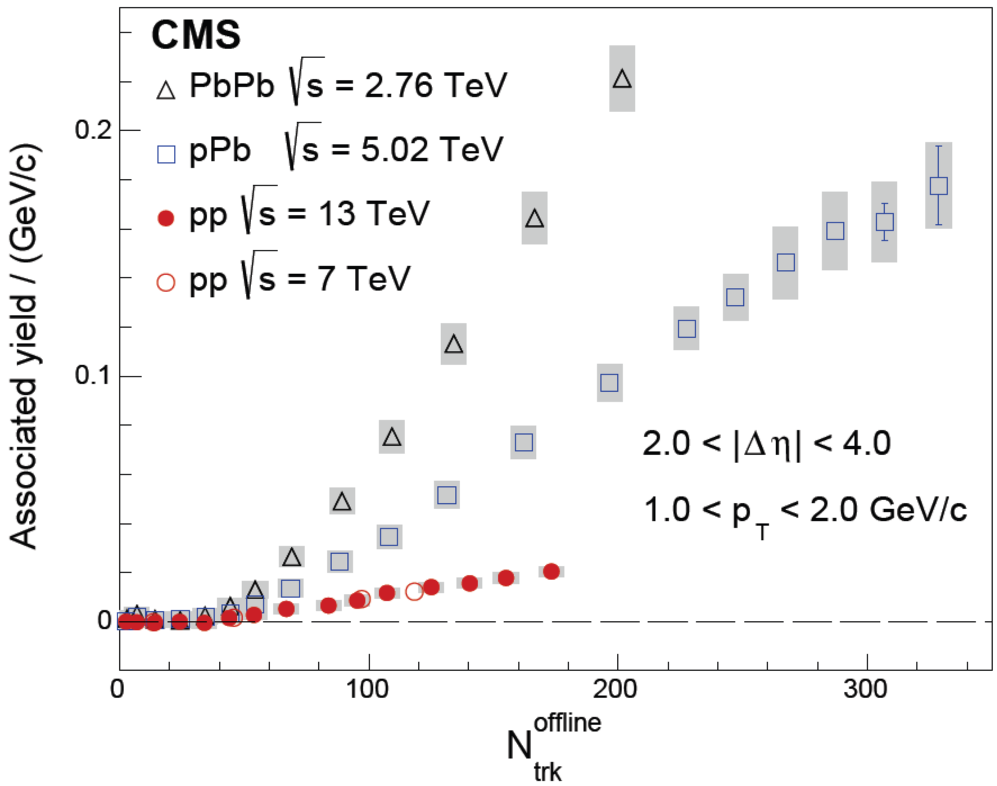
Results consistent with glasma+BFKL predictions but diverges for $N_{trk}^{offline} > 90$

Results

CMS-FSQ-15-002

Correlation yields become significant at a multiplicity ~ 40 and nearly linear increase above 40 for **all collision systems**

Strong system size dependence



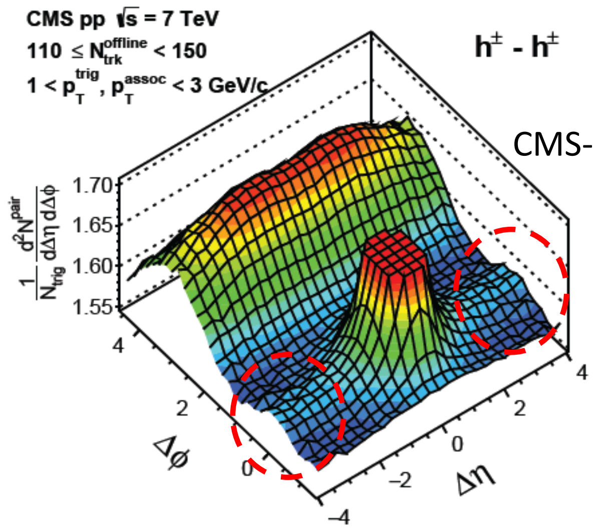
Results

$\sqrt{s_{pp}} = 7$ TeV

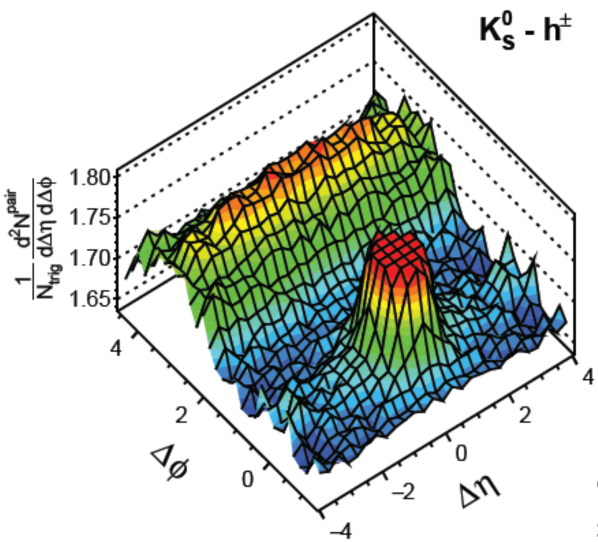
$(110 \leq N_{trk}^{offline} < 150)$

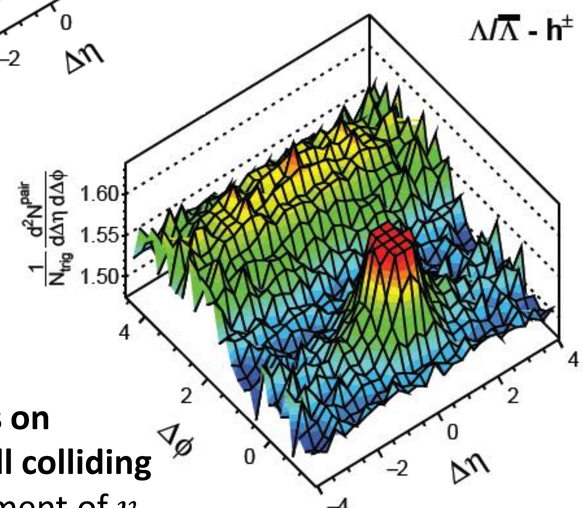
With identified particles:

- $(K_s^0 - h^{\pm}), (\Lambda/\bar{\Lambda} - h^{\pm}), (h^{\pm} - h^{\pm})$



CMS-HIN-15-009





Refer to Z. Chen, “**New results on collective phenomena in small colliding systems at CMS”** on measurement of v_n

Summary

The CMS collaboration has measured a range of phenomena relating to multi-particle dynamics and collective phenomena

Recent results from the underlying event at 2.76 TeV has been measured and fully corrected for detector effects and selection efficiencies for the *transverse*, *transMIN*, *transMAX* and *transDIF* densities

- Separation into various *transverse* activities allows for better sensitivities to ISR/FSR and MPI/BBR
- Measurement at 13 TeV ongoing

Results are compared to various PYTHIA6, PYTHIA8 and HERWIG++ Monte Carlo tunes

Comparison is made with the underlying event at 0.9 and 7 TeV for *transverse* densities

- Allows for better tuning of energy dependence of the MC

Summary

2-particle correlations in pp collisions have been measured at 13 TeV, echoing previous results at 7 TeV.

Correlation yields consistent with 0 for $N_{trk}^{offline} < 40$ and increases roughly linearly beyond that

Yields show no centre-of-mass dependence but a strong collision system size dependence

Further analysis on 2-particle correlations between identified particles from pp collisions at 7 TeV reveal similar long range near side ridge structures.

END

Thank you for your attention!

UE Appendix: pQCD regularisation in MC

Leading order pQCD $2 \rightarrow 2$ cross section divergence term:

- $\frac{1}{p_T^4} \rightarrow \frac{1}{(p_T^2 + p_{T0}^2)^2}$
- $p_{T0}(\sqrt{s}) = p_{T0}^{REF} \times \left(\frac{\sqrt{s}}{E_0}\right)^{\epsilon}$
- Tunable MC parameters: p_{T0}^{REF}, E_0, ϵ

UE Appendix: Event and track/jet selections

Event selection:

- 1 vertex (within 10 cm of beamspot)

Track selection (remove mis-reconstructed tracks):

- *Highpurity* tracks
- $p_T > 0.5$ GeV, $|\eta| < 2.0$

Impact parameter cut (remove secondary decays):

- $\frac{dz}{\sqrt{\sigma(dz)^2 + \sigma(vtx.z)^2}} \leq 3$
- $\frac{d(xy)}{\sqrt{\sigma d(xy)^2 + \sigma(vtx.x)^2 + \sigma(vtx.y)^2}} \leq 3$
- $\frac{\sigma(p_T)}{p_T} \leq 0.05$

Same tracks used for jet seeding only with $|\eta| < 2.5$:

- Leading track-jet (SisCone: $R = 0.5$; using tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$)
- $p_T > 1$ GeV, $|\eta| < 2.0$

UE Appendix: Data Correction and systematics

Data corrected with unfolding

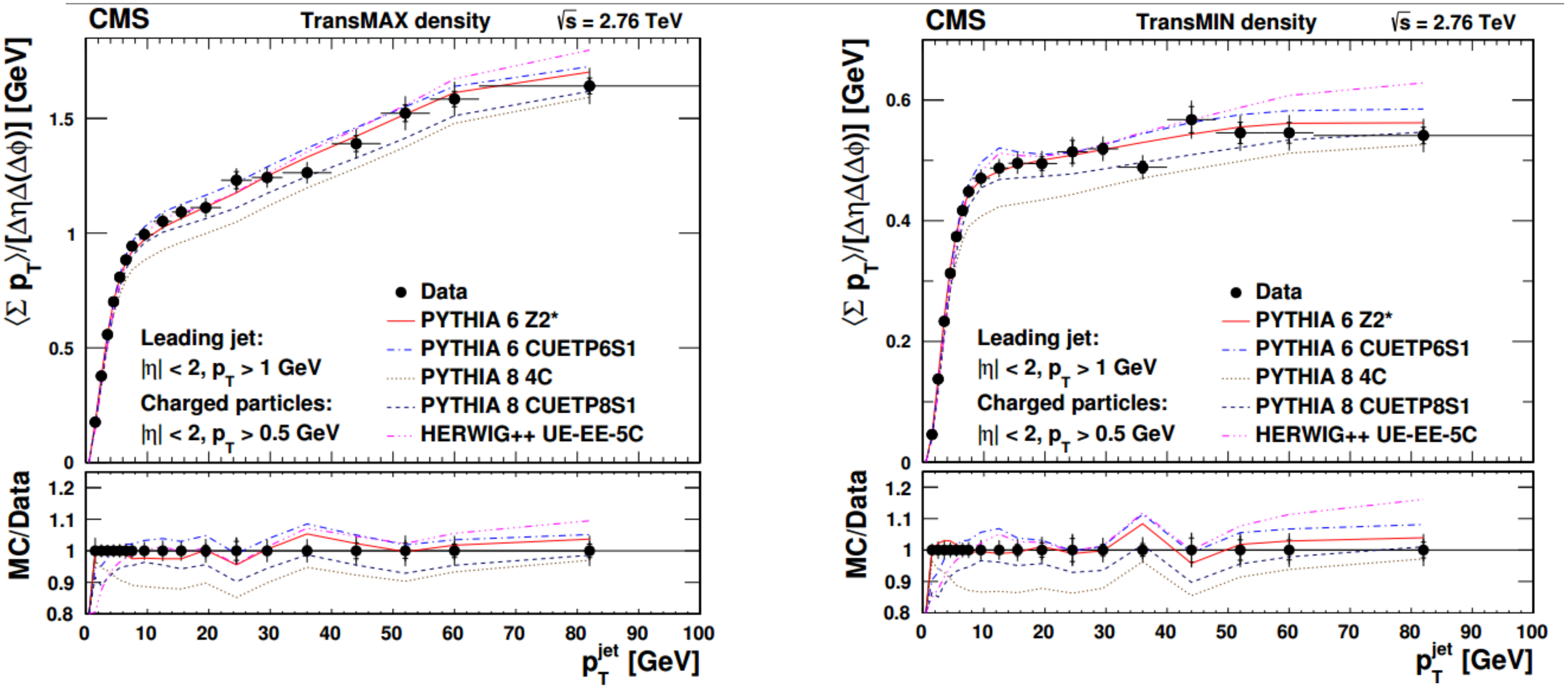
- Iterative "Bayesian" method

$$\left(X_{Tracks}, p_{T_{Leading\ TrackJet}}\right)_{2D} \xrightarrow{unfold} \left(X_{Particles}, p_{T_{Leading\ GenJet}}\right)_{2D} \xrightarrow{profile} \left(\langle X_{Particles}\rangle, p_{T_{Leading\ GenJet}}\right)_{Profile}$$

Summary of systematic uncertainties:

Source	Systematic (%)	Source	Systematic (%)
Impact Parameter Sig.	0.6-4	Dead Channel	0.1
Track sel.	0.1-0.8	Beamspot	0.2
Fake Mis-modelling	0.4-0.6	Material Budget	1.0
Model dep.	0.2-4	Tracker Alignment	0.2-0.3

UE Appendix: TransMAX/MIN energy densities



All tunes perform reasonably well. 4C has least agreement.

More distinct transition from rising to plateau region in transMIN particle density supporting hypothesis that the activity is dominated by MPI/BBR. TransMAX shows a slow rise.

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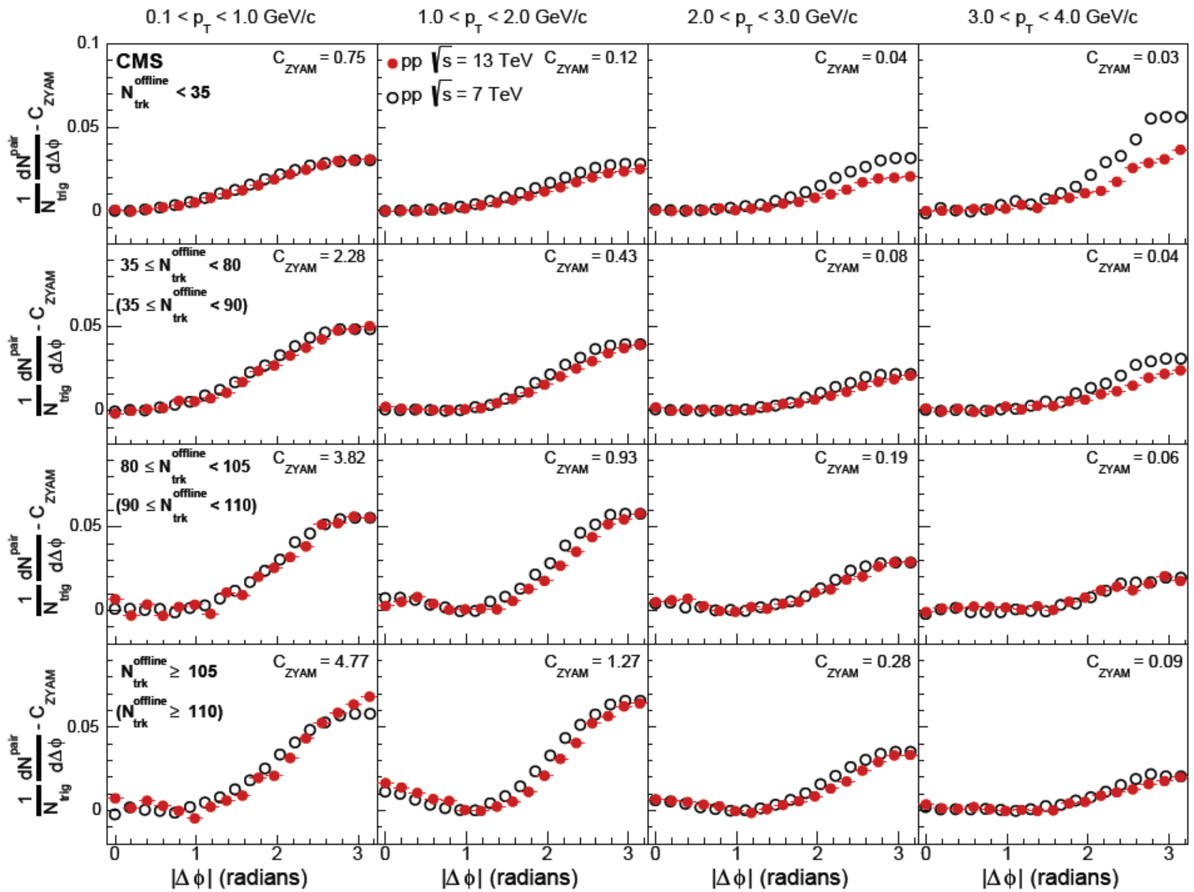
2PC Appendix: $\Delta\phi$ correlation

$\sqrt{s_{pp}} = 13$ TeV

Difference seen between 7 TeV and 13 TeV results at low multiplicity and high-p_T due to different definition of 2-particle correlation function



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2PC Appendix: systematic

$\sqrt{s_{pp}} = 13$ TeV

Uncertainty in the long range near side associated yields

Systematic uncertainty sources	Absolute uncertainty values ($\times 10^{-3}$)
Track quality requirements	0.6
Trigger efficiency	1.5
Correction for tracking efficiency	< 0.08
Effect of pile-up events	0.6
Vertex selection	1.0
ZYAM procedure	0.7
Total	2.1

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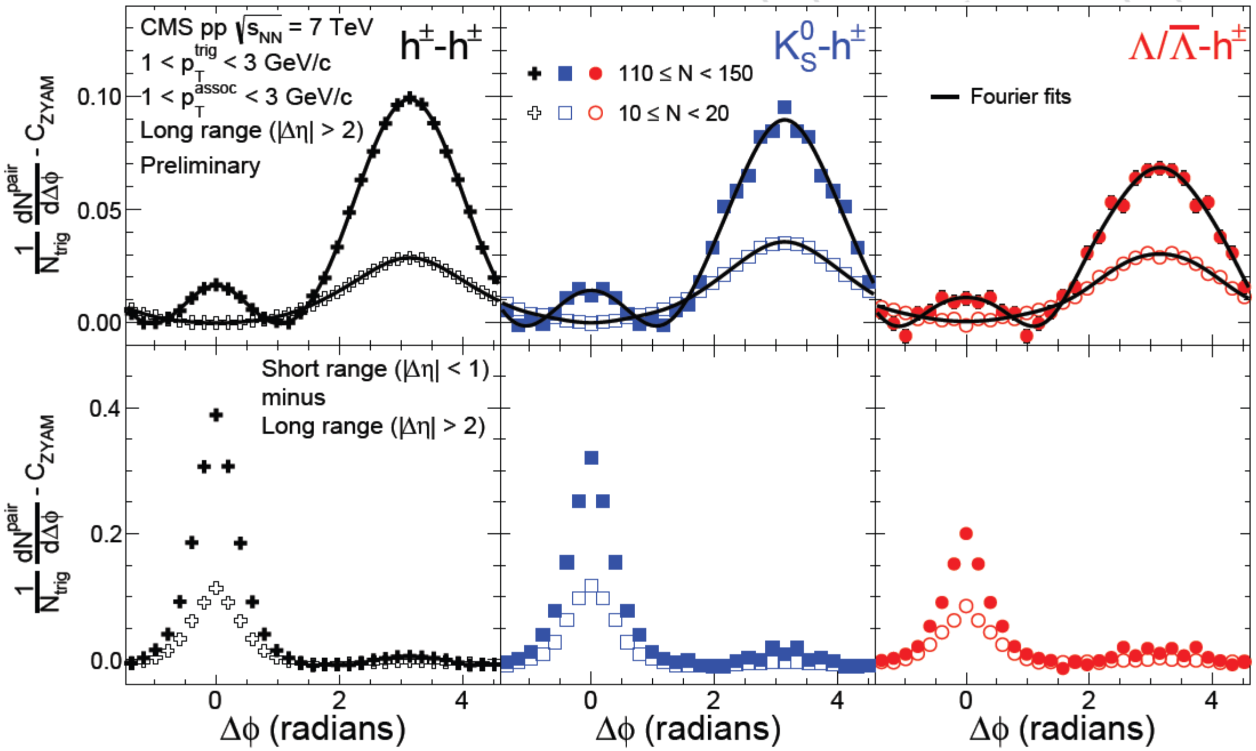
2PC Appendix: signal yield

$$\frac{dN}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{N} V_{n\Delta}\cos n\Delta\phi, \qquad v_n\left(p_T^{trig}\right) = \frac{V_{n\Delta}\left(p_T^{trig}, p_T^{ref}\right)}{\sqrt{V_{n\Delta}\left(p_T^{ref}, p_T^{ref}\right)}}$$



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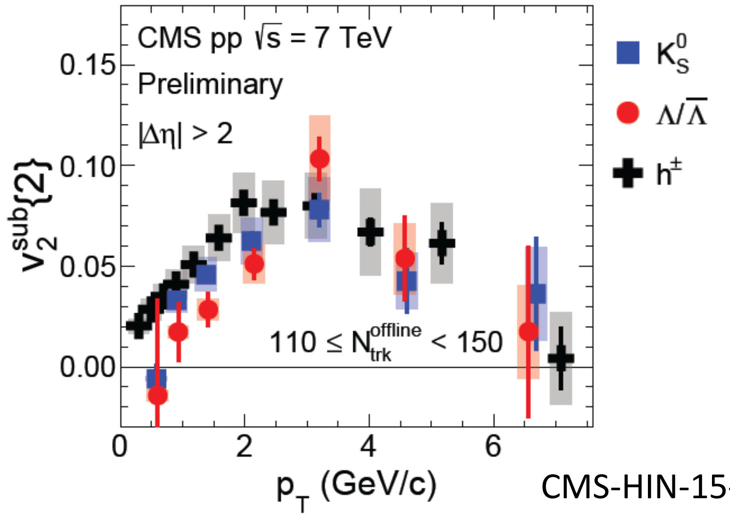
2PC Appendix: v_n

$$v_n\left(p_T^{trig}\right) = \frac{V_{n\Delta}\left(p_T^{trig}, p_T^{ref}\right)}{\sqrt{V_{n\Delta}\left(p_T^{ref}, p_T^{ref}\right)}}$$

- $v_2(\mathrm{pp}) < v_2(\mathrm{pPb}) < v_2(\mathrm{PbPb})$
- $v_3(\mathrm{pp}) \approx v_3(\mathrm{pPb}) \approx v_3(\mathrm{PbPb})$,
  - but $v_3(\mathrm{pp})$ deviates for $N_{trk}^{offline} \gtrsim 90$
- Mass ordering for $v_2^{sub}\{2\}$ at low p_T



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Flow parameter analysis