The 9th Asian Triangle Heavy-Ion Conference

Application of the Momentum Kick Model with multiplicity dependence to the pp collisions at $\sqrt{s} = 13$ TeV

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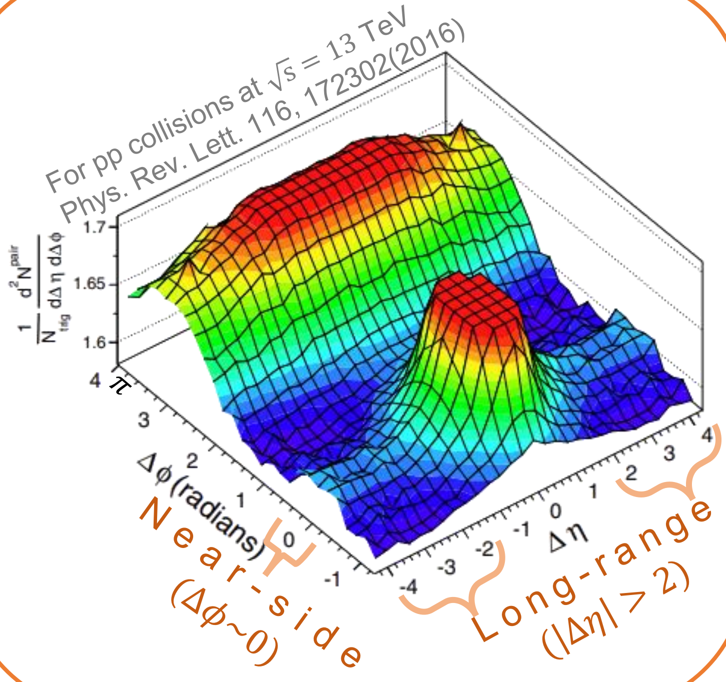
Apr 26. 2023

Motivation

Ridge structure

- Two-particle(trigger and associated particles) correlation phenomenon.
- Similar to “mountain ridge.”
- Provide insight into particle production.

Heavy-Ion collisions (such as PbPb and AuAu collisions) → Explained well by QGP (hydrodynamic models) → Small systems & High-multiplicity (such as pp and p-Pb collisions)



Limitation

Insufficient density and temperature in small systems.

Therefore, the hydrodynamic models are still **controversial**.

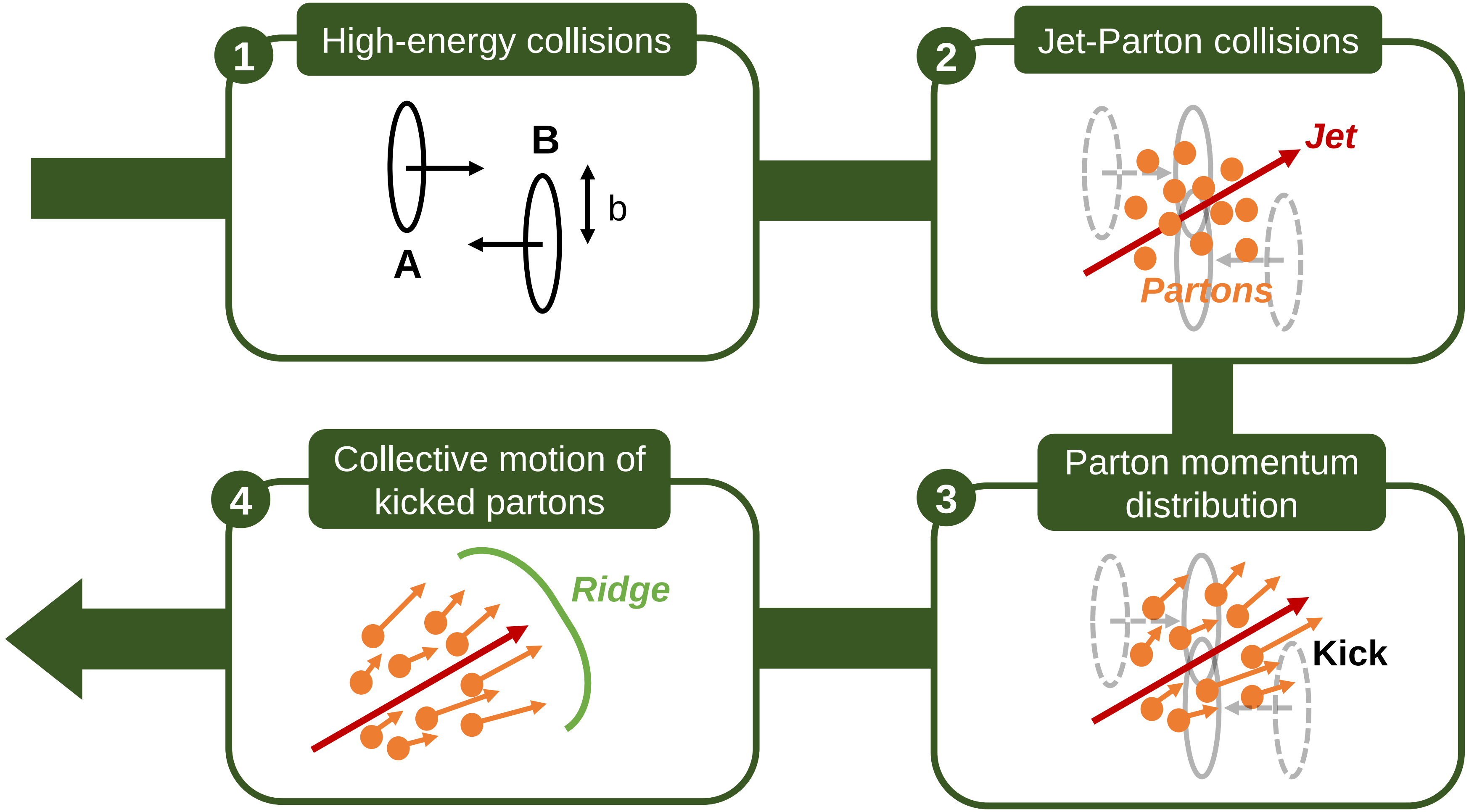
∴ Momentum Kick Model (MKM)

can explain the near-side long-range ridge structure in small systems.

Momentum Kick Model

How explain the ridge structure?

Kinematic process



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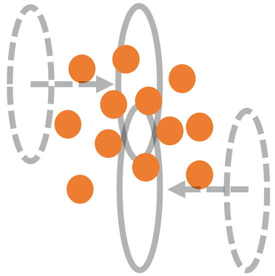
Formalism

for the **MKM**

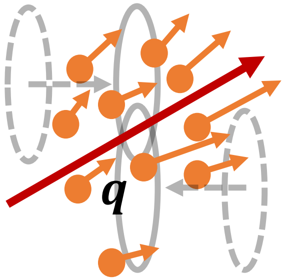
Initial parton momentum distribution



$\boldsymbol{P}_i(p_{T_i}, \Delta y_i, \Delta\phi_i)$

→ **parameterize**

Final parton momentum distribution



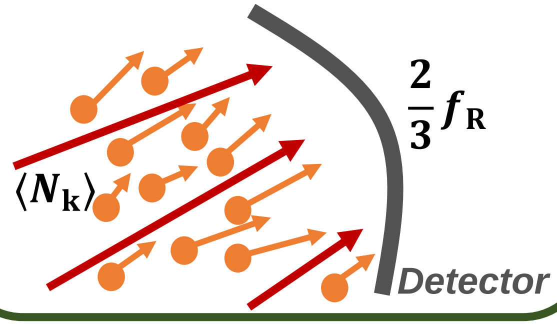
$$\boldsymbol{P}_f(p_{T_f}, \Delta\eta_f, \Delta\phi_f) = \left[\boldsymbol{P}_i(p_{T_i}, \Delta y_i, \Delta\phi_i) \times L^*\right]_{\boldsymbol{p}_i = \boldsymbol{p}_f - \boldsymbol{q}^\dagger} \times J^\ddagger(\Delta y \to \Delta\eta)$$

*Lorentz invariant ensuring factor

†Average momentum transfer

‡Jacobian

Collective motion of kicked partons



$$\boldsymbol{Y}_{\mathrm{assoc}}(p_{T_f}, \Delta\eta_f, \Delta\phi_f) = \frac{2}{3} \times f_{\mathrm{R}}^* \times \langle N_{\mathrm{k}} \rangle^\dagger \times \boldsymbol{P}_f(p_{T_f}, \Delta\eta_f, \Delta\phi_f)$$

*Survival factor reaching the detector

†The average number of kicked partons

※ q, f_R, and $\langle N_{\mathrm{k}} \rangle$ are important parameters in this topic.

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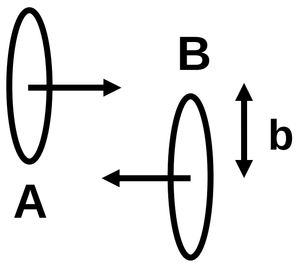
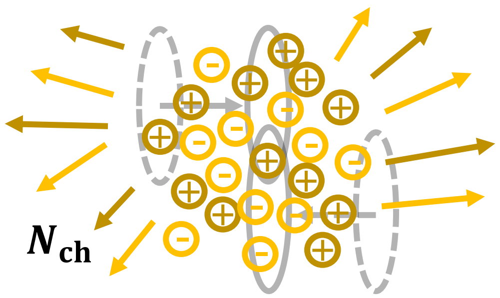
Formalism

for the **multiplicity dependence**

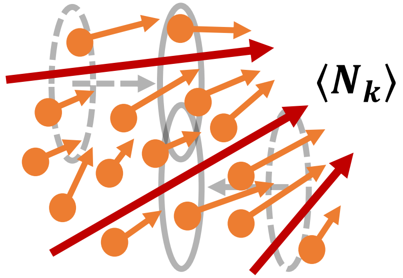
Glauber model



Multiplicity



The average number of kicked partons



$$\frac{dN_{\mathrm{particp}}}{d\boldsymbol{b}'} = T_A^{\dagger}(\boldsymbol{b}_A) + T_B(\boldsymbol{b}_B)$$

†**Thickness function.**

$$N_{\mathrm{ch}}(\boldsymbol{b}) = \frac{2}{3} \times \frac{\langle N_{\mathrm{ch}} \rangle}{\langle N_{\mathrm{particp}} \rangle} \times \int d\boldsymbol{b}' \frac{dN_{\mathrm{particp}}}{d\boldsymbol{b}'}$$

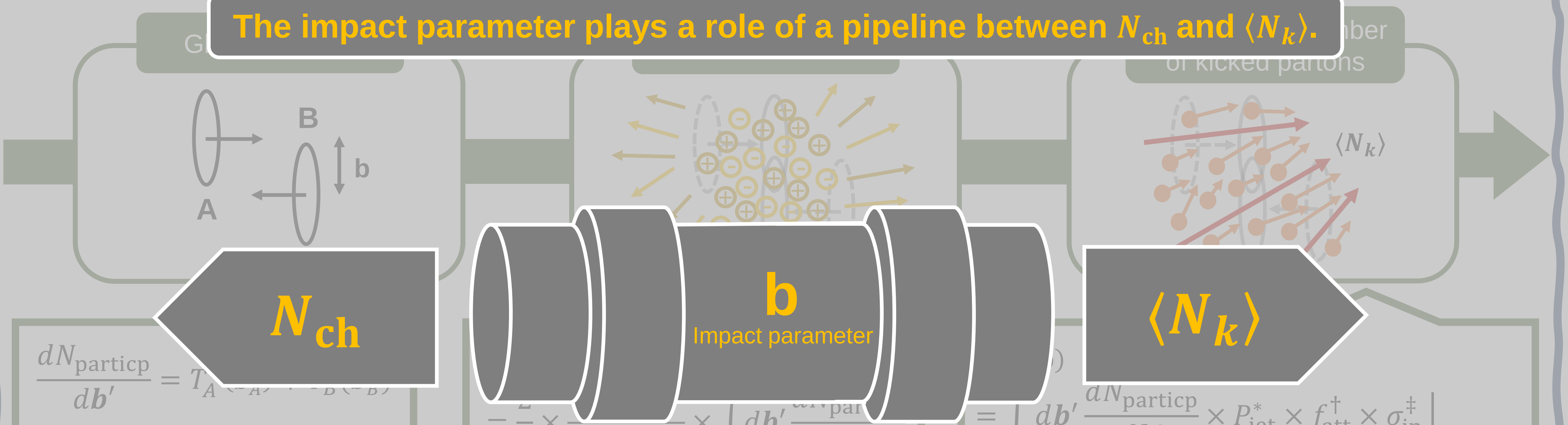
$$\langle N_{\mathrm{k}} \rangle(\boldsymbol{b}) = \int d\boldsymbol{b}' \frac{dN_{\mathrm{particp}}}{d\boldsymbol{b}'} \times P_{\mathrm{jet}}^{*} \times f_{\mathrm{att}}^{\dagger} \times \sigma_{\mathrm{jp}}^{\ddagger} \Big|_{\mathrm{average}}$$

***Jet production probability.**
†**Jet attenuation factor.**
‡**Jet-Parton cross-section.**

Formalism

for the **multiplicity dependence**

The impact parameter plays a role of a pipeline between N_{ch} and $\langle N_k \rangle$.



$$\frac{dN_{particp}}{db'} = T_A$$

†Thickness function.

$$= \frac{2}{3} \times \frac{1}{\langle N_{particp} \rangle} \times \int db' \frac{dN_{par}}{db'}$$

$$= \int db' \frac{dN_{particp}}{db'} \times P^{*}_{jet} \times f^{\dagger}_{att} \times \sigma^{\ddagger}_{jp} \Big|_{average}$$

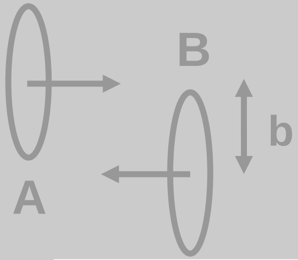
*Jet production probability.
†Jet attenuation factor.
‡Jet-Parton cross-section.

Formalism

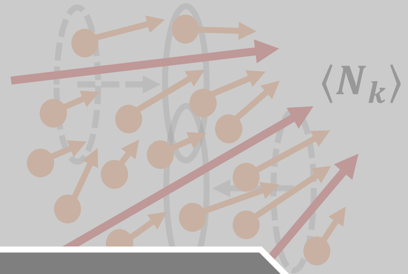
for the **multiplicity dependence**

The matching result between N_{ch} and $\langle N_k \rangle$.

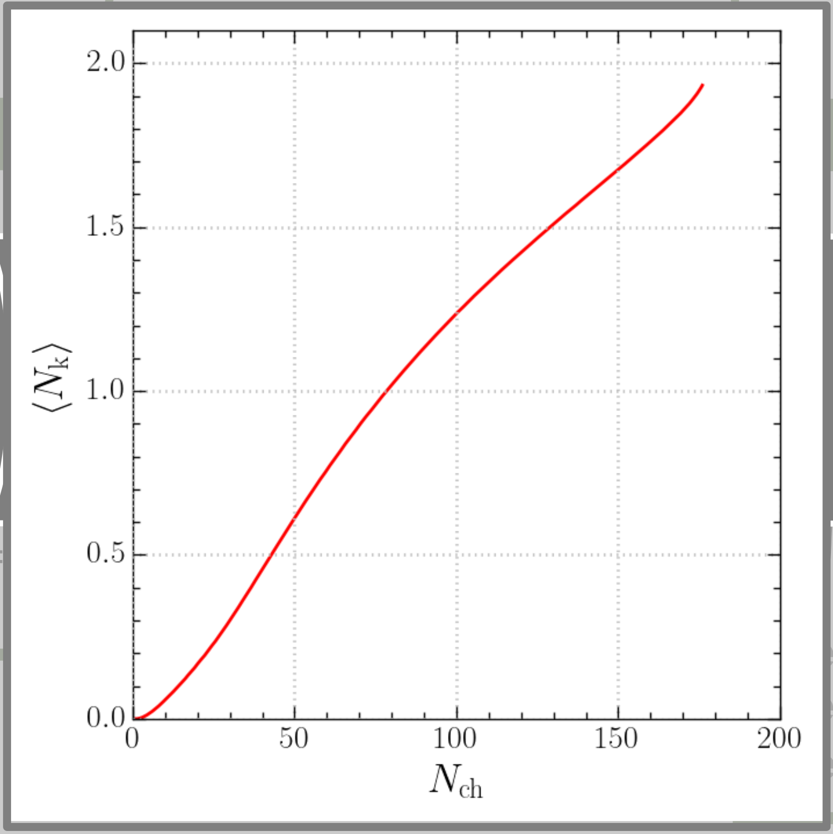
Glauber model



The average number of kicked partons



N_{ch}



$\langle N_k \rangle$

$\frac{dN_{\mathrm{particp}}}{d\boldsymbol{b}'} = T_A$ …

†**Thickness function.**

$d\boldsymbol{b}' \, \frac{dN_{\mathrm{particp}}}{d\boldsymbol{b}'} \times P^{*}_{\mathrm{jet}} \times f^{\dagger}_{\mathrm{att}} \times \sigma^{\ddagger}_{\mathrm{jp}} \Big|_{\mathrm{average}}$

…t production probability.

…t attenuation factor.

…t-Parton cross-section.

Application results

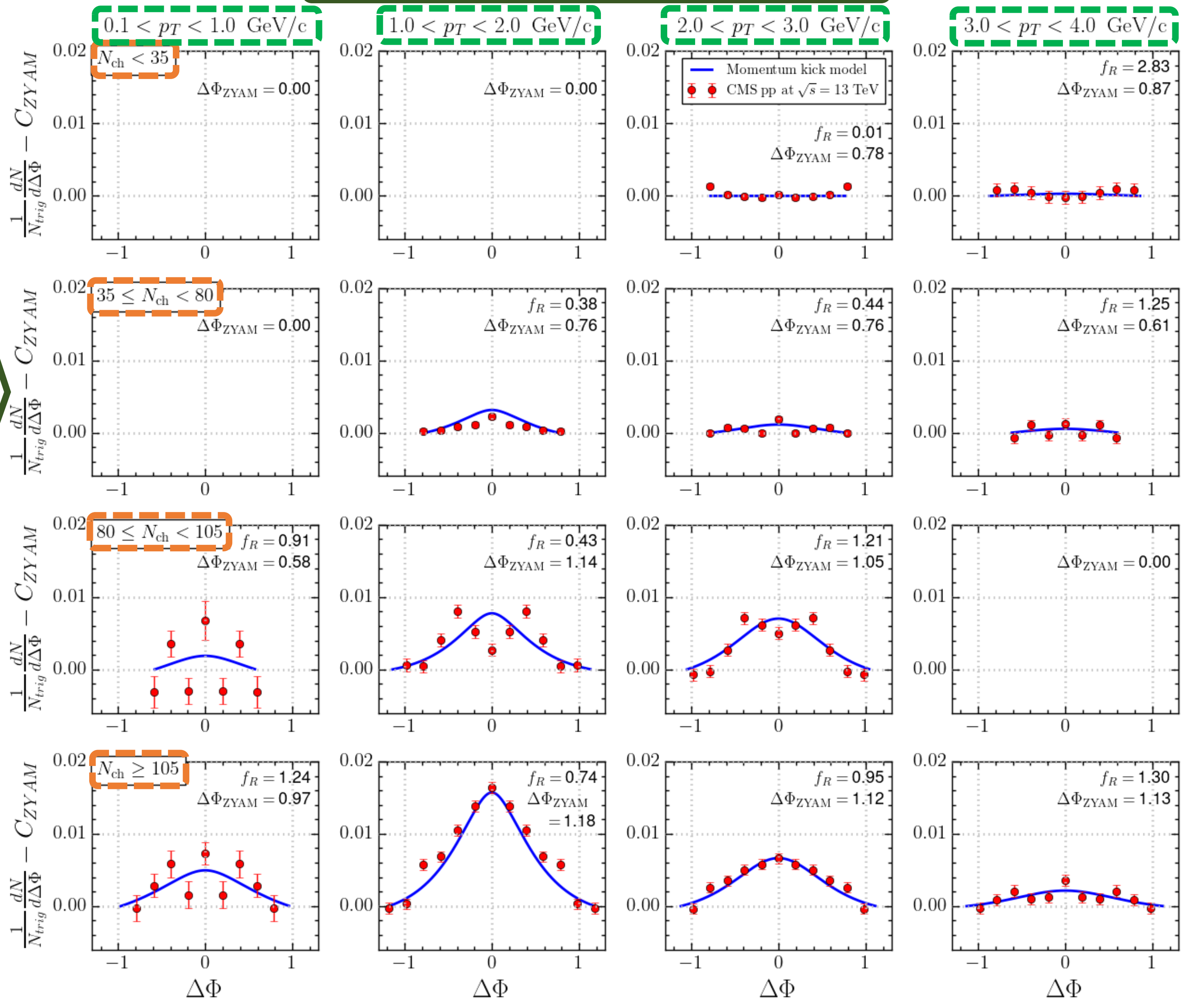
CMS data at $\sqrt{s} = 13$ TeV for pp collisions

Red circles → CMS data.
Blue curves → MKM results.

Columns → Different p_T ranges.
Rows → Different N_{ch} ranges.

- Averaged over $2 < |\Delta\eta| < 4$.
- ZYAM(zero-yield-at-minimum) procedure.
  - Minimum yield at $\Delta\phi_{ZYAM}$.
  - Making yield at $\Delta\phi_{ZYAM}$ zero by subtracting C_{ZYAM}.
- Least-Square-Fitting-Method: q and f_R.
  - $q = 1.2$ GeV/c.
  - f_R increases with p_T.

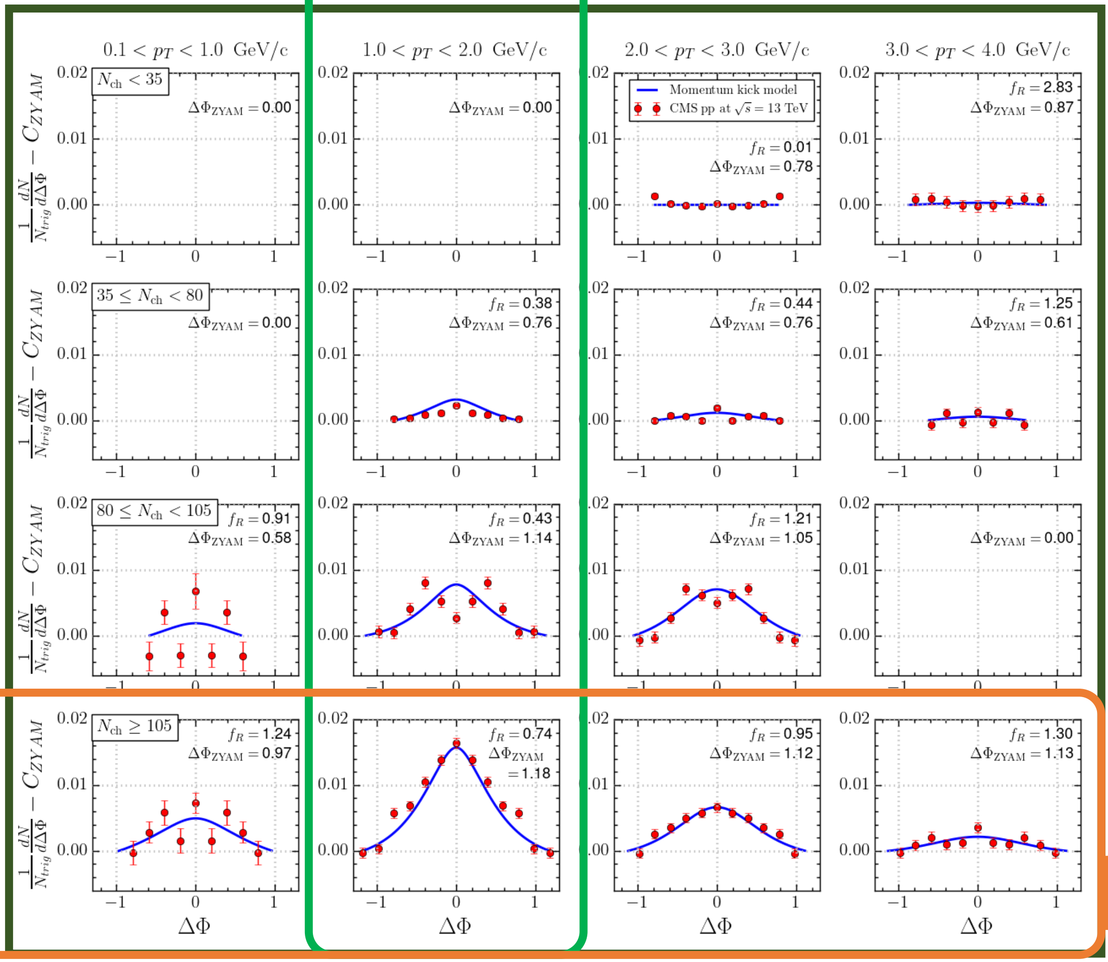
Yield per trigger as a function of ΔΦ



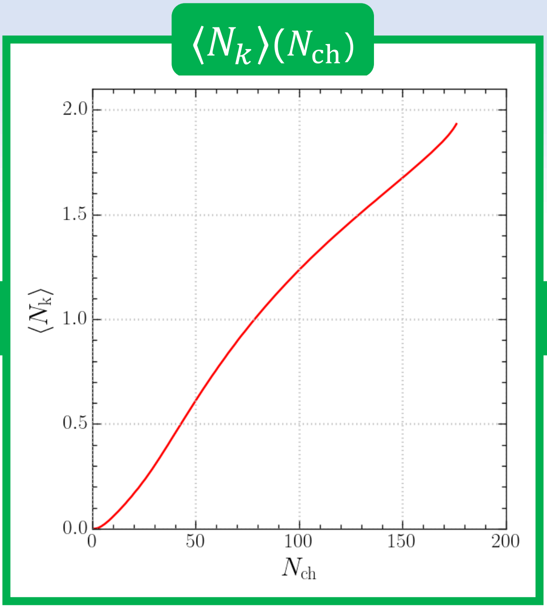
Phys. Rev. Lett. 116, 172302(2016)

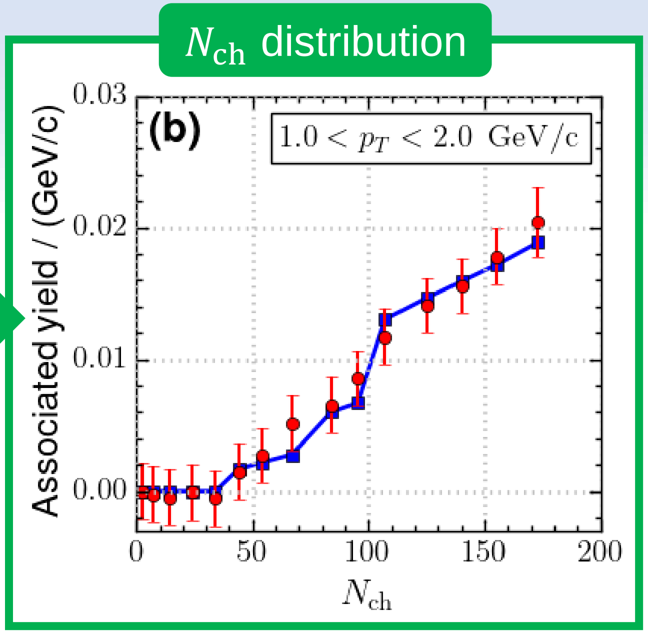
Application results

CMS data at $\sqrt{s} = 13$ TeV for pp collisions

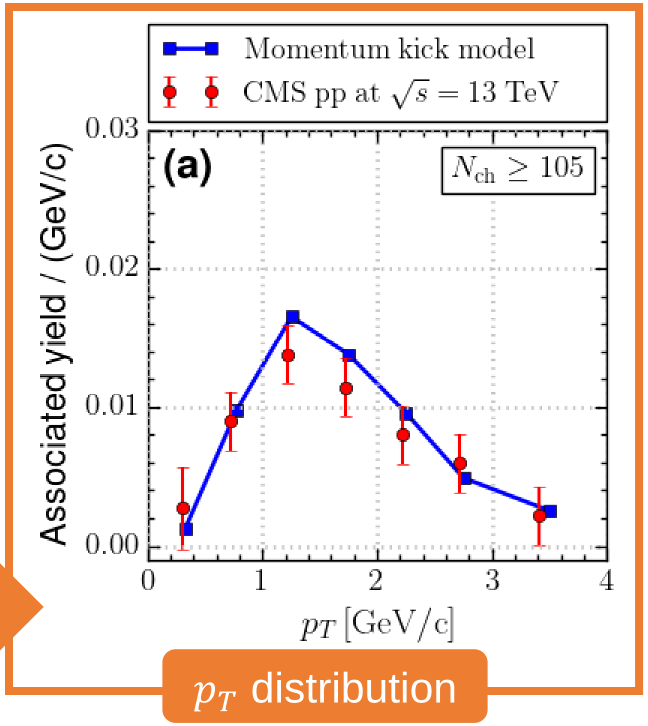


Integrated over $|\Delta\phi| < \Delta\phi_{ZYAM}$





Integrated over $|\Delta\phi| < \Delta\phi_{ZYAM}$



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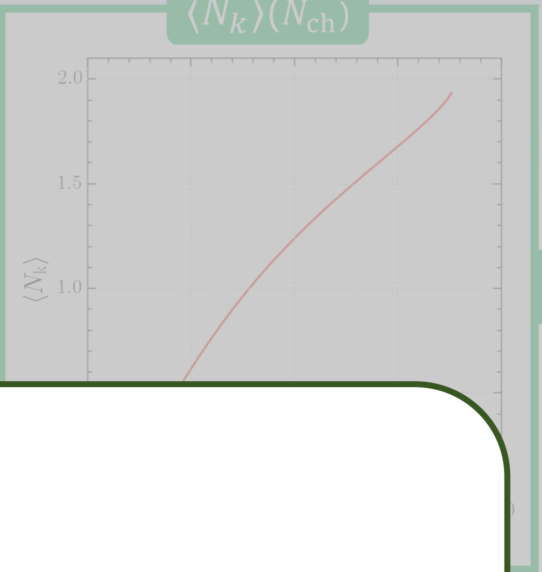
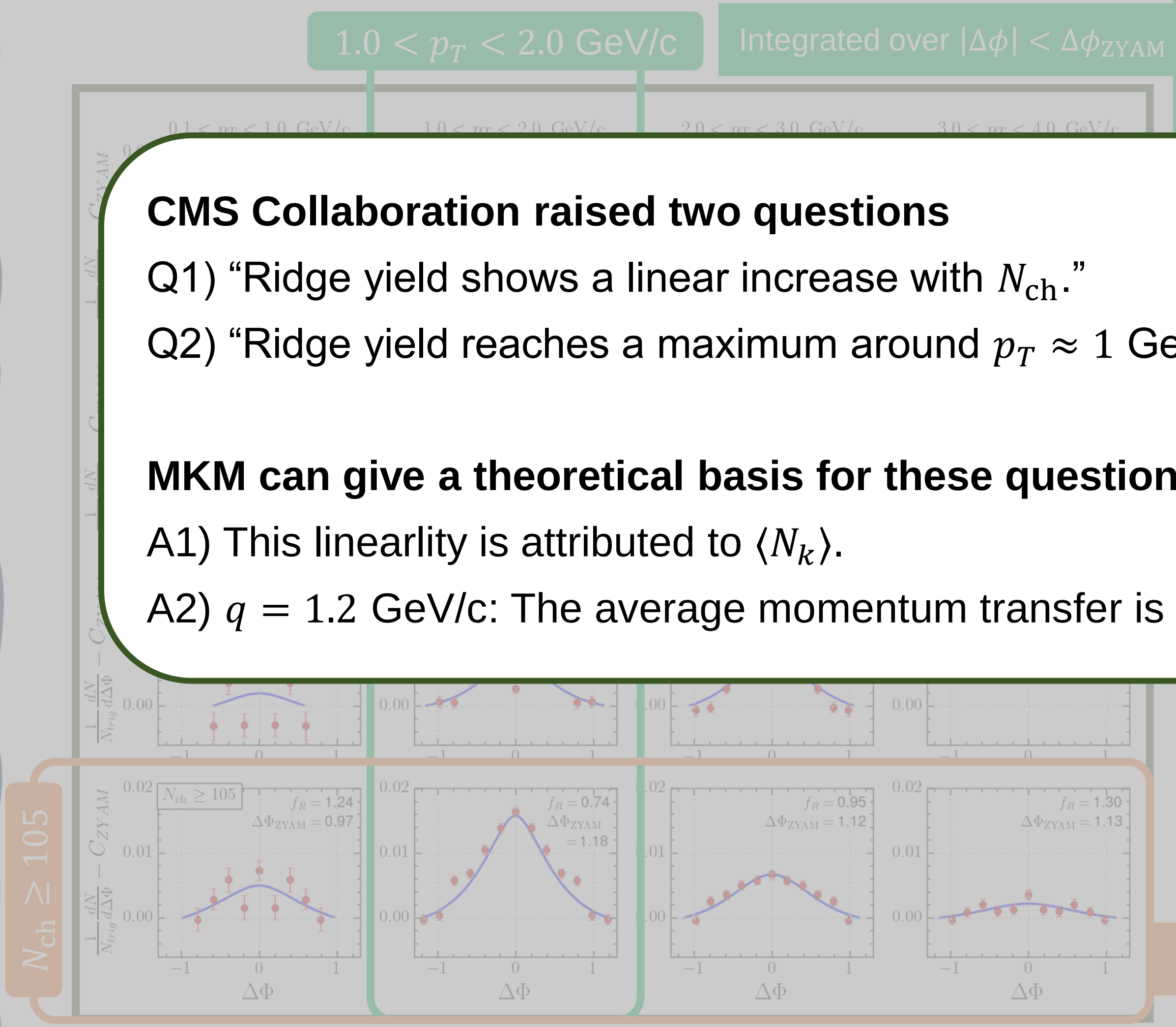
Application results

CMS data at $\sqrt{s} = 13$ TeV for pp collisions





CMS Collaboration raised two questions

Q1) "Ridge yield shows a linear increase with N_{ch}."

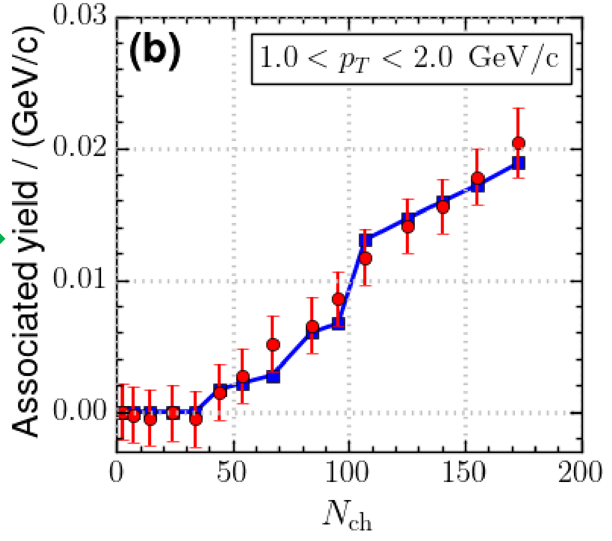
Q2) "Ridge yield reaches a maximum around $p_T \approx 1$ GeV/c."

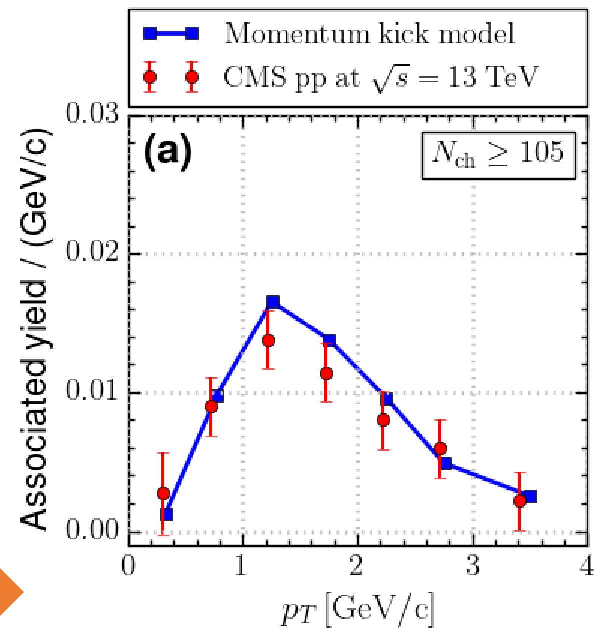
MKM can give a theoretical basis for these questions

A1) This linearlity is attributed to $\langle N_k \rangle$.

A2) $q = 1.2$ GeV/c: The average momentum transfer is active at $p_T = 1.2$ GeV/c.

N_{ch} distribution





p_T distribution

Application results

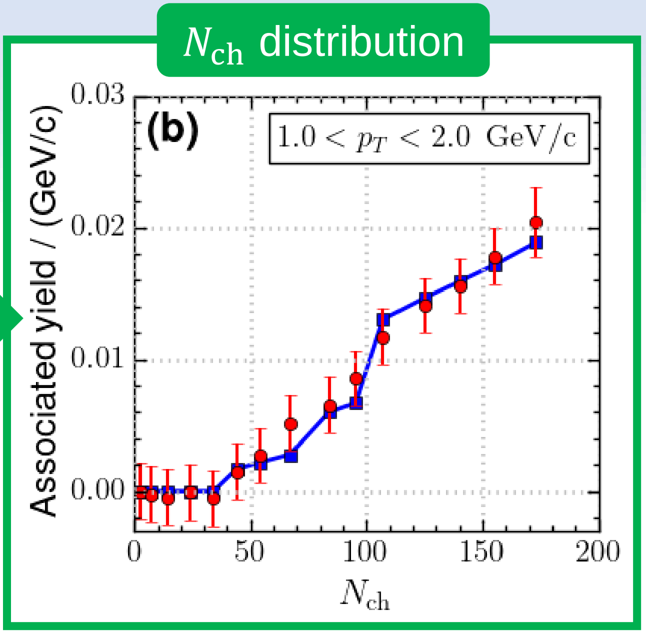
CMS data at $\sqrt{s} = 13$ TeV for pp collisions

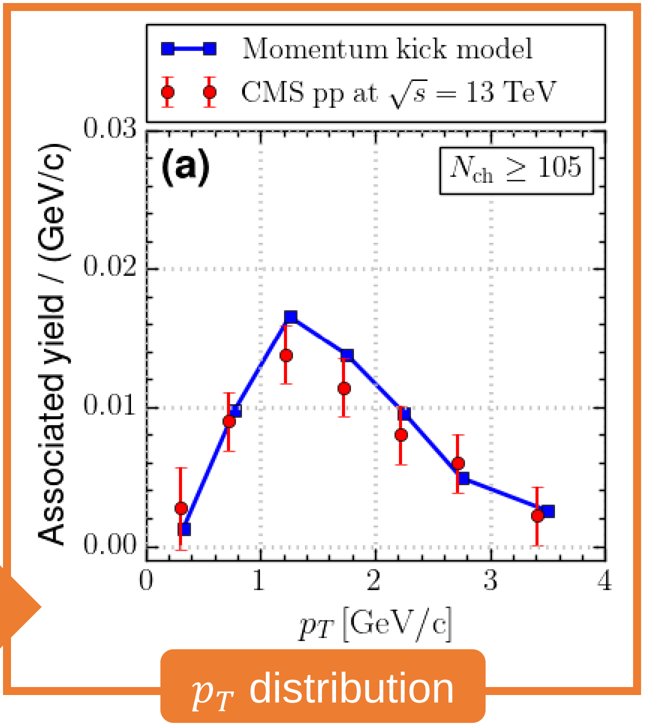
CMS Collaboration

- Near-side long-range ridge structures: at $\sqrt{s} = 13$ TeV **vs** at $\sqrt{s} = 7$ TeV.
  - ➢ The ridge structures for pp collisions do not have clear collision energy dependence.

MKM predictions

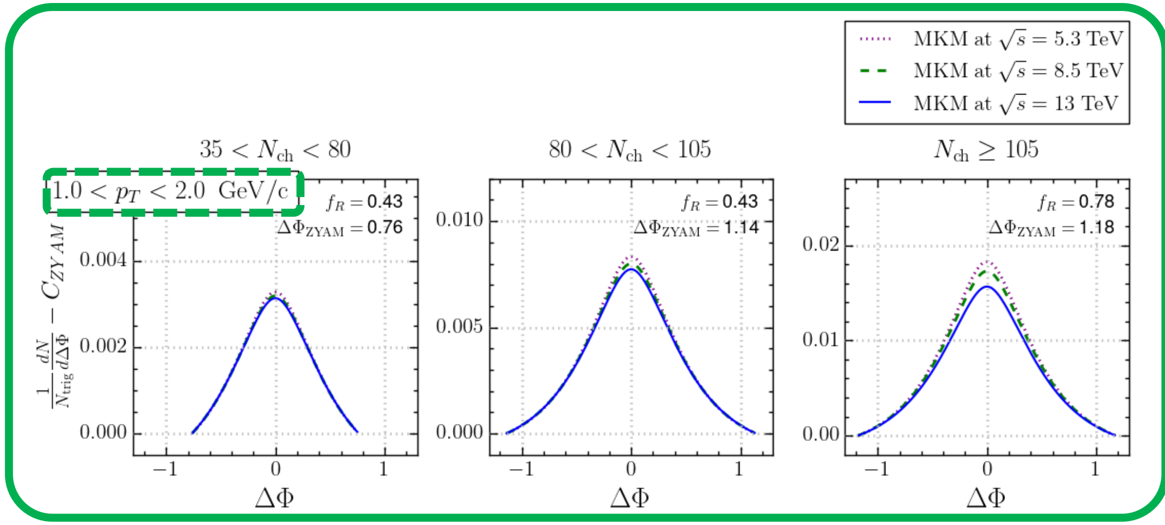
- Around $q = 1.2$ GeV/c, regardless of collision energy for pp collisions.
  - ➢ Confirming $q = 1.1$ GeV/c at $\sqrt{s} = 7$ TeV.
- LHC Run3 is conducting measurements for pp collisions at $\sqrt{s} = 5.3$ & 8.5 TeV
  - ➢ We can try!



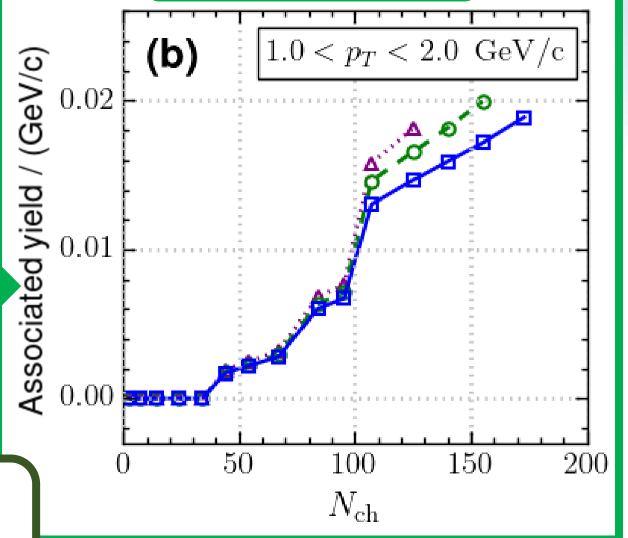


Predictions

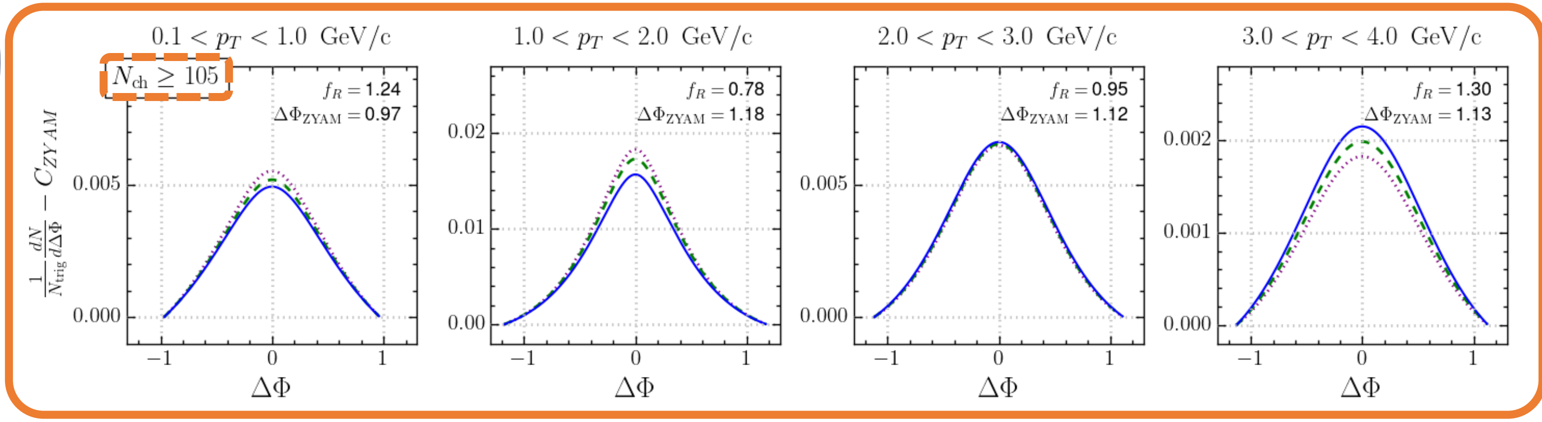
at $\sqrt{s}$ = 5.3 and 8.5 TeV for pp collisions



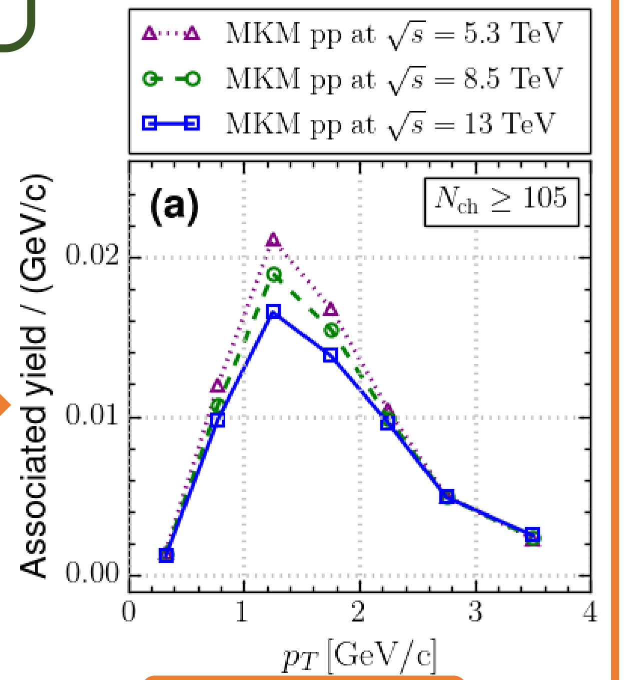
Integrated over $|\Delta\phi| < \Delta\phi_{ZYAM}$



- q = 1.2 GeV
- Using f_R & $\Delta\Phi_{ZYAM}$ at $\sqrt{s}$ = 13 TeV

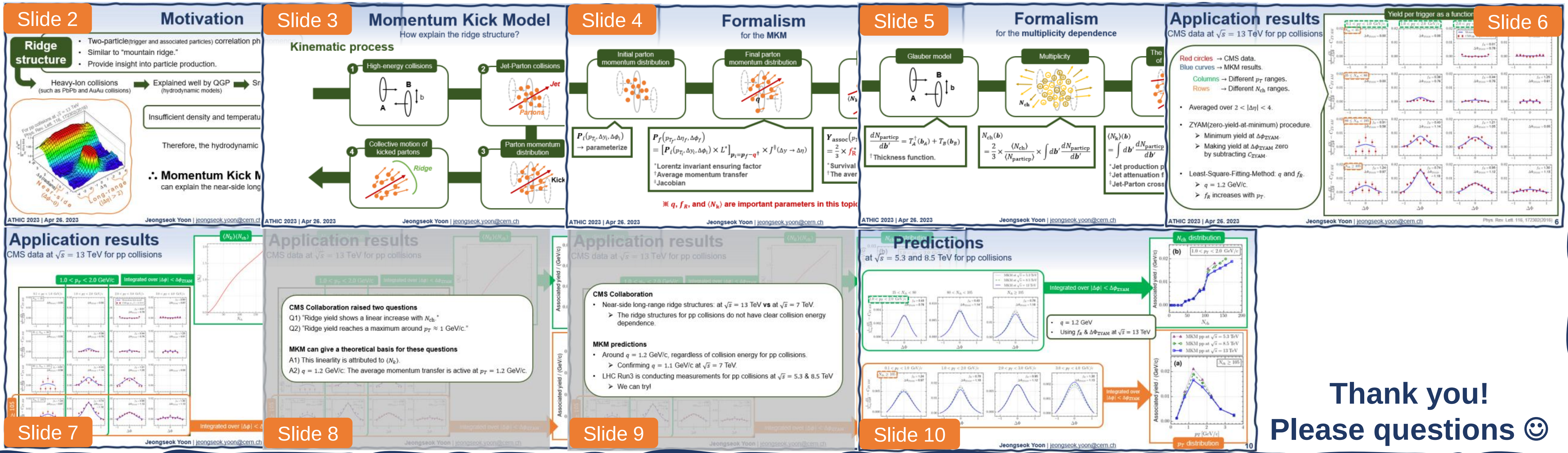


Integrated over $|\Delta\phi| < \Delta\phi_{ZYAM}$



Summary

- MKM explains the near-side long-range ridge structure in small systems.
- By linking $\langle N_k \rangle$ with N_{ch} via impact parameter, MKM has multiplicity dependence.
- MKM with multiplicity dependence successfully describes the CMS data at $\sqrt{s} = 13$ TeV.
- CMS Collaboration provided a good surmise that ridge structures for pp collisions do not have clear collision energy dependence.
- Through the result of $q = 1.2$ GeV/c, MKM can predict the ridge structures at $\sqrt{s} = 5.3$ & 8.5 TeV.



Thank you!
Please questions ☺

BACK UP

Formalism

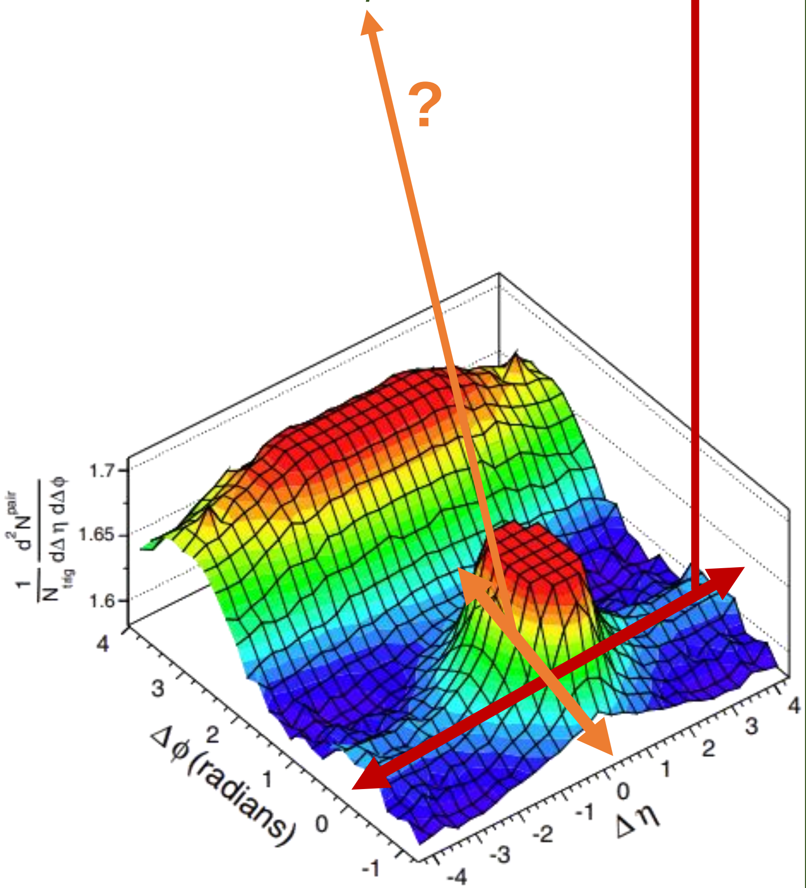
- **Associated Yield**
  - $$\left[\frac{1}{N_{\text{trig}}}\frac{dN_{\text{ch}}}{p_T dp_T d\Delta\eta d\Delta\phi}\right]^{AA}_{\text{total}} = \left[f_R \frac{2}{3}\langle N_k\rangle \frac{dF}{p_T dp_T d\Delta\eta d\Delta\phi}\right]^{AA}_{\text{ridge}} + \left[f_J \frac{dN^{pp}_{\text{jet}}}{p_T dp_T d\Delta\eta d\Delta\phi}\right]^{AA}_{\text{jet}}$$

- **Ridge**
  - $$\frac{dF}{p_T dp_T d\eta d\phi} = \left[\frac{dF}{p_{Ti} dp_{Ti} dy_i d\phi_i}\frac{E}{E_i}\right]_{p_i=p-q} \times \sqrt{1-\frac{m_\pi^2}{(m_\pi^2+p_T^2)\cosh^2 y}}$$
  - $$\frac{dF}{p_{Ti} dp_{Ti} dy_i d\phi_i} = A_{\text{ridge}}(1-x)^a \frac{\mathrm{e}^{-\sqrt{m_\pi^2+p_{Ti}^2}/T}}{\sqrt{m_d^2+p_{Ti}^2}}$$
  - $$x = \frac{\sqrt{m_\pi^2+p_{Ti}^2}}{m_b}\mathrm{e}^{|y_i|-y_b}$$
  - $$y_b = \cosh^{-1}\left(\frac{\sqrt{s_{NN}}}{2m_b}\right)$$

- **Jet**
  - $$\frac{dN^{pp}_{\text{jet}}}{p_T dp_T d\Delta\eta d\Delta\phi} = N_{jet}\frac{\exp\left[\left(\mathrm{m}_\pi-\sqrt{m_\pi^2+p_T^2}\right)/T_{\text{jet}}\right]}{T_{\text{jet}}(m_\pi+T_{\text{jet}})} \times \frac{1}{2\pi\sigma_\phi^2}\mathrm{e}^{-\left[(\Delta\phi)^2+(\Delta\eta)^2\right]/2\sigma_\phi^2}$$

Question

- The ridge structure appears broadly in $\Delta\eta$.
- What about in $\Delta\phi$?

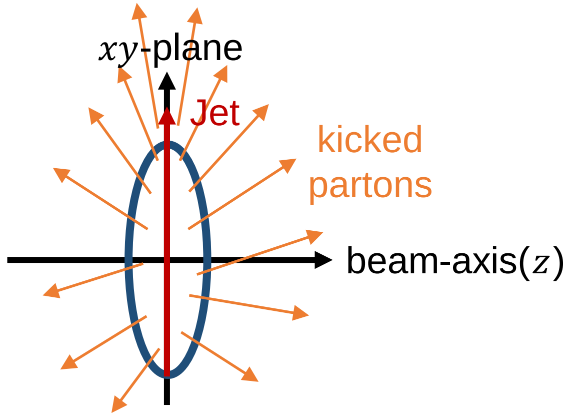


In the case of $\Delta\phi \approx 0$

- Pseudo-rapidity of two particles,

$$\Delta\eta = \eta_{\text{kp}} - \eta_{\text{jet}} = \frac{1}{2}\ln\frac{p_0 + p_3}{p_0 - p_3},$$

where $\eta_{\text{jet}} = 0$ for convenient calculation.



- Final parton momentum

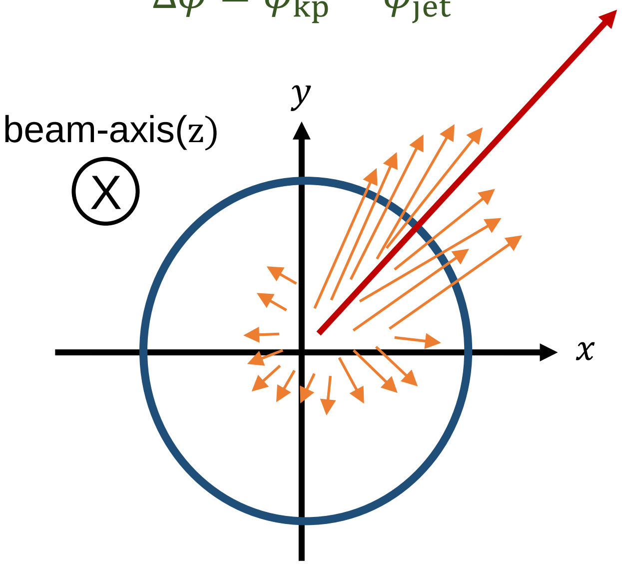
✓ Assuming that $p_3 = 1.0$ GeV.

1) In the case of $p_0 = 1.1$ GeV,
   - $\Delta\eta = \frac{1}{2}\ln\frac{1.1+1.0}{1.1-1.0} = 1.5.$
2) In the case of $p_0 = 1.01$ GeV,
   - $\Delta\eta = \frac{1}{2}\ln\frac{1.01+1.0}{1.01-1.0} = 2.7.$
3) In the case of $p_0 = 1.001$ GeV,
   - $\Delta\eta = \frac{1}{2}\ln\frac{1.001+1.0}{1.001-1.0} = 3.8.$ etc…

In the case of $\Delta\eta \approx 0$

- The region of $\Delta\phi \approx 0$ is relatively more dominant than the other regions.

$$\Delta\phi = \phi_{\text{kp}} - \phi_{\text{jet}}$$



Conclusion

- In the case of $\Delta\phi \approx 0$, the ridge structure appears broadly in $\Delta\eta$.
- In the case of $\Delta\eta \approx 0$, the ridge structure is aligned to the direction of jet.

Momentum Kick Model

Other processes

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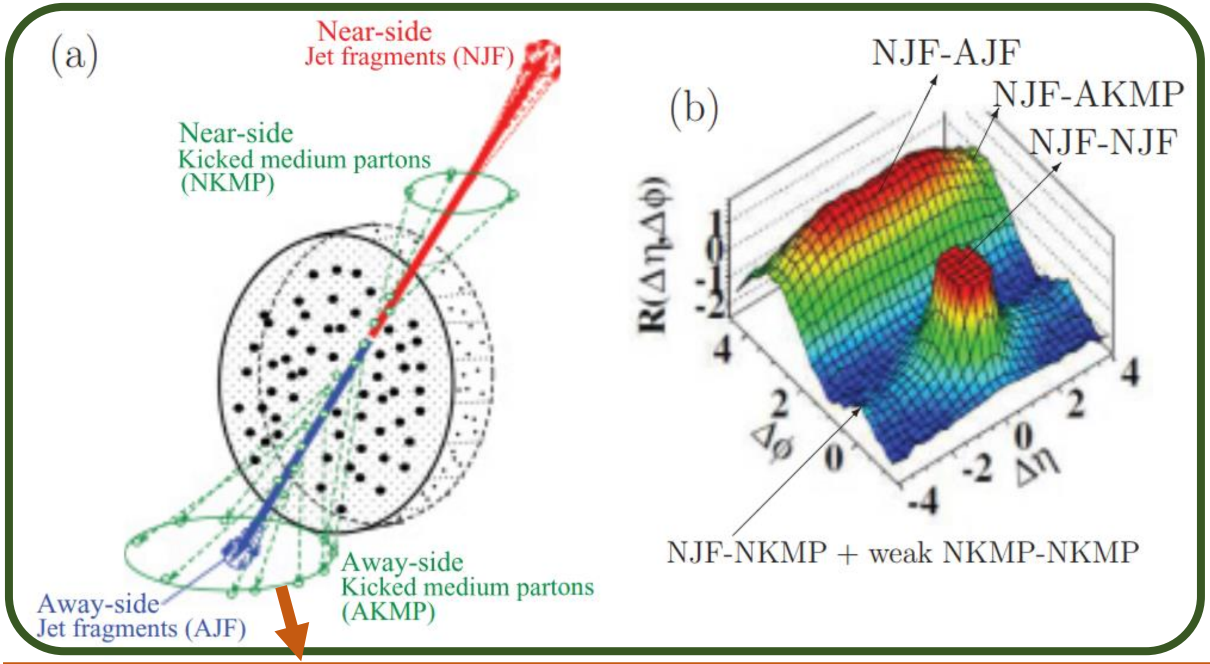

The strength of the NJF-AJF correlation will be substantially quenched.
Therefore, it will become a broad shape.

Two particle correlation
"trigger" + "associated" particles

Many different correlations

① NJF-NJF correlation
② NJF-NKMP correlation
③ NJF-AKMP correlation
④ NJF-AJF correlation
⑤ NKMP-NKMP correlation
⑥ NKMP-AKMP correlation
⑦ NKMP-AJF correlation

(①–④) high-p_T trigger particles **NJF**

+

(⑤–⑦) low-p_T trigger particles **NKMP**

Minimum-(p_T)-bias

Near-side ($\Delta\phi \sim 0$): ①, ②, ⑤ → We focus on it!

Away-side ($\Delta\phi \sim \pi$): ③, ④, ⑥, ⑦