New results on “soft" probes in PbPb collisions from Run 2

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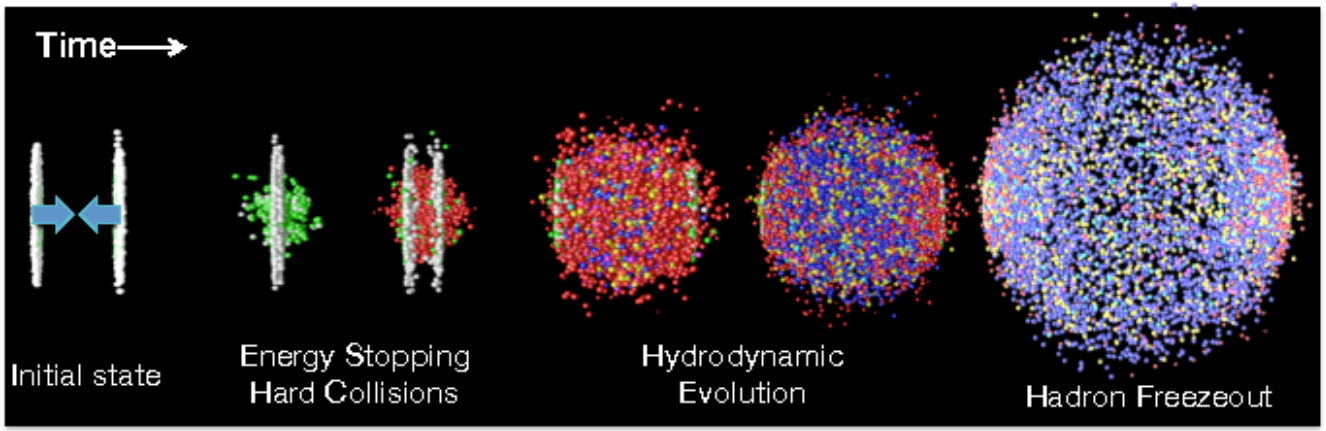
Rice University
On behalf of CMS collaboration
Lund, Sweden 2016

Heavy ion collisions



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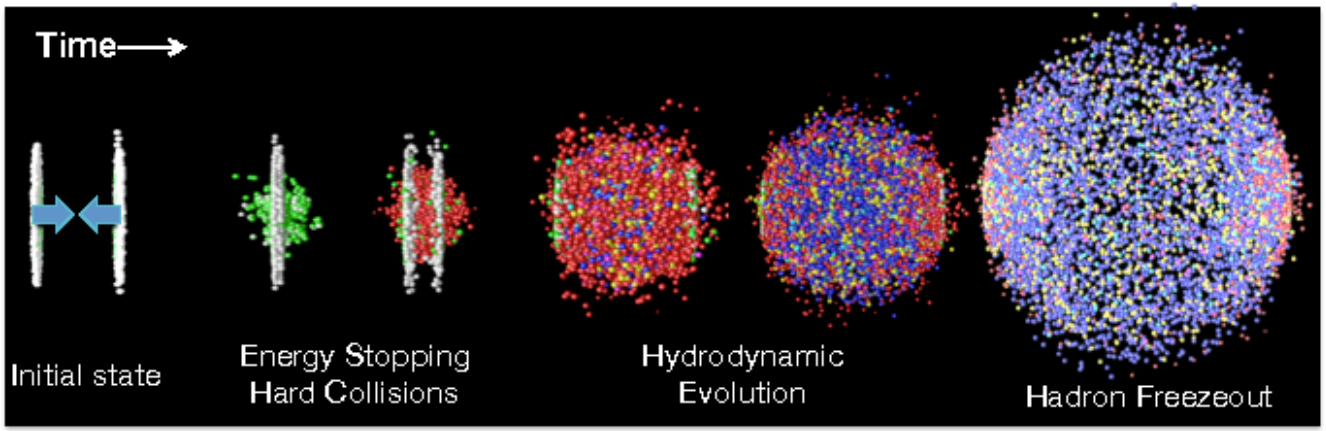
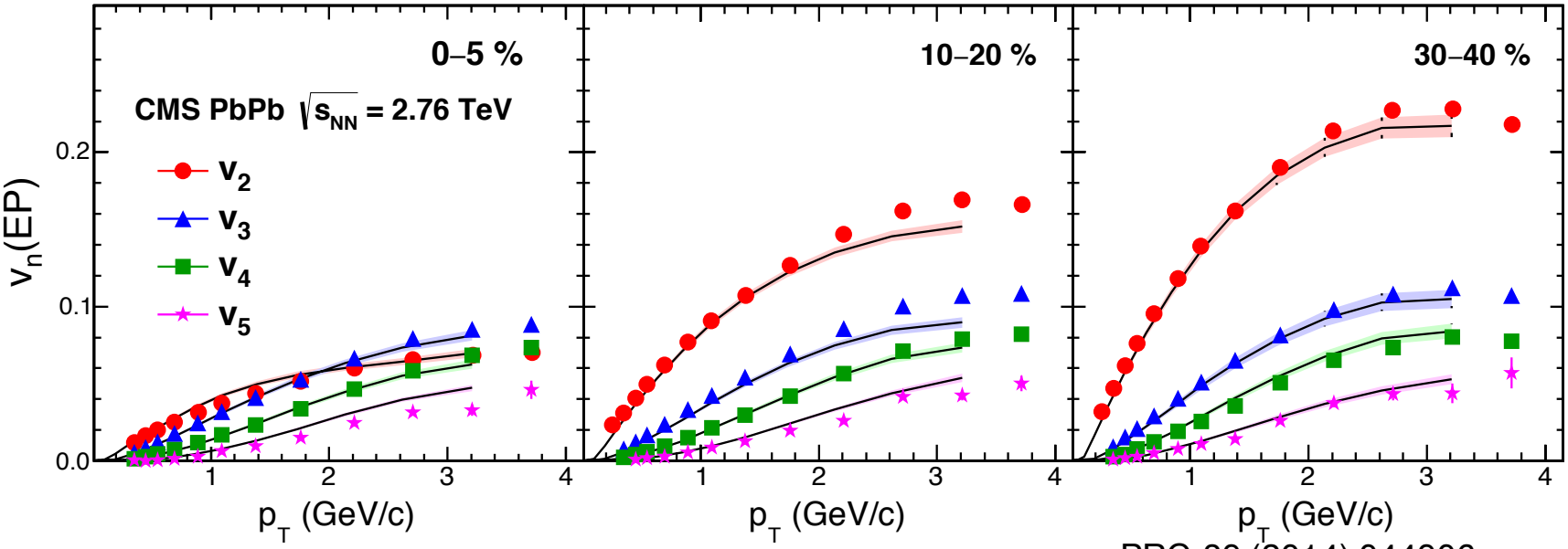
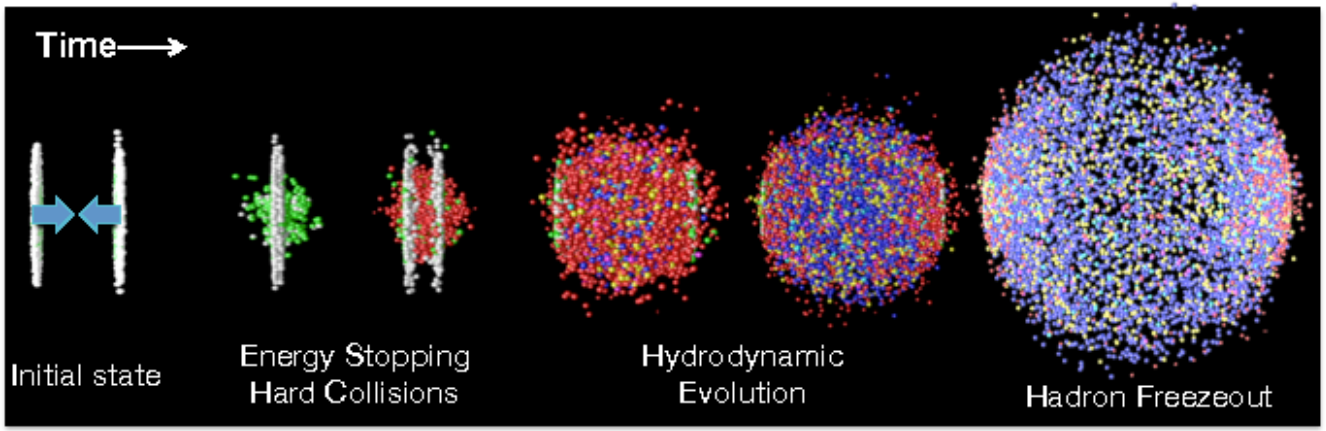


"Glauber-like" IS + (η/s ≈ 0.2)



PRC 89 (2014) 044906

Heavy ion collisions



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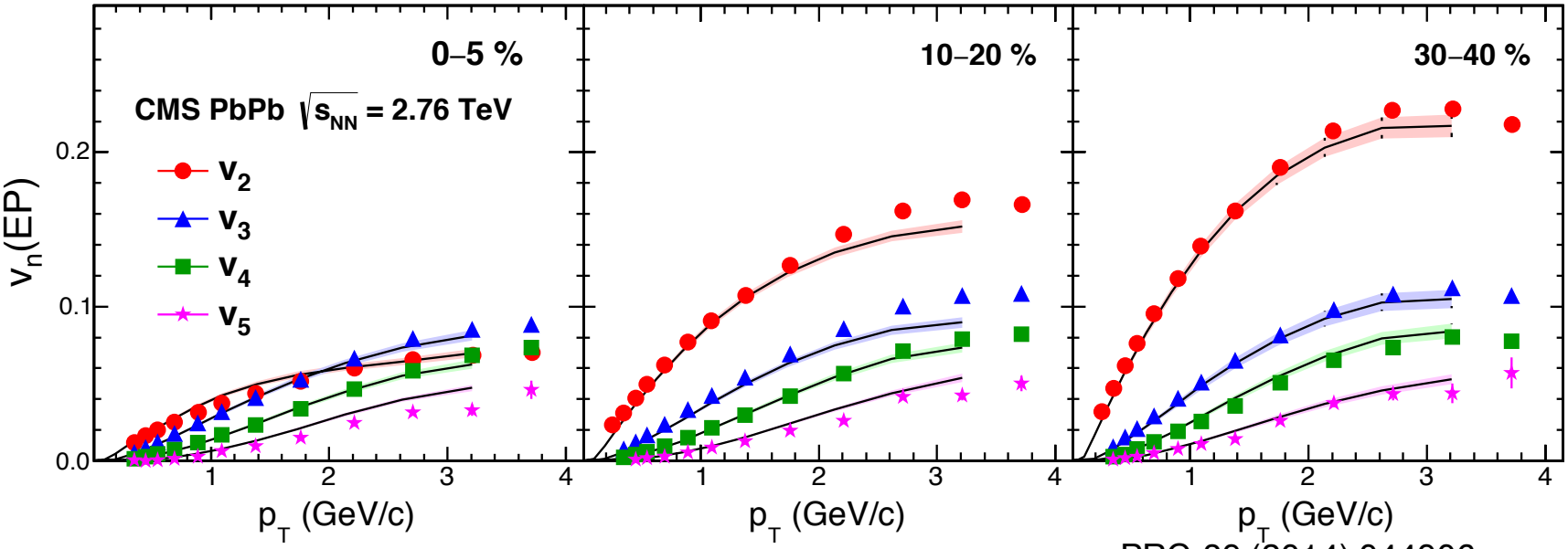
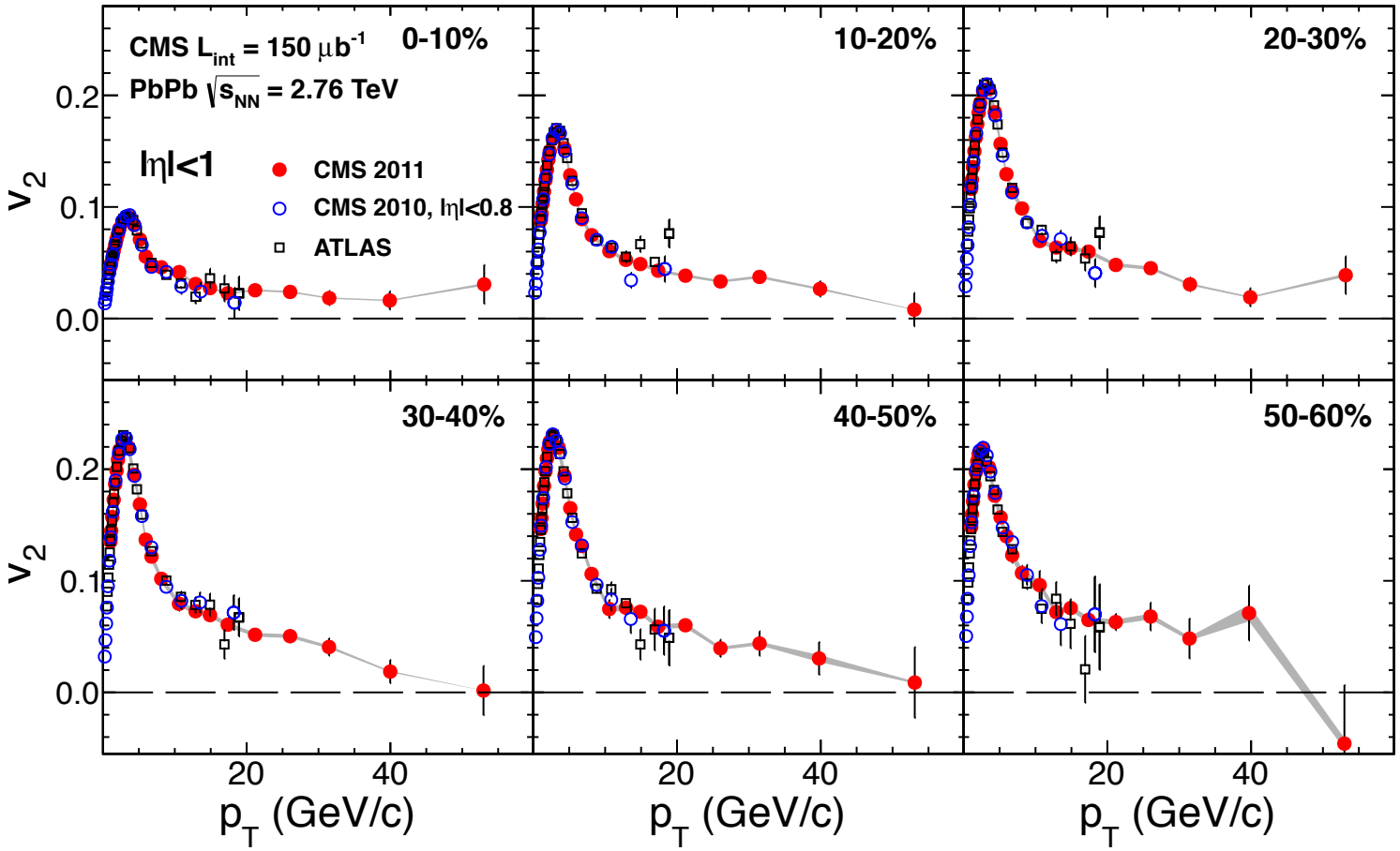


PRC 89 (2014) 044906

low shared viscosity → **A "perfect" fluid**

Previous measurement

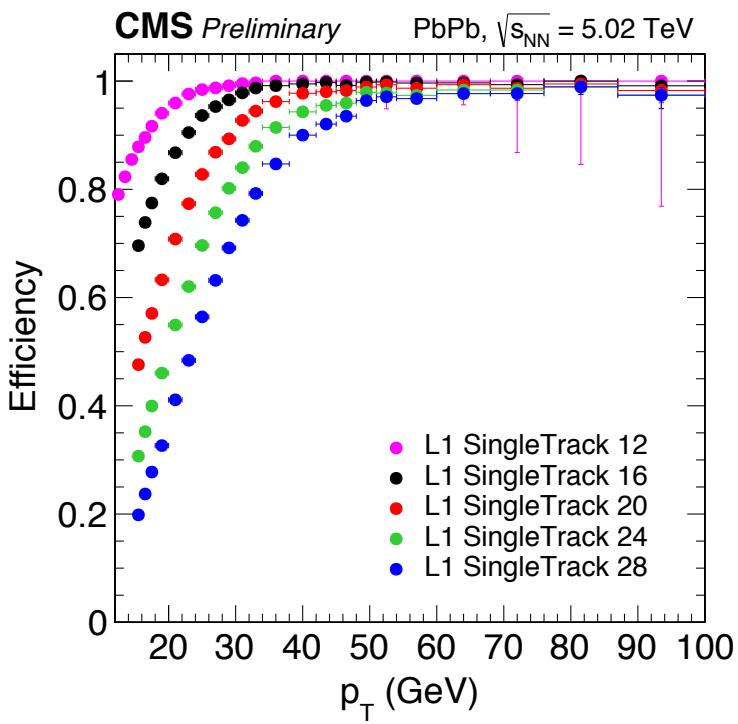
Phys.Rev.Lett. 109 (2012) 022301

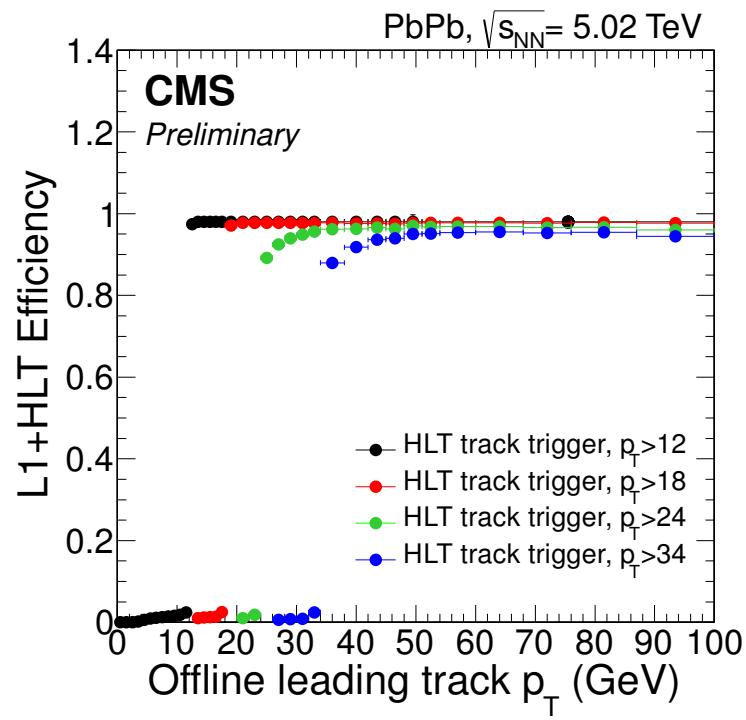


- CMS from RUN 1 measured v_2 up to 60 GeV/c
- Can RUN 2 do better?

High-p_T trigger

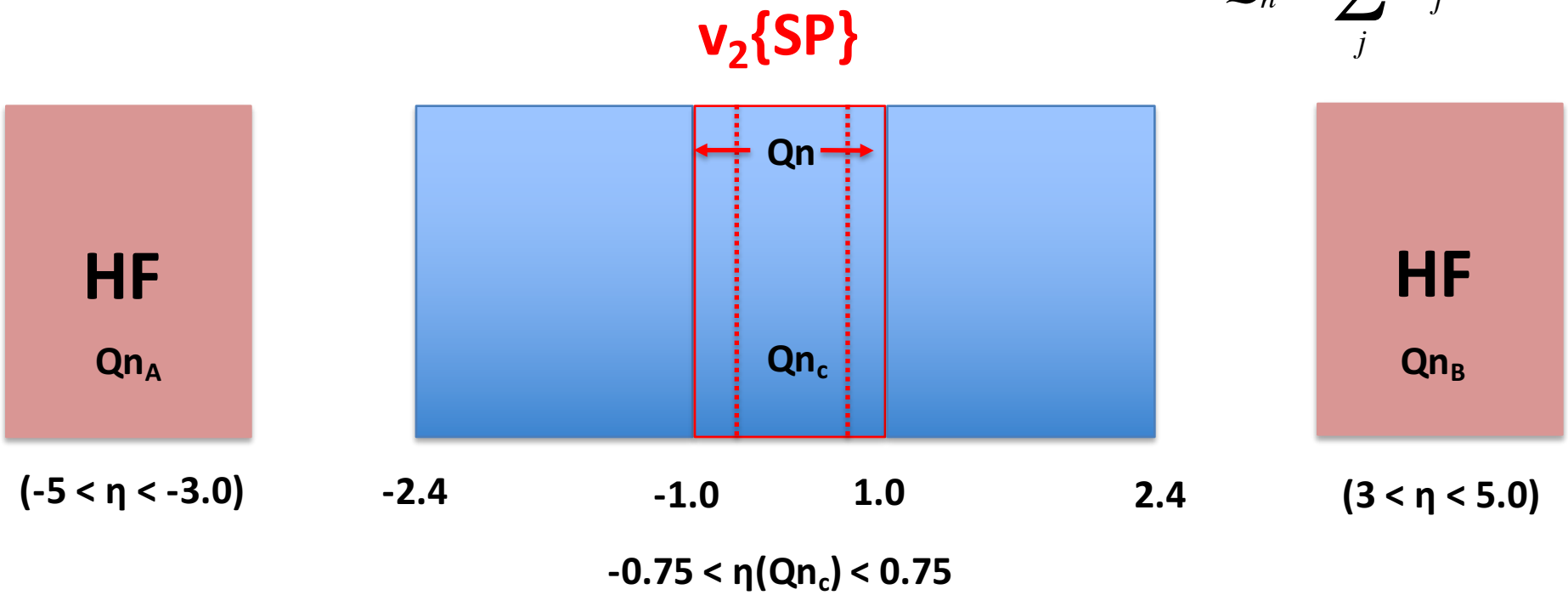
- 2015 PbPb run at LHC
  - $\sqrt{s_{NN}}$ = 5.02 TeV, 404 μb^{-1}
  - MinimumBias (p_T < 14 GeV/c)
- High p_T track trigger
  - $|\eta| < 1.0$, $14.0 < p_T < 100$ GeV/c





How to measure v_n

$$Q_n = \sum_j w_j e^{in\phi_j}$$



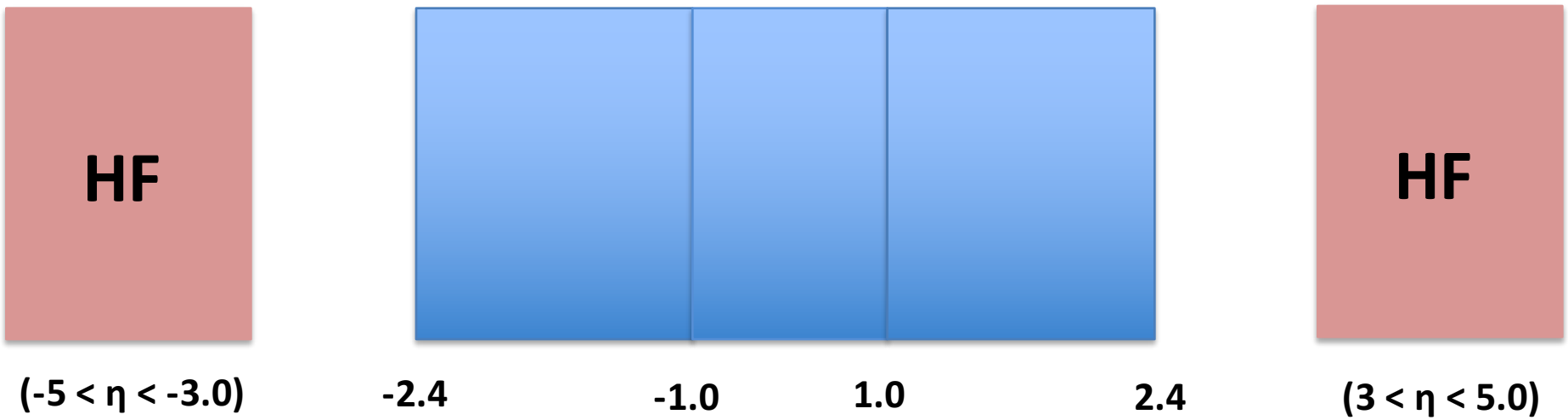
- η gap > 3.0
- It's measuring v2 RMS

$$v_n\{\mathrm{SP}\} = \frac{\left\langle Q_n \cdot Q_{nA}^* \right\rangle}{\sqrt{\dfrac{\left\langle Q_{nA} \cdot Q_{nB}^* \right\rangle \left\langle Q_{nA} \cdot Q_{nC}^* \right\rangle}{\left\langle Q_{nB} \cdot Q_{nC}^* \right\rangle}}}$$

How to measure v_n

$$Q_n = \sum_j w_j e^{in\phi_j}$$

Cumulant



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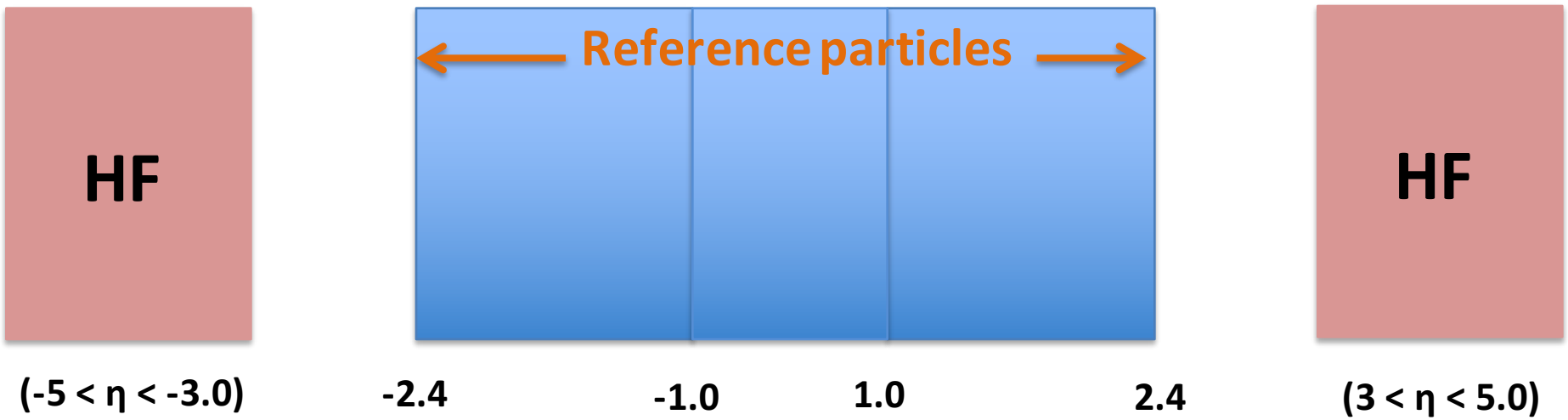

Reference flow

- **$1.0 < p_T < 5.0$ GeV/c**
- **Full tracker region**

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4}$$

$$v_n\{8\} = \sqrt[8]{-c_n\{8\}/33}$$

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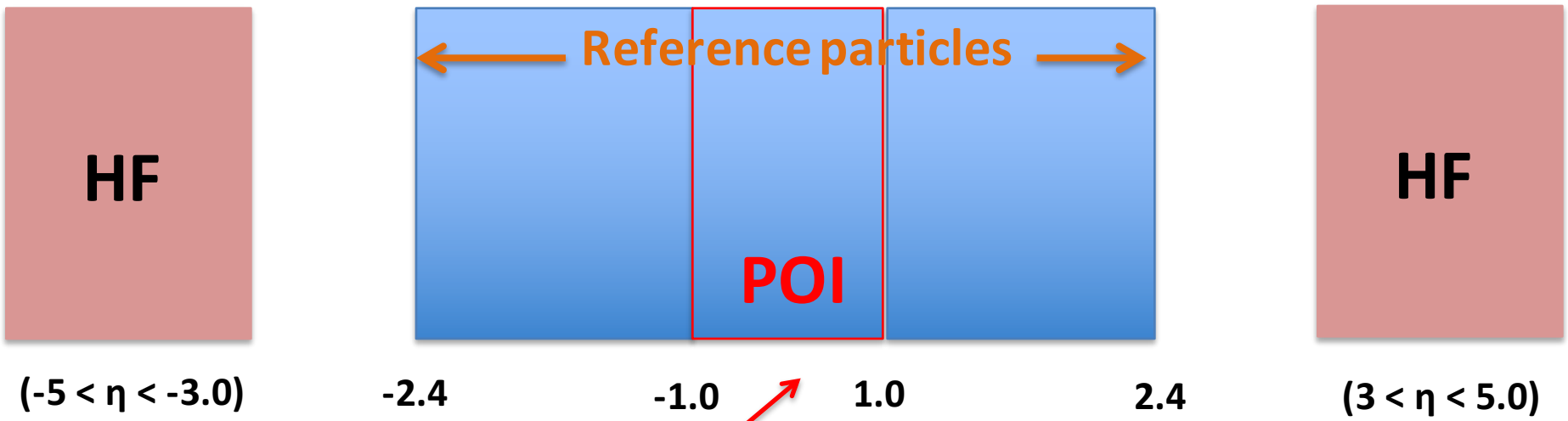

Differential flow
- **1 particle at a given p_T**
- **(m-1) Ref particles**

Reference flow
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$$v_n\{4\}(p_T) = -d_n\{4\} / (-c_n\{4\})^{3/4}$$

$$v_n\{6\}(p_T) = \frac{d_n\{6\}}{4} \Big/ \left(\frac{c_n\{6\}}{4}\right)^{5/6}$$

$$v_n\{8\}(p_T) = \frac{-d_n\{8\}}{33} \Big/ \left(\frac{-c_n\{8\}}{33}\right)^{7/8}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

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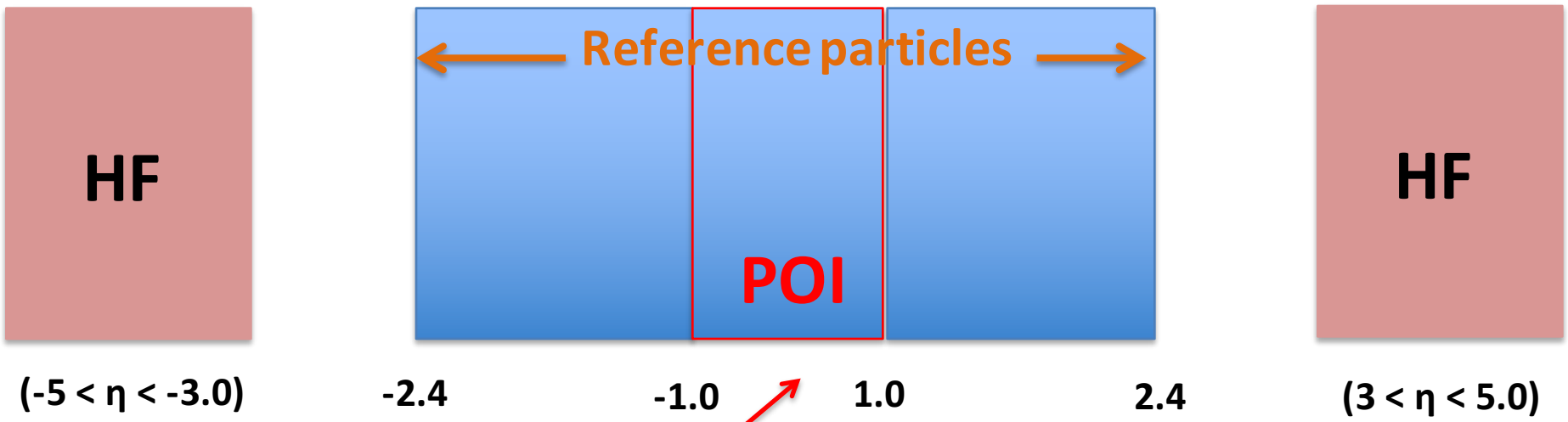
How to measure v_n

$$Q_n = \sum_j w_j e^{in\phi_j}$$

Cumulant → $v_2\{2\} \approx v_2\{SP\}$



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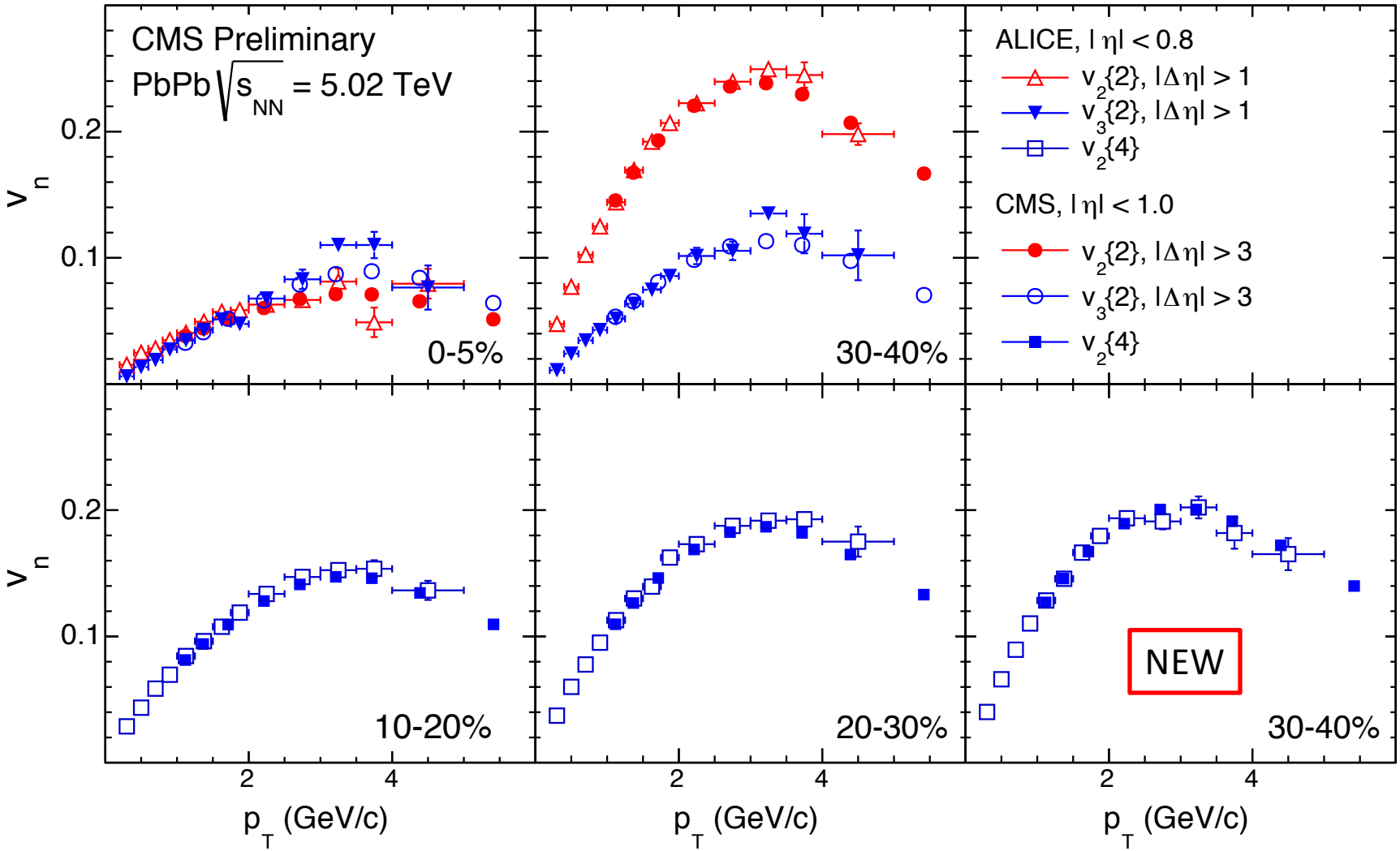
Soft probe, low p_T v_2 @ 5TeV



Link

Consistent results observed with other experiment

High-p_T v_n is ~~NOT flow~~

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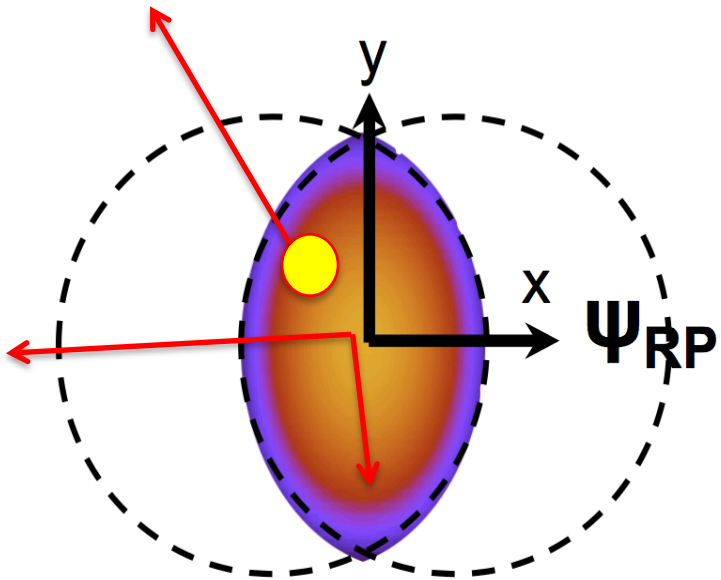

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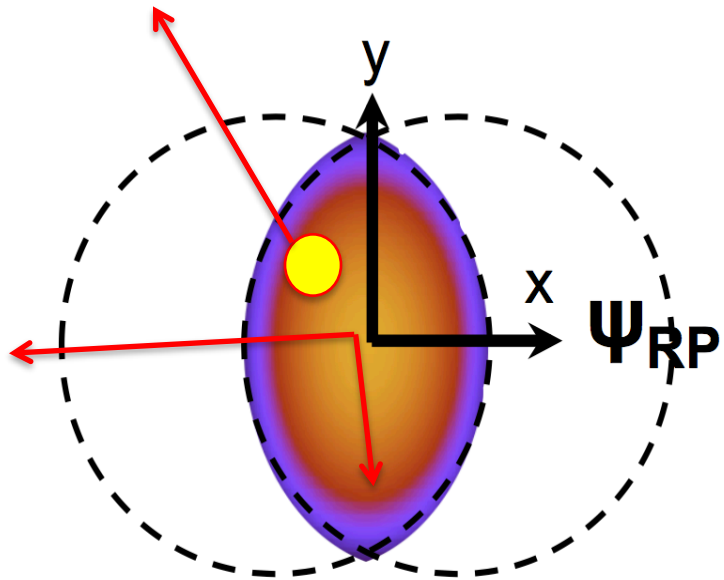
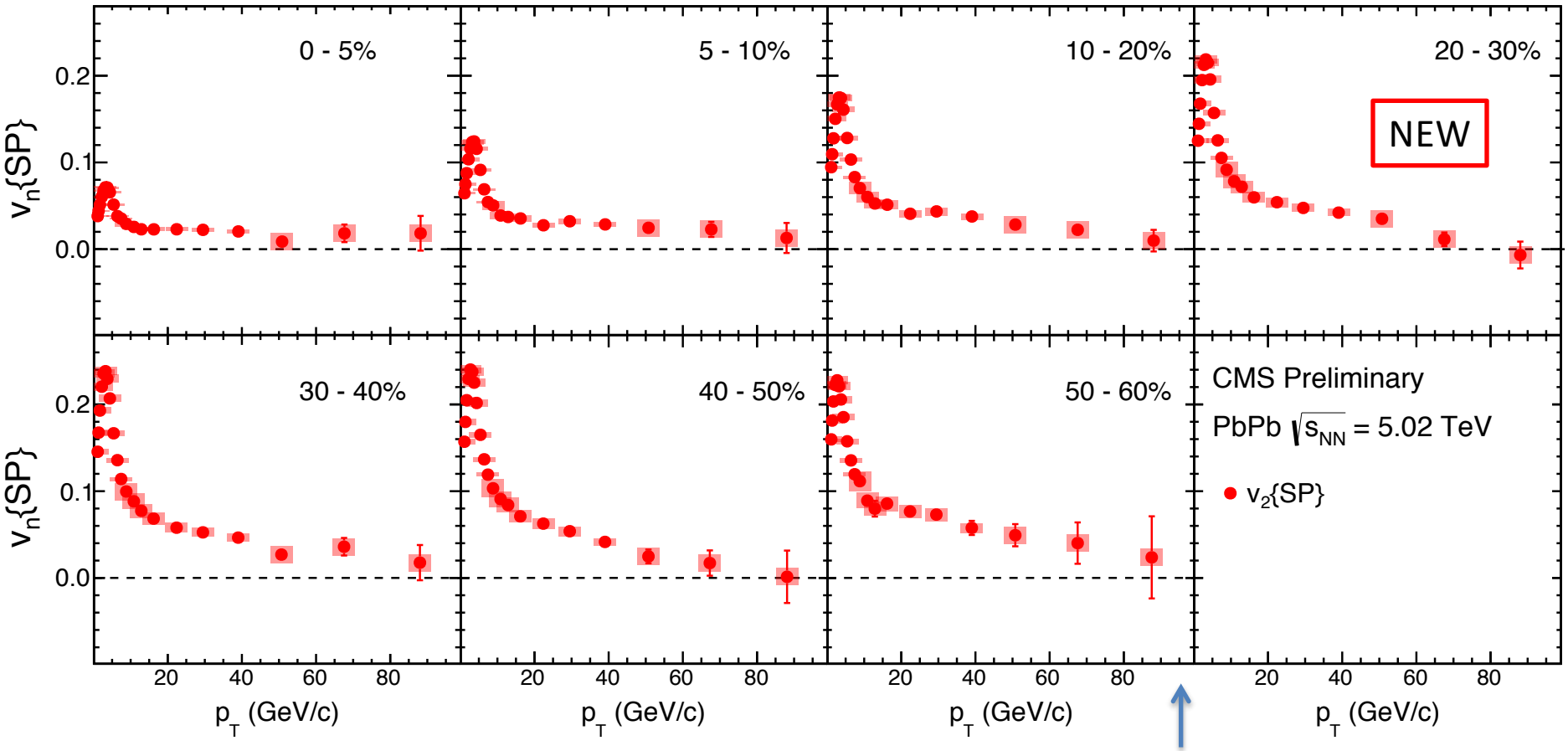


- A high energy jet interacts with the medium → "Jet quenching"

- High-p_T v_2 tells us the energy loss mechanism from:
  - Geometry , path length dependence
  - Initial state fluctuations

High-p_T v_2

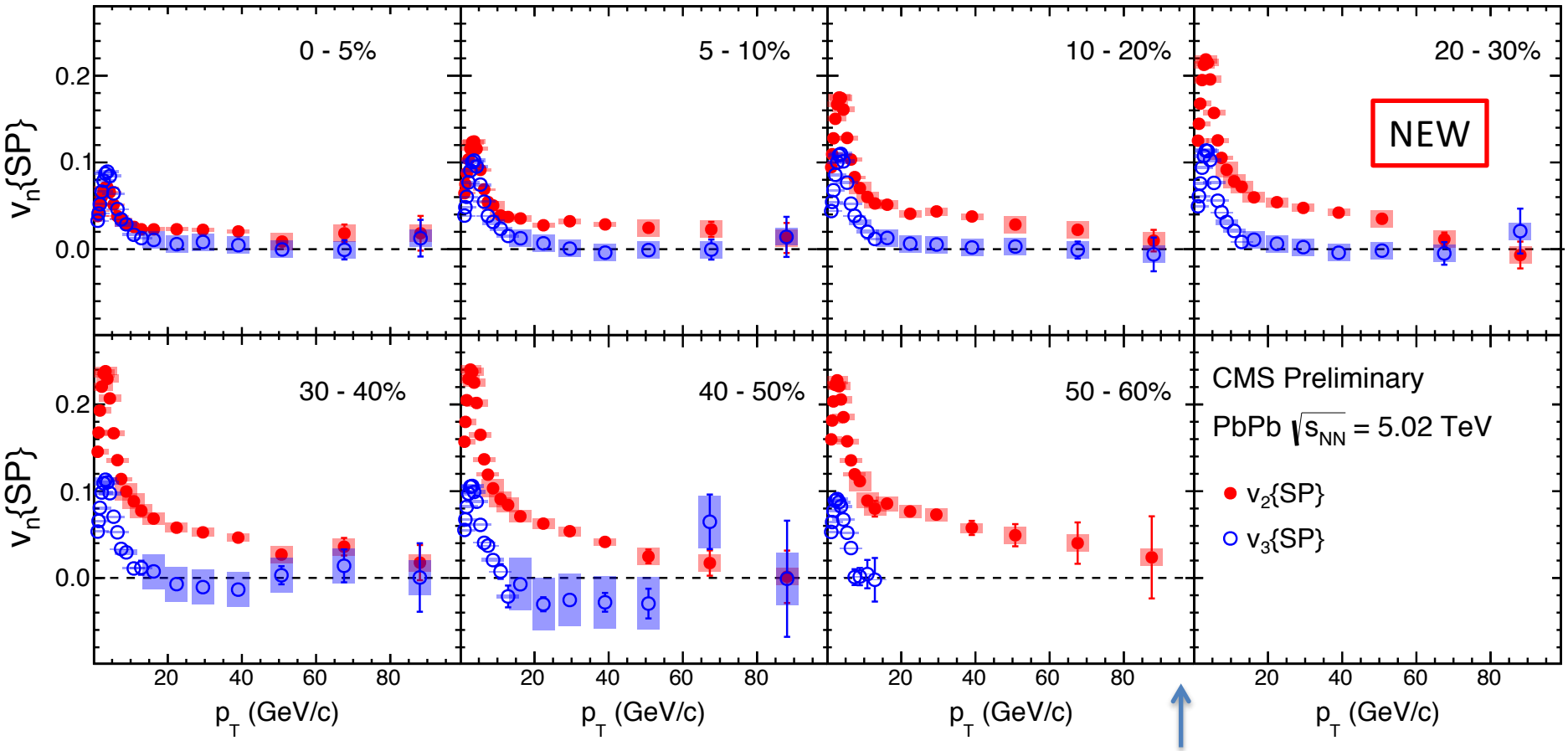


Link to plot

First time up to 100 GeV/c

- Non-zero v_2 at very high p_T, indicating energy loss depends on "directions" and/or initial state fluctuations

High-p_T v_3

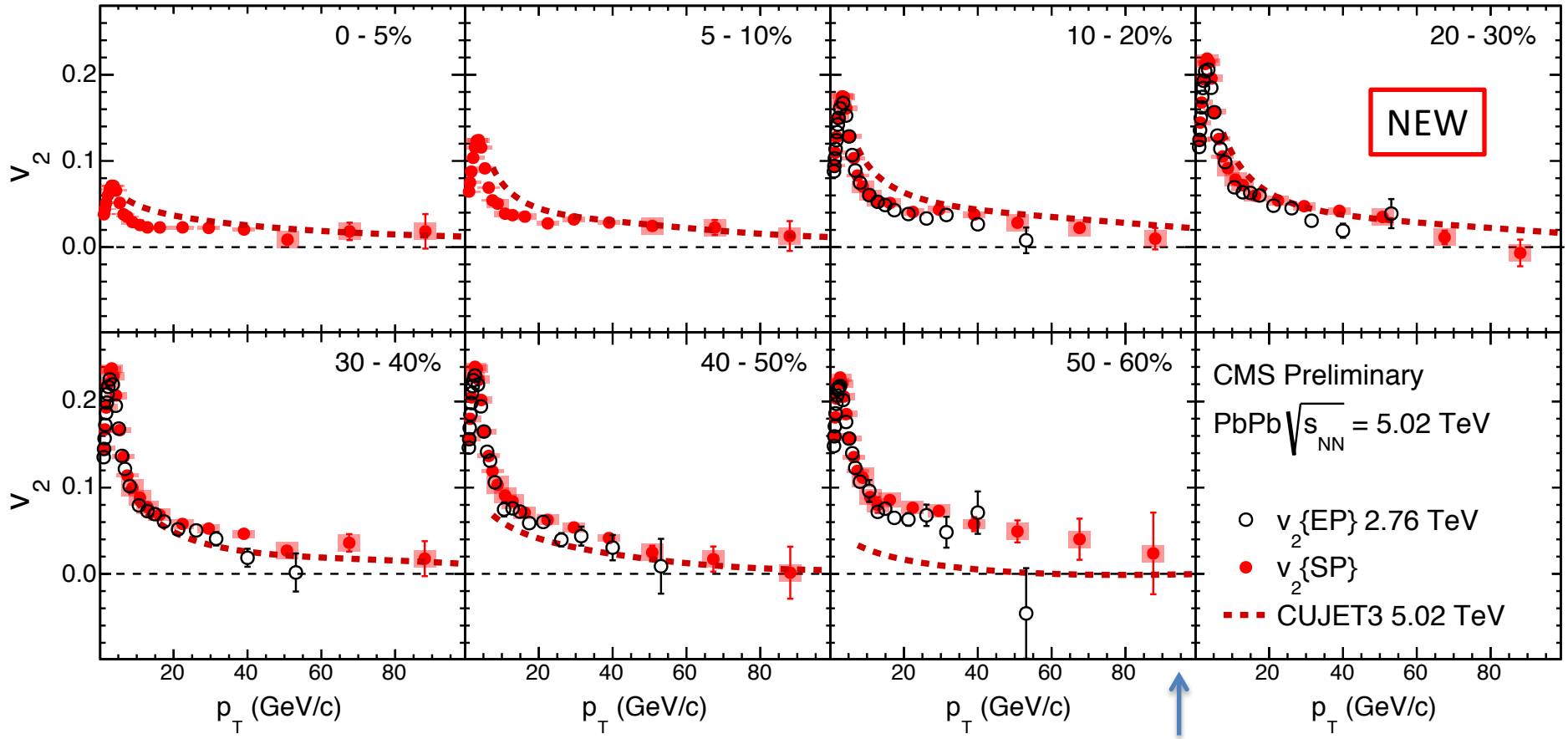


Link to plot

First time up to 100 GeV/c

- Non-zero v_2 at very high p_T, indicating energy loss depends on "directions" and/or initial state fluctuations
- First time measurement of high p_T v_3 up to 100 GeV!

High-p_T v_2 compare with theory



Link to plot

First time up to 100 GeV/c

- CUJET calculation can describe part of the data!
- Missing initial state fluctuations ?

$$v_n^{\text{high}}(p_T \gtrsim 10\,\text{GeV}) = \frac{\langle v_n^s v_n(p_T) \cos[n(\psi_n^s - \psi_n(p_T))]\rangle}{\sqrt{\langle (v_n^s)^2\rangle}},$$

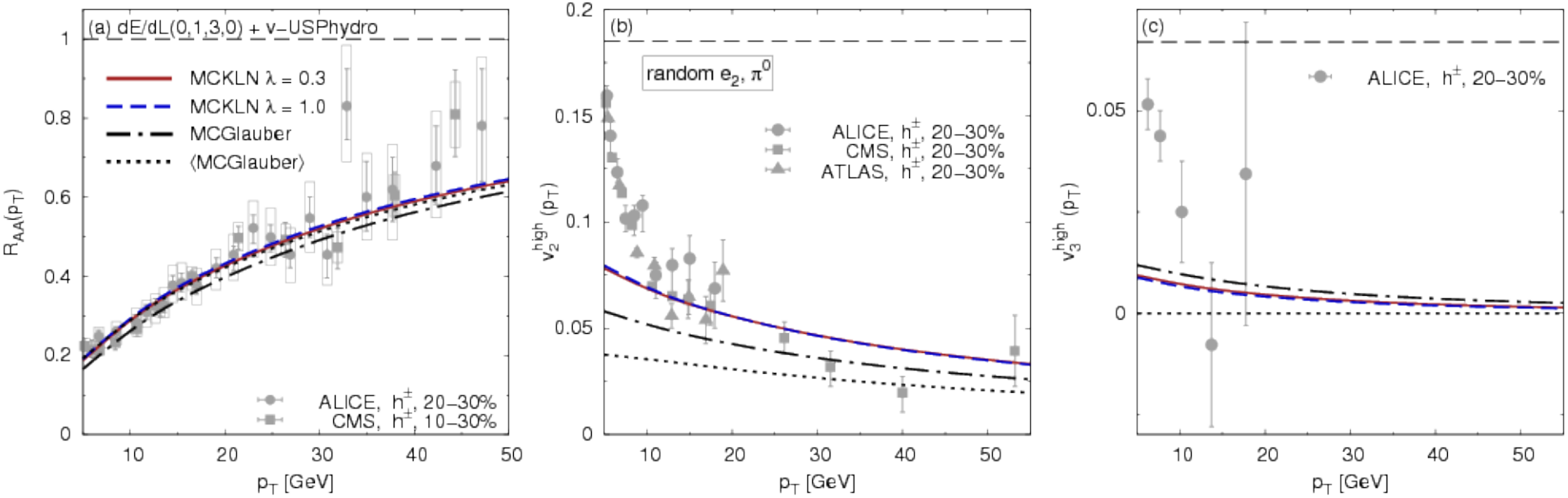
Soft

Hard

v_2 vs R_{AA}

$$R_{AA}(p_T) = \frac{d^2N_{ch}^{AA}/dp_T\,d\eta}{\langle T_{AA}\rangle\, d^2\sigma_{ch}^{pp}/dp_T\,d\eta}$$

- V_2 and R_{AA} both describe the energy loss of the medium
- But it's a puzzle to model them simultaneously



RUN1 DATA

arXiv:1602.03788

- Models with initial state fluctuations. Puzzle solved?

- Looking forward to 5 TeV calculations!

$$v_n^{\text{high}}(p_T \gtrsim 10\,\text{GeV}) = \frac{\langle v_n^s v_n(p_T) \cos[n(\psi_n^s - \psi_n(p_T))]\rangle}{\sqrt{\langle (v_n^s)^2\rangle}},$$

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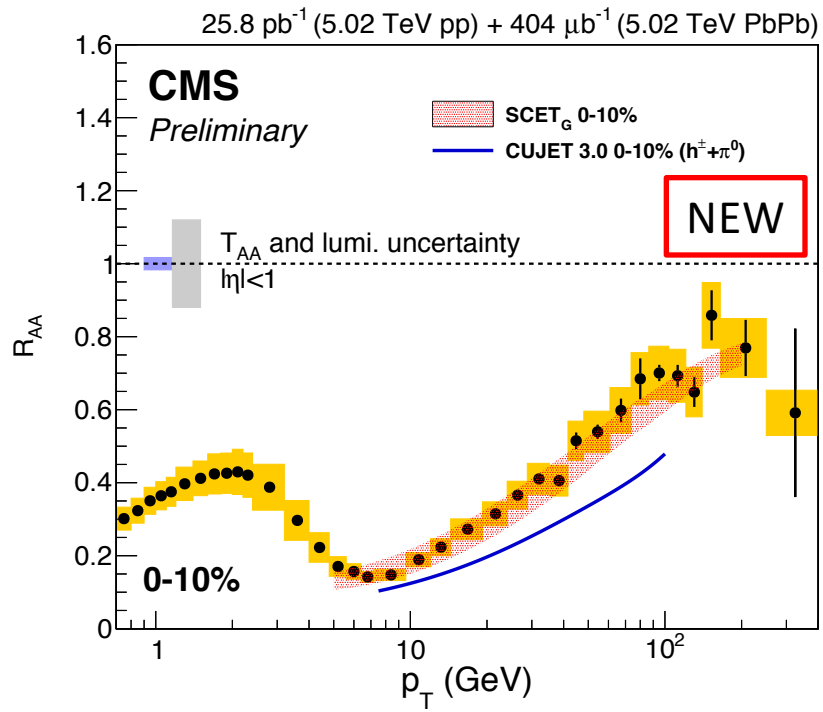
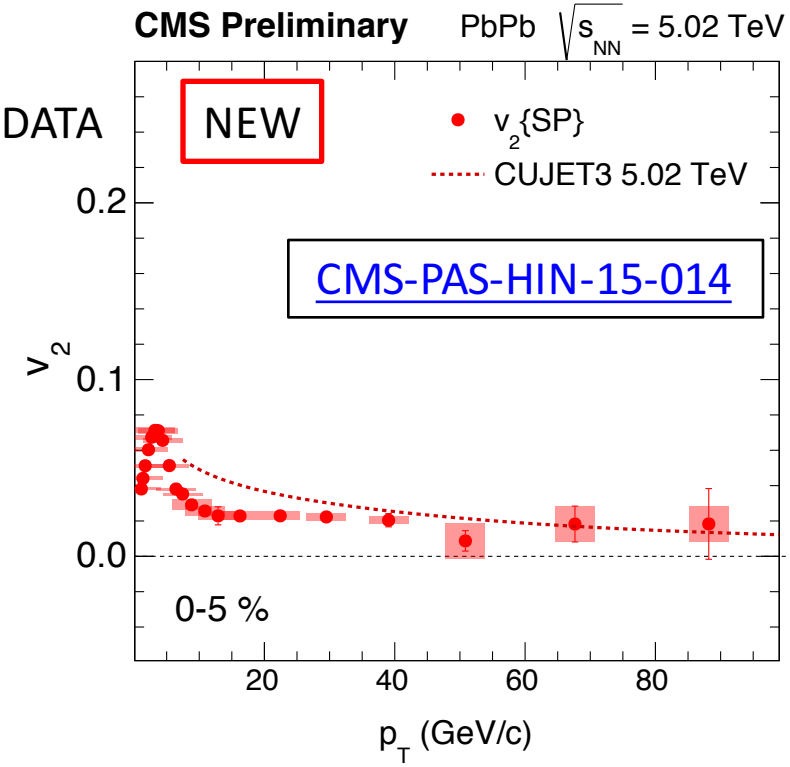


CMS-PAS-HIN-15-015

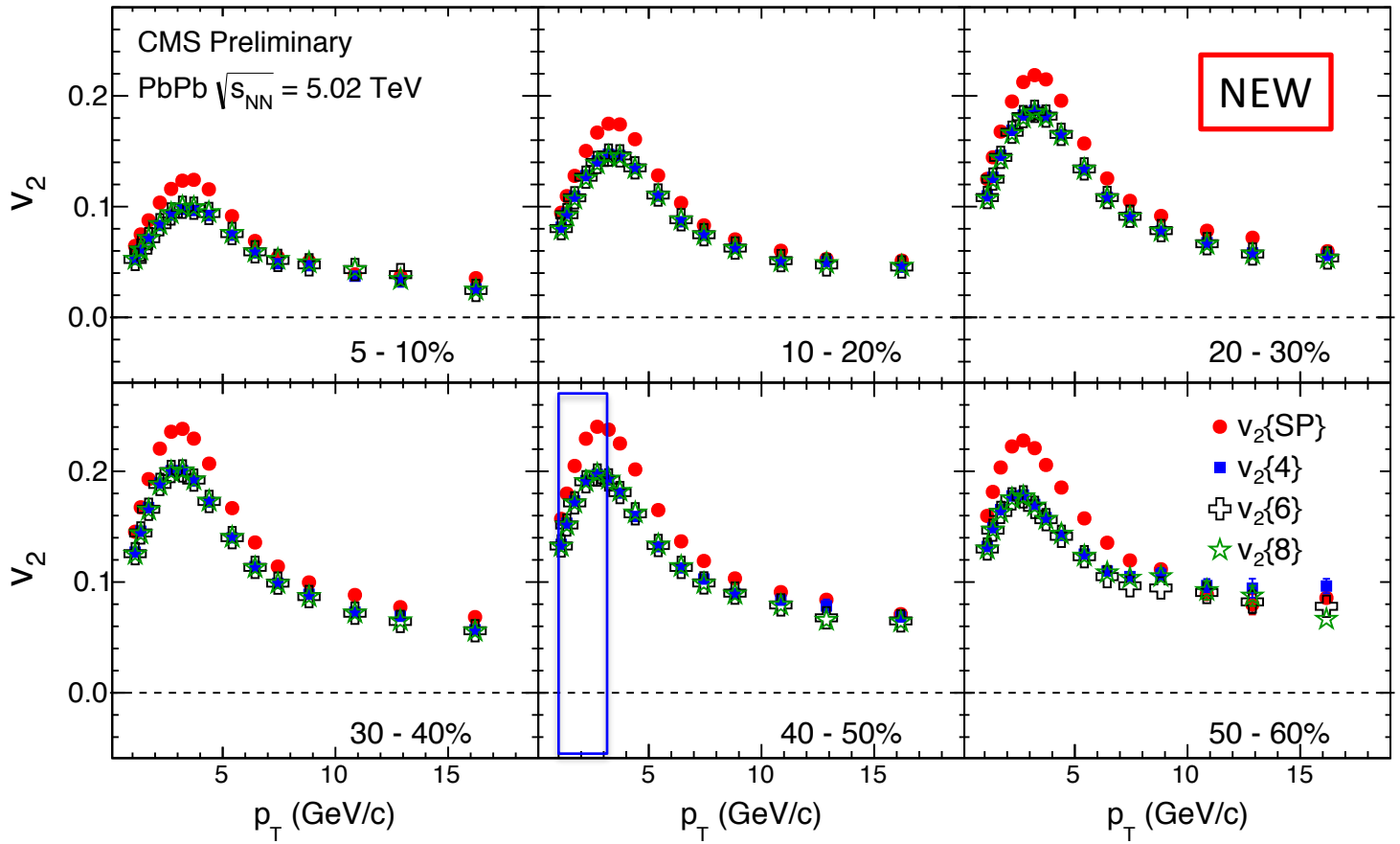
RUN2 DATA



CMS has measured both v_n and R_{AA} up to very high p_T @ 5 TeV!

Multi-particle v_2

$v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



- Collectivity observed in soft region from Run 1

Multi-particle v_2

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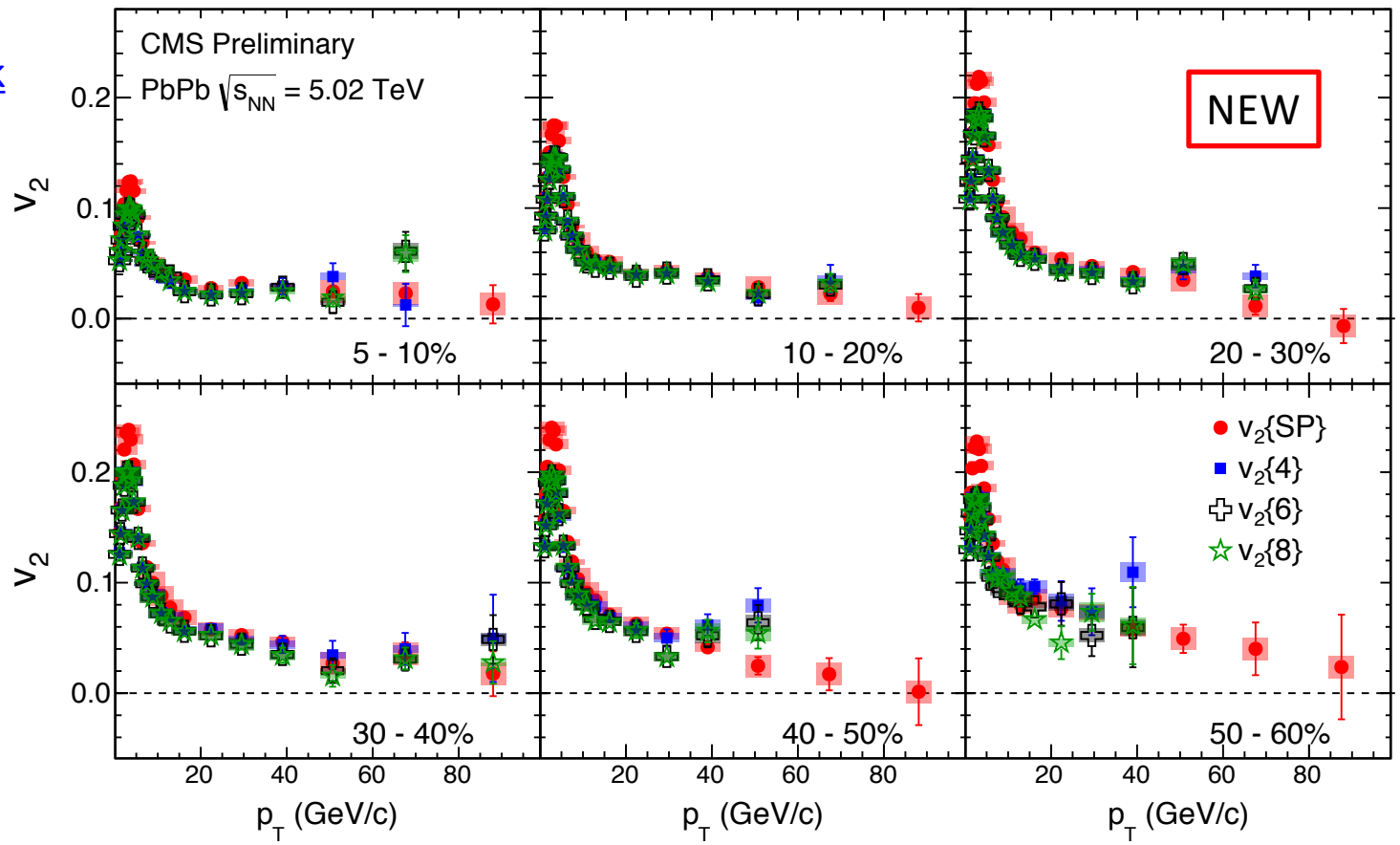
Link



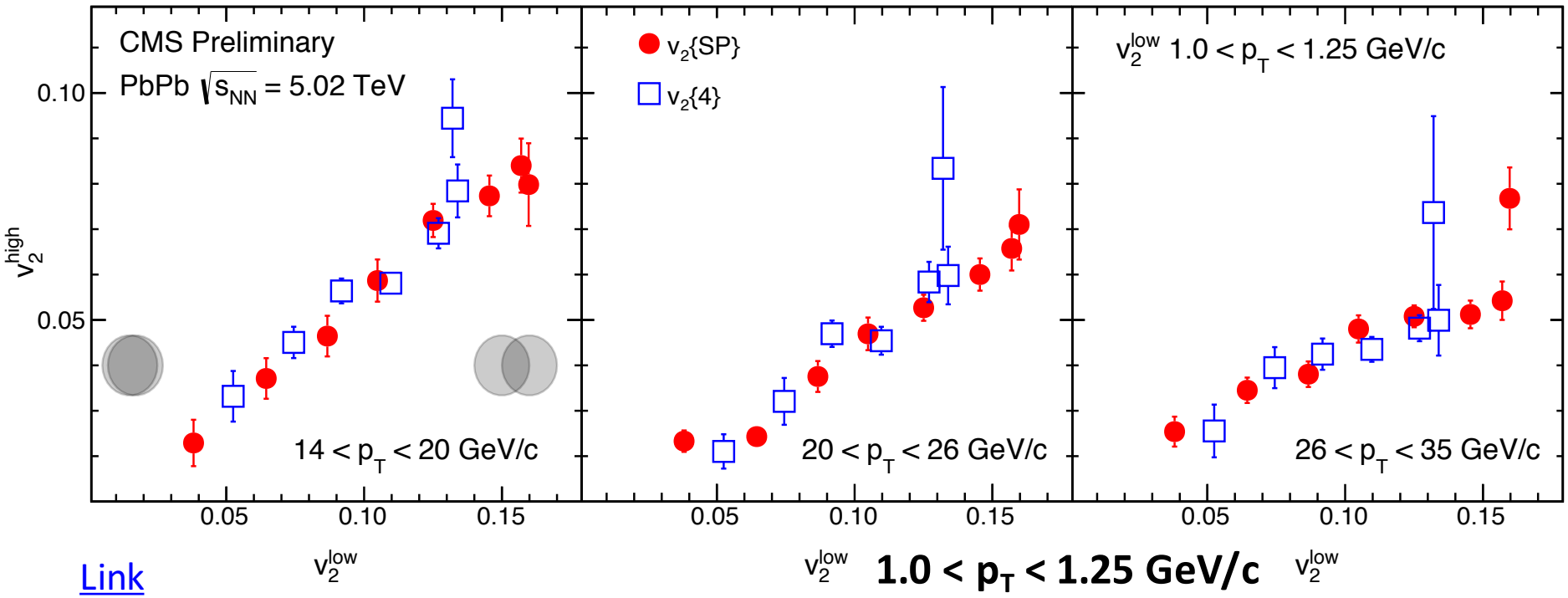
- Multi-particle v_2 measured up to 100 GeV/c

- Collectivity holds up to high p_T

Soft correlates with Hard?

Soft correlates with Hard?

NEW

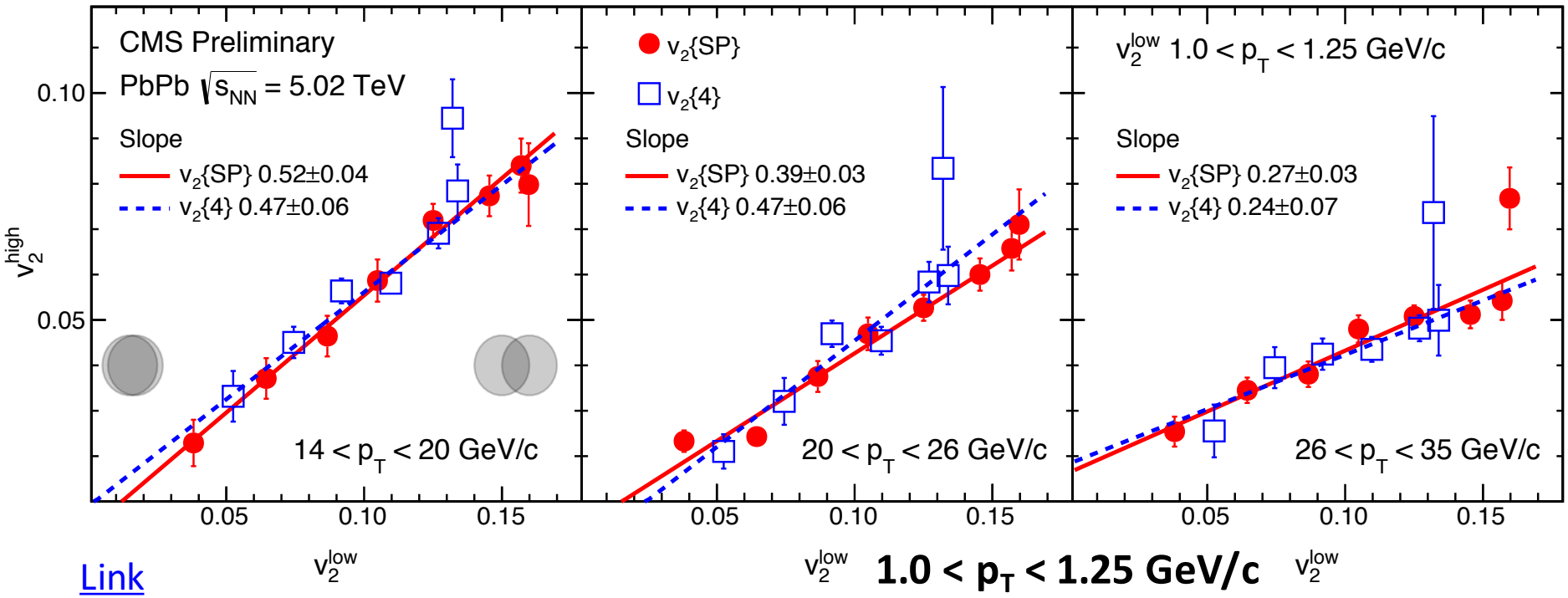


Link

- v_2 is linear between soft and hard particles as in different centralities

Soft correlates with Hard?

NEW



Link

v_2^{low} **$1.0 < p_T < 1.25$ GeV/c** v_2^{low}

- v_2 is linear between soft and hard particles as in different centralities
- Indicates similar origin of the correlation (Geometry + fluctuations)

What do we learn so far?

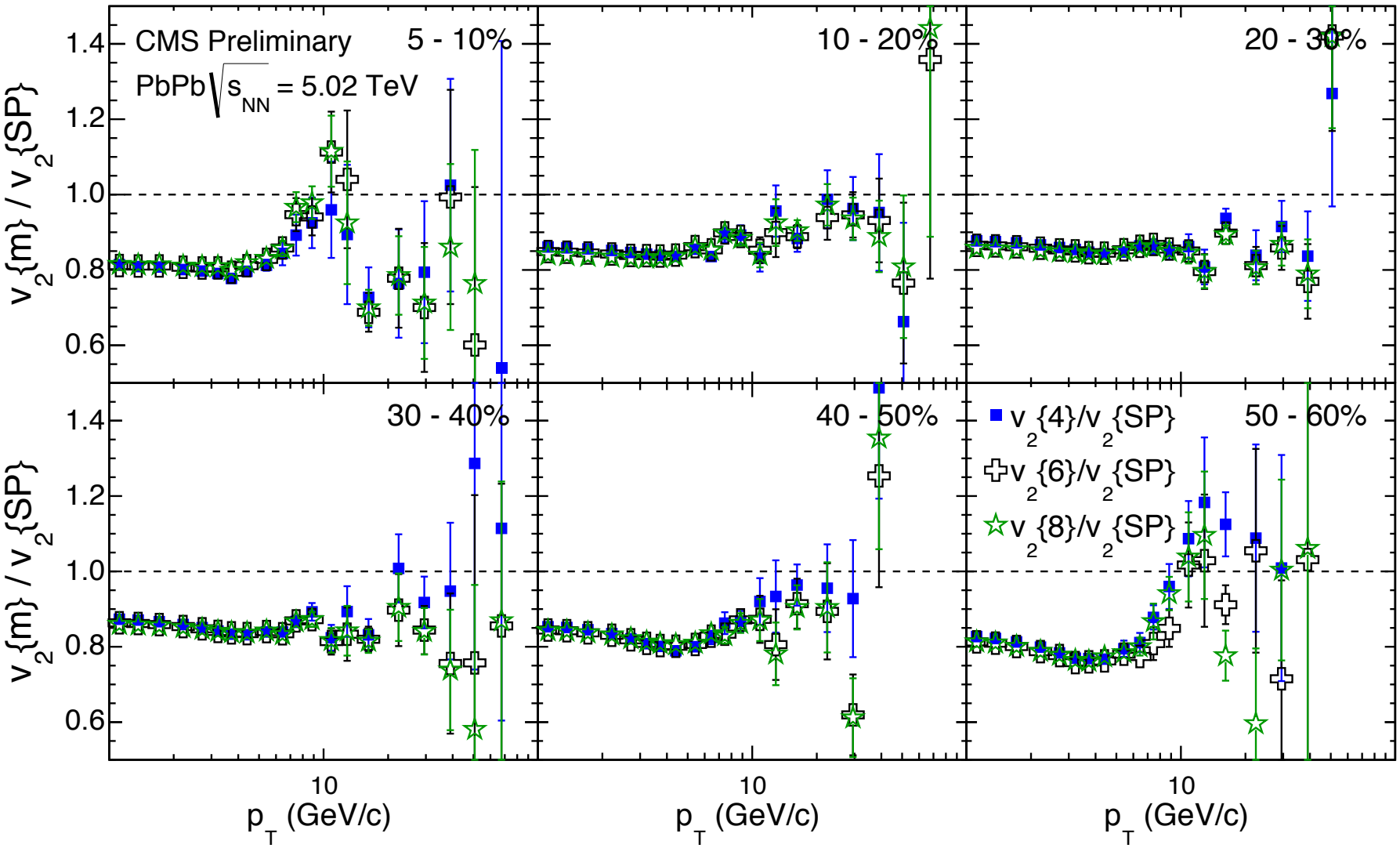
- V_n has been measured at the highest nuclear-nuclear energy @ 5TeV
  - V_2 & V_3 measured up to 100 GeV/c → constrain the energy loss models
  - Multi-particle correlation → collectivity from soft region to intermediate (hard) region
  - Strong correlation between soft (low p_T) and hard (high p_T) particles → same origin

Link to Physics Analysis Summary (PAS)

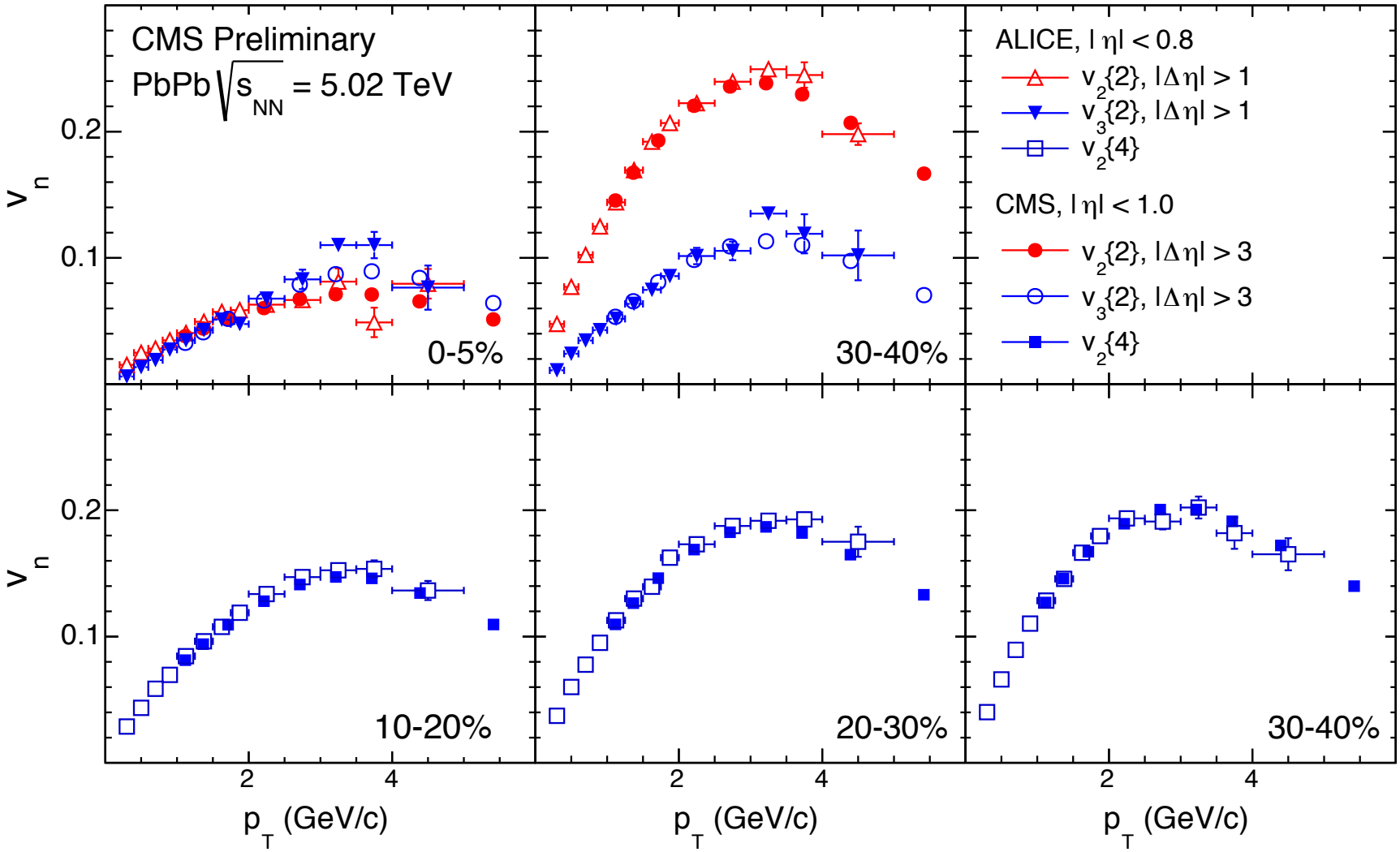
Stay tuned! pPb @ 8 TeV is coming later this year

Backups

Backups


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
5 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
$v_2\{4\}/v_2\{SP\}$
$v_2\{6\}/v_2\{SP\}$
$v_2\{8\}/v_2\{SP\}$
$v_2\{m\} / v_2\{SP\}$
p_T (GeV/c)

Backups



Phys.Rev.Lett. 116 (2016) 132302

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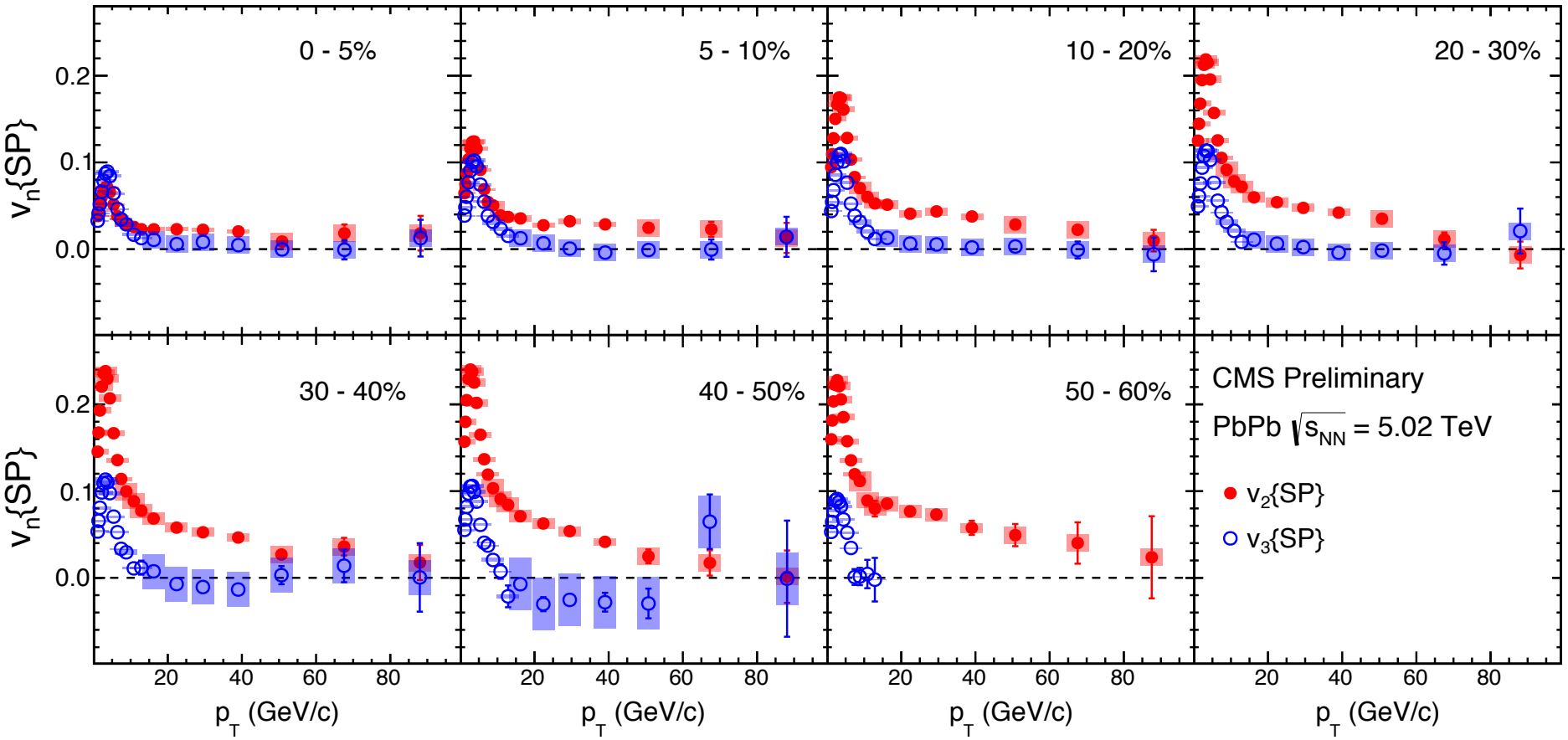
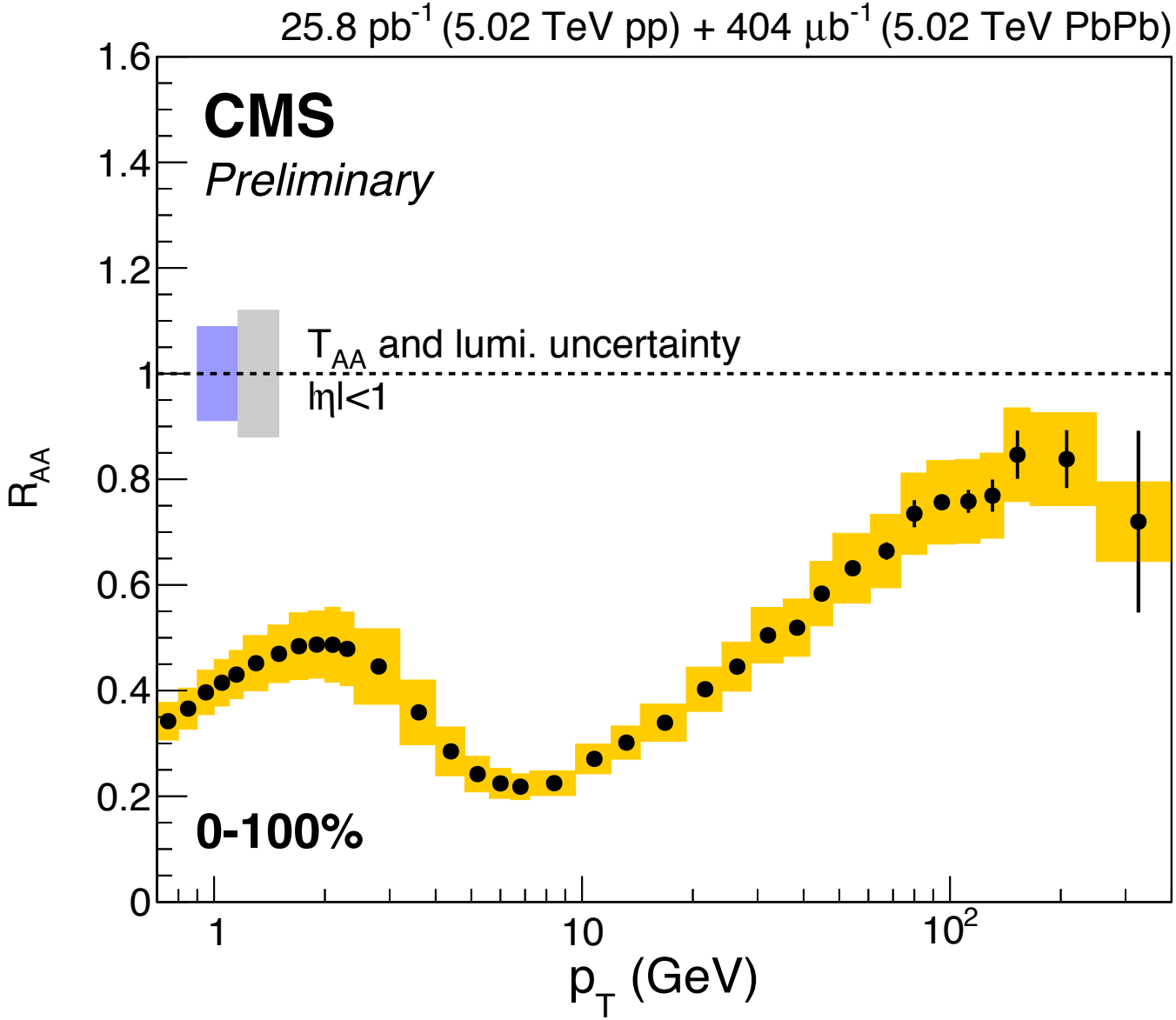
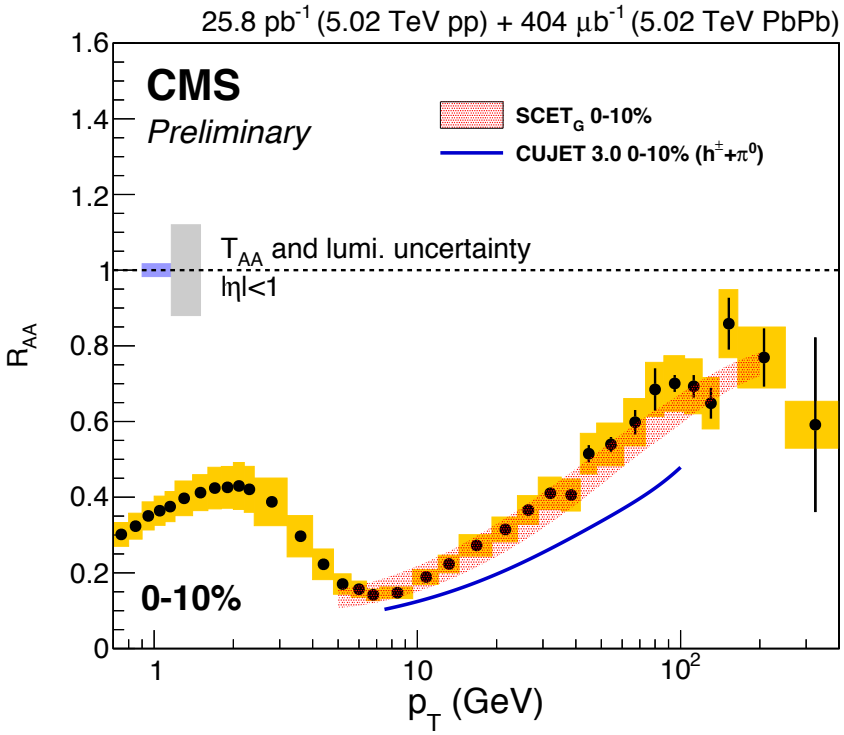


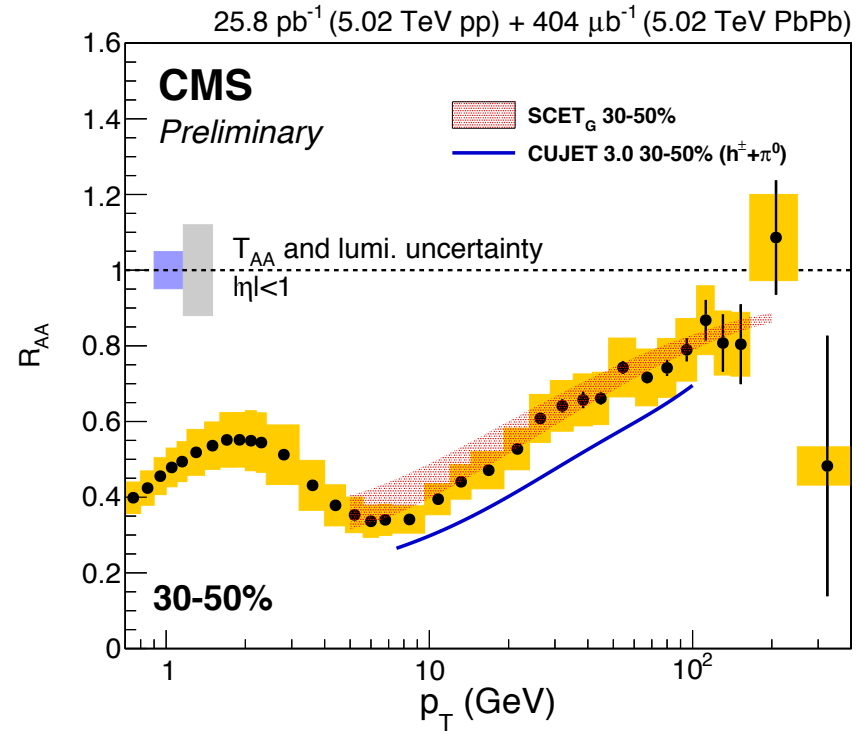
- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for p_T > 20 GeV/c

Backups


25.8 pb^{-1} (5.02 TeV pp) + 404 μb^{-1} (5.02 TeV PbPb)
CMS
Preliminary
T_{AA} and lumi. uncertainty
|η|<1
0-100%
R_{AA}
p_T (GeV)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2

Backups


25.8 pb^{-1} (5.02 TeV pp) + 404 μb^{-1} (5.02 TeV PbPb)
CMS
Preliminary
SCET$_G$ 0-10%
CUJET 3.0 0-10% (h$^{\pm}$+π^0)
T$_{AA}$ and lumi. uncertainty
|η|<1
0-10%
R$_{AA}$
p$_T$ (GeV)


25.8 pb^{-1} (5.02 TeV pp) + 404 μb^{-1} (5.02 TeV PbPb)
CMS
Preliminary
SCET$_G$ 30-50%
CUJET 3.0 30-50% (h$^{\pm}$+π^0)
T$_{AA}$ and lumi. uncertainty
|η|<1
30-50%
R$_{AA}$
p$_T$ (GeV)