Overview of CMS results from heavy-ion collisions

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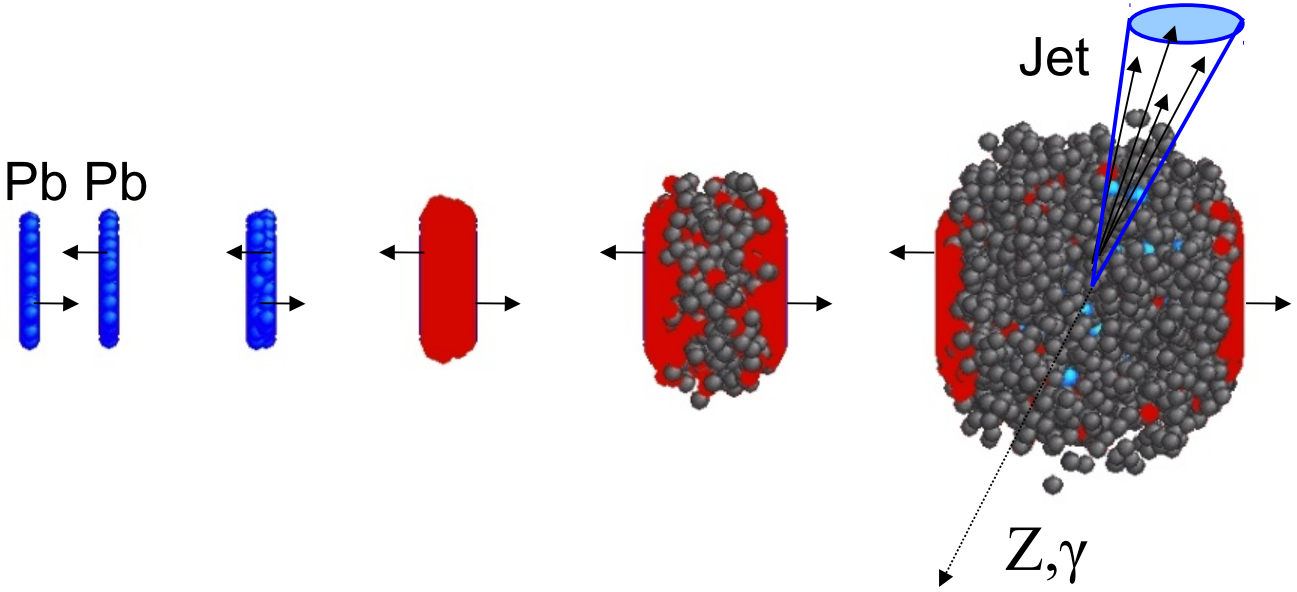
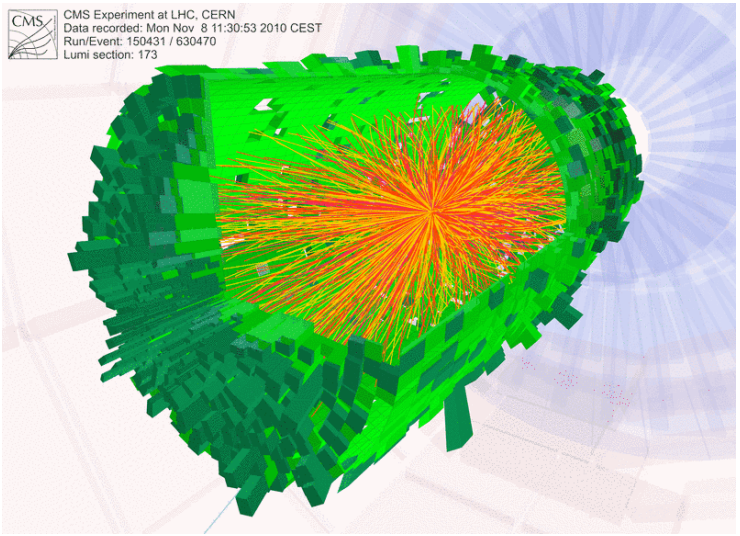
for the CMS Collaboration

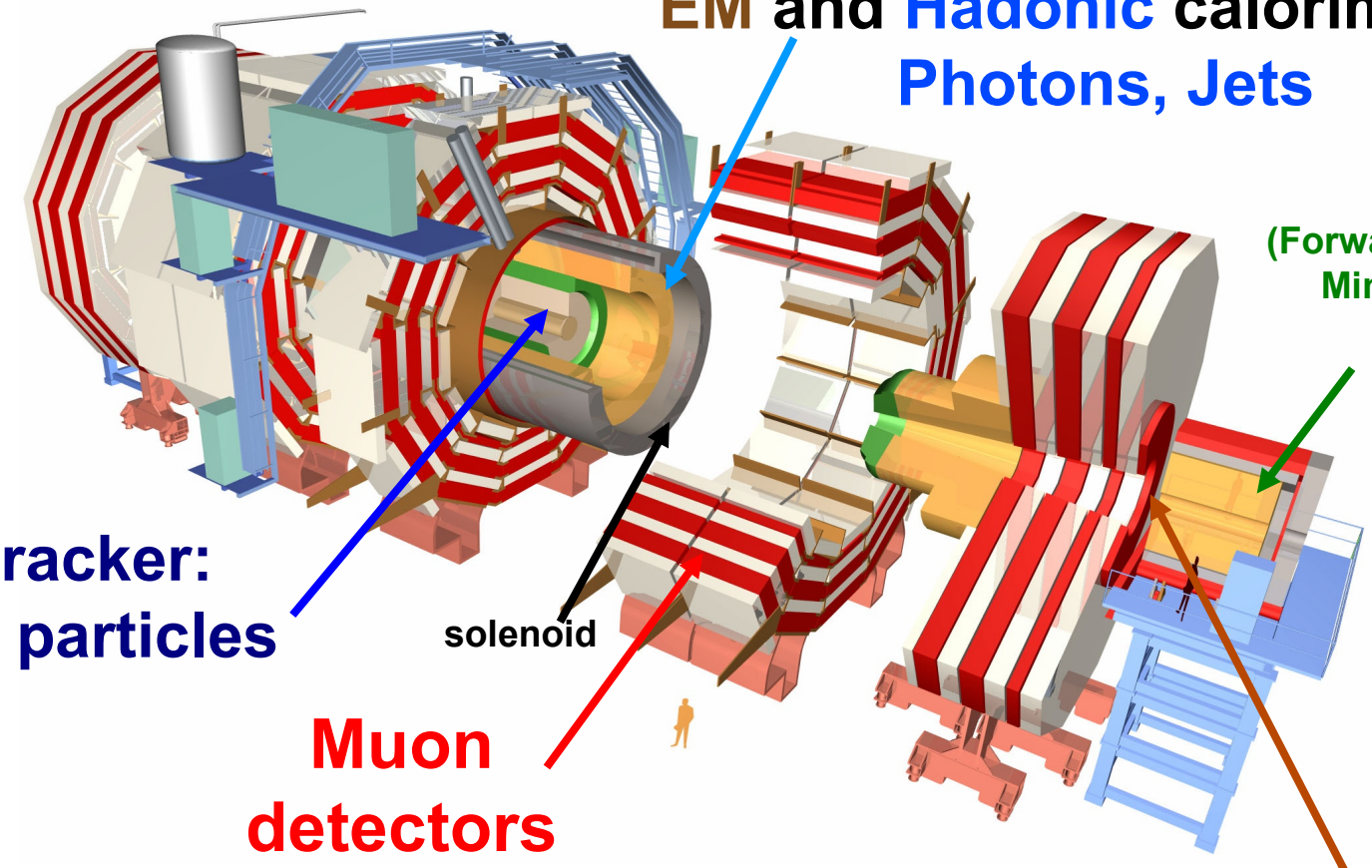
CMS studies of the PbPb collision

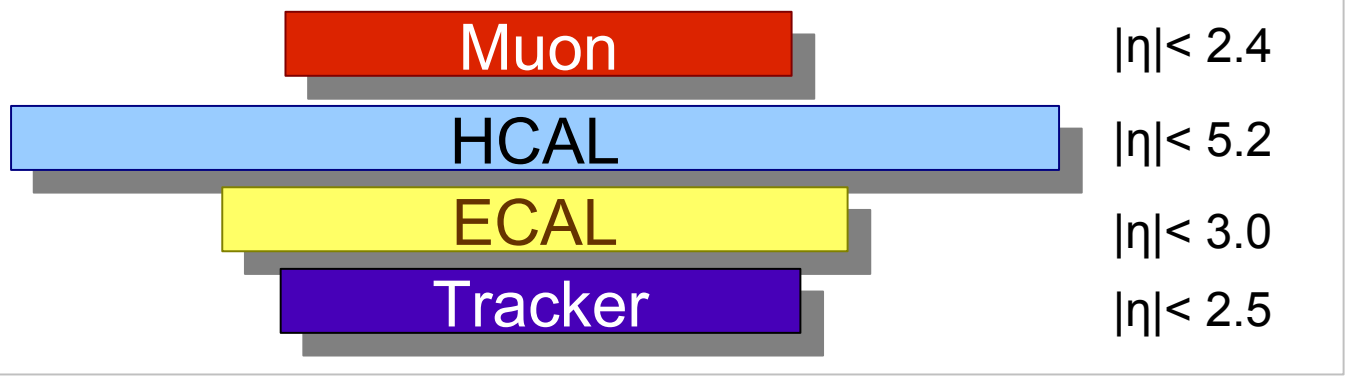




- Bulk property: charged particle production, elliptic flow, two-particle correlations
- Study of the initial state: Z and photons
- Study of the medium property:
  - Medium modification to hard probes
  - Quarkonium

CMS detector





Data taking during PbPb run

CMS configured in a dedicated mode for heavy ions

Turn off zero suppression

Taking data at up to 220 Hz

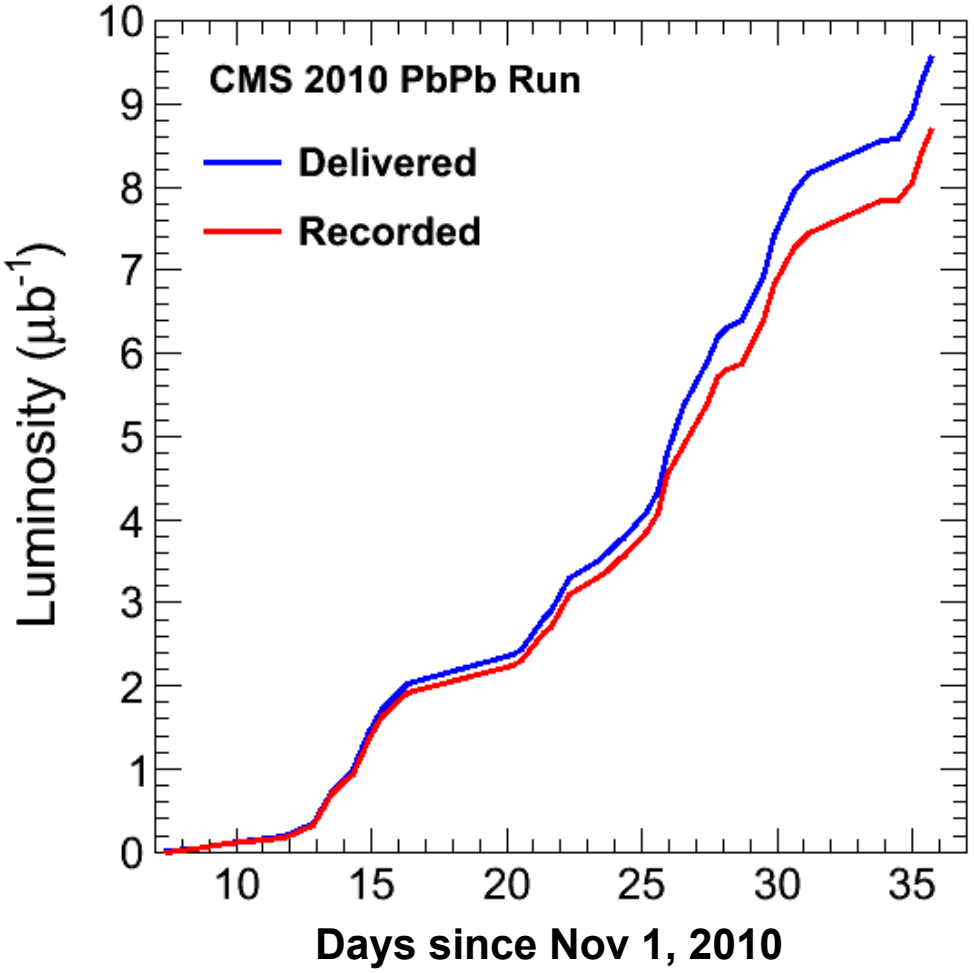
12 MB event size

Triggering on minimum bias, jets, muons and photons

ALL rare probes written to tape

~half of minimum bias written

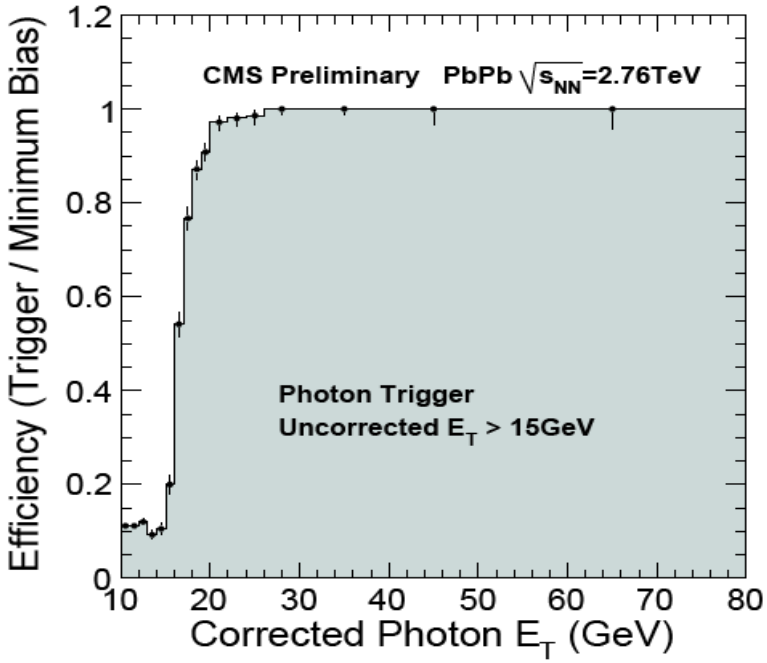
Recorded luminosity PbPb 8.7 μb-1
Recorded luminosity pp@2.76 TeV 241 nb-1
Total PbPb data volume ~0.89 PetaByte

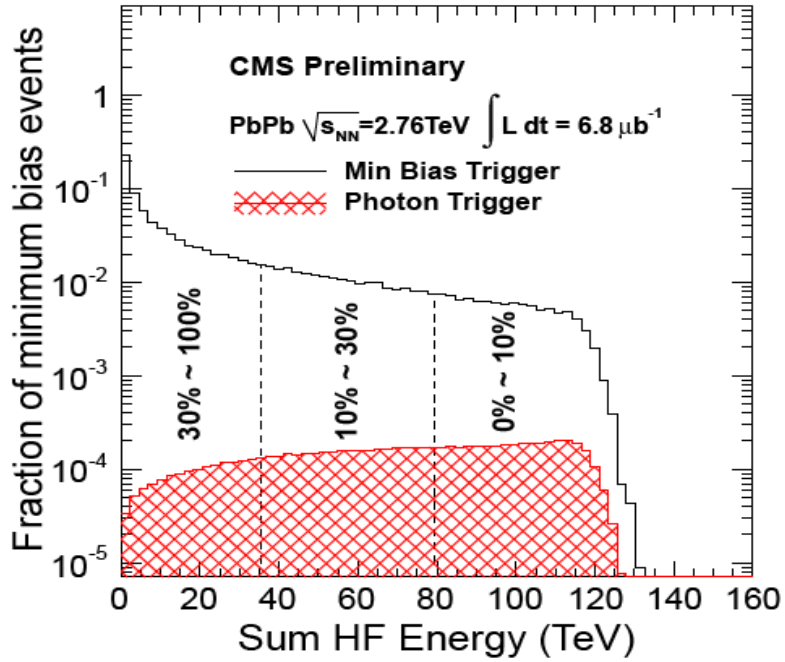


Note: luminosities will be rescaled by few% after complete analysis of Van der Meer scans

Trigger and event selection

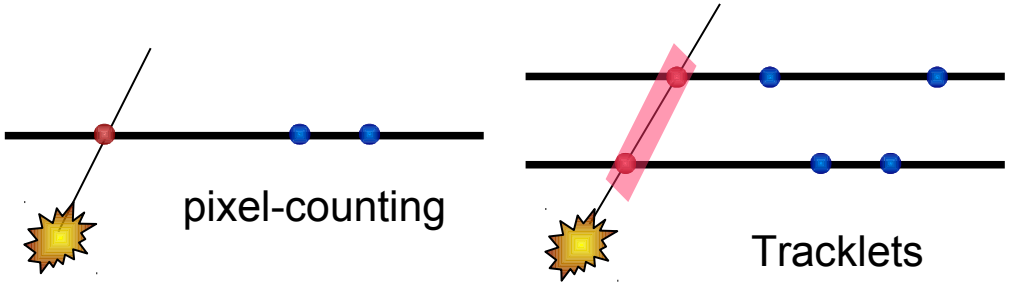
- MinBias Trigger:
  - Coincidence of BSC or Forward calorimeter signal
  - Trigger efficiency: 97% ± 3%
- Di-Muon Trigger:
  - Two reconstructed tracks in the muon detector with p_T > 3 GeV/c
- Photon Trigger:
  - Uncorrected photon E_T> 15 GeV
- Jet Trigger: [gives high p_T reach]
  - Uncorrected jet E_T> 35, 50 GeV
- Centrality determination:
  - Forward calorimeter (HF) energy

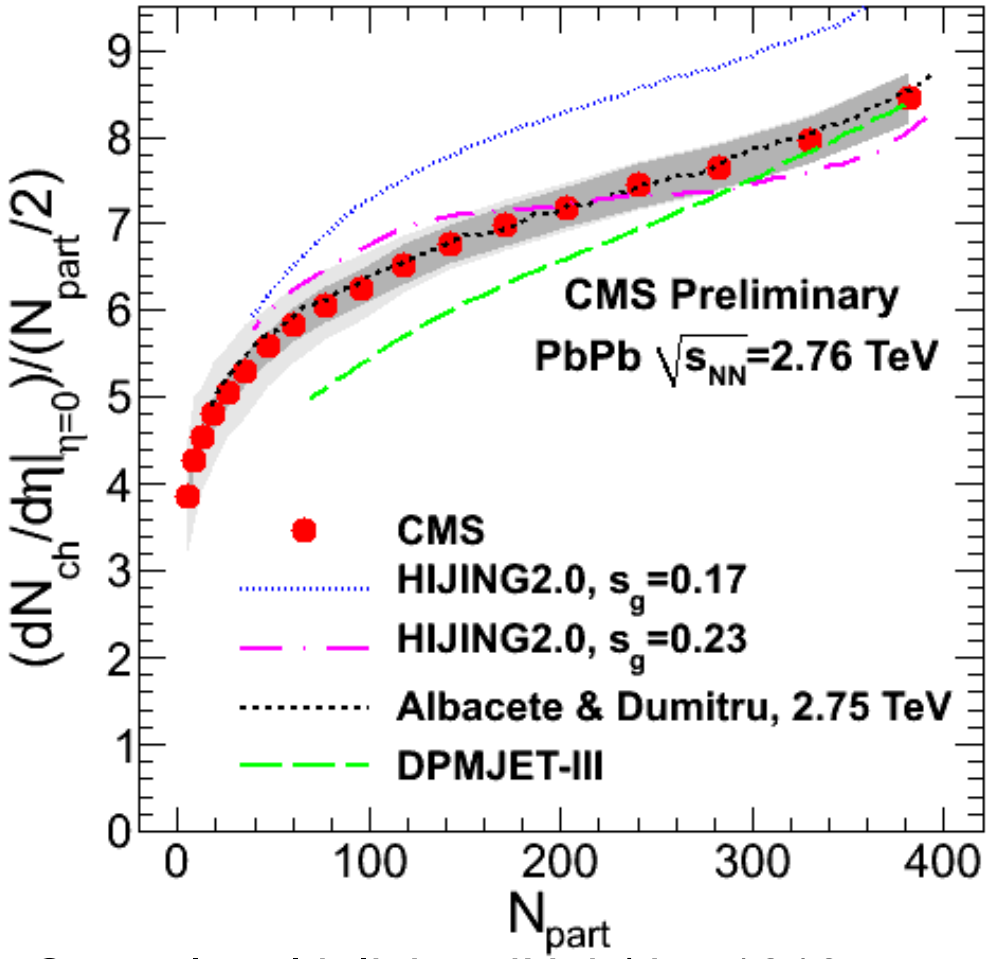


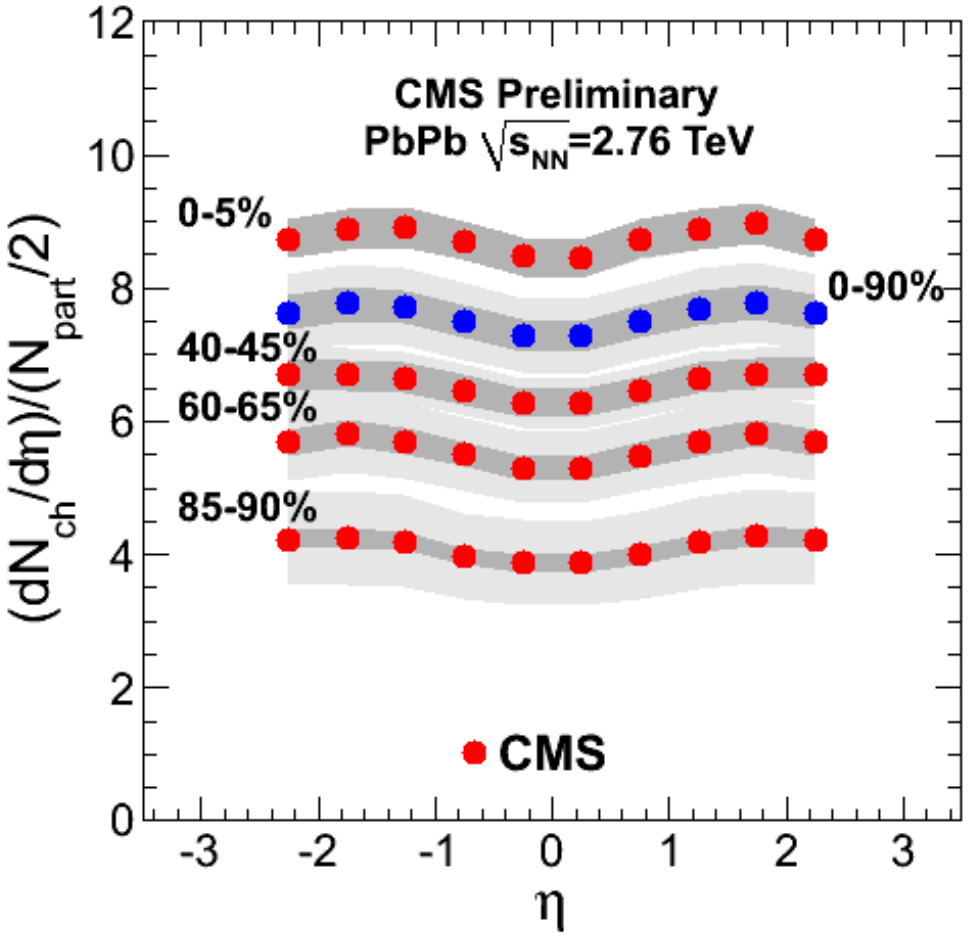


Charged particle multiplicity

Uses pixel tracker and two methods
Data taken with no magnetic field, B=0T
Trigger with 99% efficiency,
1% UPC contamination







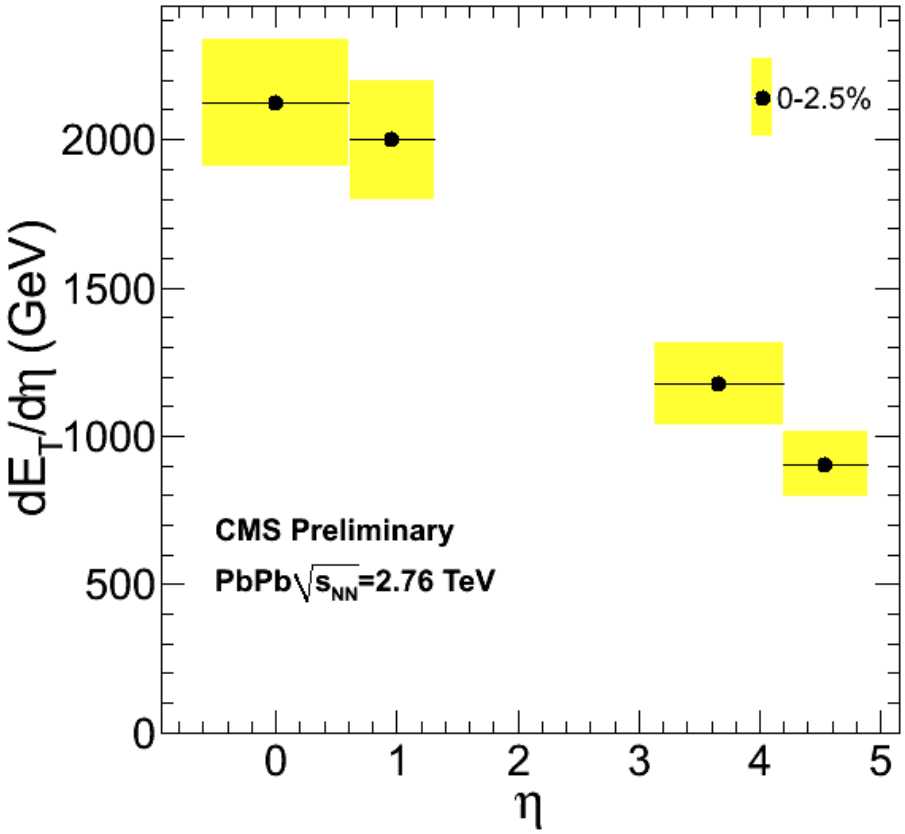
Central multiplicity dNch/dη=1610 ± 55 for 0-5% centrality

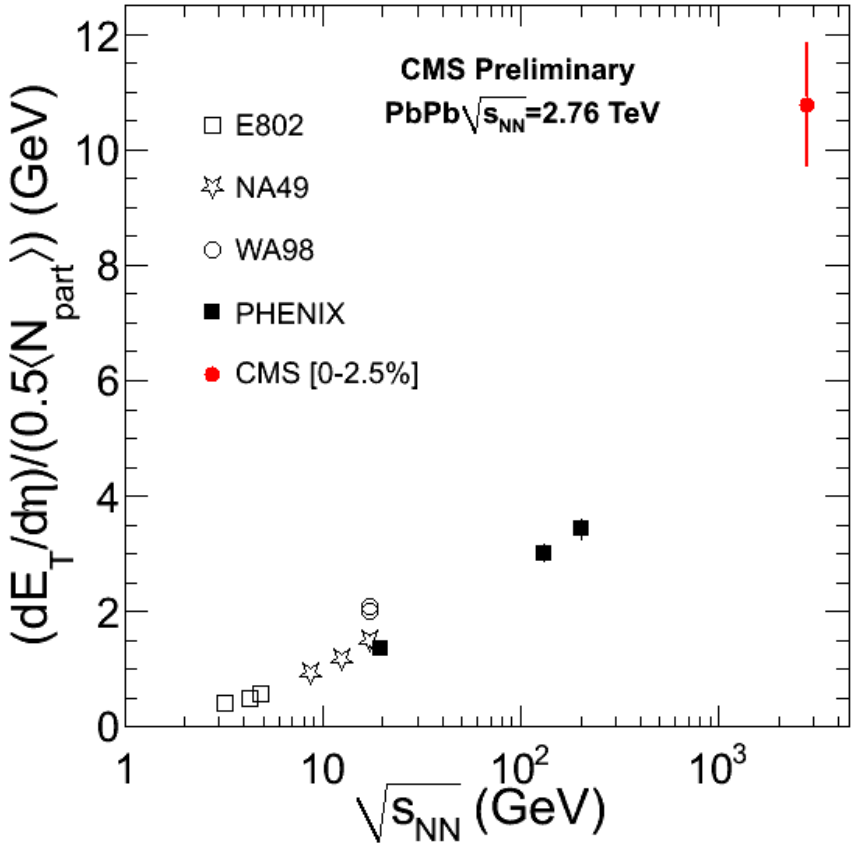
CMS PAS HIN-10-001

dET/dη: 2 TeV at mid-rapidity

Three times larger than at RHIC energies

Measured over wide range of pseudorapidity

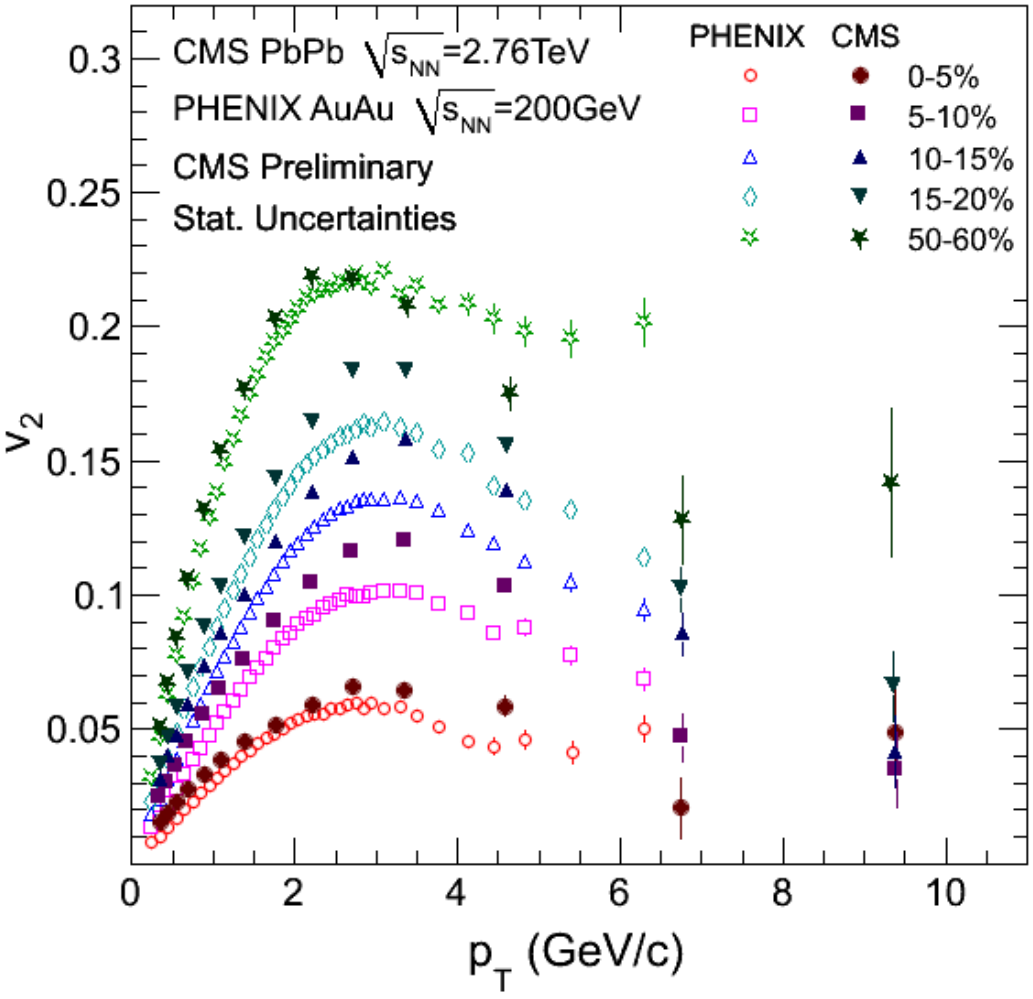


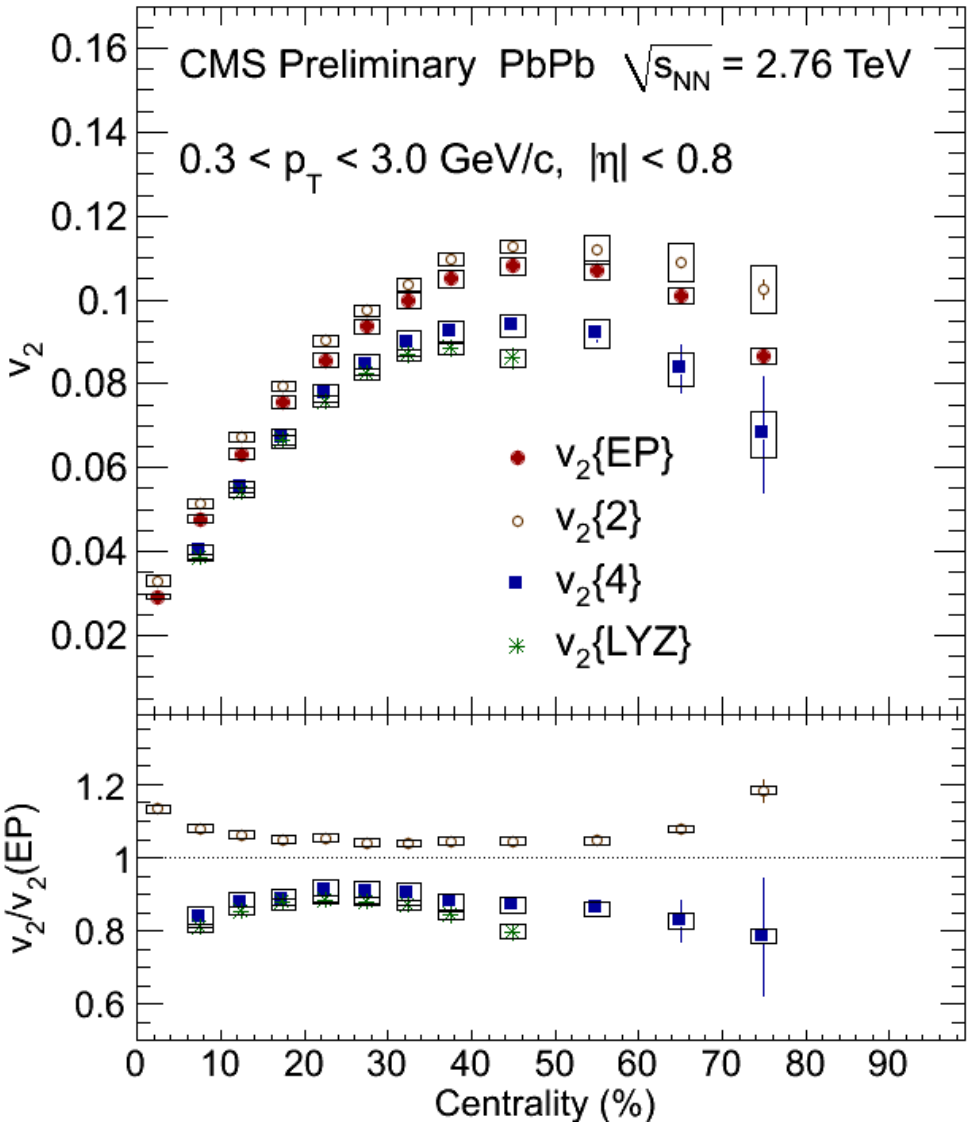


CMS PAS HIN-11-003

v_2 at mid-η

CMS PAS HIN-10-002

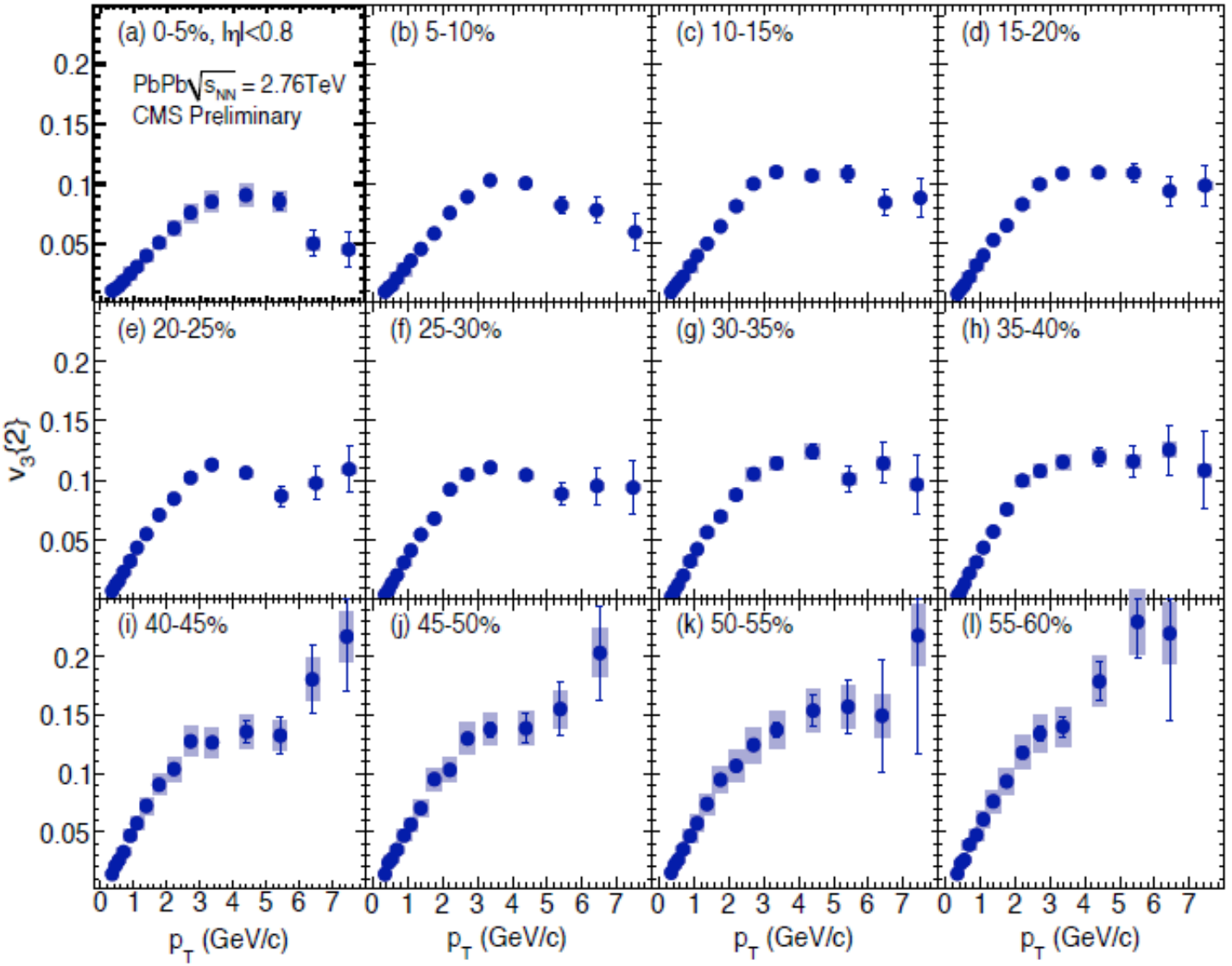


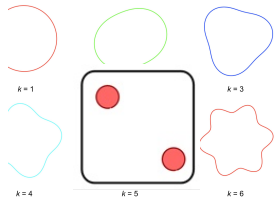


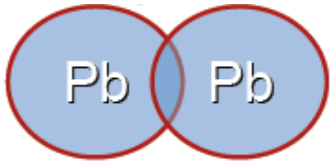
Magnitude is similar to what is seen at RHIC

v_2 rises up to 40-50% , then decreases

$v_3(p_T)$ at mid-rapidity $|\eta|< 0.8$







Sizable signal; weak centrality dependence

v3 at mid-rapidity driven by fluctuations

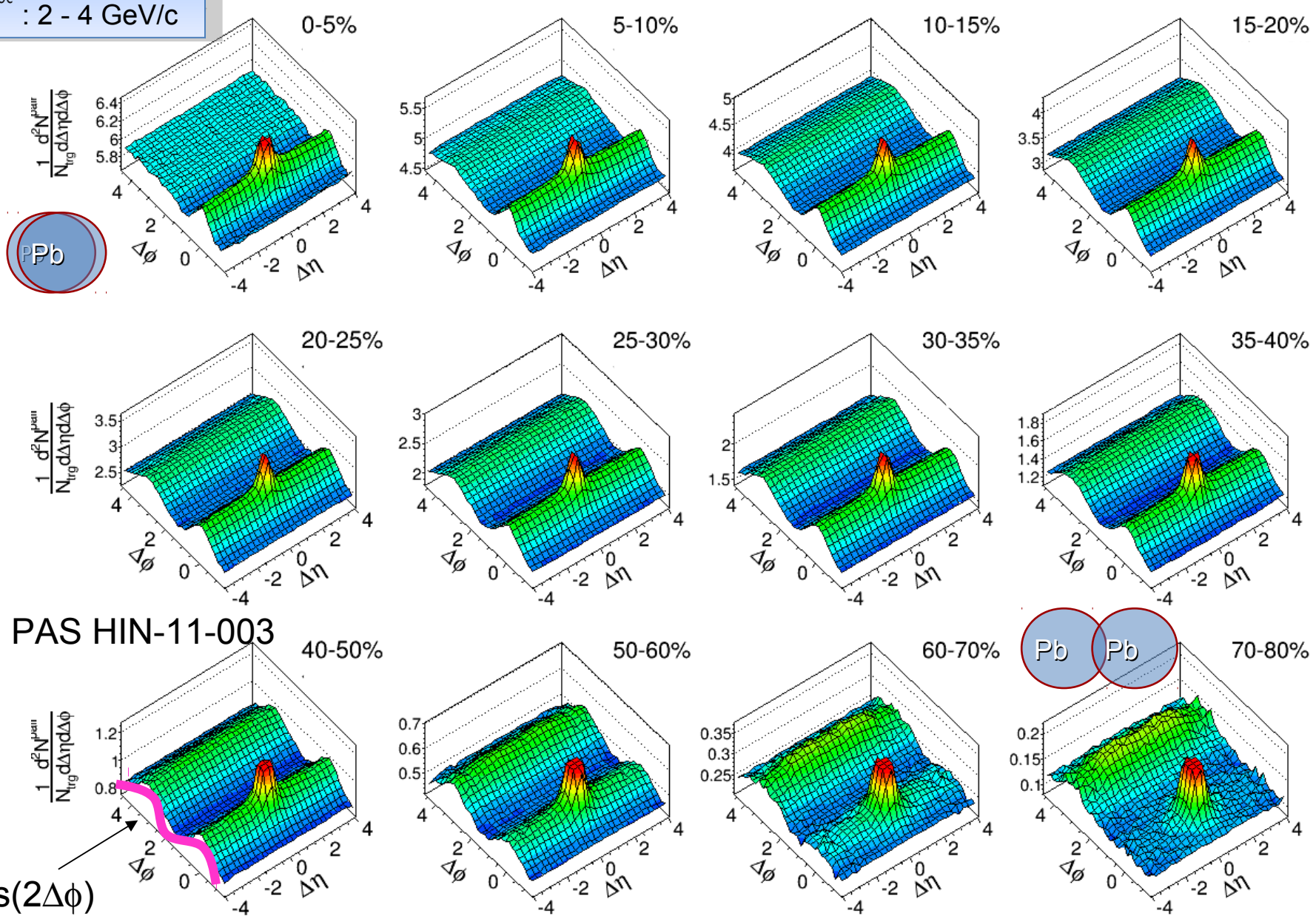
CMS PAS HIN-11-005

Two-particle correation: Centrality dependence in PbPb

p_T^{trig} : 4 - 6 GeV/c
p_T^{assoc} : 2 - 4 GeV/c

PbPb 2.76 TeV

CMS Preliminary

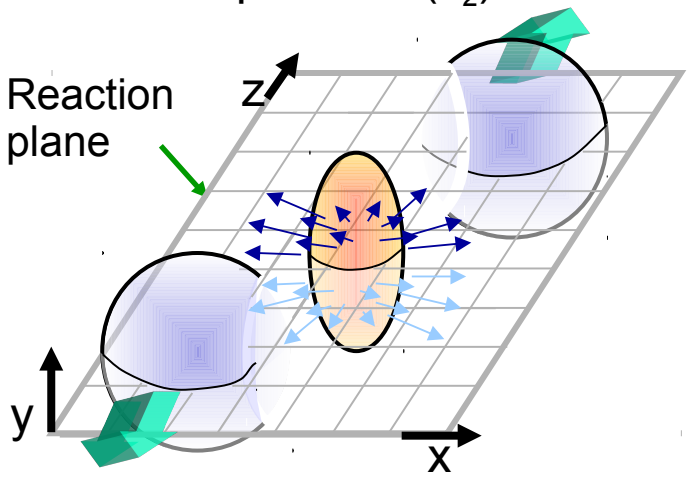


CMS PAS HIN-11-003

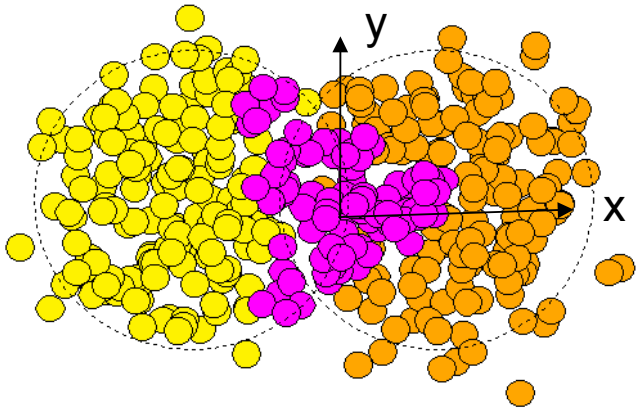
Fourier analysis

It was recently realized that the ridge may be induced just by higher order flow terms (v_2, v_3, v_4, v_5, …)

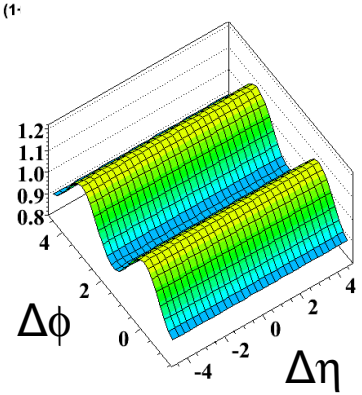
Elliptic flow (v_2)



Triangular flow (v_3) from event-by-event fluctuation

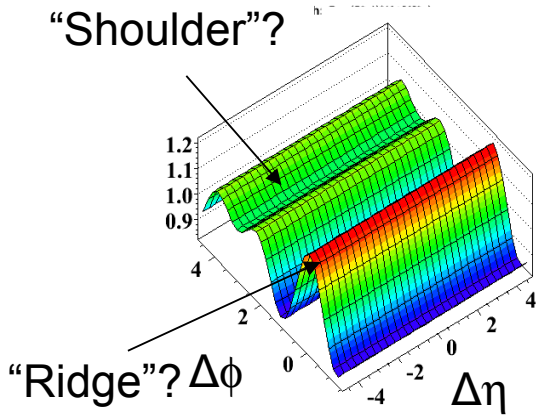


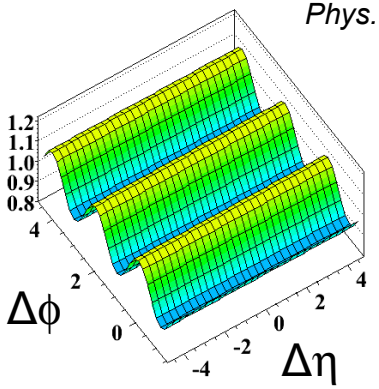
Phys. Rev. C81:054905, 2010



~ $V_2 \cos(2\Delta\phi)$

Add V_2 and V_3



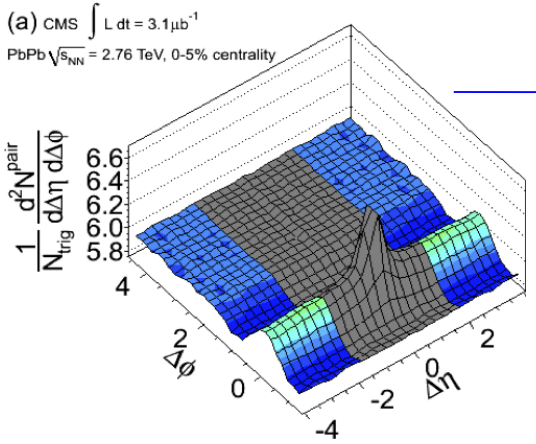


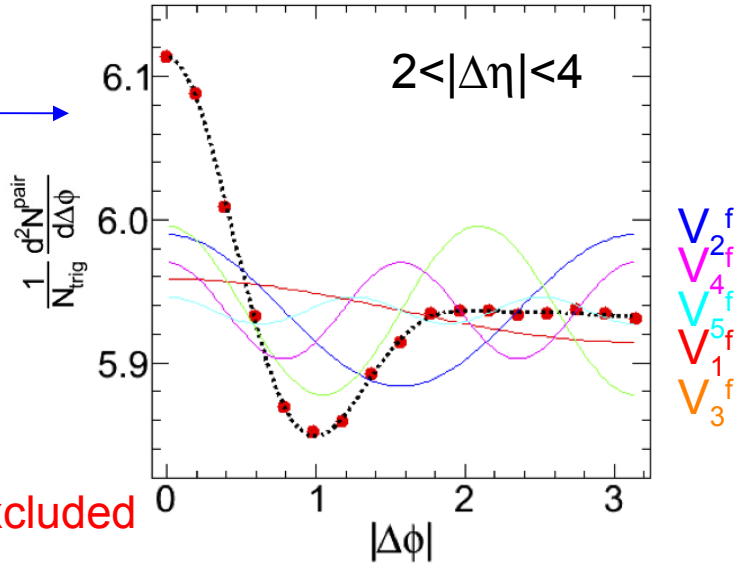
~ $V_3 \cos(3\Delta\phi)$

Fourier analysis of Δϕ correlations

Fourier decomposition

$$\frac{1}{N_{\text{trig}}}\frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left\{1 + \sum_{n=1}^{\infty} 2V_{n\Delta}\cos(n\Delta\phi)\right\}$$





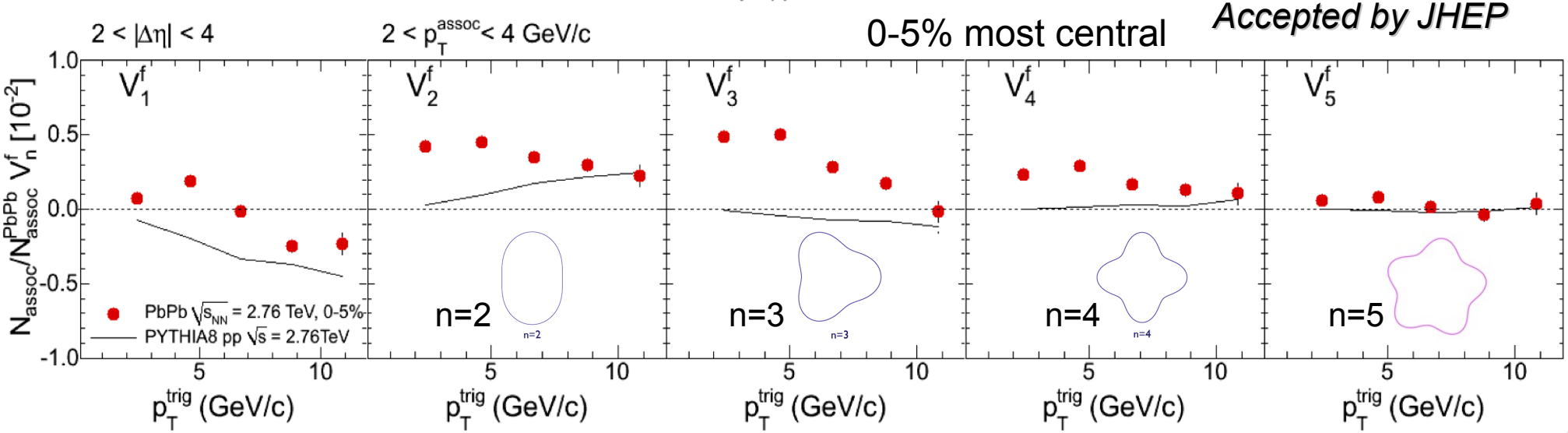
Flow driven correlations:

$$V_{n\Delta} \sim v_n^{\text{trig}} \times v_n^{\text{assoc}}$$

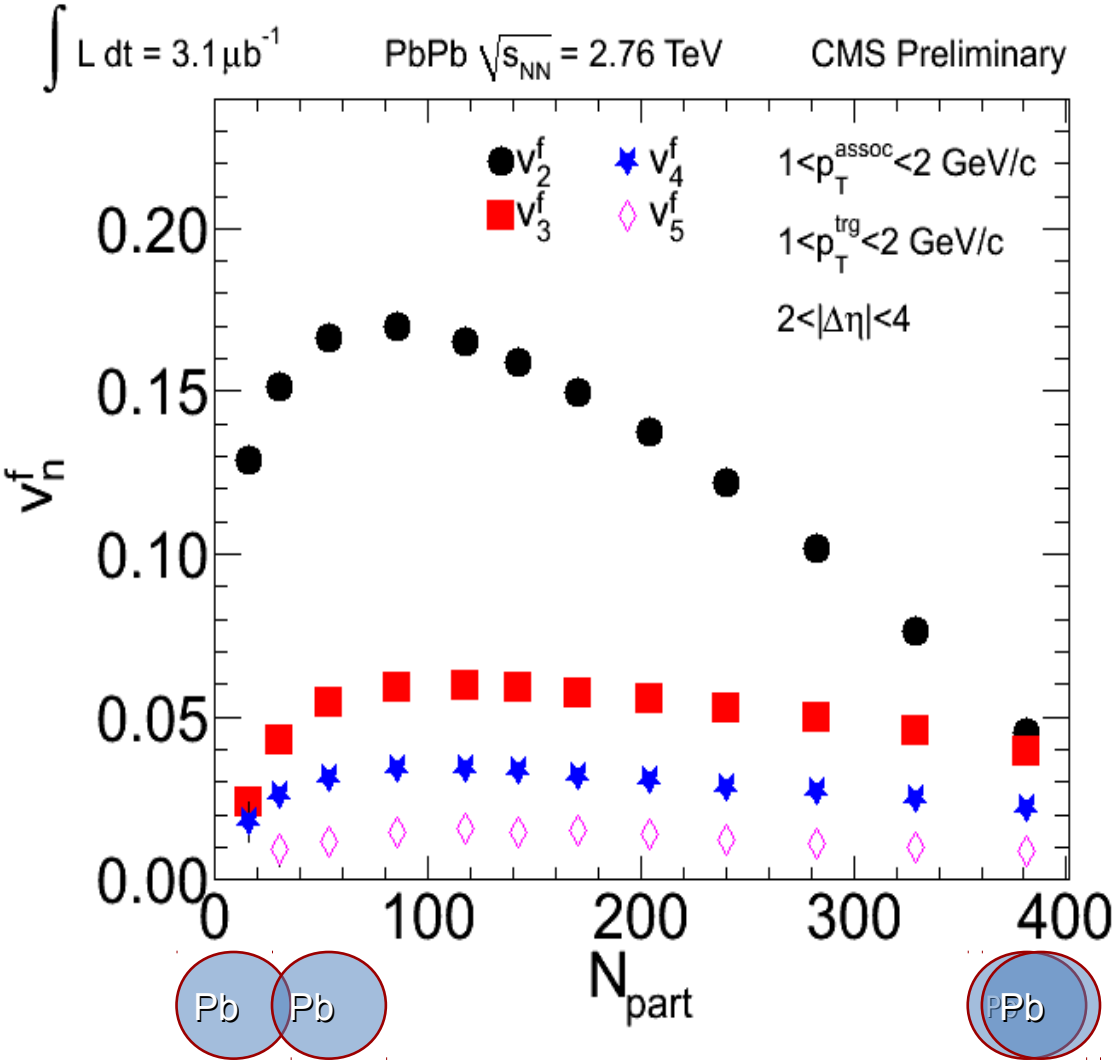
(f: Fourier analysis of long-range dihadron correlations)

Short-range non-flow effects excluded

ArXiv:1105.2438
Accepted by JHEP



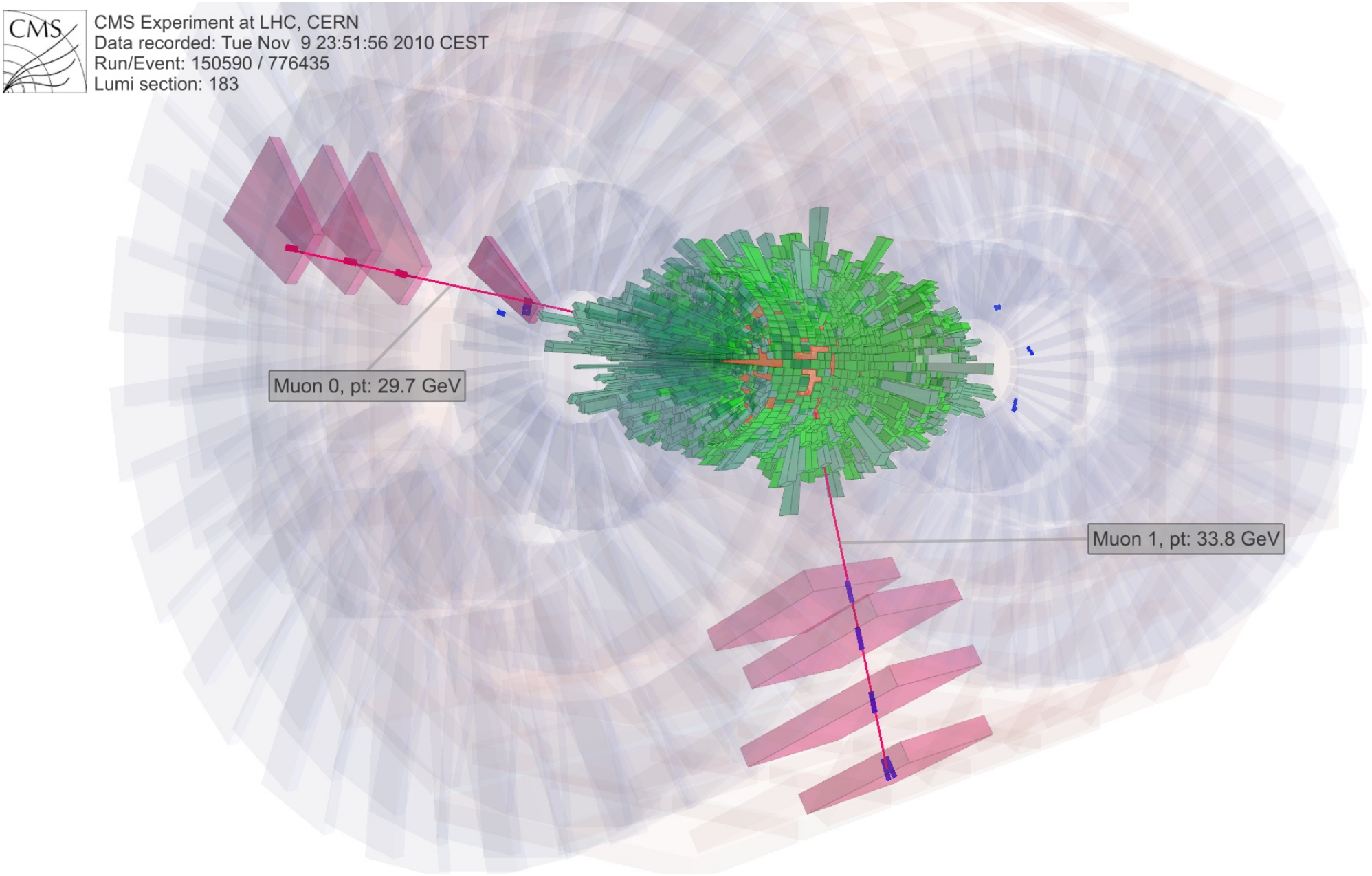
Flow coefficients (v^f_n) vs centrality



CMS PAS HIN-11-005

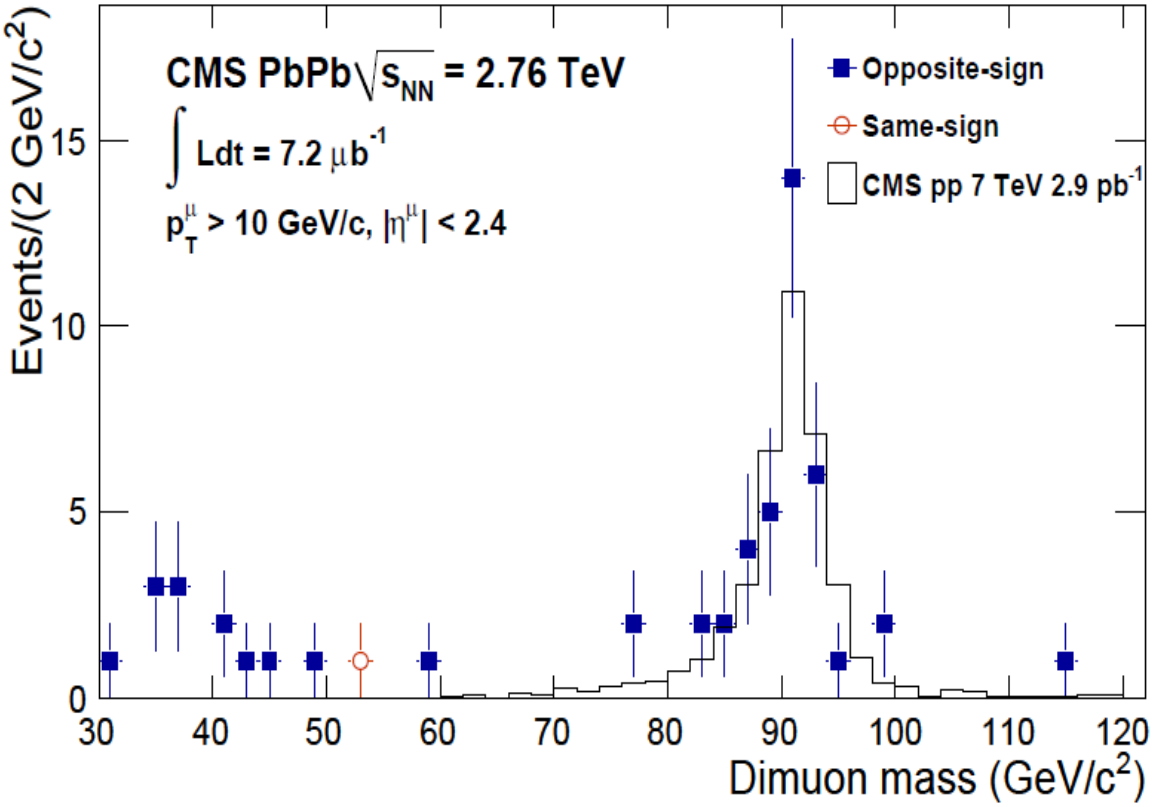
- Powerful constraints on the viscous property of the medium
- Additional handle on the initial condition of heavy-ion collisions

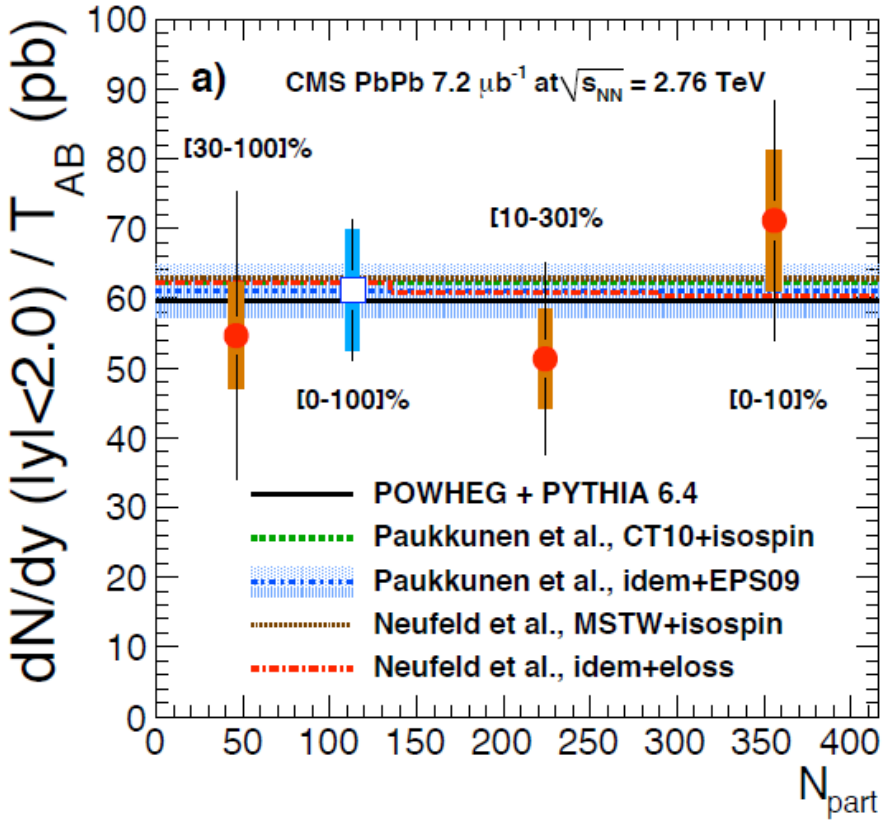
Our first Z → $\mu^+\mu^-$ candidate in PbPb



Study of Z→ $\mu^+\mu^-$ in PbPb collisions

ArXiv:1102.5435
PRL 106 (2011) 212301

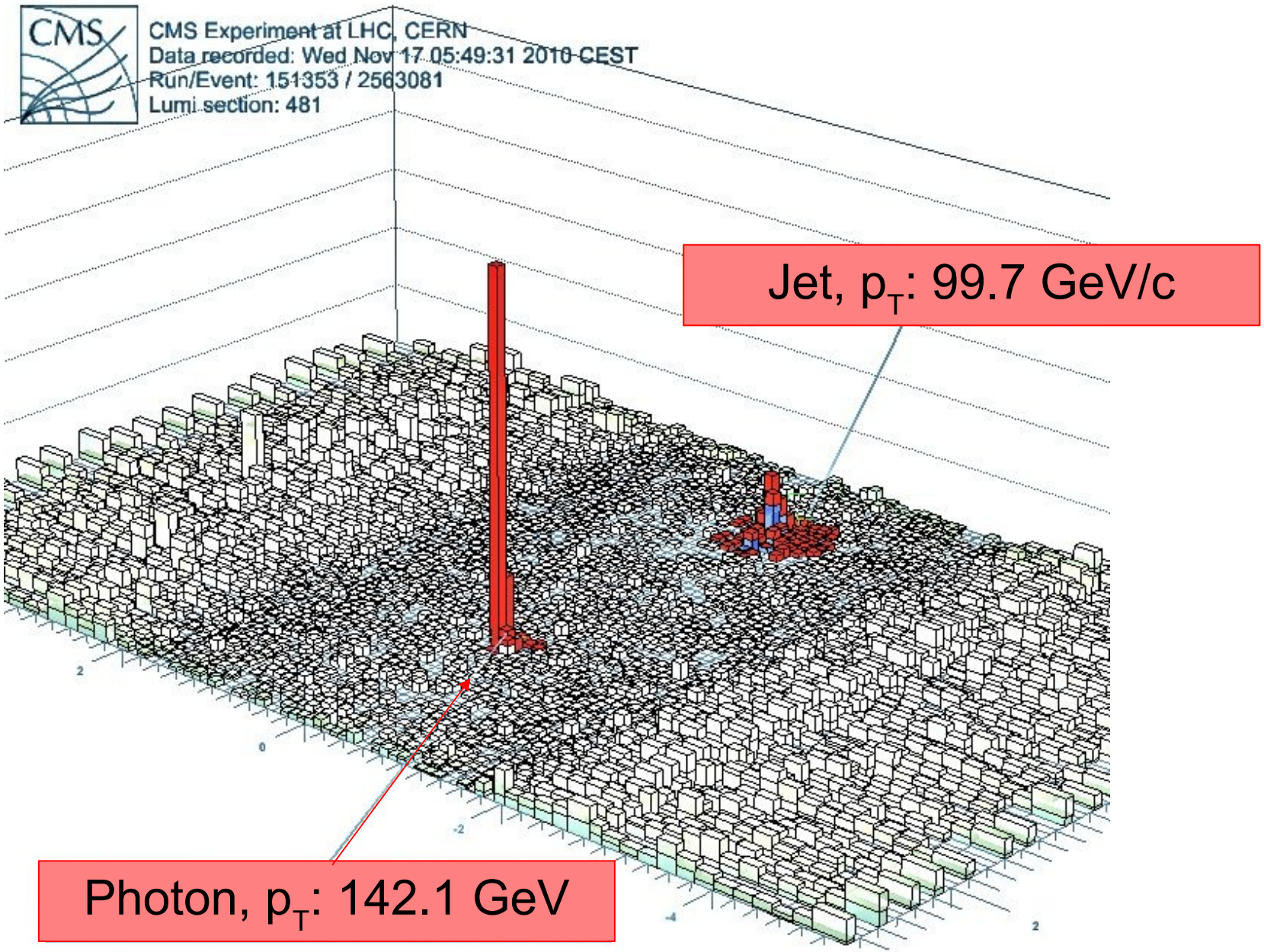




- Clean Z signals from opposite-sign di-muon
- T_{AA} normalized yield is consistent with POWHEG (NLO)
- No modification is found with respect to the pp reference

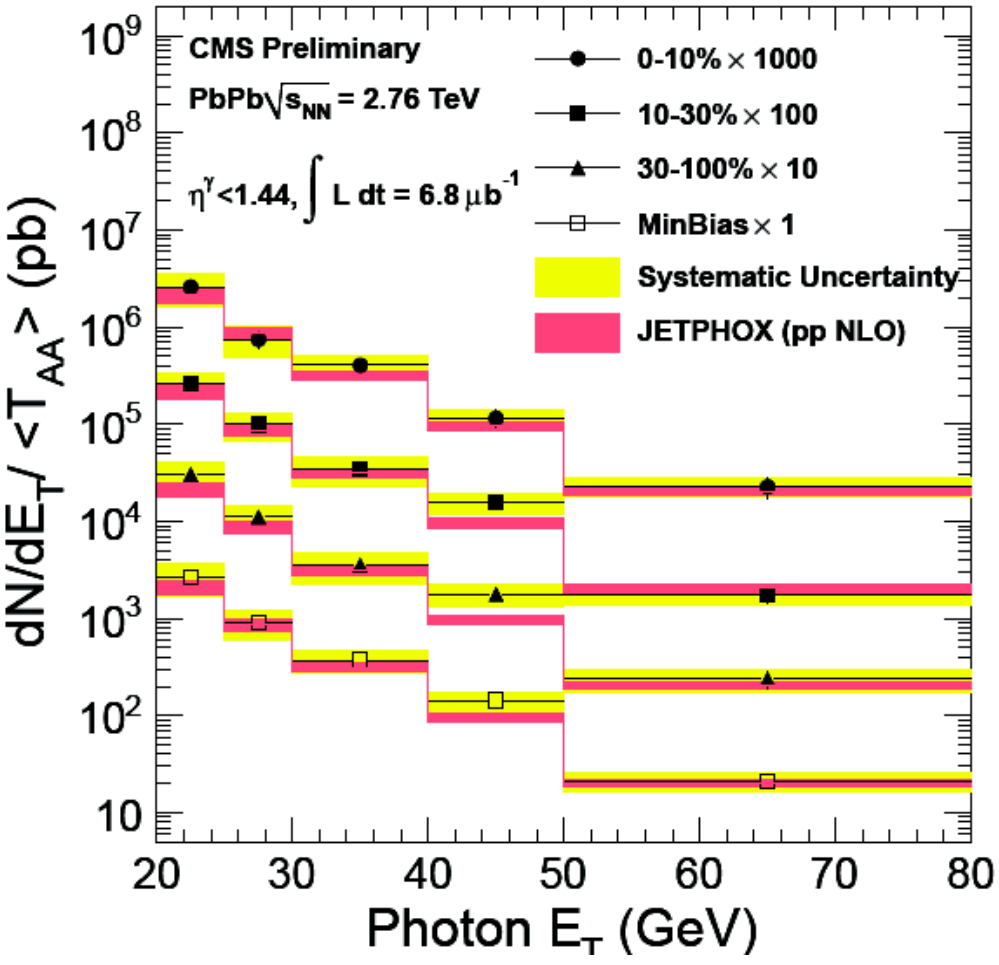
$$T_{AA} = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}}$$

Jets and photons in PbPb collisions

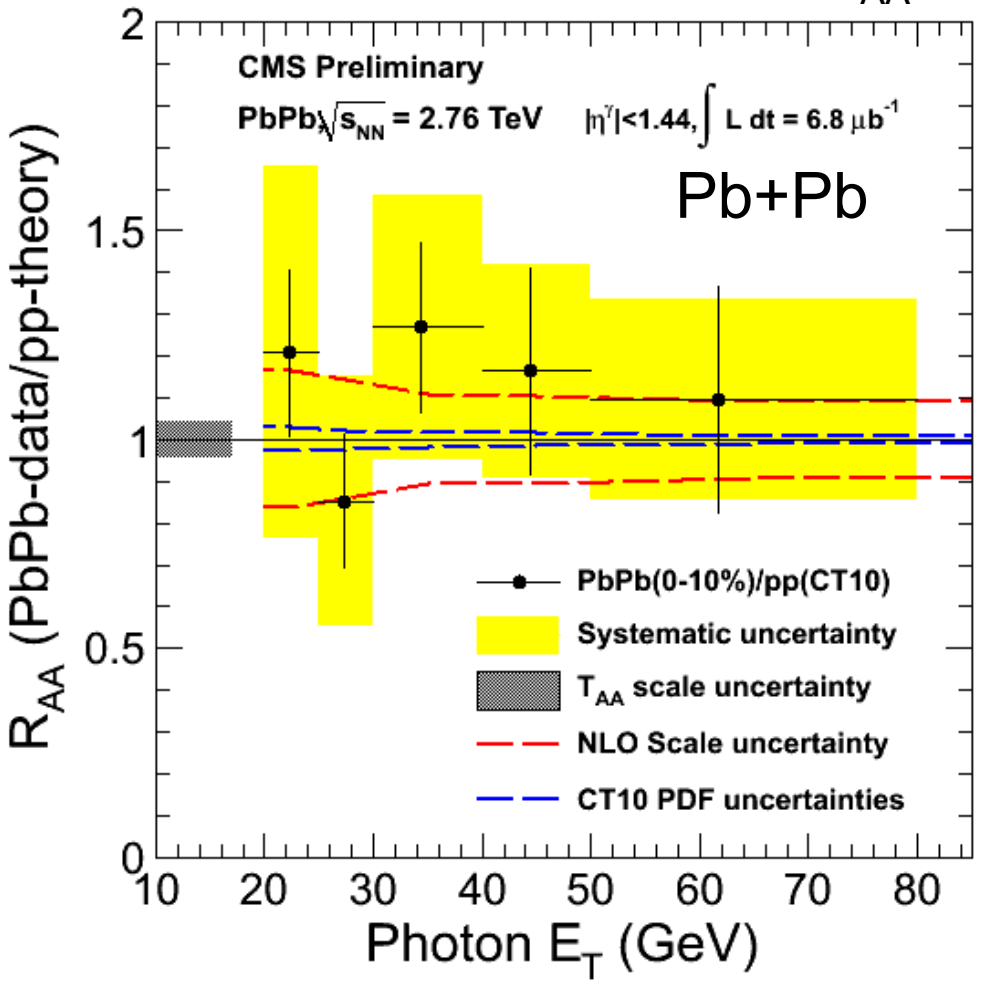


Isolated photon R_{AA} in 0-10% PbPb collisions

CMS PAS HIN-11-002



PbPb 0-10% Photon R_{AA}



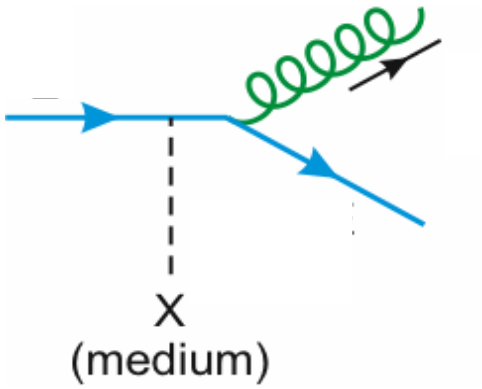
- CMS measured the isolated photon R_{AA} for the first time
- The photon R_{AA} at 0-10% is consistent with unity

Parton energy loss

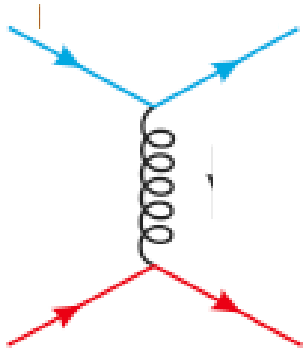
Key ingredients of parton energy loss calculations:

Parton propagation in the nuclear medium

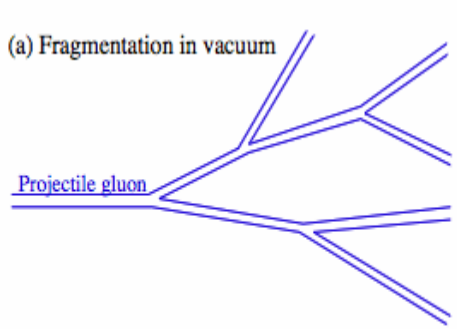
Radiative-

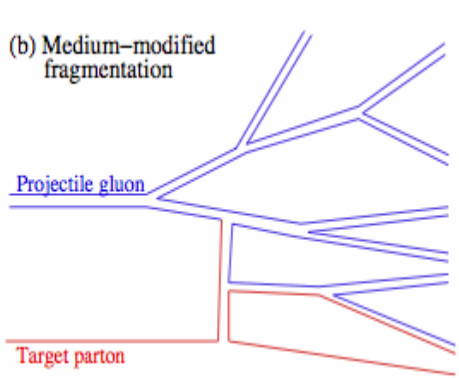


Collisional-energy loss



Parton Showering (Fragmentation)



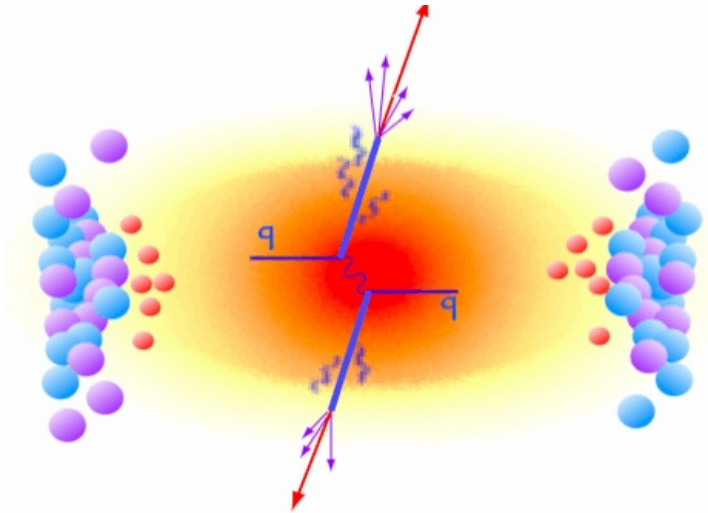


Components sensitive to

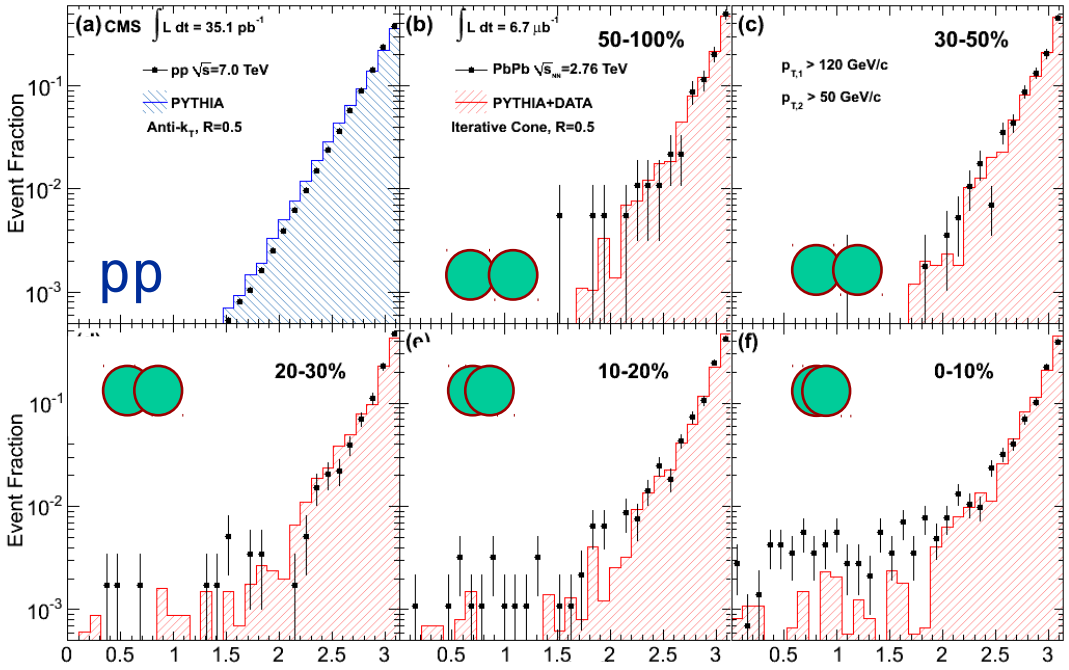
- medium properties
- where and when the process happens

Reconstructed dijets

- full final state of hard scatterings
- study the individual components contributing to the parton energy loss



Di-jet imbalance



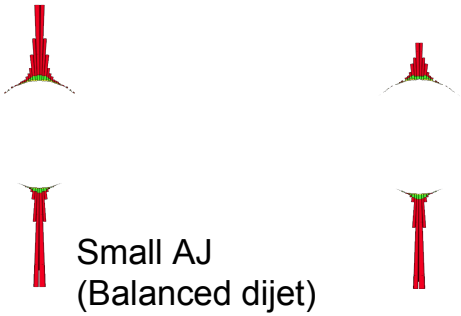
$\Delta\phi_{12}$(rad)

CMS PAS HIN-10-004
Arxiv 1102.1957 Accepted by PRC

Parton energy loss is observed as a pronounced Energy imbalance in central PbPb

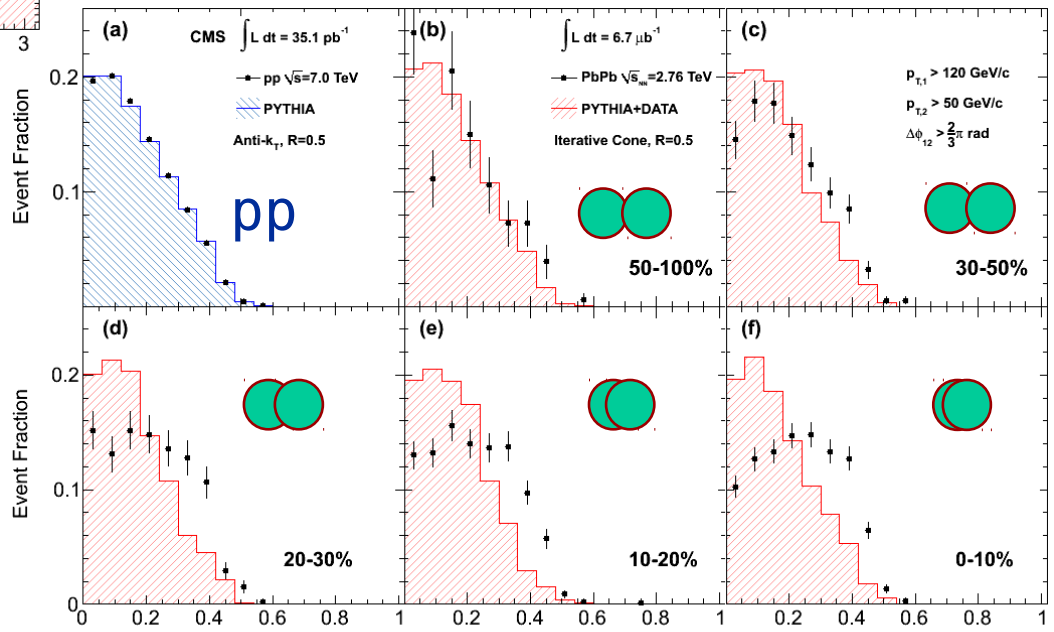
Talk by Frank Ma 7/21 16:30

The propagation of high p_T partons in a dense nuclear medium does not lead to a visible angular decorrelation



Small AJ
(Balanced dijet)

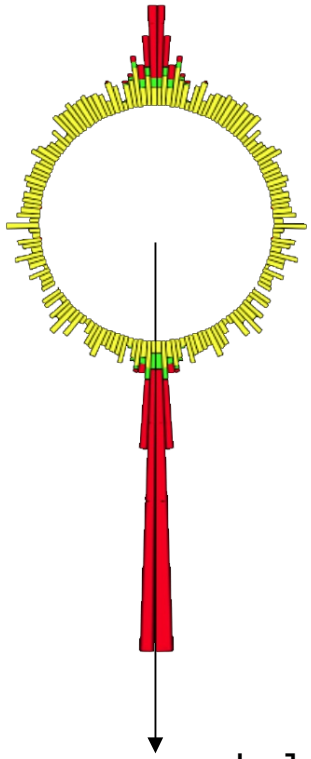
Large AJ
(Un-balanced dijet)

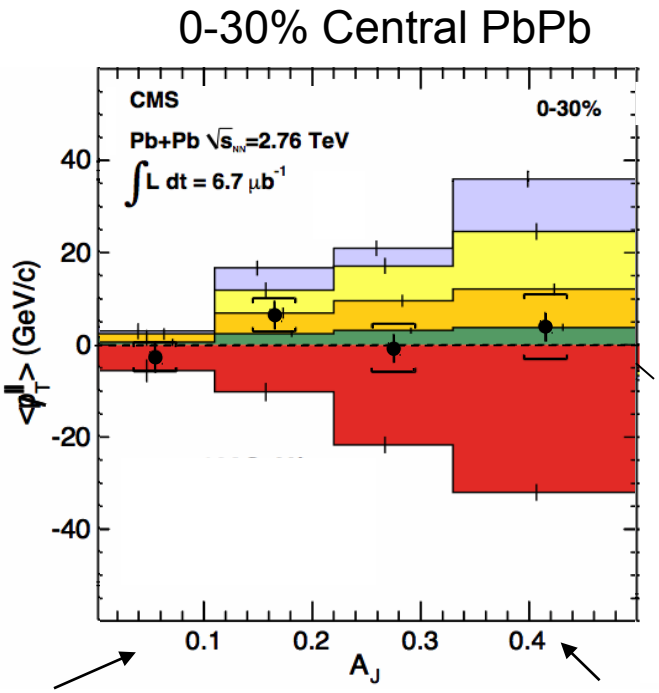


$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

Missing-$p_T^{||}$

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$





excess away from leading jet

excess towards leading jet

Calculate missing p_T in ranges of track p_T:

- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

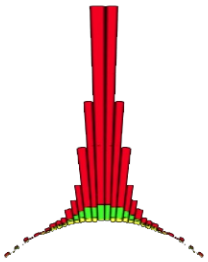
The momentum difference in the dijet is balanced by low p_T particles

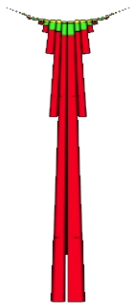
CMS PAS HIN-10-004
Arxiv 1102.1957 Accepted by PRC

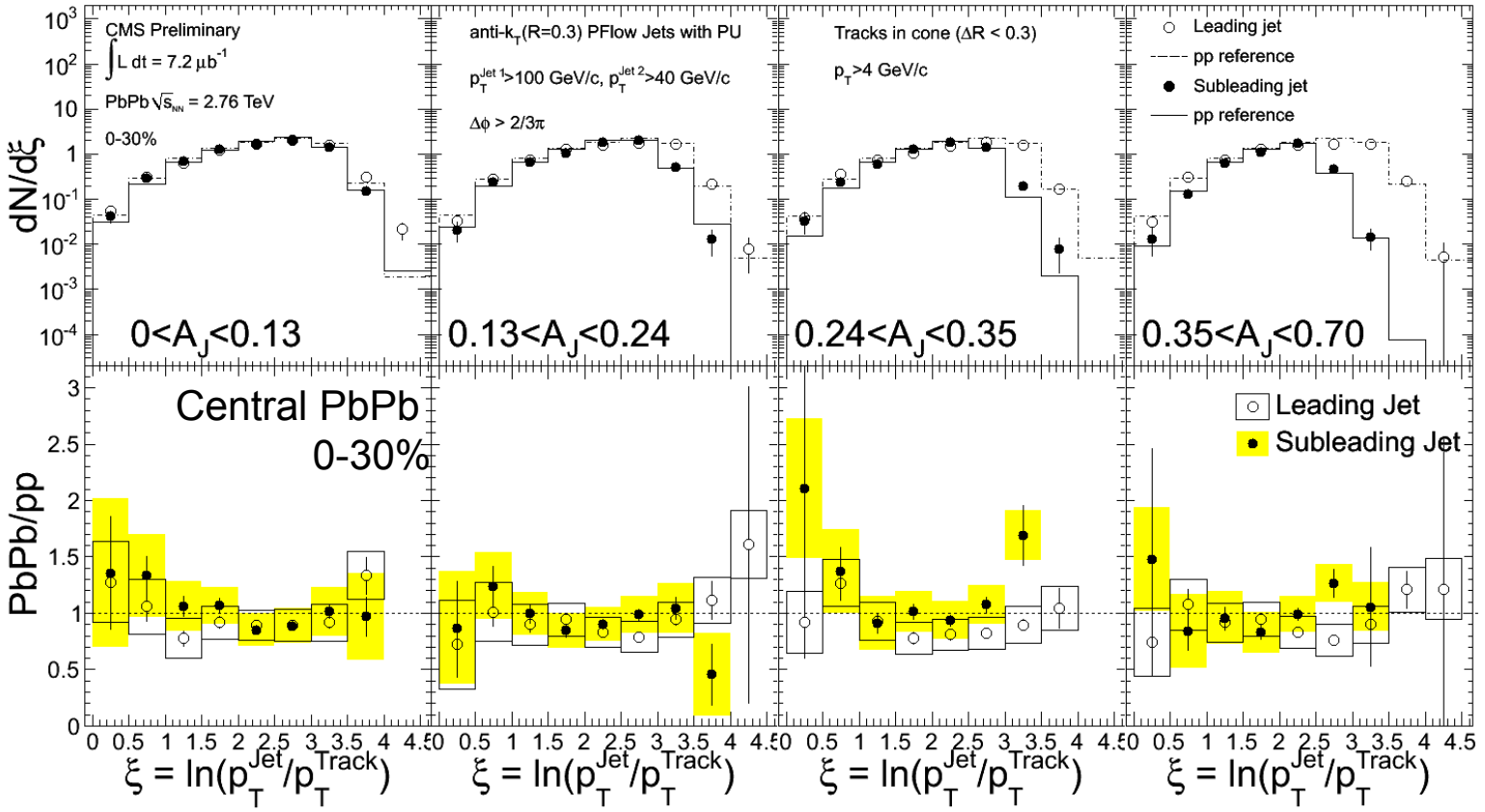
Jet fragmentation function

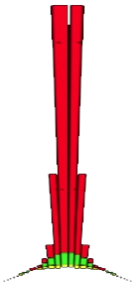
CMS PAS HIN-11-004

Select Tracks in $\Delta R=0.3$ cone
$p_T > 4$ GeV/c



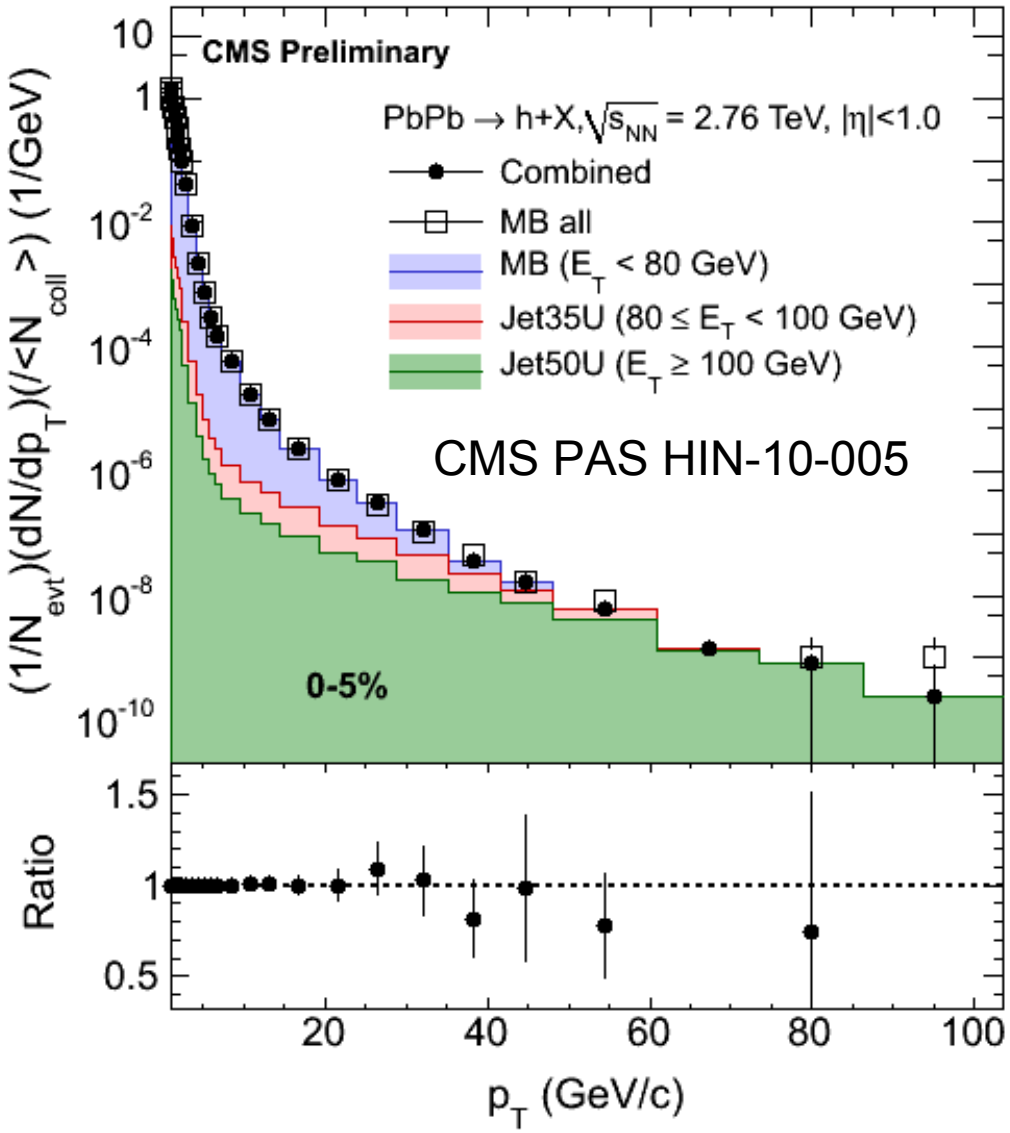


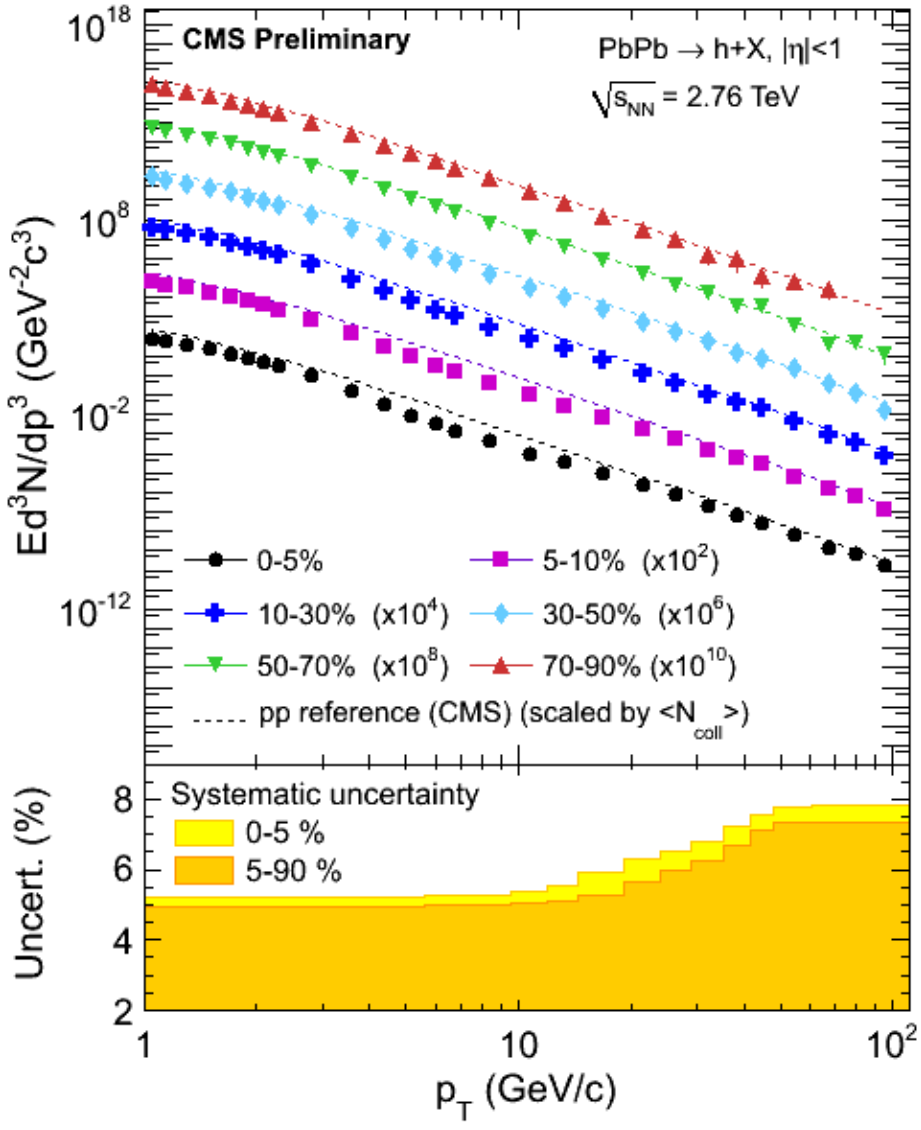




Fragmentation pattern independent of energy lost in medium
Consistent with partons fragmenting in vacuum

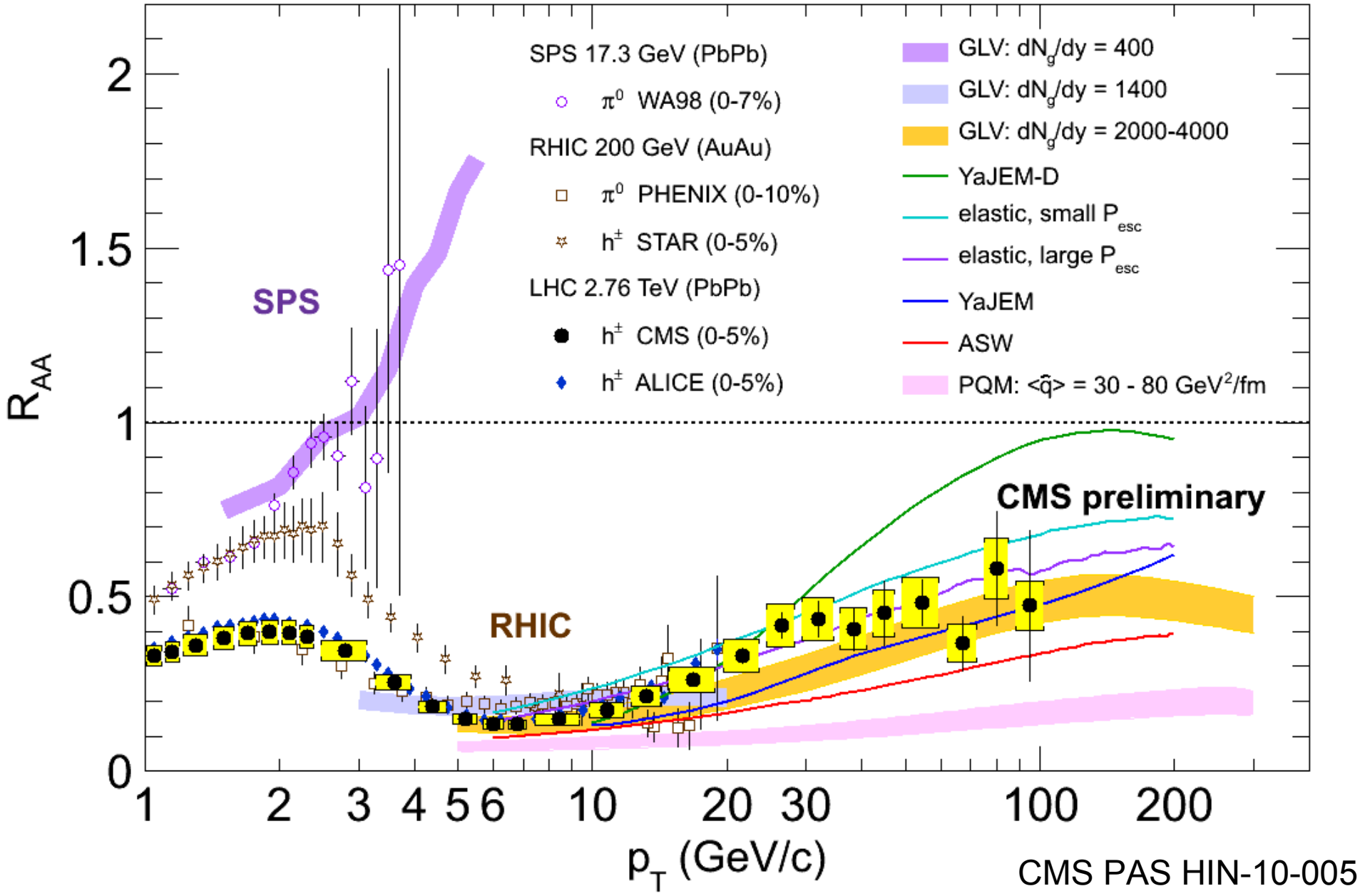
Charged particle spectra in PbPb collisions





- Extended the p_T reach with jet triggers up to 100 GeV/c

Charged particle R_{AA} compared to models

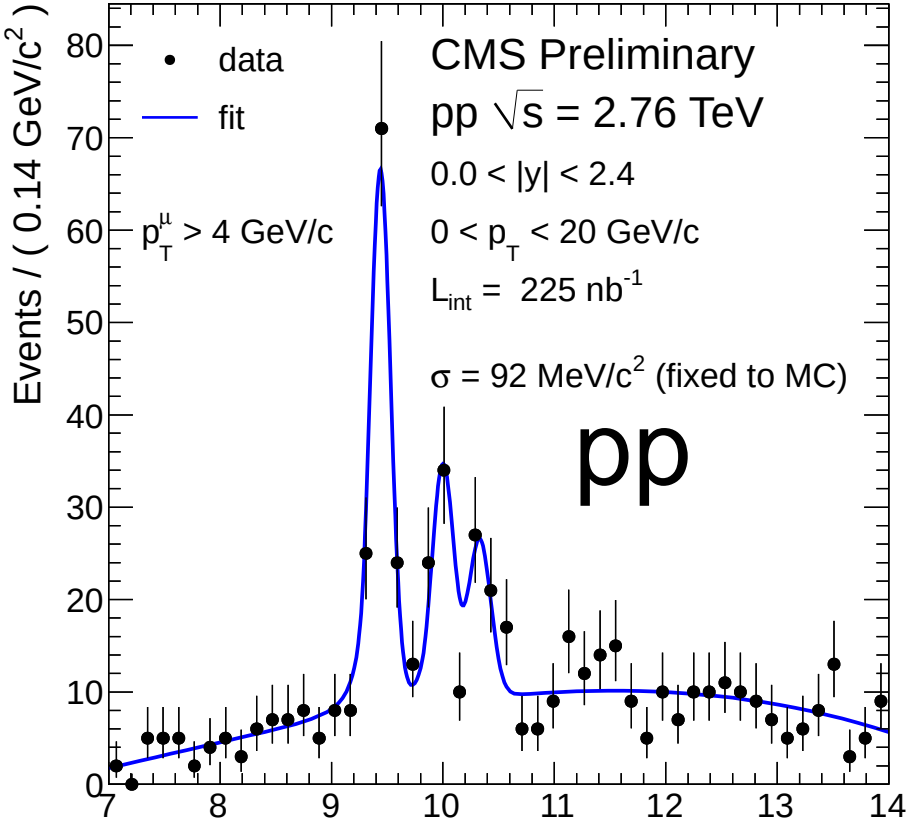


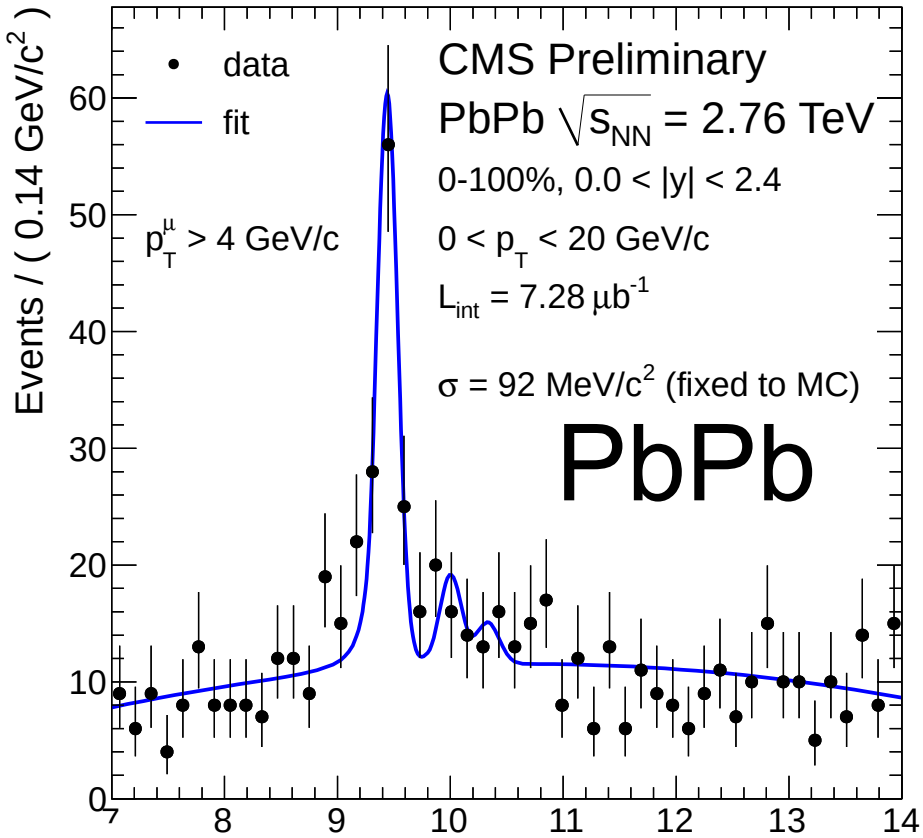
CMS PAS HIN-10-005

Strong constraint on the parton energy loss models

Υ(2S+3S) Suppression

Talk by Catherine Silvestre 7/21 18:00





arXiv : 1105.4894
accepted by PRL

p_T^μ > 4 GeV/c

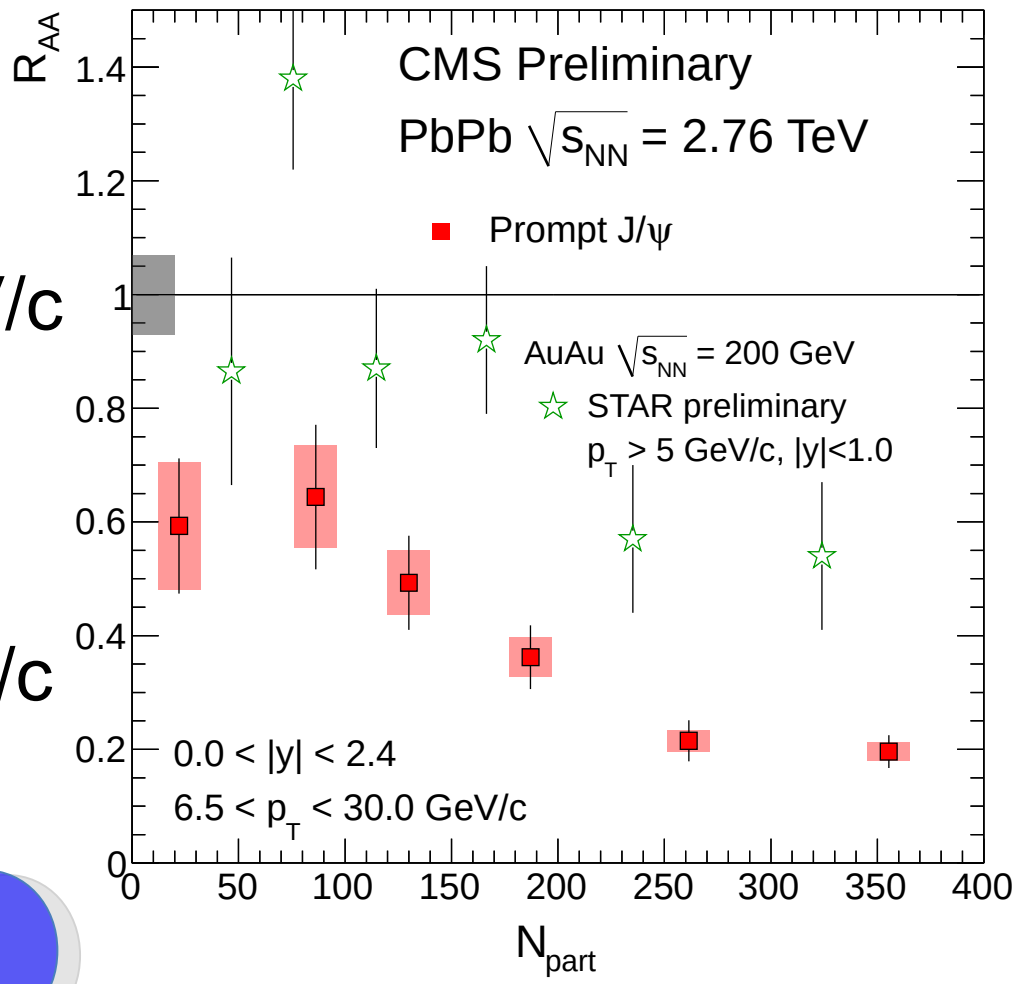
Υ(2S+3S) production relative to Υ(1S) in pp and PbPb

Compare pp and PbPb through a simultaneous fit

J/ψ R_{AA} vs. N_{part} Comparison

Talk by Catherine Silvestre 7/21 18:00

CMS PAS HIN-10-006



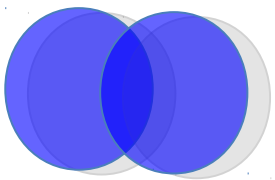
CMS
$p_T^{J/\psi} > 6.5$ GeV/c

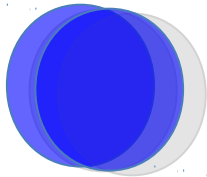
STAR
$5 < p_T^{J/\psi} < 8$ GeV/c

40-80%

Compatible with ATLAS
$R_{cp} = 0.5 \pm 0.2$

Phys.Lett.B697: 294-312,2011

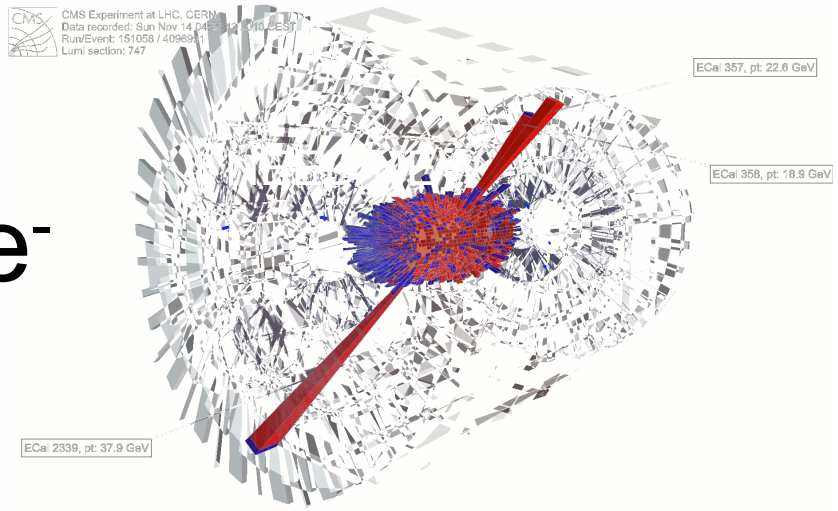


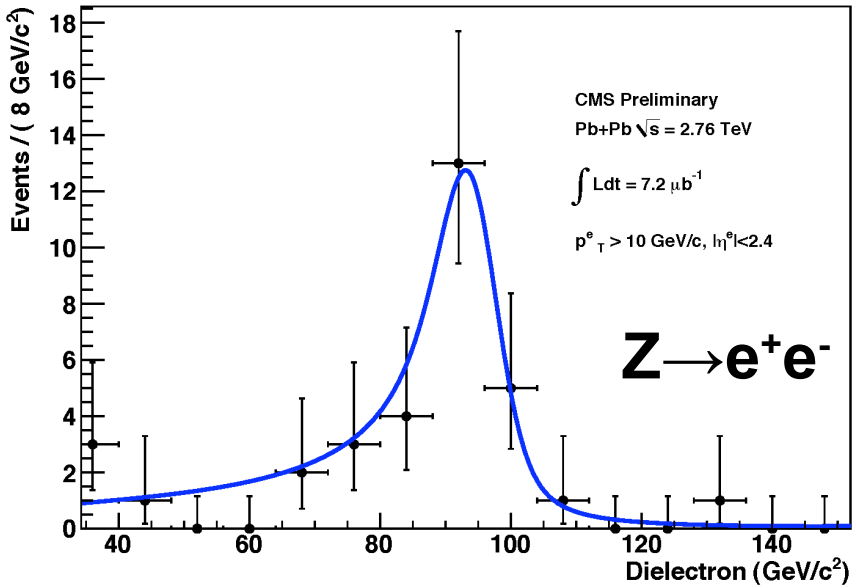


Stronger suppression seen in CMS than at STAR

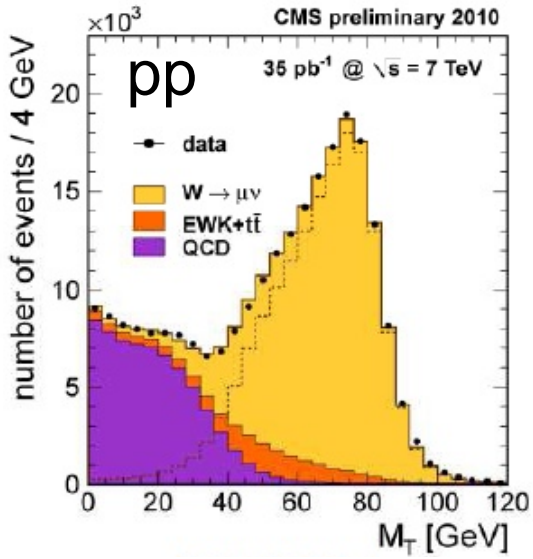
$Z \rightarrow e^+e^-$ and $W \rightarrow \mu\nu$

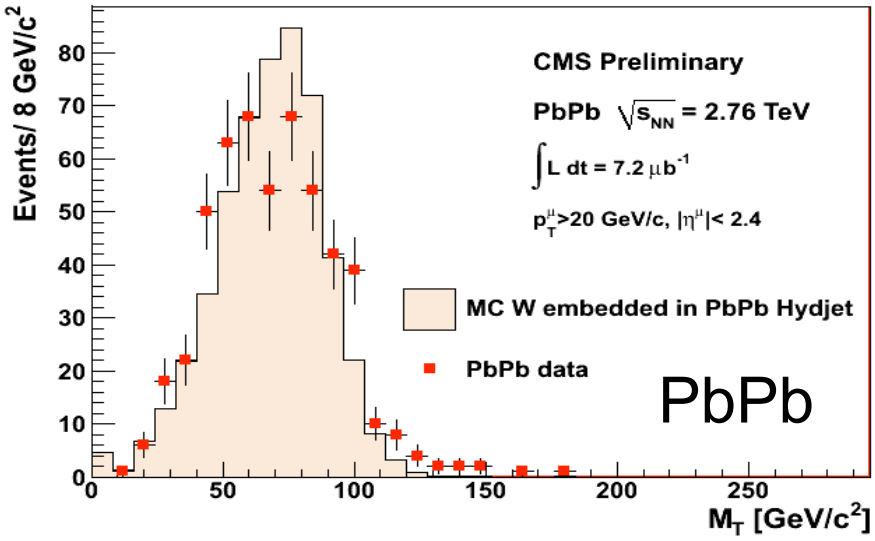
$Z \rightarrow e^+e^-$





Hint of W





$$M_T = \sqrt{2 p_{T\mu} p_{T\nu} (1 - \cos\varphi_{\mu\nu})}$$

Summary

- Initial state:
  - No modification is observed in Z and photon production. Confirmation of the Glauber scaling for the pQCD probes
  - v3 measurement and Fourier decomposition of two particle azimuthal correlation support the picture of initial state fluctuation.

- Bulk property:
  - Measured charged particle density and energy density
  - v2 as a function of pT is similar to what is observed at RHIC.

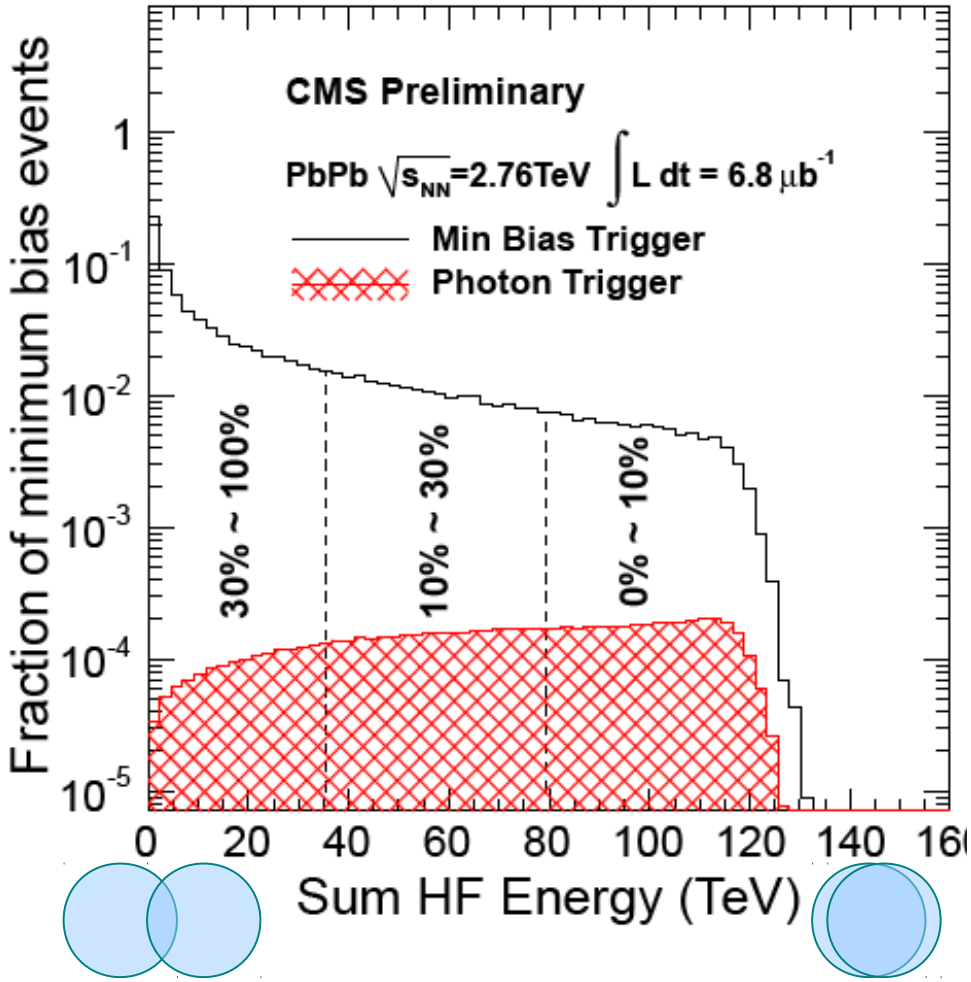
- Medium modification:
  - Large suppression is observed in the PbPb charged particle spectra
  - Large di-jet asymmetry, balanced by low pT particle at large angle
  - Di-jet fragmentation is unmodified

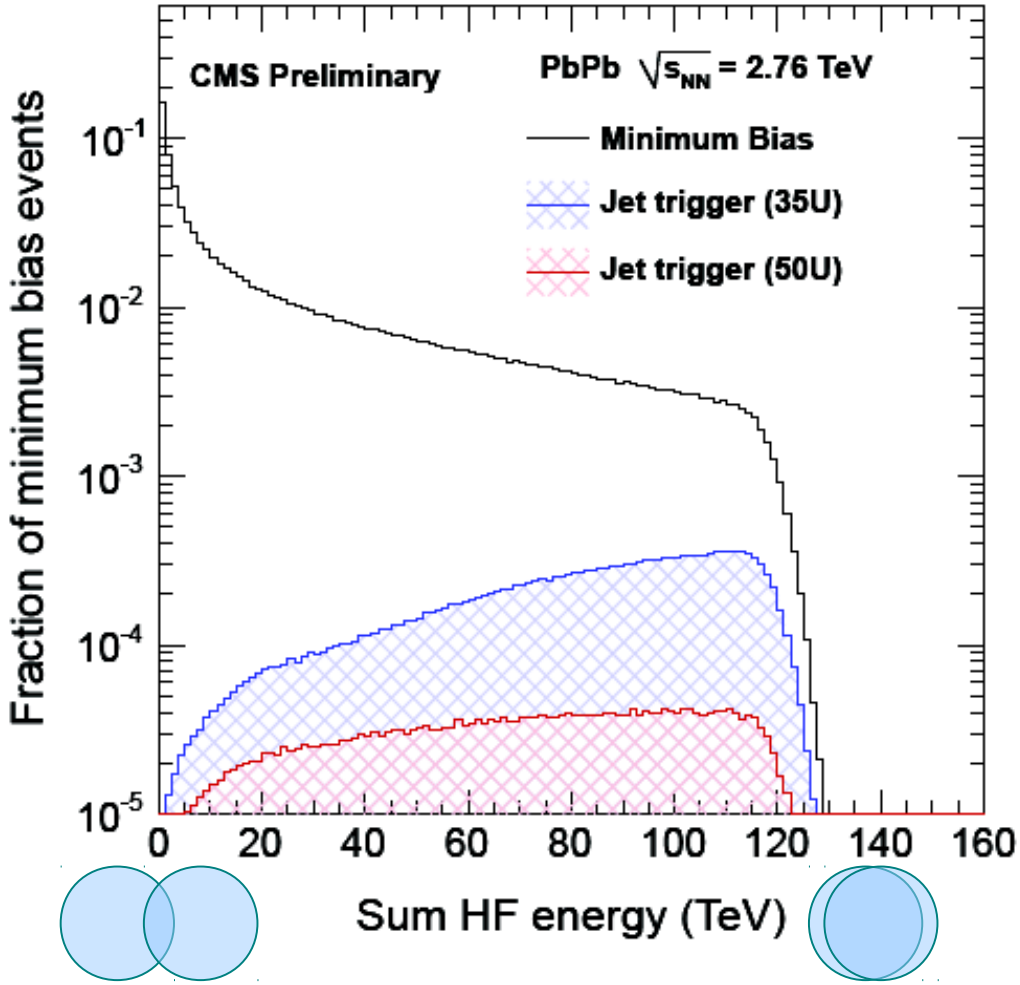
- Quarkonium:
  - Large suppression of J/ψ
  - Evidence of sequential melting of Y(2S,3S) states.

Backup slides

Centrality Determination

- Forward calorimeter (HF) is used for centrality determination.
- The distribution of the total energy in HF is used to divide the sample into centrality bins.

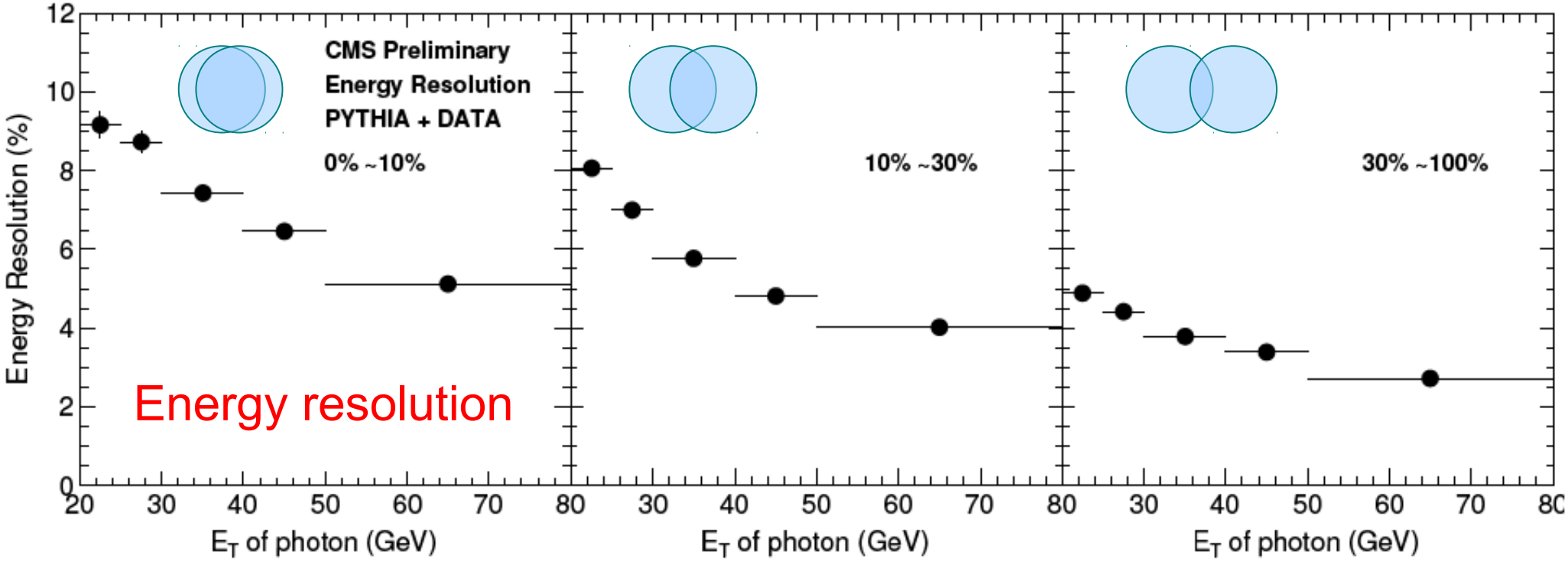




Photon

- Reconstructed from CMS ECAL Barrel ($|\eta|<1.44$) and $E_T > 20$ GeV
- Additional photon energy correction is applied to remove the underlying Pb+Pb event contribution. (1 – 11%). Corrected statistically by PYTHIA + MB.

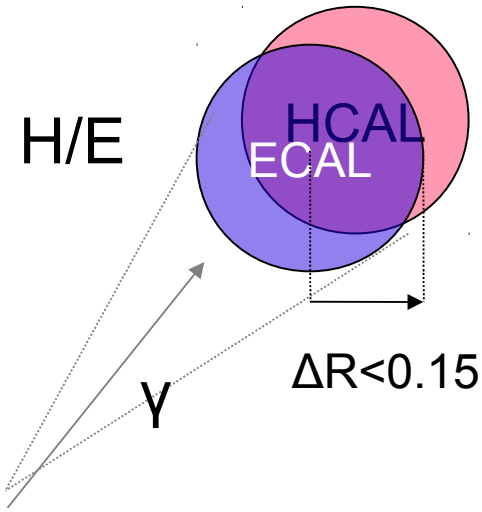
- Photon energy resolution is 2 – 10% as a function of event centrality and photon pT (20 – 80 GeV).

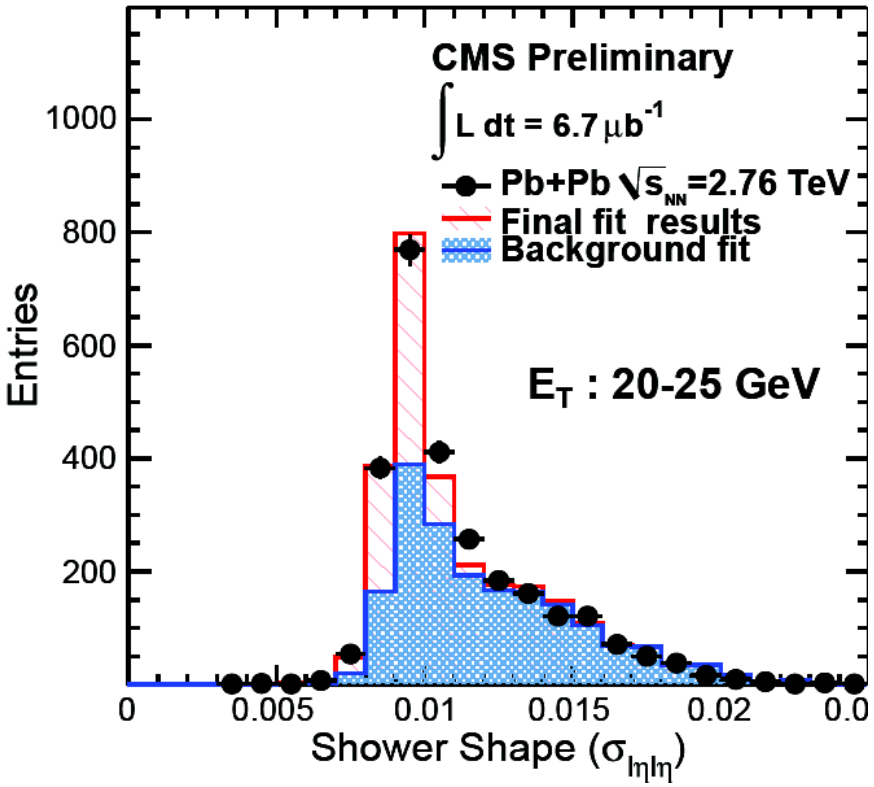


Photon ID and isolation

- Photon ID:
  - Hadronic / EM energy < 20%
- SumIso: (Iso_{ECAL} + Iso_{HCAL} + Iso_{Track})
  - Background subtracted.
  - Photon candidate E_T subtracted in ECAL.
  - Cone size: ΔR < 0.4
  - SumIso < 5 GeV
- Signal Extraction:
  Transverse shower shape $\sigma_{i\eta i\eta}$
  - Shower width in the η direction
  - Data driven background shape.
  - Separate isolated photons from the isolated π^0, η

See Yongsun Kim's talk on 5/27 5pm





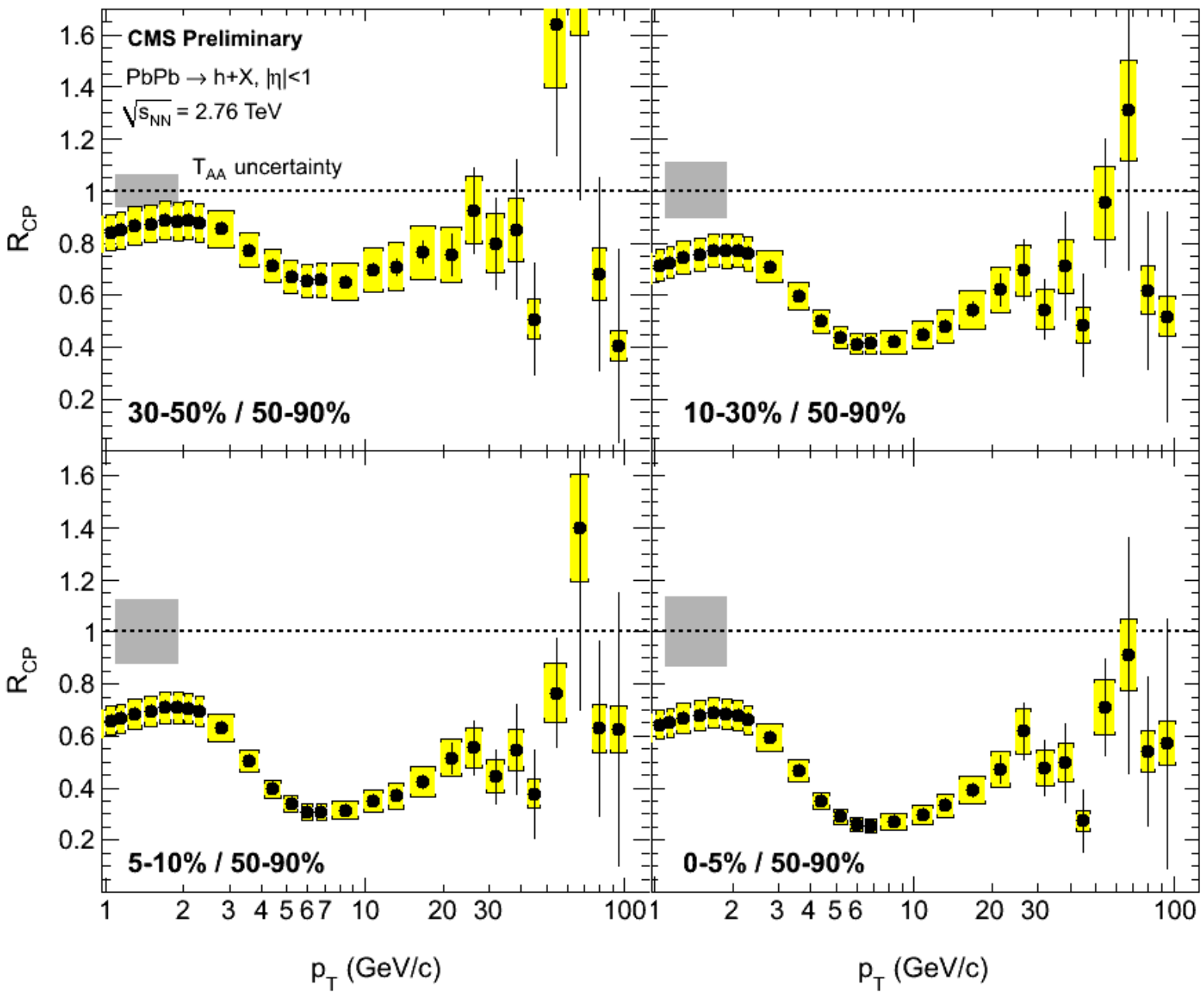
Charged particle systematic uncertainties

Source	Uncertainty [%]
Reconstruction efficiency	3.0–4.5
Non-primary and fake tracks	2.5–4.0
Momentum resolution and binning	3.0
Normalization of jet-triggered spectra	0.0–4.0
Total for PbPb spectra	4.9–7.8

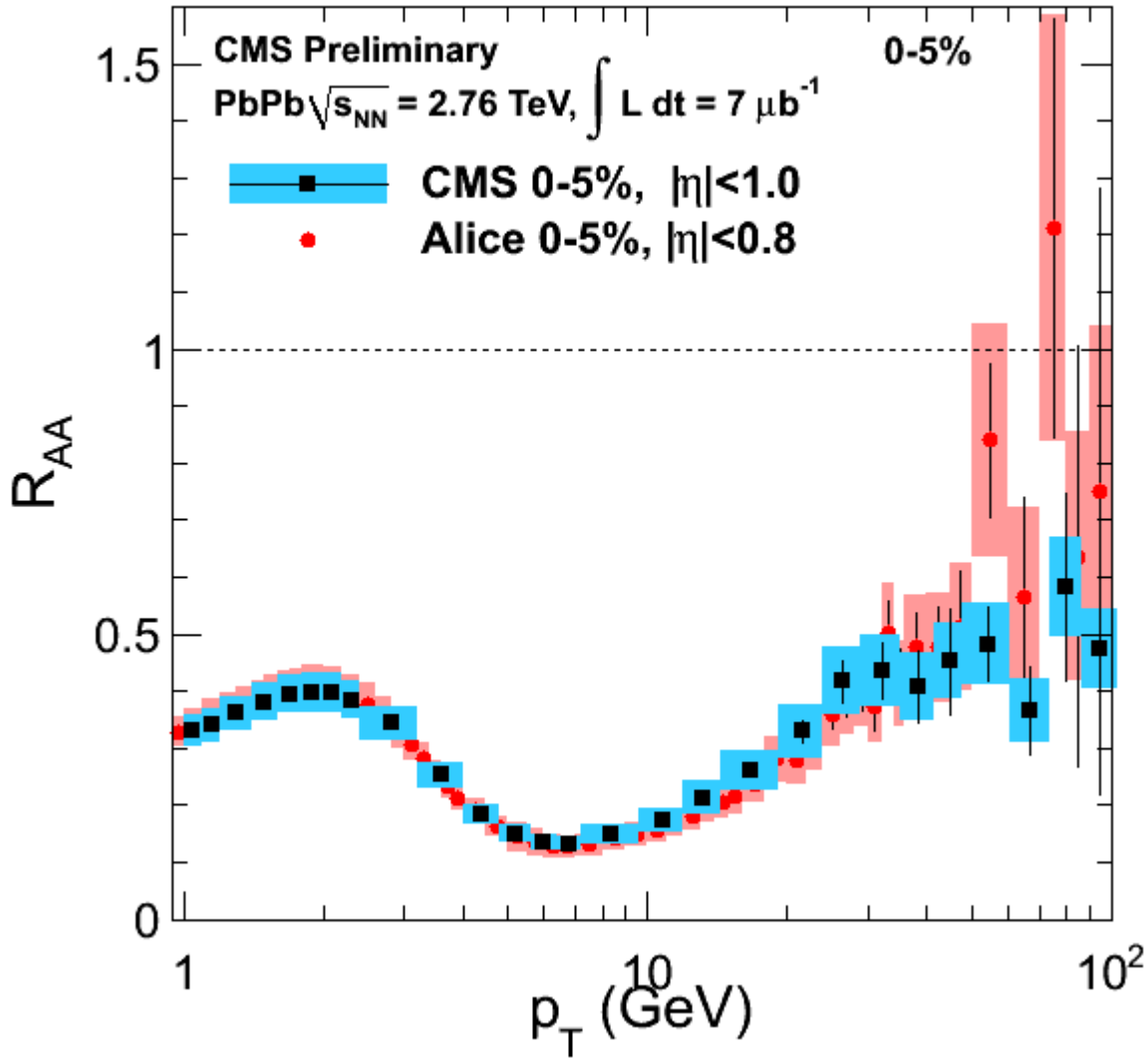
Source	Uncertainty [%]
Total for PbPb spectra	4.9–7.8
T_{AA} determination	4.1–18
Interpolated pp reference spectrum	6.8–13
Total for R_{AA}	9.3–24

$R_{CP}(p_T)$ for Different Centralities

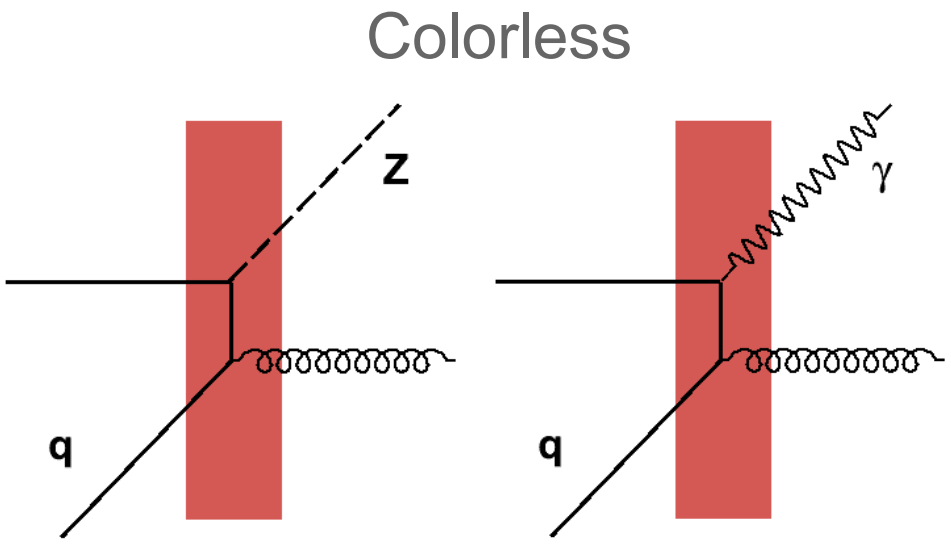
$$R_{CP} = \frac{d^2N_{AA} / dp_T d\eta / N_{coll}(\text{central})}{d^2N_{AA} / dp_T d\eta / N_{coll}(\text{peripheral})}$$

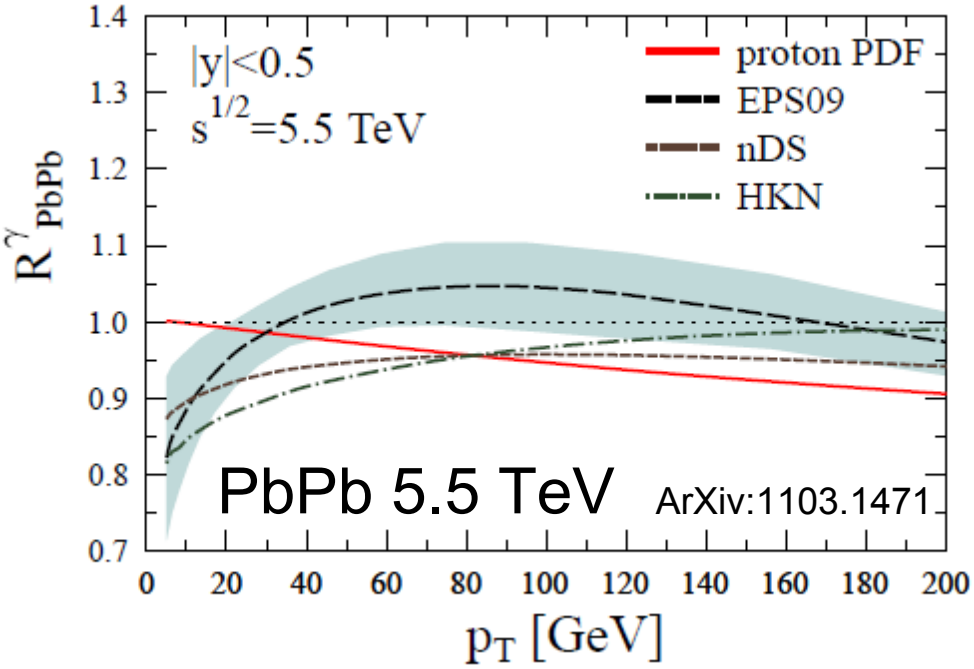


Comparison between CMS and ALICE R_{AA}



CMS studies of the colorless probes

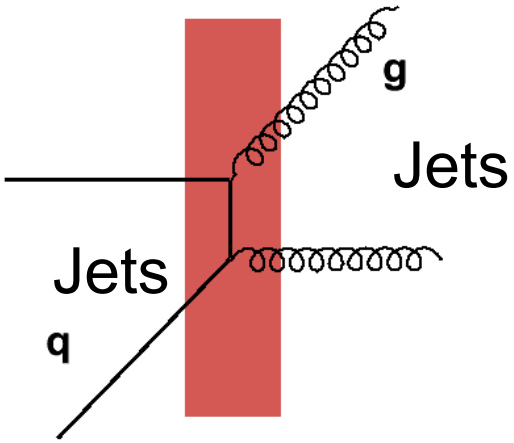


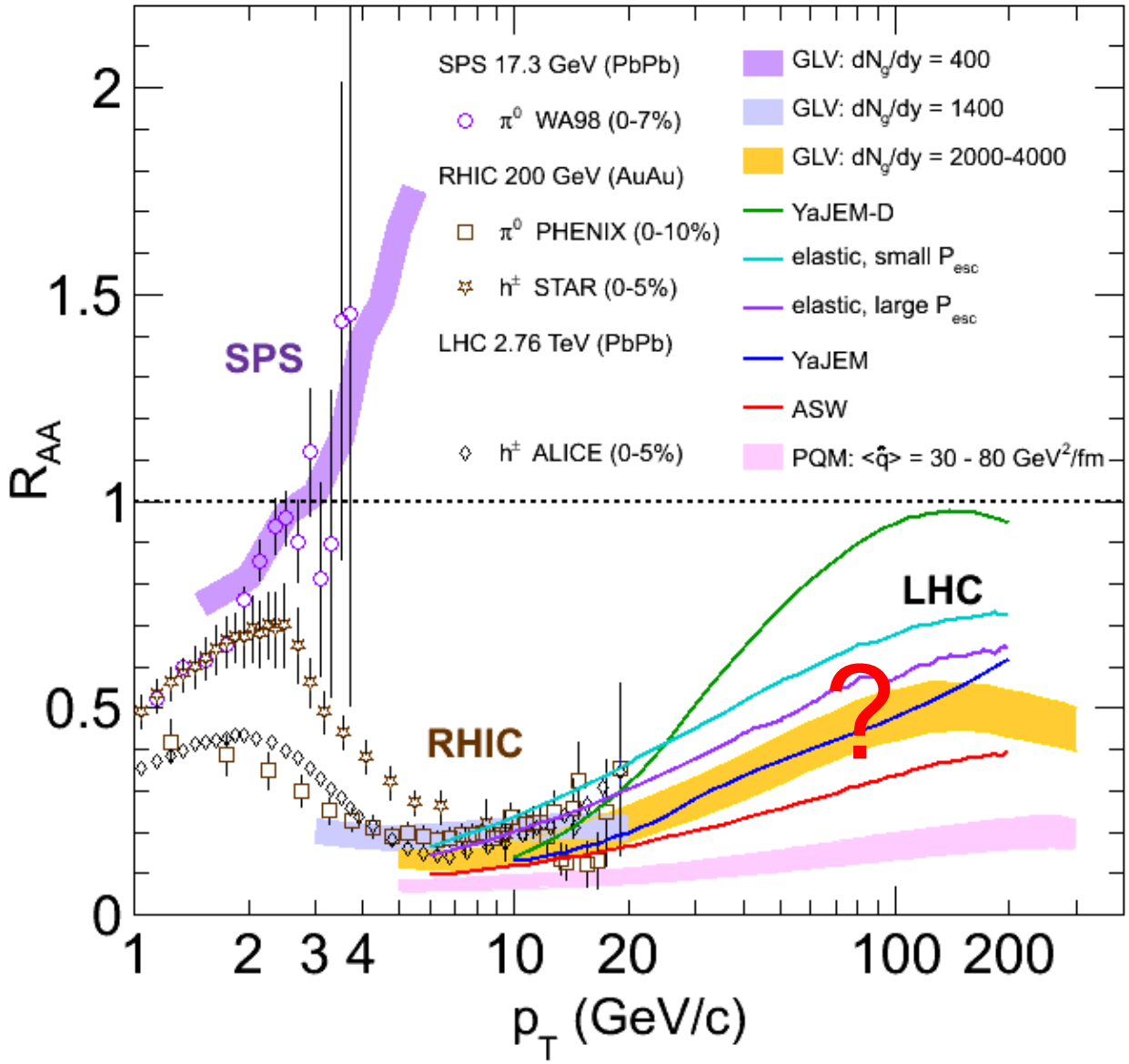


- Z bosons:
  - First measurement of the Z boson production in PbPb
- Photons:
  - Measurement of isolated photons to reject decay photons
  - Probe the nuclear parton distribution function
  - Future analysis: shadowing effect at low p_T and isospin effects at high p_T
- Used to check the initial state and # of binary collisions

CMS studies of the charged particles

Color charged

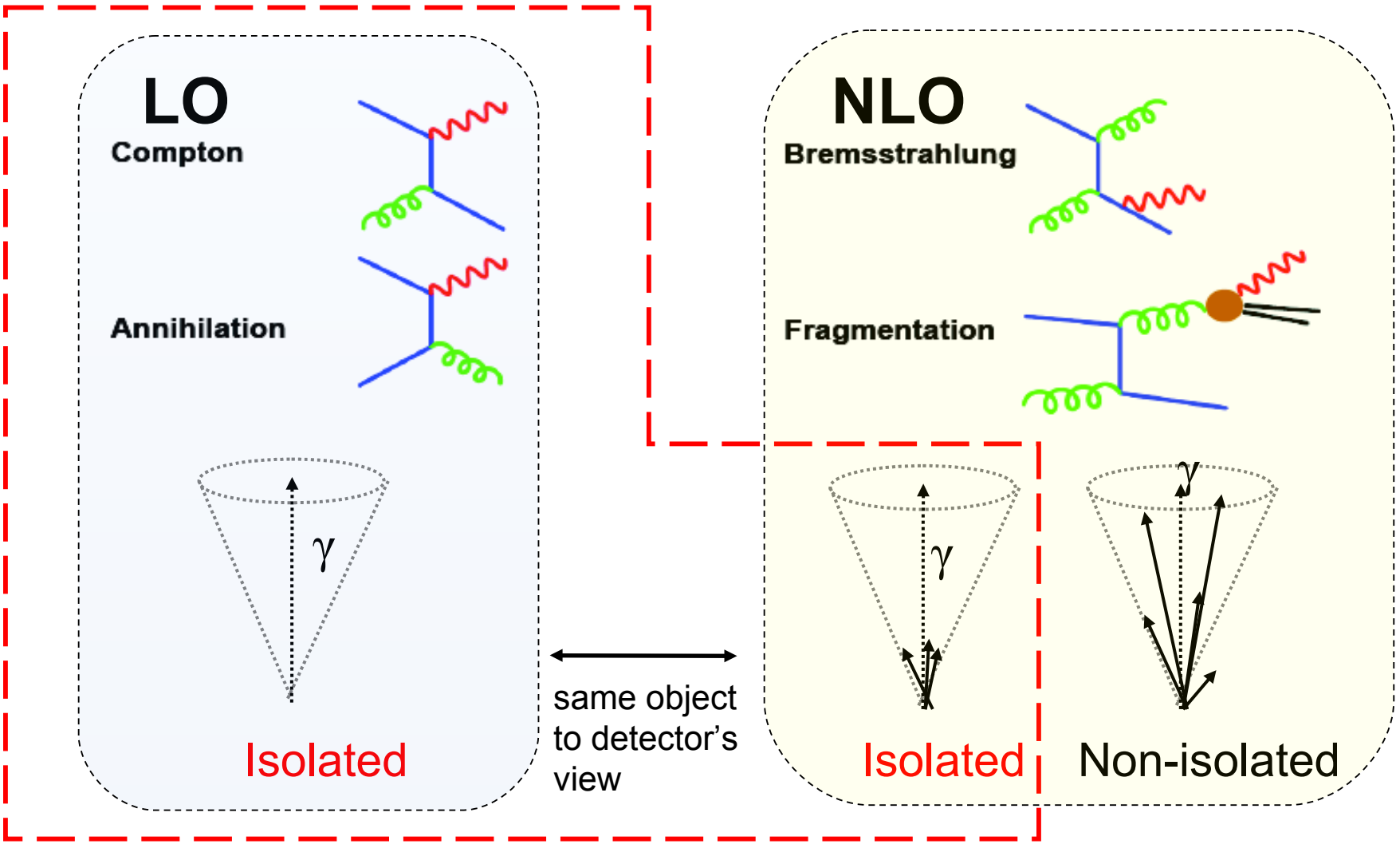




- Charged particles:
  - Large suppression observed at RHIC
  - Study of the final state and medium modification

Isolated high p_T photons

- Ideal: Direct photon from hard scattering
- Real world: Background from the decay and fragmentation photons.
- Solution: Measurement of the isolated photons



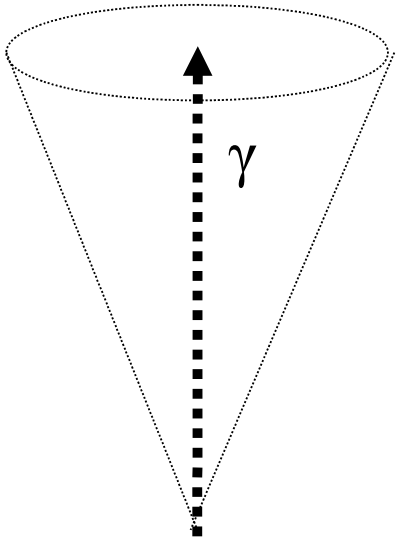
Photon isolation in PbPb

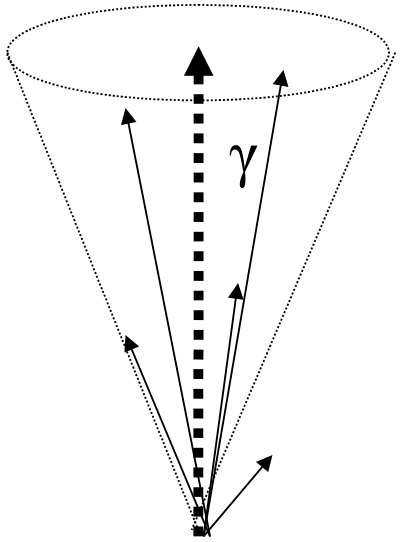
Generator level

$\Delta R<0.4$, $\Sigma E_T^{\text{IsoCone}} < 5$ GeV

with only particles from the same hard scattering

Particles from the same hard scattering



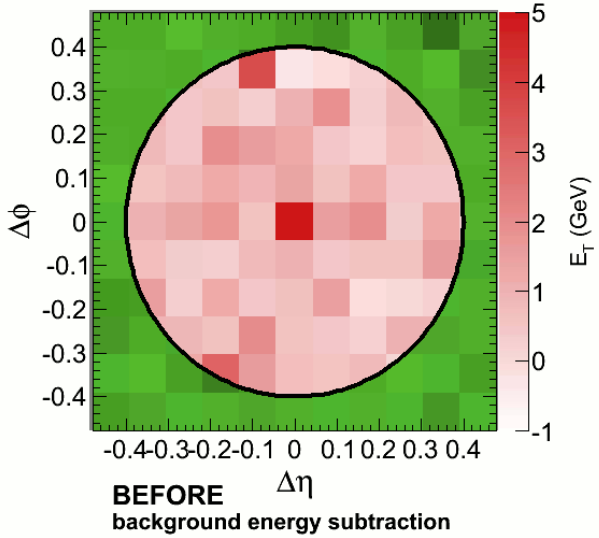


CMS Experiment

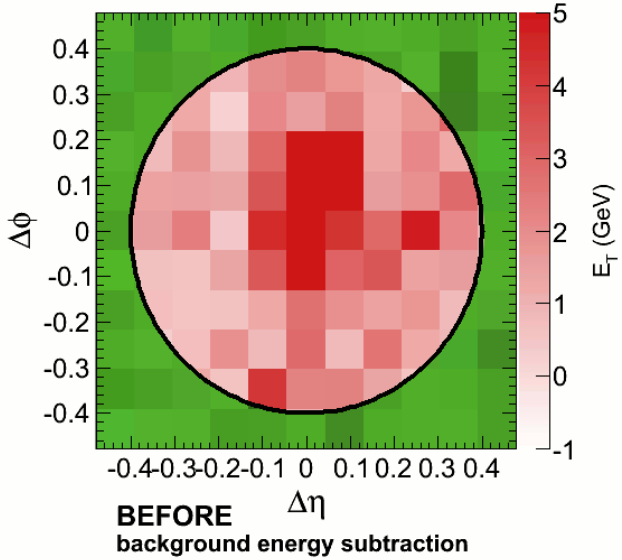
Sum E_T (p_T) from Calorimeter and tracker

Contribution from underlying event

Isolated photon

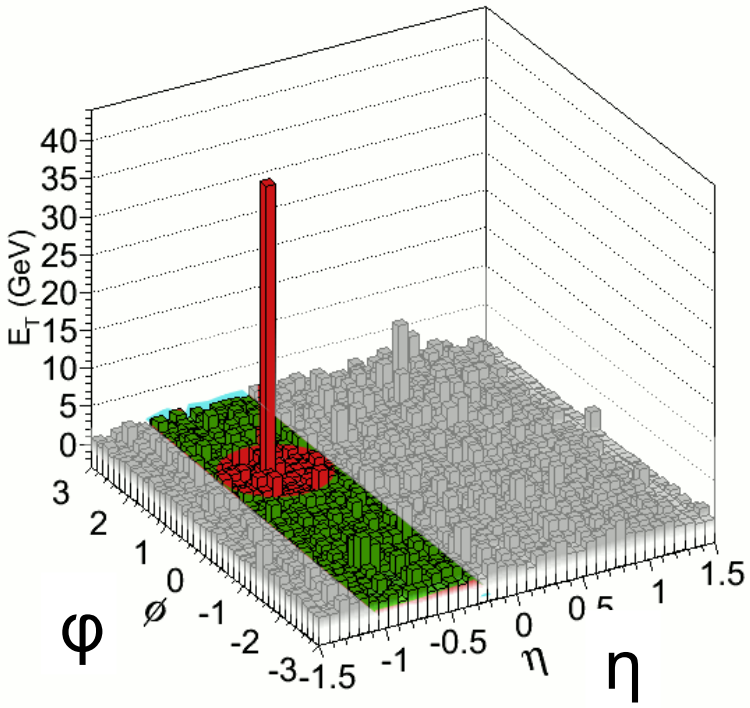


Photon candidate from jet

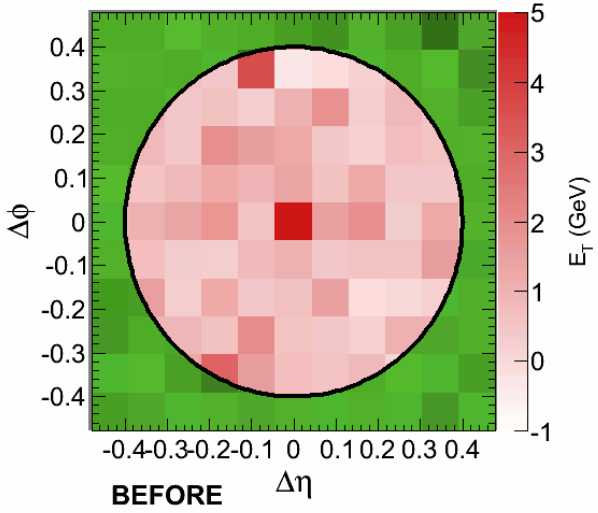


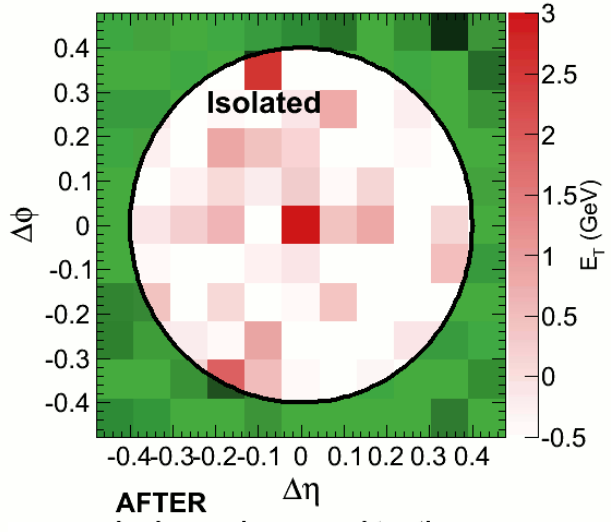
Background subtraction

- Background subtracted isolation by using the mean E_T per unit area in the η strip and remove the underlying event contribution inside the isolation cone

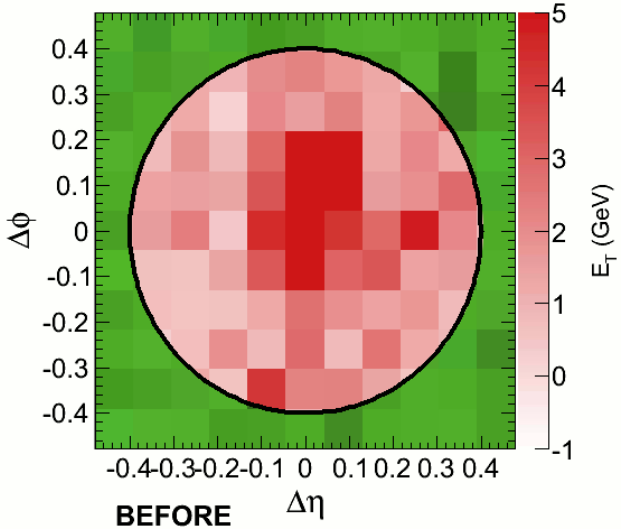


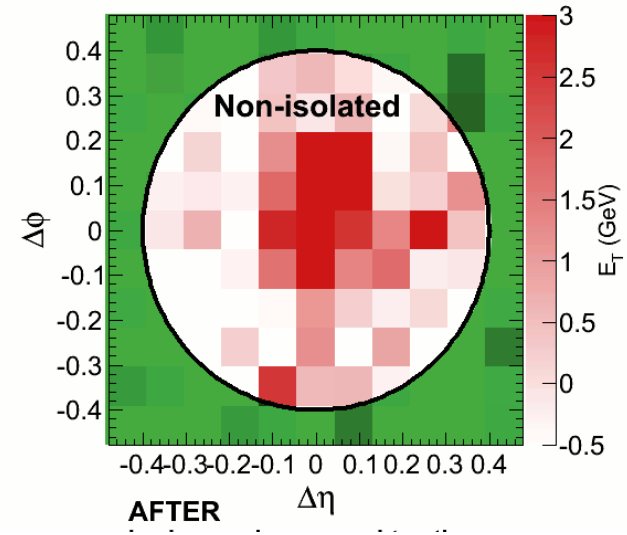
Isolated photon





Photon candidate from jet



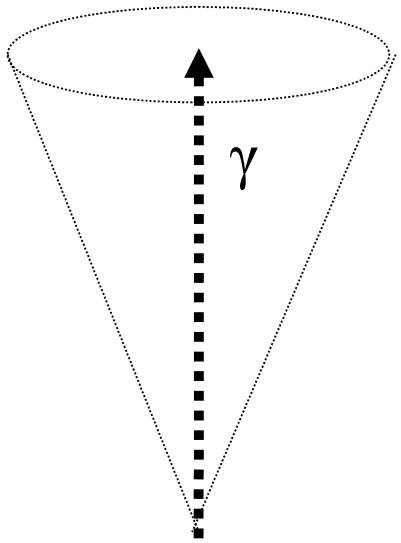


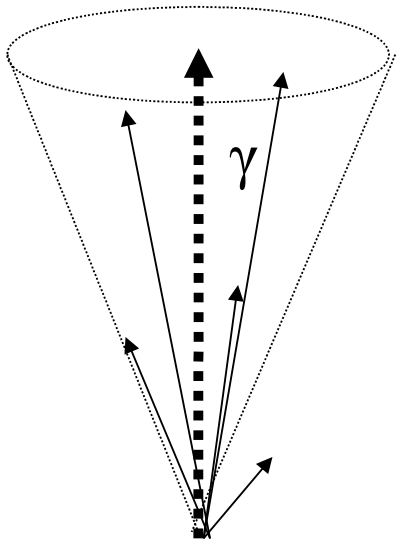
See Yongsun Kim's talk on Fri 5pm

Background subtracted isolation in PbPb

Generator level
$\Delta R<0.4$, $\Sigma E_T^{IsoCone} < 5$ GeV
with only particles from the same hard scattering

Particles from the same hard scattering

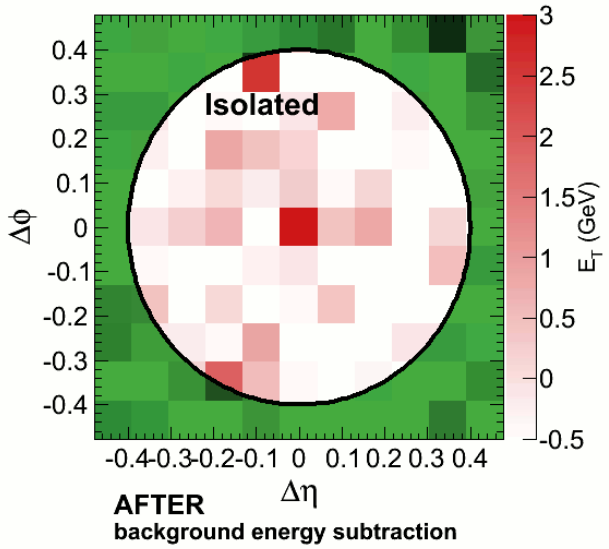




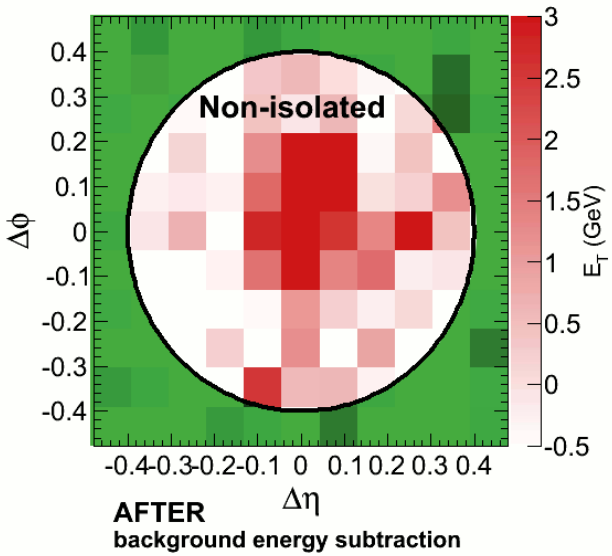
CMS Experiment

Sum E_T (p_T) from Calorimeter and tracker < 5 GeV with background subtracted

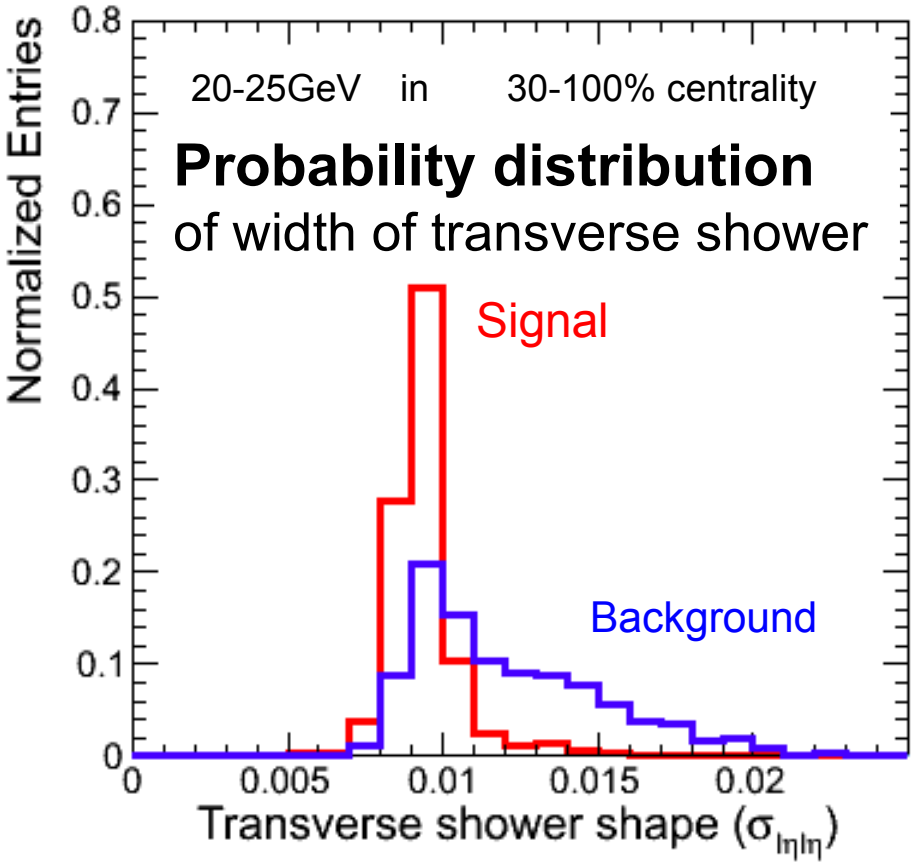
Isolated photon



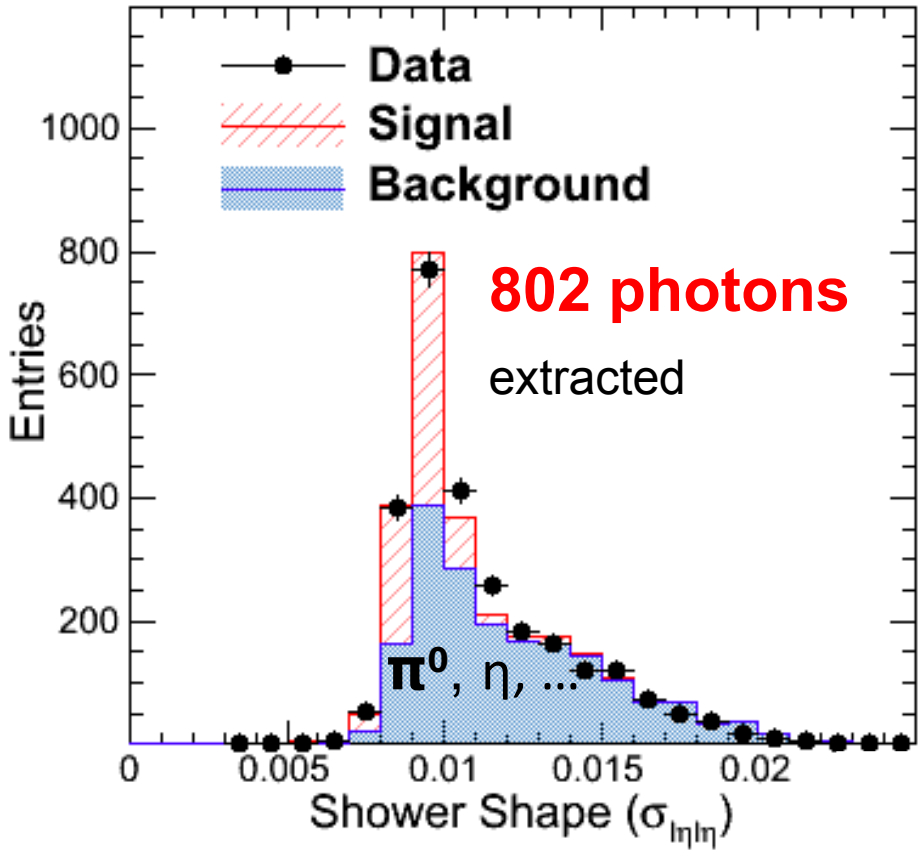
Photon candidate from jet



Photon signal extraction



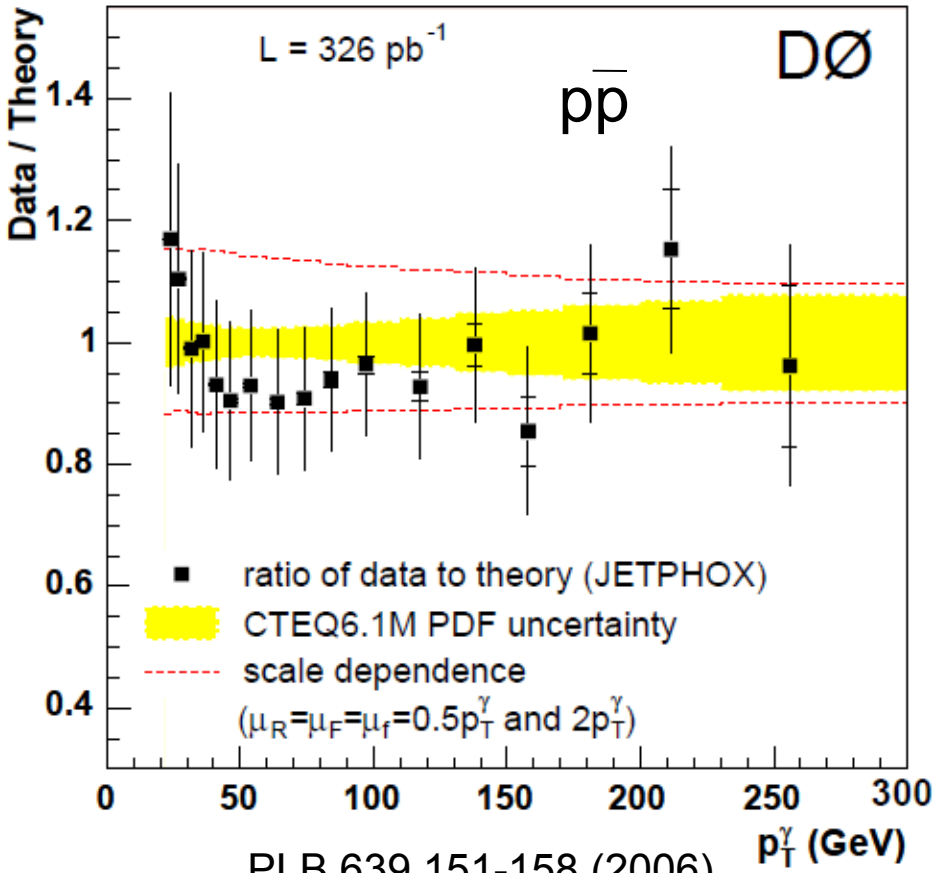
Fit



- A technique used in CMS pp analysis
- Signal template: obtained from PYTHIA+MinBias data
- Background template: obtained from non-isolated π^0, η in jet, obtained using a data driven method

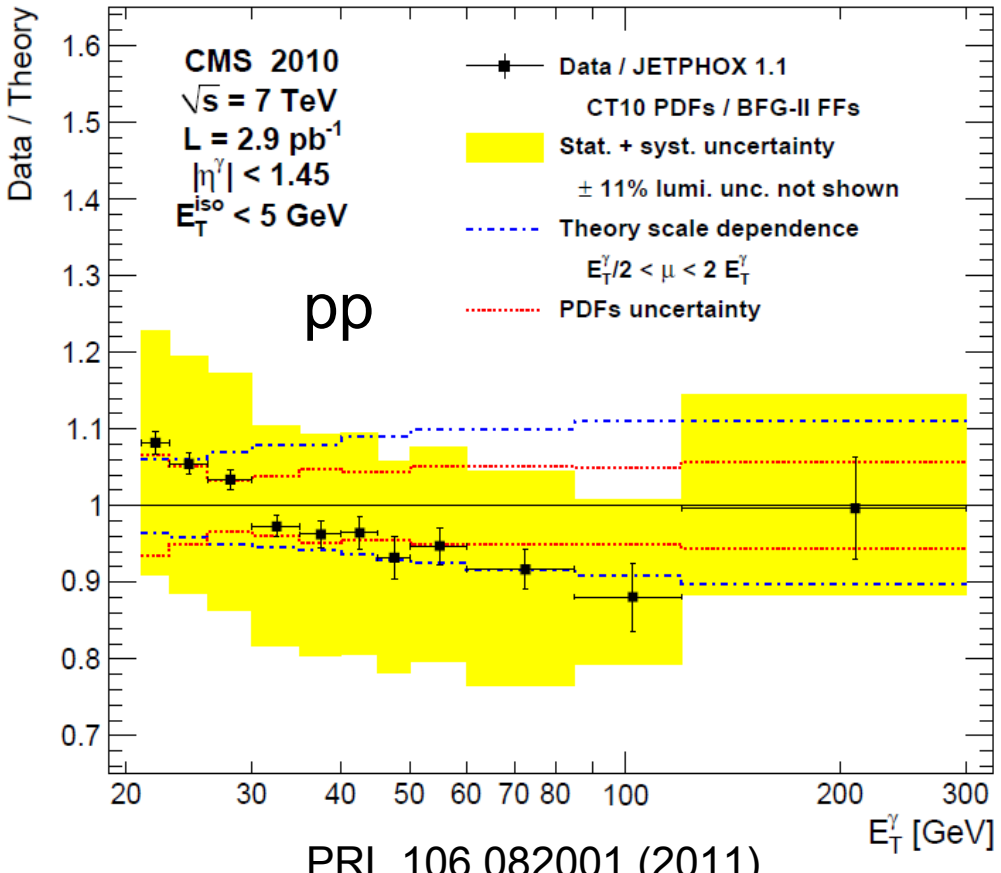
Photon pp reference spectrum

$p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV



PLB 639,151-158 (2006)

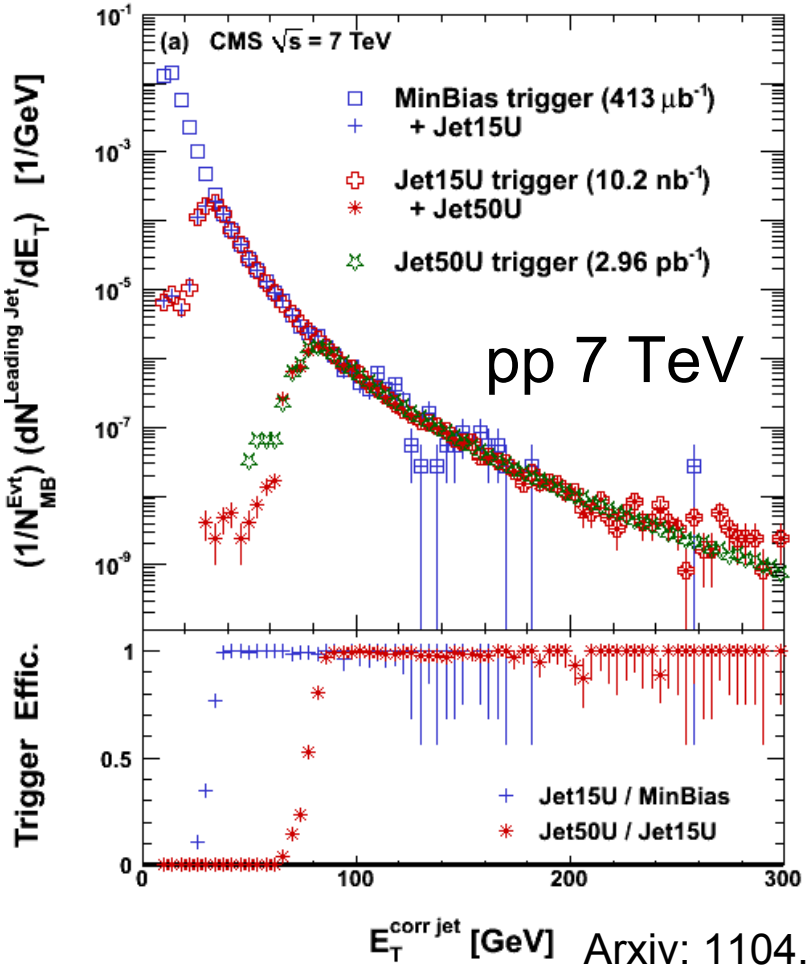
pp at $\sqrt{s}$ = 7 TeV

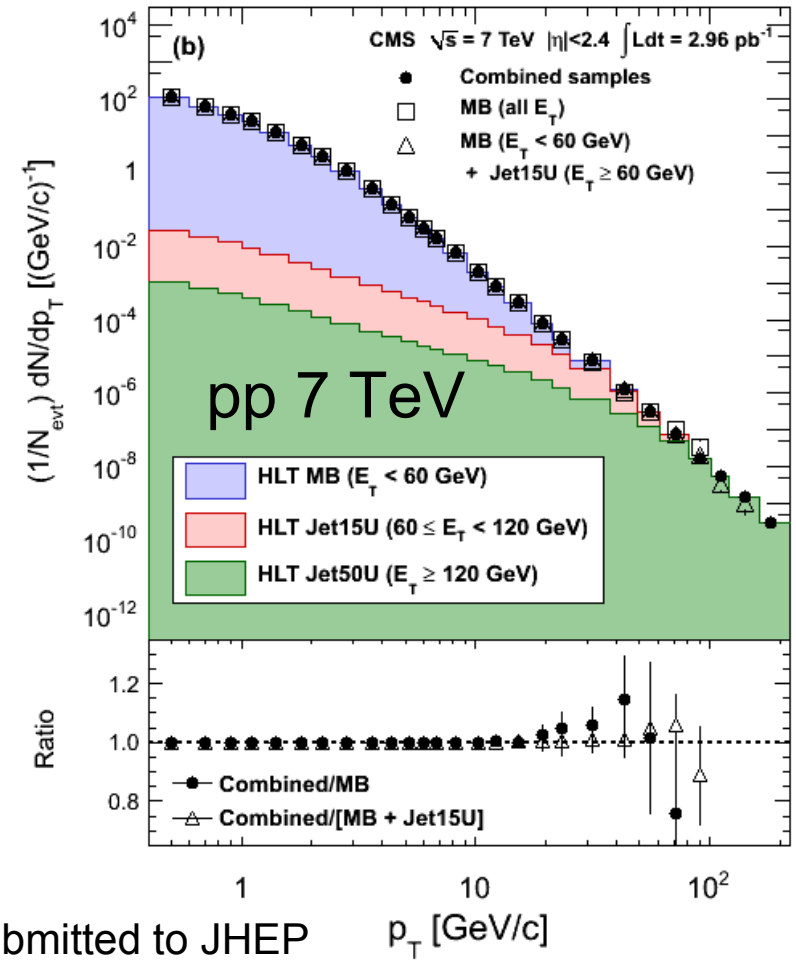


PRL 106,082001 (2011)

- JETPHOX calculation agrees with data within 20%
- Photon pp reference:
  - NLO calculation from JETPHOX with CT10 PDFs / BFG-II FFs
  - Photon isolation requirement: E_T<5 GeV in a cone of ΔR<0.4

Charged particles spectra in pp collisions





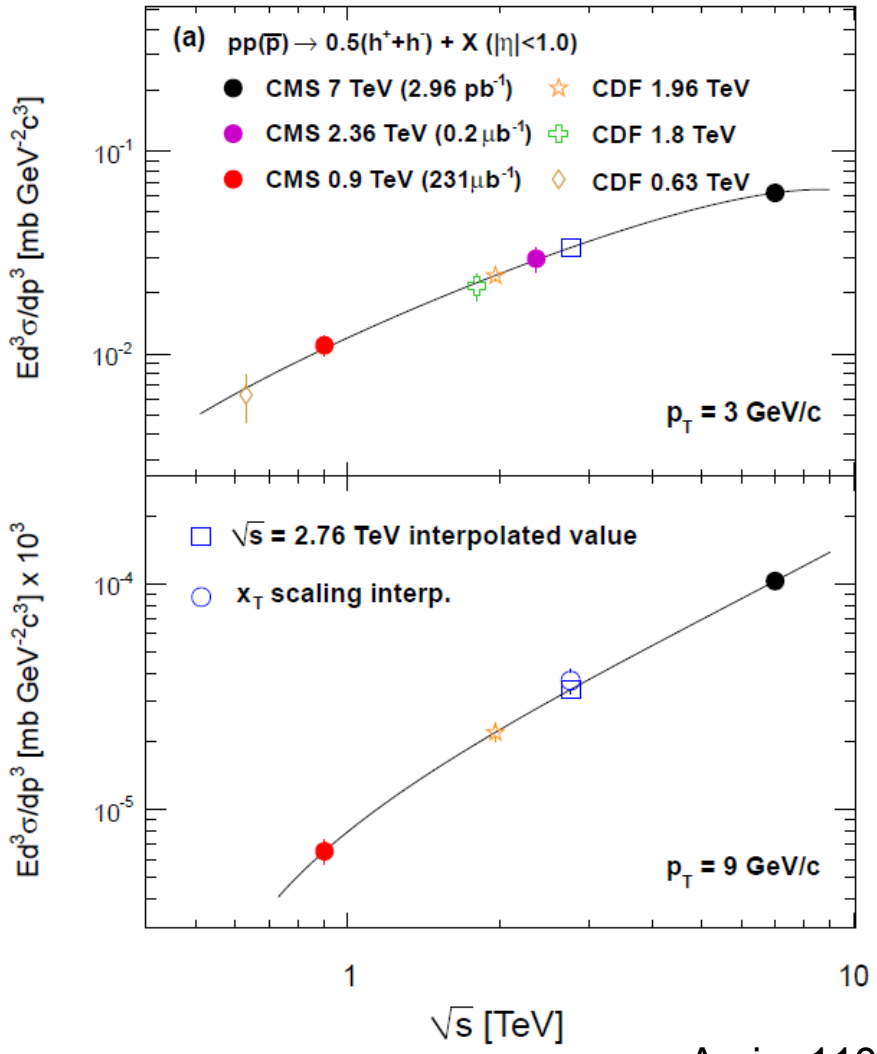
Arxiv: 1104.3547 submitted to JHEP

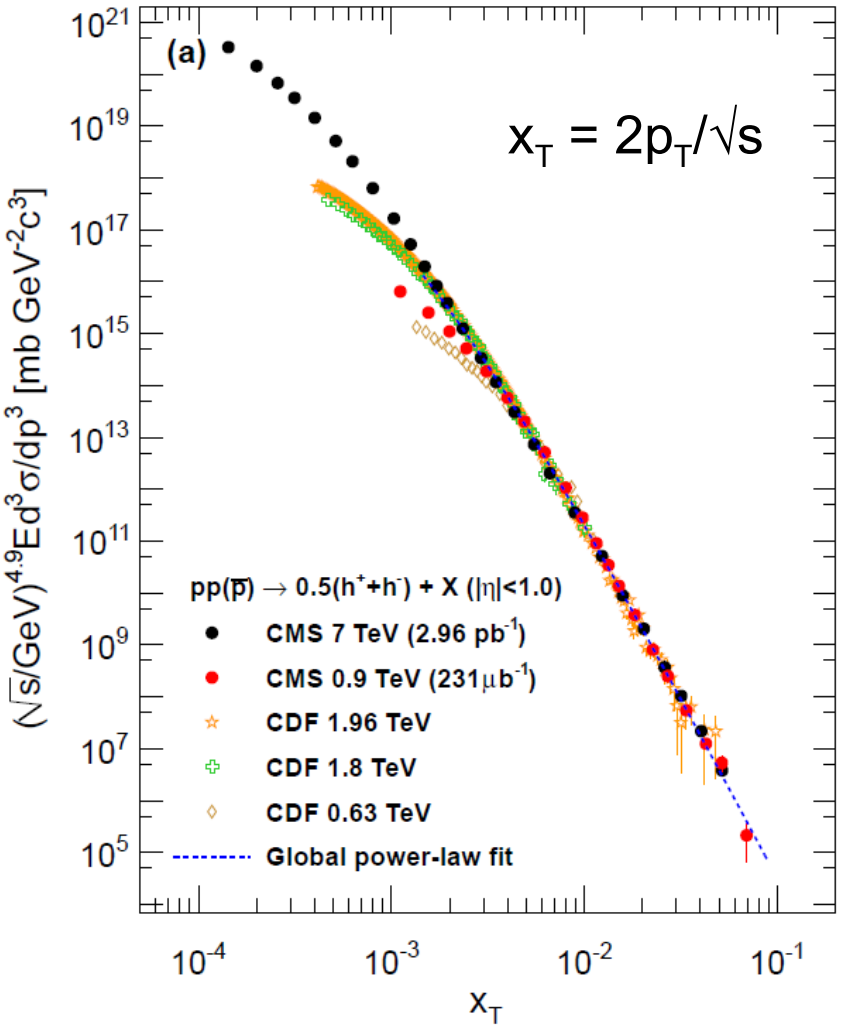
- Measurements in pp collisions at $\sqrt{s}$ = 0.9, 7 TeV with jet trigger
- 4 times higher p_T reach than any other experiments
- Calorimeter triggering:
  Lower the fake rate of the high p_T tracks

Charged particle pp reference

For p_T<10 GeV/c: Bin-by-bin interpolation from experimental data

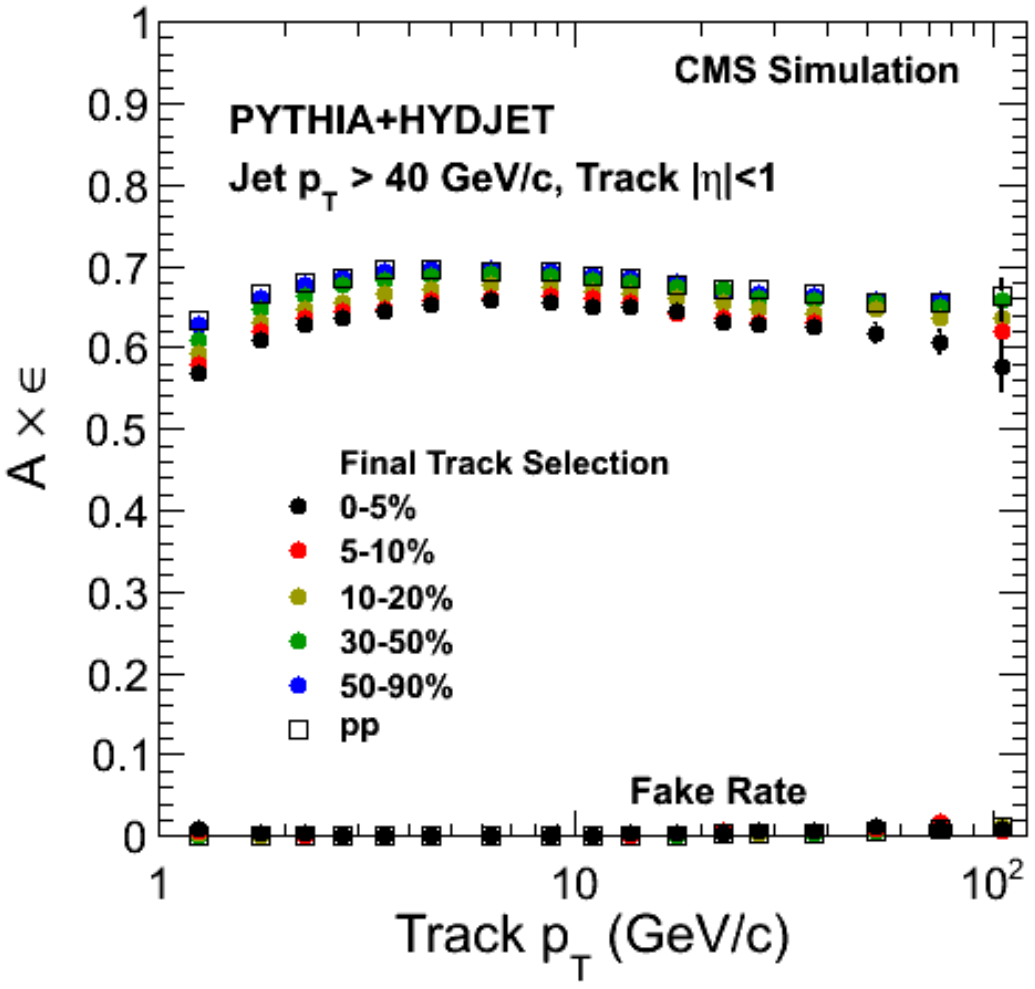
For p_T>10 GeV/c: (NLO-based) x_T-scaling of existing data





Arxiv: 1104.3547 submitted to JHEP

Tracking Performance in CMS



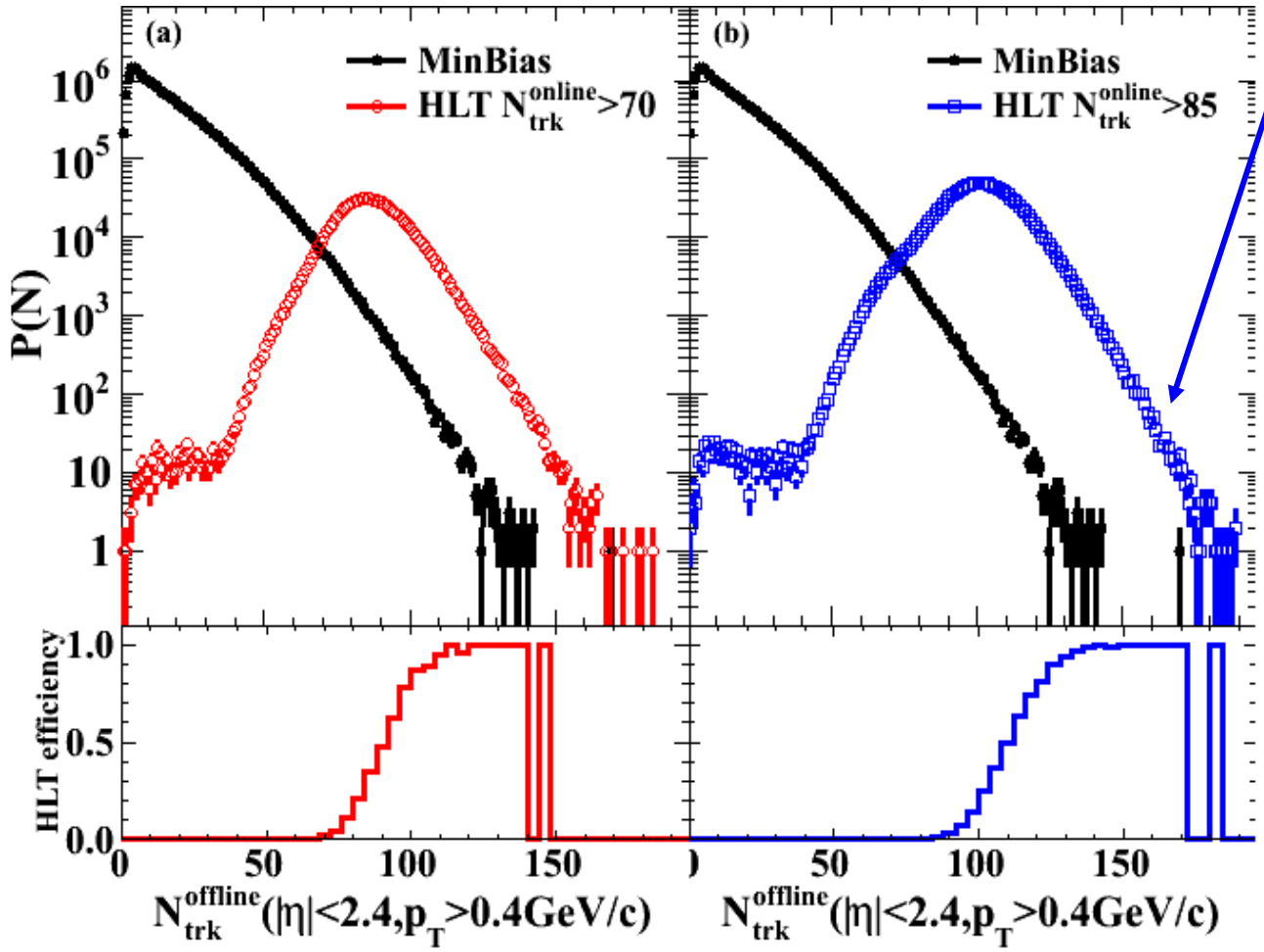
- Efficiency ~65% and Fake < 3% up to 100 GeV/c
- Momentum resolution is below 3% (correction < 3%) up to 100 GeV/c
- Fake rates cross-checked by calorimeter matching and sideband of the impact parameter distributions

High multiplicity pp collisions

See talk by Dragos Velicanu (05/23, 3:00pm)

Very high particle density regime

Is there anything interesting happening?



Dedicated triggers on high multiplicity events from a single collisions (not pileup!)

N^{online} > 85 trigger un-prescaled for full 980nb^{-1} data set

JHEP 09 (2010) 091

~350K top multiplicity events (N>110) out of 50 billion collisions!

Nuclear modification factor

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum”}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)

PbPb measurements

Z boson

Isolated photon

Charged particle

pp reference spectrum

NLO calculation from POWHEG
JHEP 07(2008)06

NLO calculation of isolated photon from JETPHOX
JHEP 0205 (2002) 028

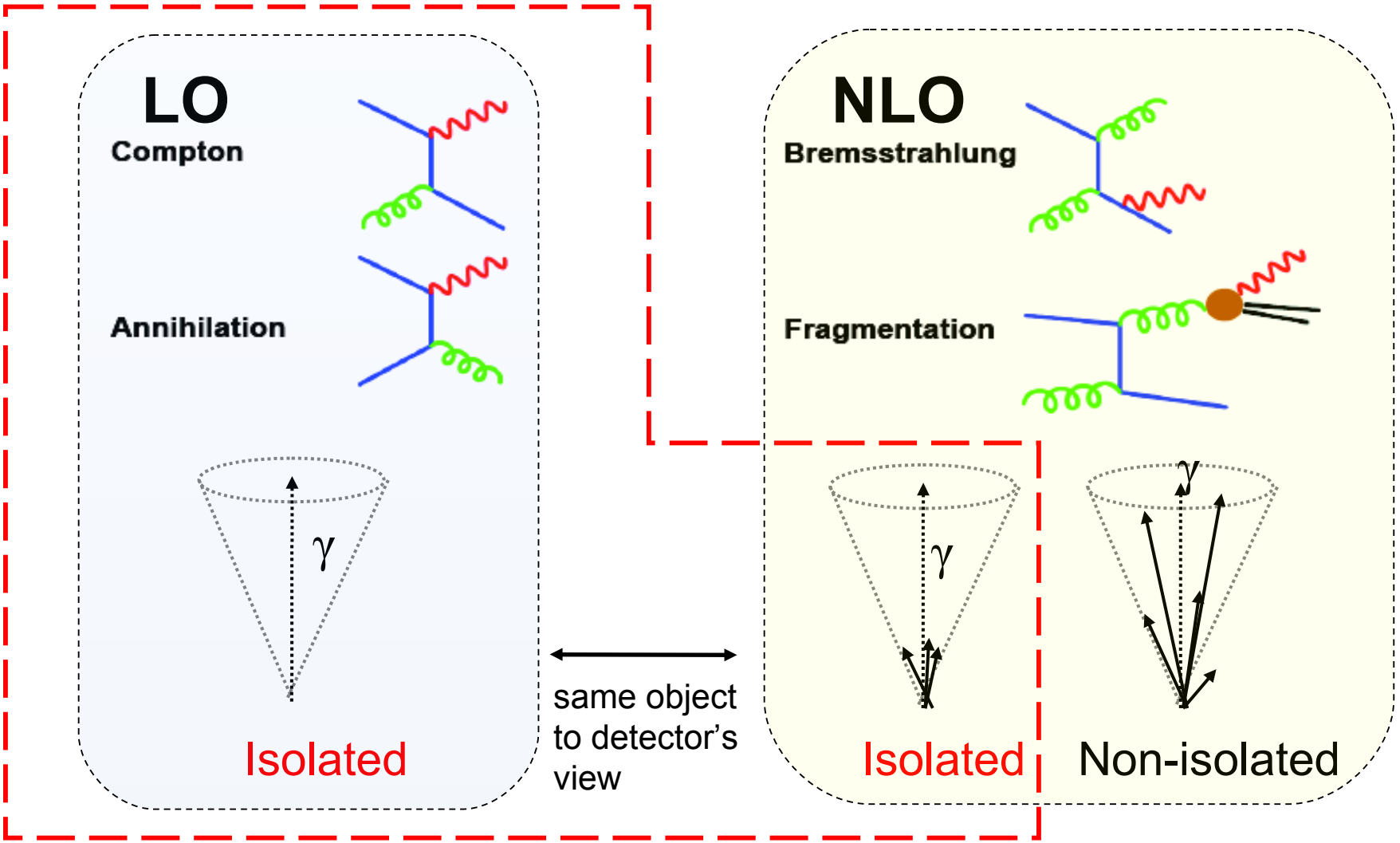
Interpolation from CMS pp measurements at 0.9, 2.36 and 7 TeV.
Arxiv: 1104.3547 submitted to JHEP

$$T_{AA} = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per AA collision"

Isolated high p_T photons

- Ideal: Direct photon from hard scattering
- Real world: Background from the decay and fragmentation photons.
- Solution: Measurement of the isolated photons



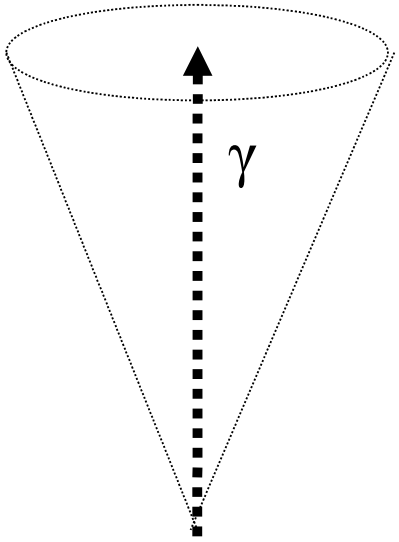
Photon isolation in PbPb

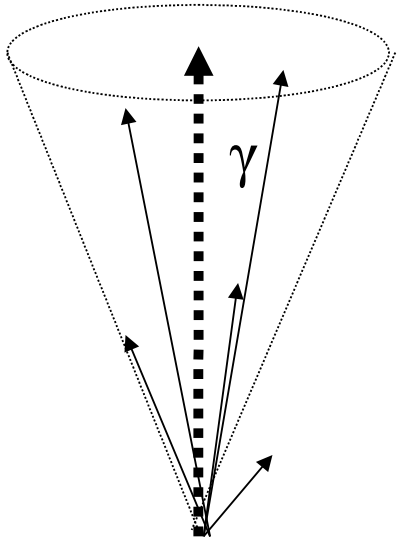
Generator level

$\Delta R<0.4$, $\Sigma E_T^{\text{IsoCone}} < 5$ GeV

with only particles from the same hard scattering

Particles from the same hard scattering



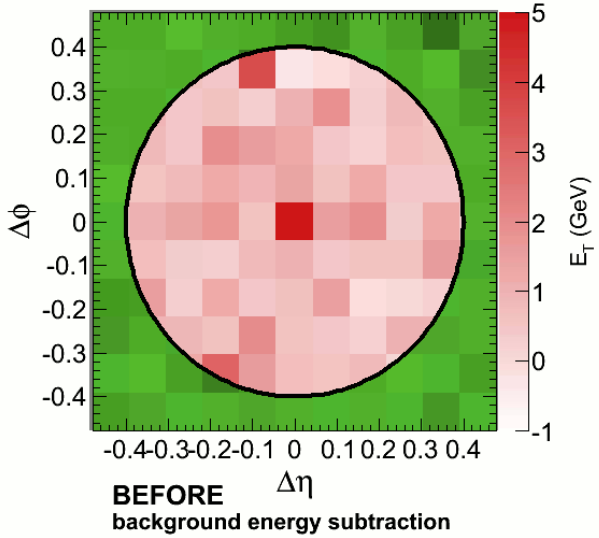


CMS Experiment

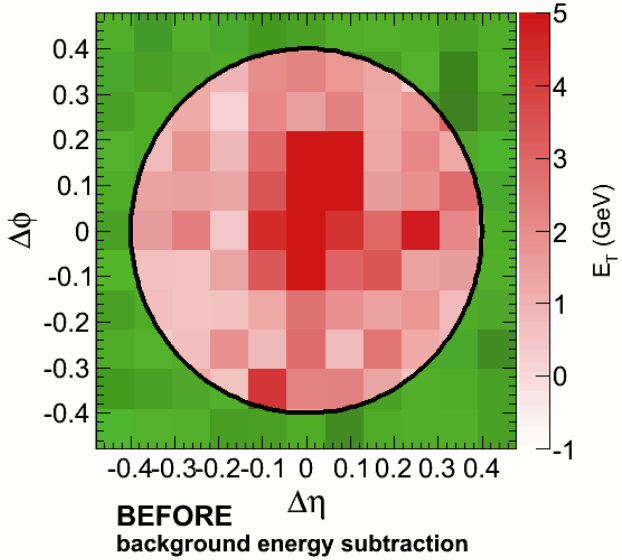
Sum E_T (p_T) from Calorimeter and tracker

Contribution from underlying event

Isolated photon

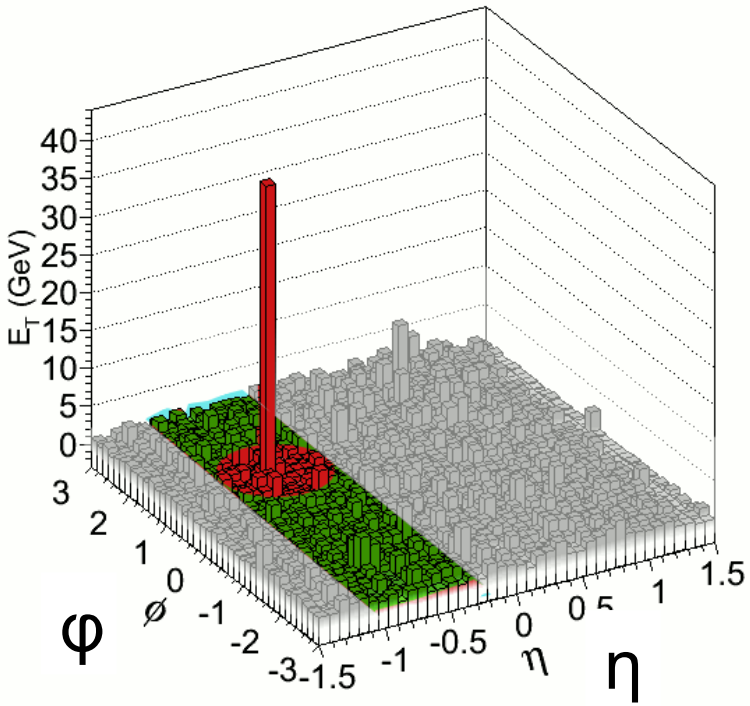


Photon candidate from jet

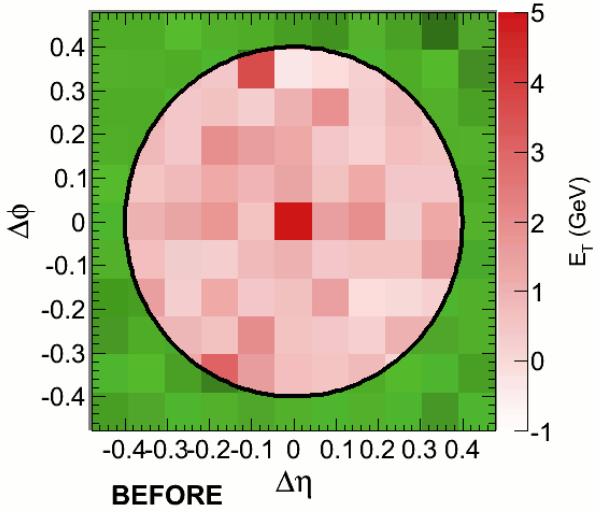


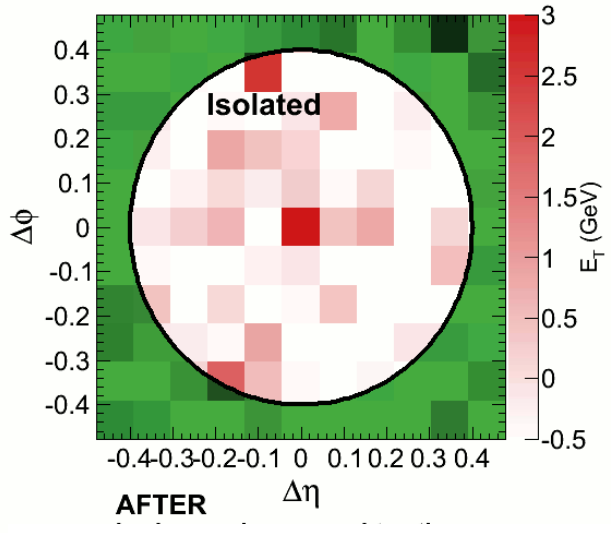
Background subtraction

- Background subtracted isolation by using the mean E_T per unit area in the η strip and remove the underlying event contribution inside the isolation cone

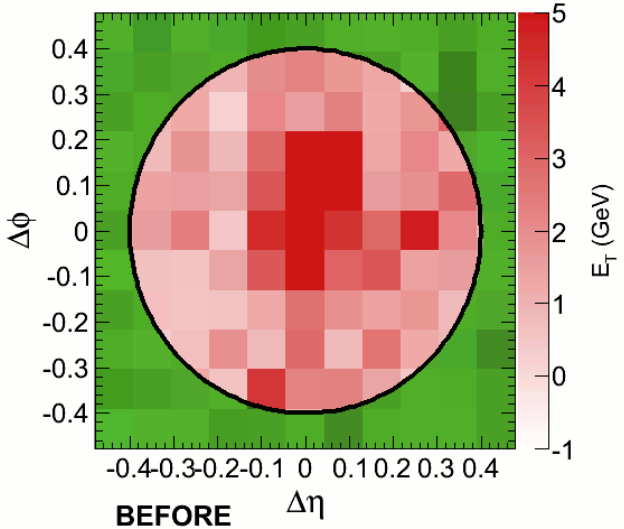


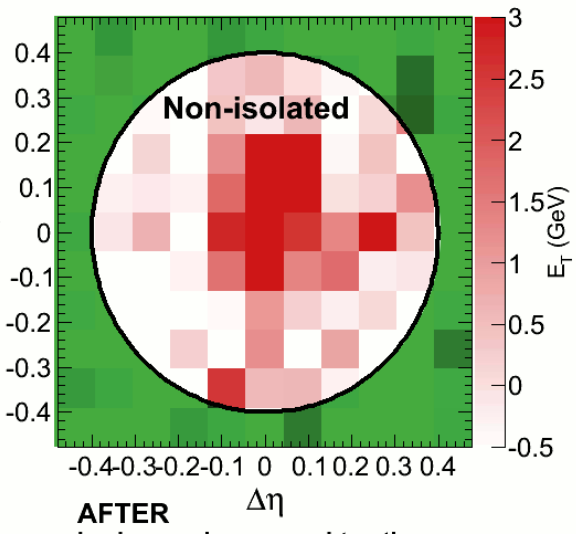
Isolated photon





Photon candidate from jet



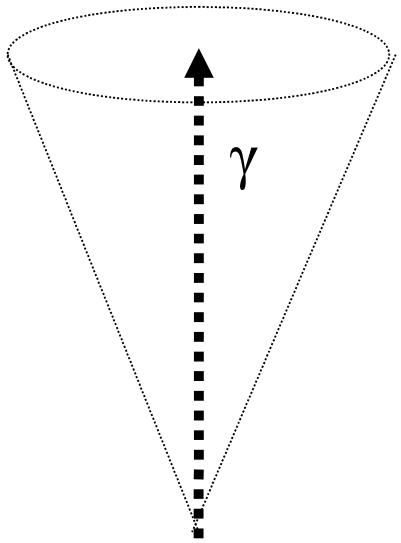


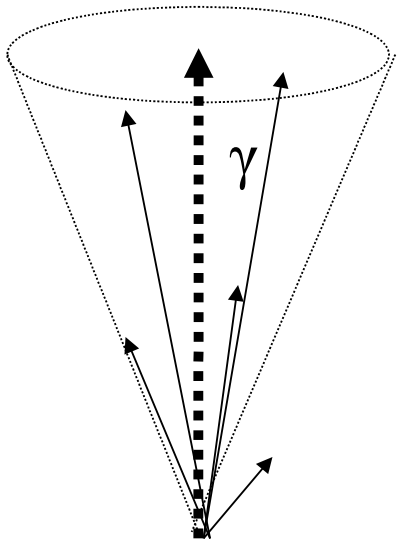
See Yongsun Kim's talk on Fri 5pm

Background subtracted isolation in PbPb

Generator level
$\Delta R<0.4$, $\Sigma E_T^{IsoCone} < 5$ GeV
with only particles from the same hard scattering

Particles from the same hard scattering

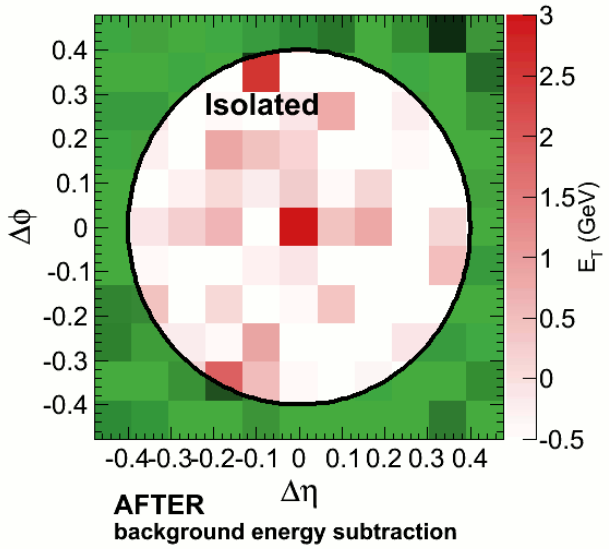




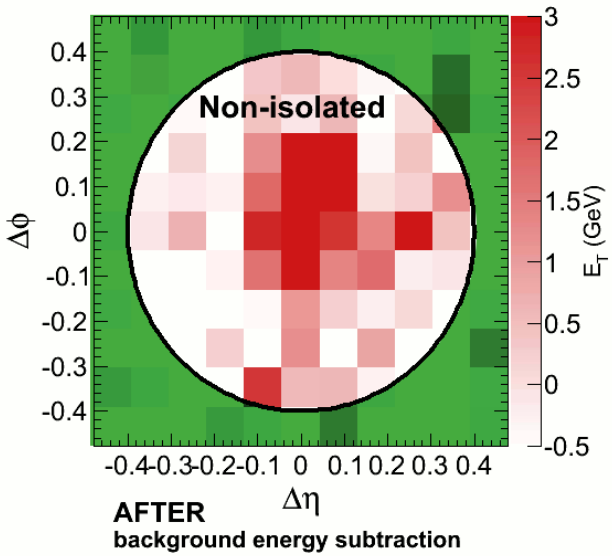
CMS Experiment

Sum E_T (p_T) from Calorimeter and tracker < 5 GeV with background subtracted

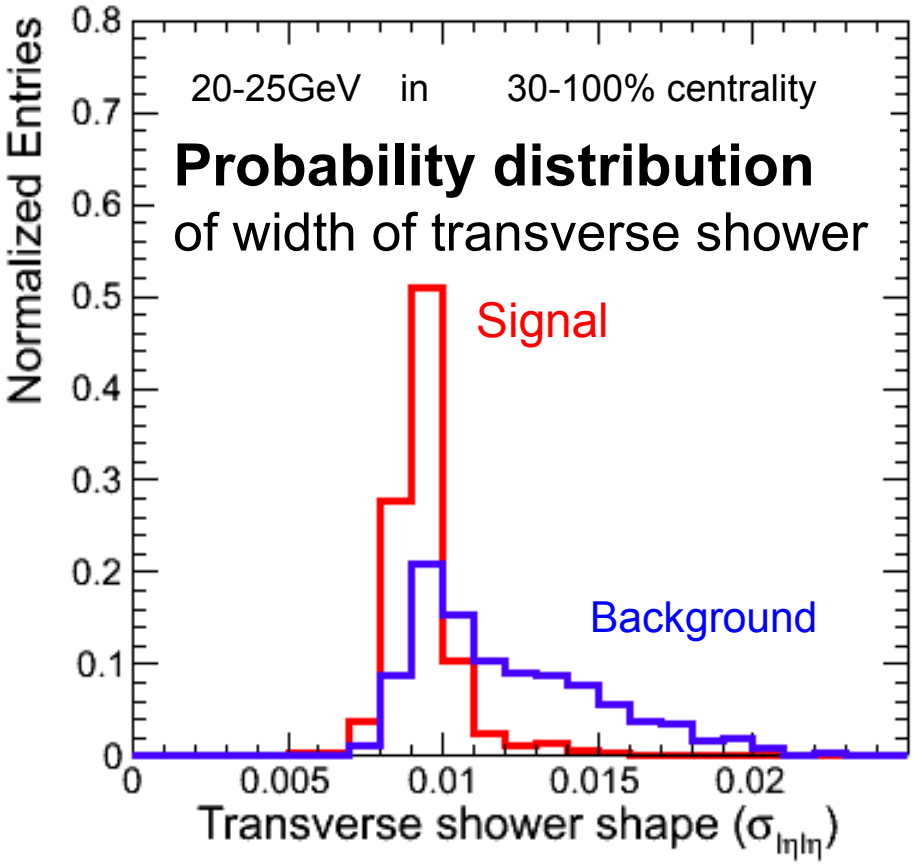
Isolated photon



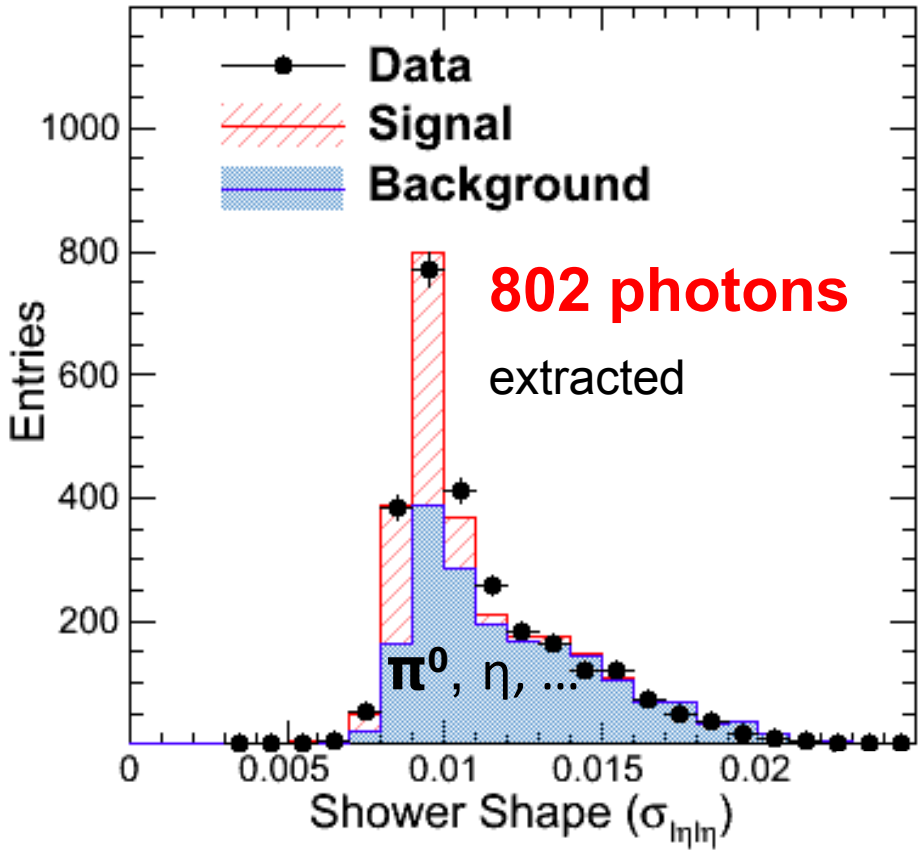
Photon candidate from jet



Photon signal extraction

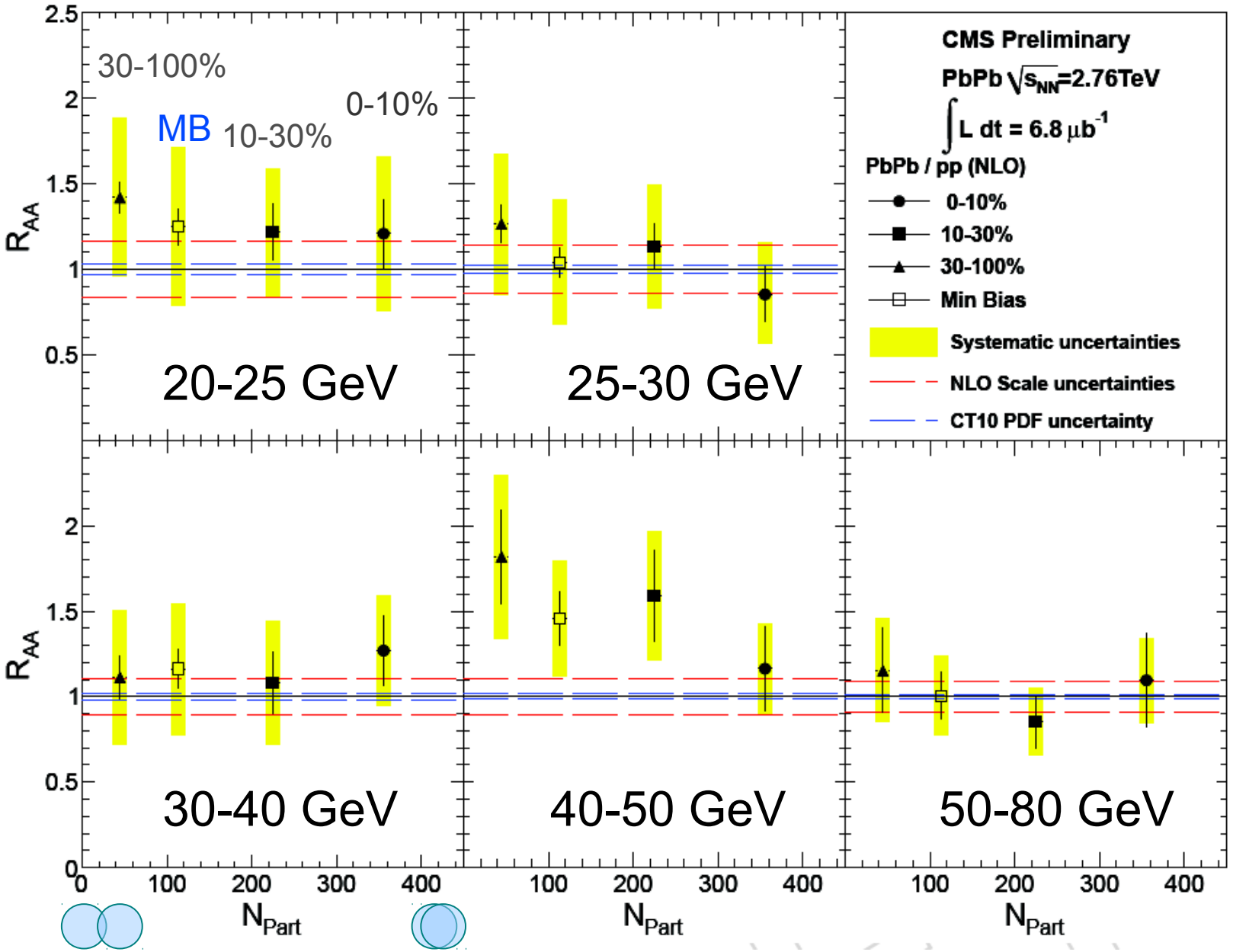


Fit



- A technique used in CMS pp analysis
- Signal template: obtained from PYTHIA+MinBias data
- Background template: obtained from non-isolated π^0, η in jet, obtained using a data driven method

Isolated photon R_{AA} vs N_{Part}



No centrality dependence

Summary of colorless probes

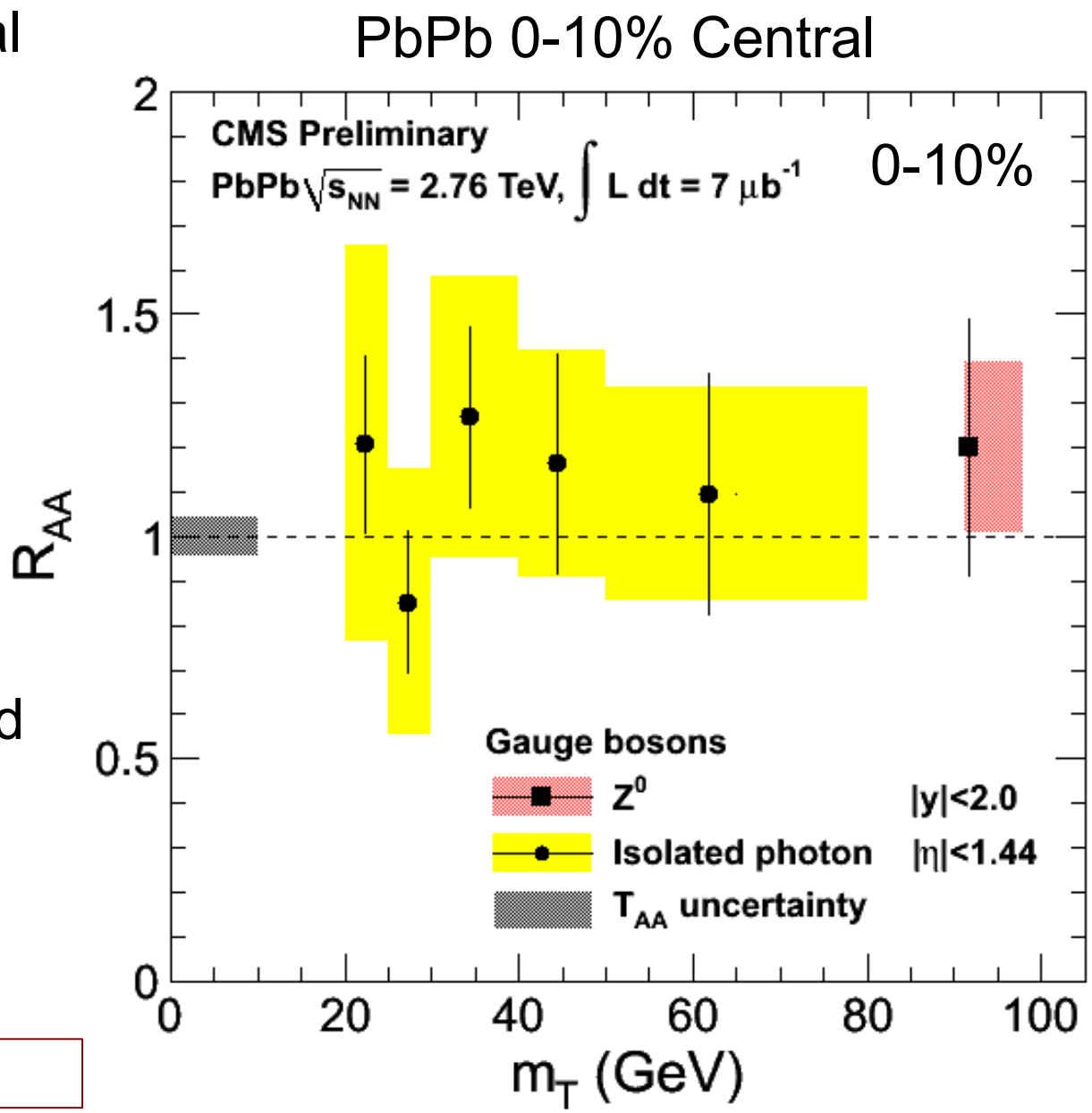
- No modification of the initial state. The hard scattering processes scale with the number of binary collisions from the Glauber model

- Baseline for the study of charged particle production

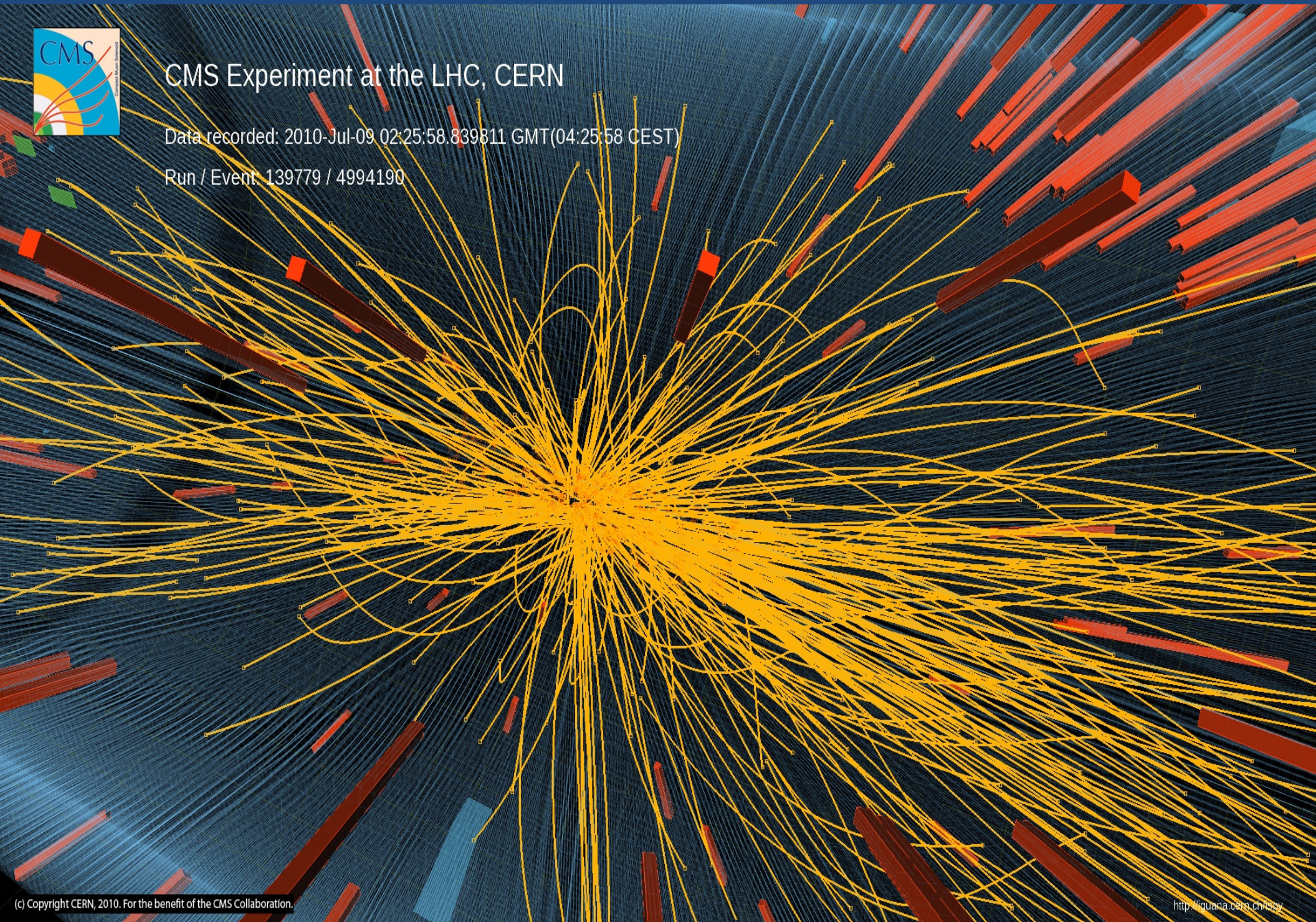
- High statistics run in 2011 will shrink both statistical and systematic uncertainties

Analysis of $Z \rightarrow e^+e^-$ and $W \rightarrow \mu\nu$ are on-going

See Lamia Benhabib's poster



High multiplicity pp collisions

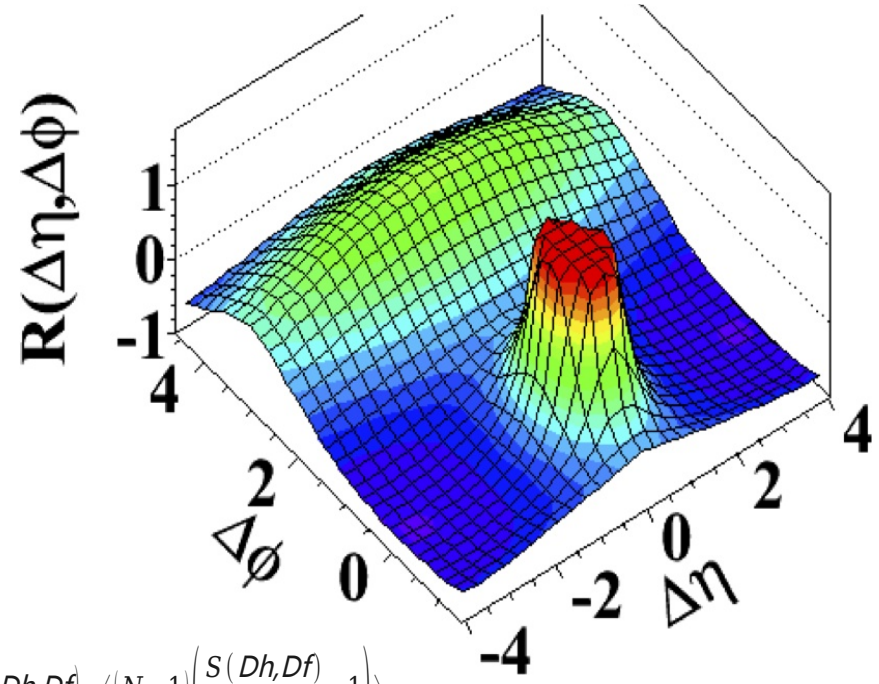


Ridge in high multiplicity pp

Intermediate p_T: 1-3 GeV/c

350K events

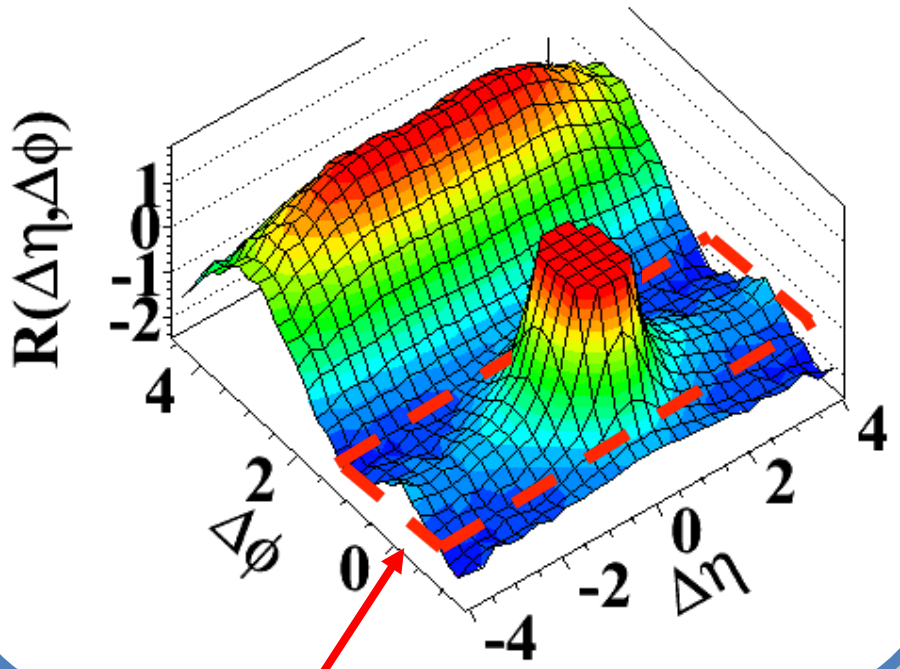
Minimum Bias pp (<N> ~ 15)



$$R(Dh,Df) = \langle (N-1)\left(\frac{S(Dh,Df)}{B(Dh,Df)} - 1\right)\rangle_N$$

peak truncated

High multiplicity pp (N ≥ 110)



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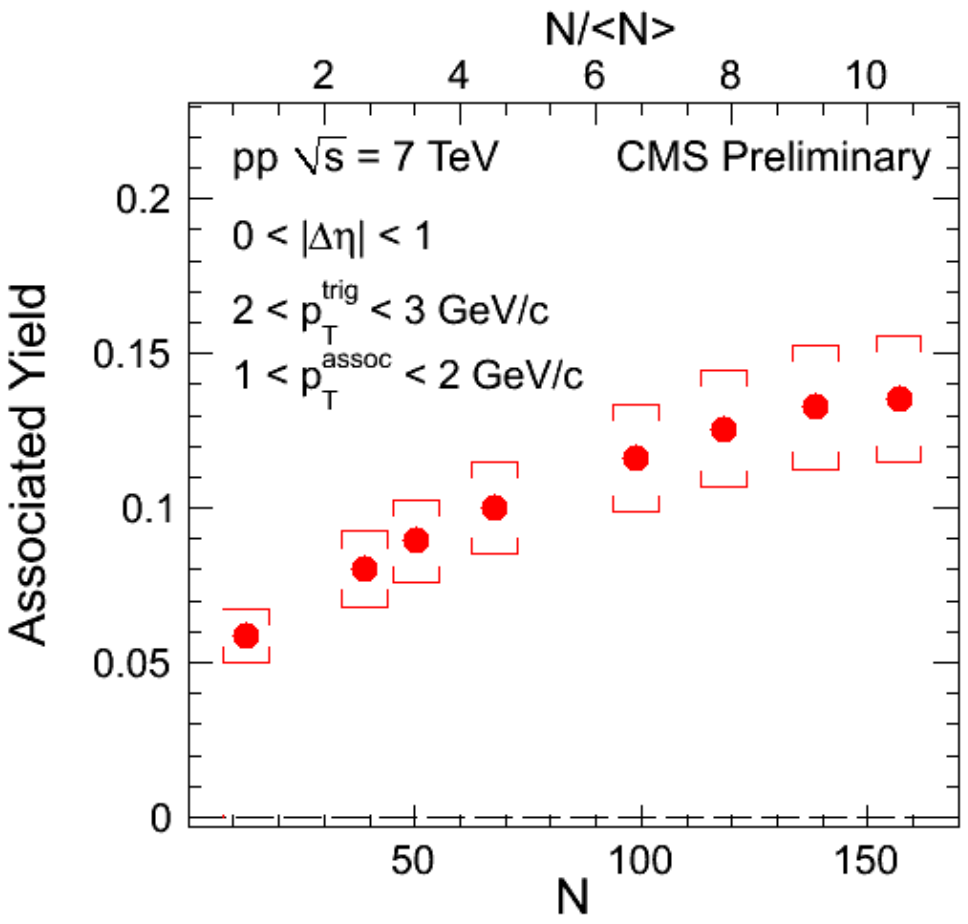
Striking "ridge-like" structure extending over Δη at Δφ ~ 0

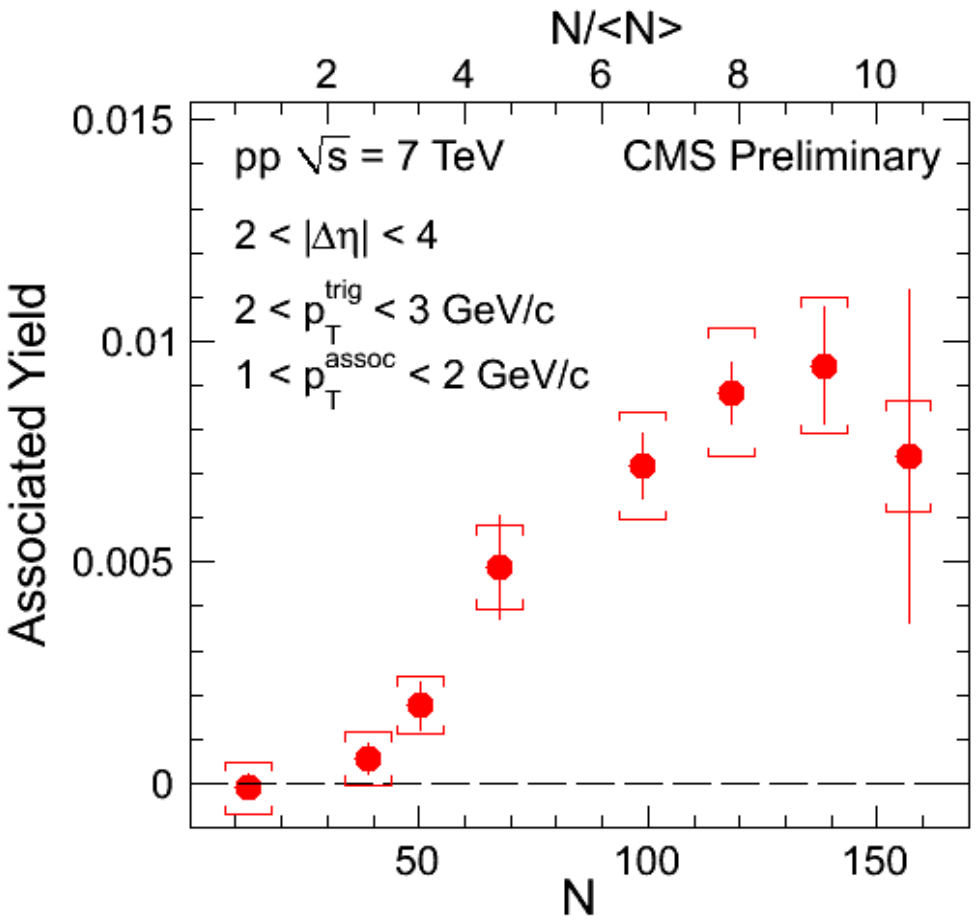
(not observed before in hadron collisions or MC models)

Near-side yield vs multiplicity in pp

Jet region (|Δη|<1)



Ridge region (2<|Δη|<4)

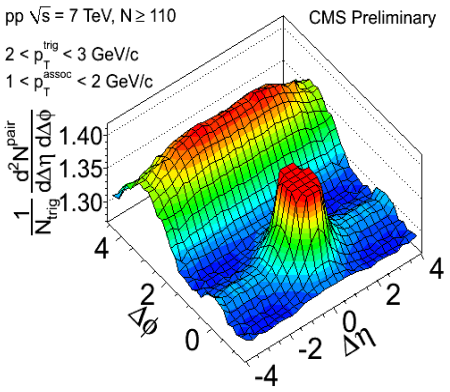


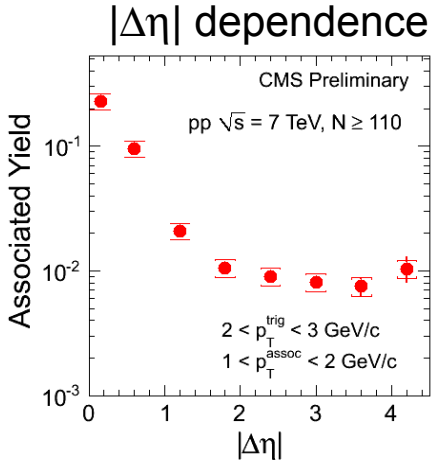
- Jet yield in pp monotonically increases with N
- Ridge in pp turns on around N ~ 50 – 60 (4 x MinBias) smoothly

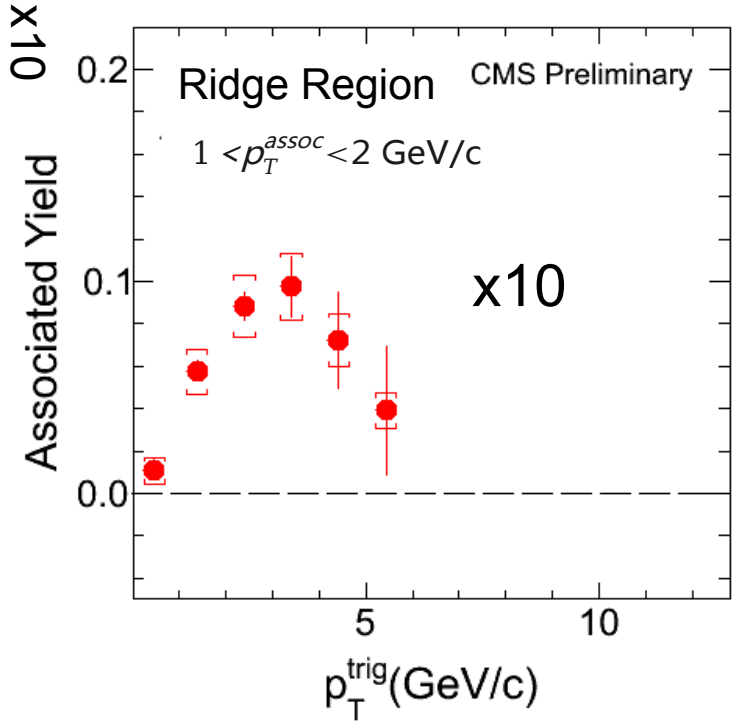
(<N> ~ 15 in MinBias pp events)

Ridge in pp and PbPb

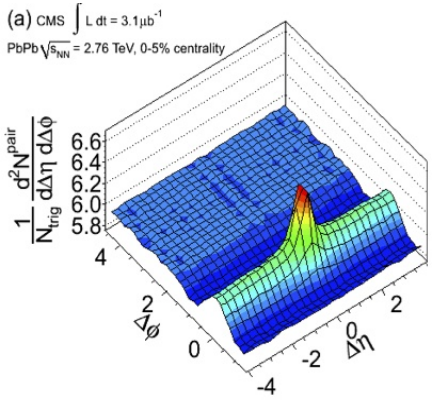
CMS pp 7 TeV, N ≥ 110

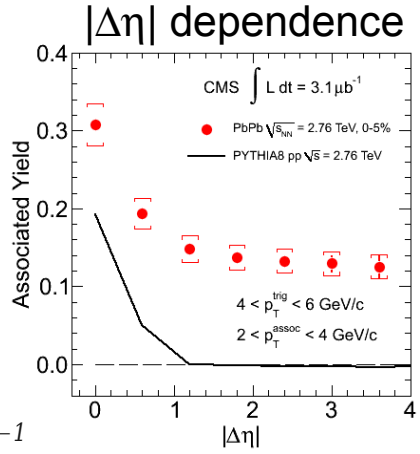




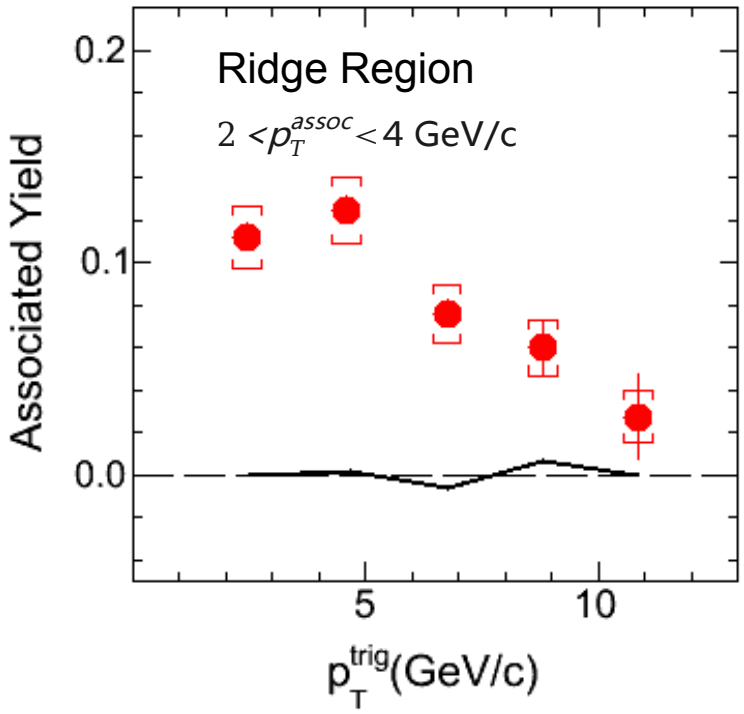


CMS PbPb 2.76 TeV, 0-5%

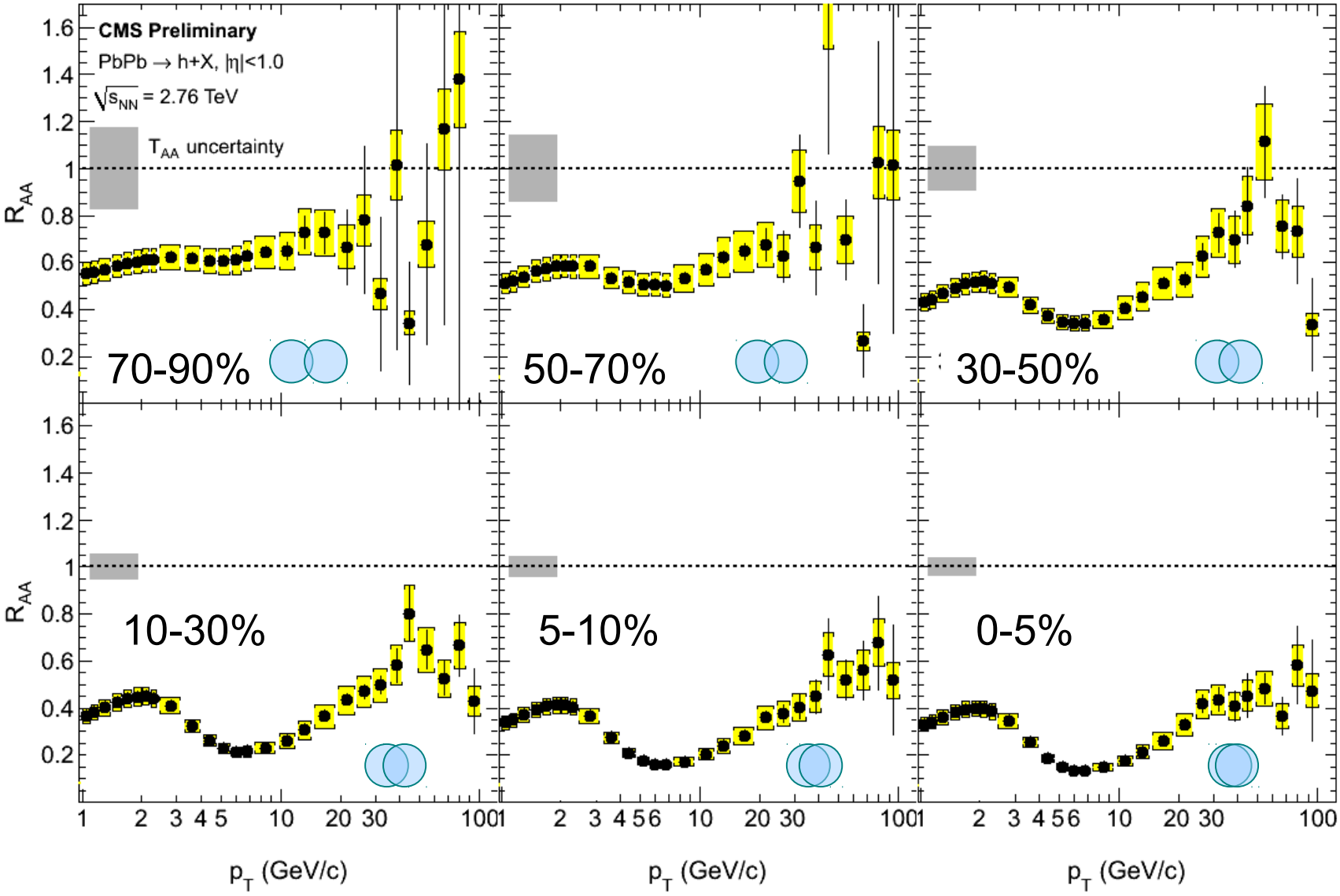




CMS $\int L = 3.1\,mb^{-1}$



Charged particle R_{AA} in different centralities



- Dip structure developing as a function of centrality
- R_{AA} increases as a function of p_T in the p_T>10 GeV/c region