Jets and charged hadrons results from CMS

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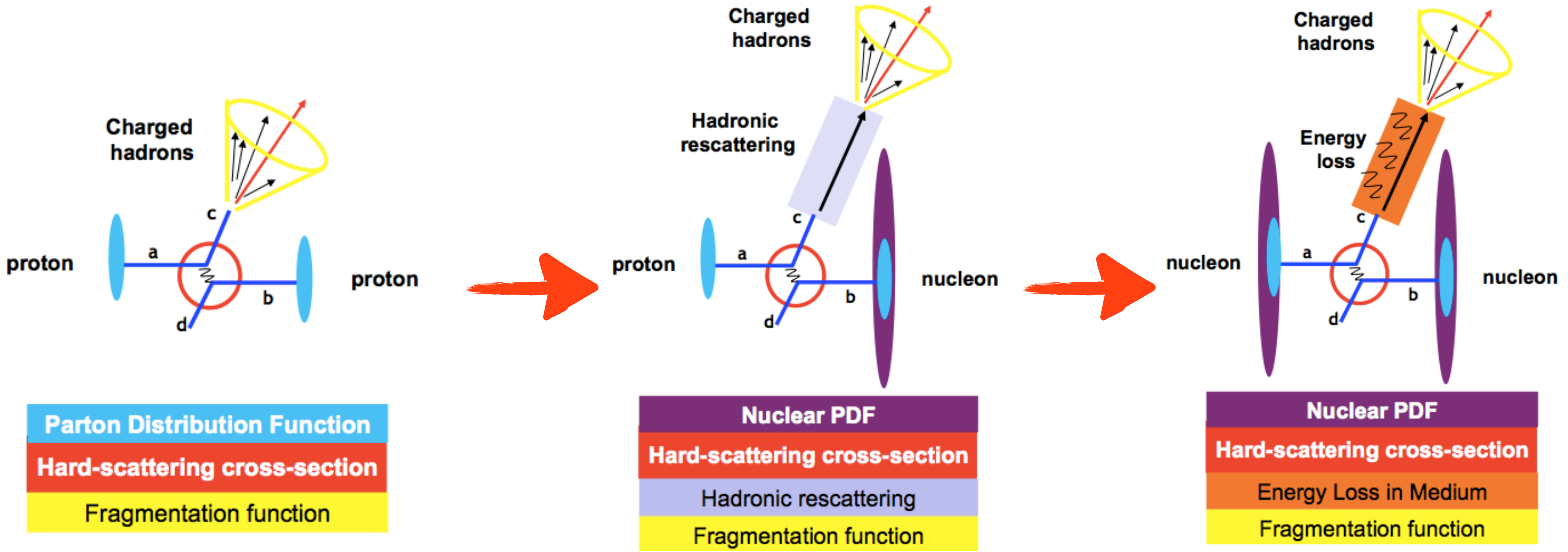
for the CMS Collaboration

VANDERBILT UNIVERSITY

International Conference on the Initial Stages in High-Energy Nuclear Collisions
December 3rd-7th, 2014

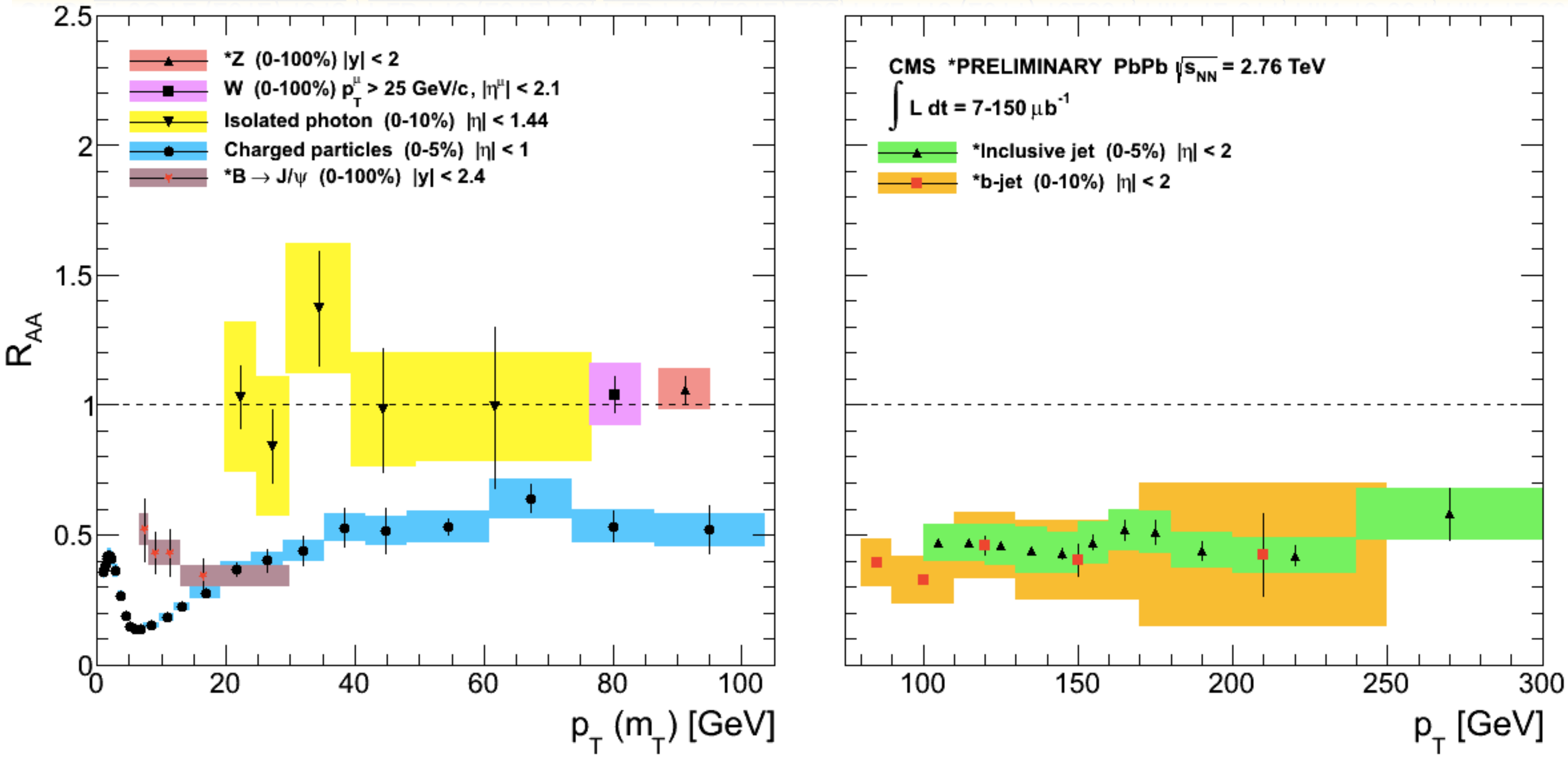
Nuclear effects in heavy ion collisions



- Elements of proton-proton as well as nucleus-nucleus collisions
- Disentangle initial and final state effects
- Characterize nuclear PDFs

Previous measured nuclear modifications in HI collisions

CMS: EPJC 72 (2012) 1945 , PLB 715 (2012) 66, PLB 710 (2012) 256, PRL 113 (2014) 132301, HIN-12-014, HIN-13-004, HIN-12-004



$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T\,d\eta}{d^2\sigma_{pp}/dp_T\,d\eta}$$

- R_{AA}: Nuclear modification factor
- High p_T final state charged hadrons and jets are strongly suppressed
  - ➡ Initial-state and final-state effects combined
  - ➡ Need study of nuclear modifications in pPb to separate initial and final state effect

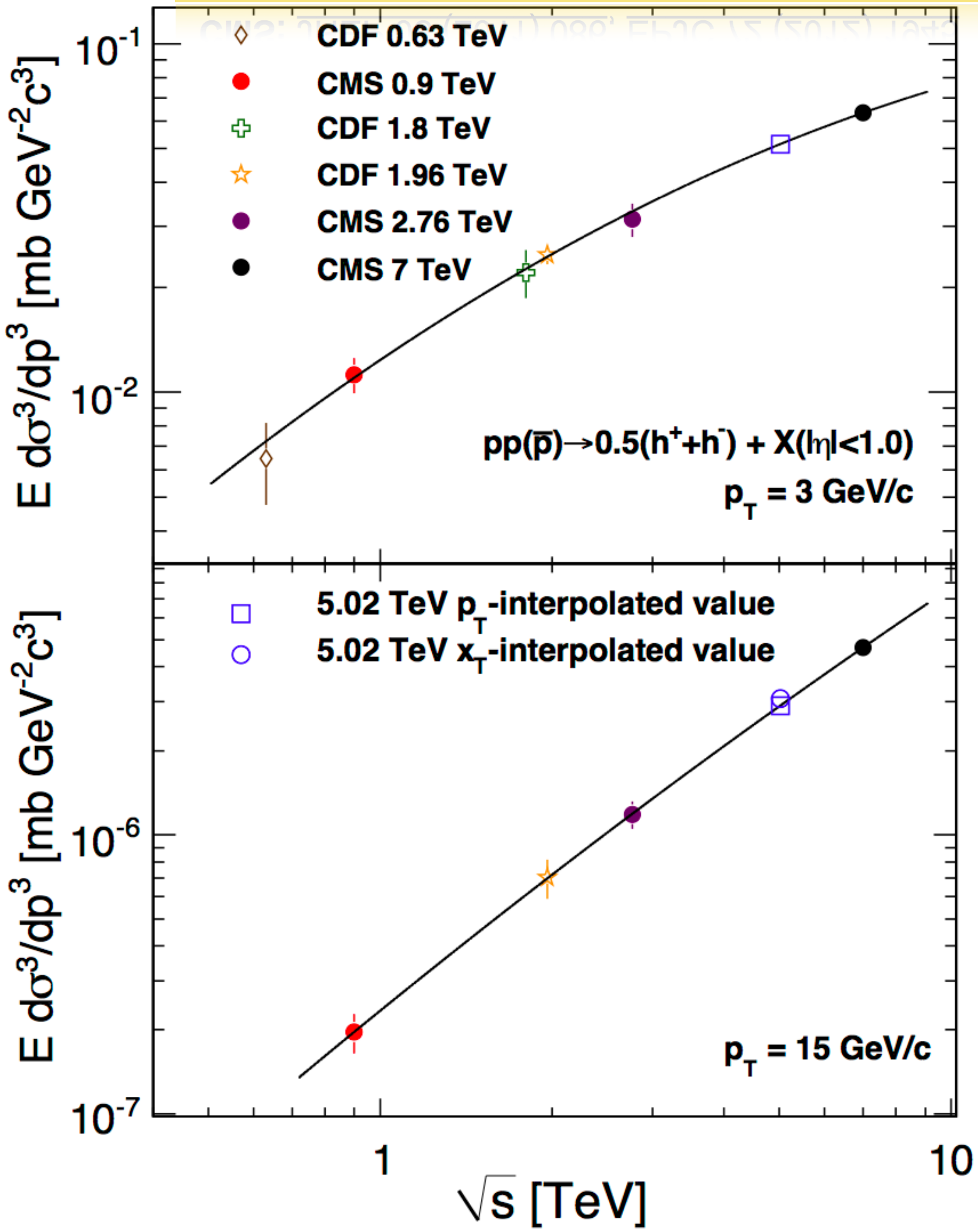
Nuclear modification factor R_{pA} in pPb

- Nuclear modification factor $$R_{pA} = \frac{dN_{pA}/dp_T}{\langle N_{coll}\rangle dN_{pp}/dp_T}$$
- Number of binary collisions is calculated in a Glauber model: $\langle N_{coll}\rangle = 6.9 \pm 0.6$
- For pQCD processes: if $R_{pA} \approx 1 \rightarrow$ pPb collision is approximately a superposition of independent proton-nucleon collisions and no nuclear effects are present
- Challenge: pPb collision at a different energy than pp and PbPb, no direct reference measurement from real data

➡ Interpolation/Extrapolation from other $\sqrt{s}$ measurements to build up the reference spectrum in pp

Charged particle pp reference spectrum

CDF: PRL 61 (1988) 1819, PRD 82 (2010) 119903
CMS: JHEP 08 (2011) 086, EPJC 72 (2012) 1945

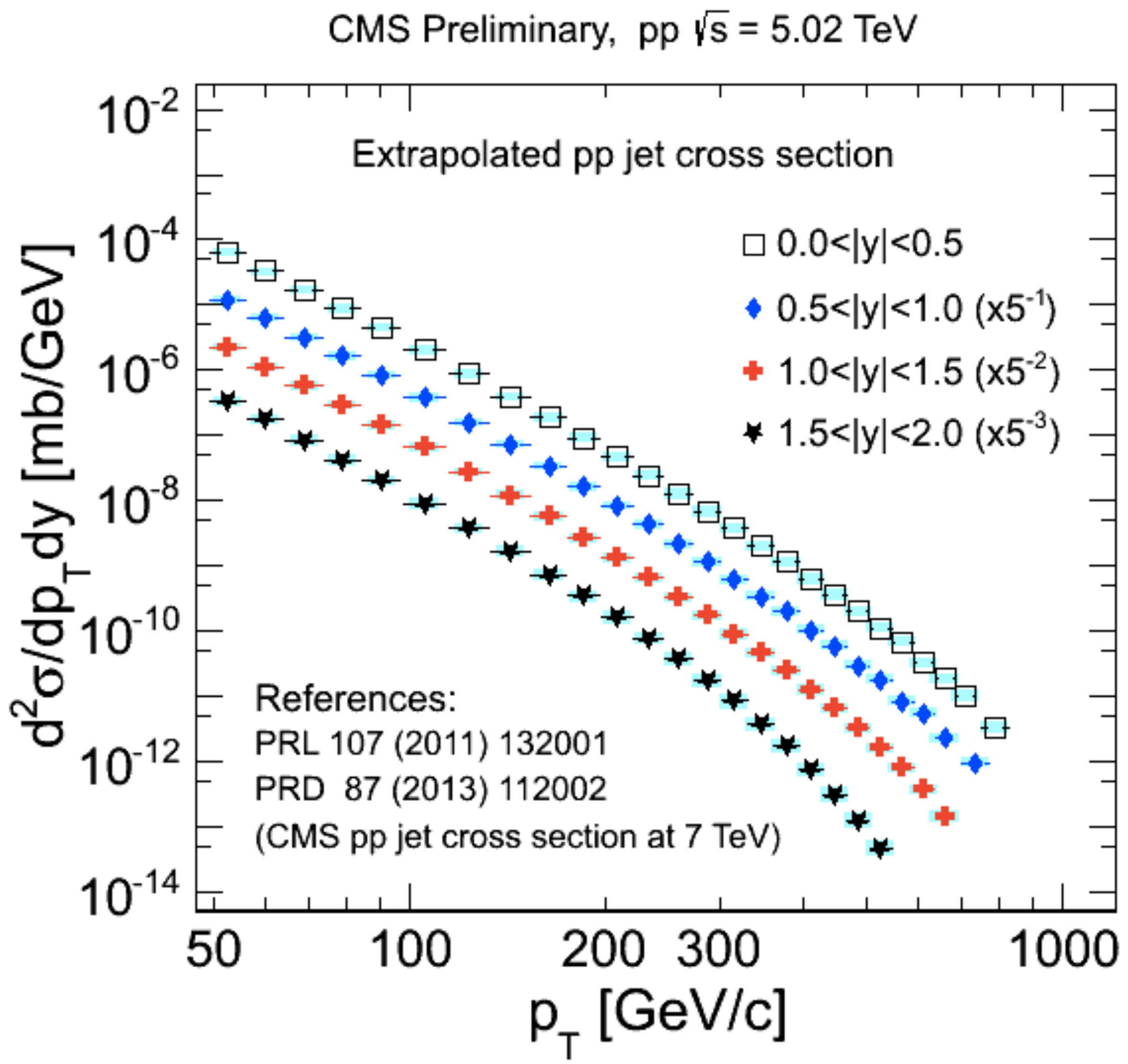


Direct data interpolation method

- Six datasets used from published papers with $\sqrt{s}$ from 0.63 to 7 TeV
- Only the 2.76 and 7 TeV data extend to high p_T beyond 30-40 GeV/c
- Technique for high-p_T interpolation: use $x_T = 2 p_T / \sqrt{s}$
- Total uncertainty: 10%

Jet reference spectrum in pp

CMS-PAS-HIN-14-001



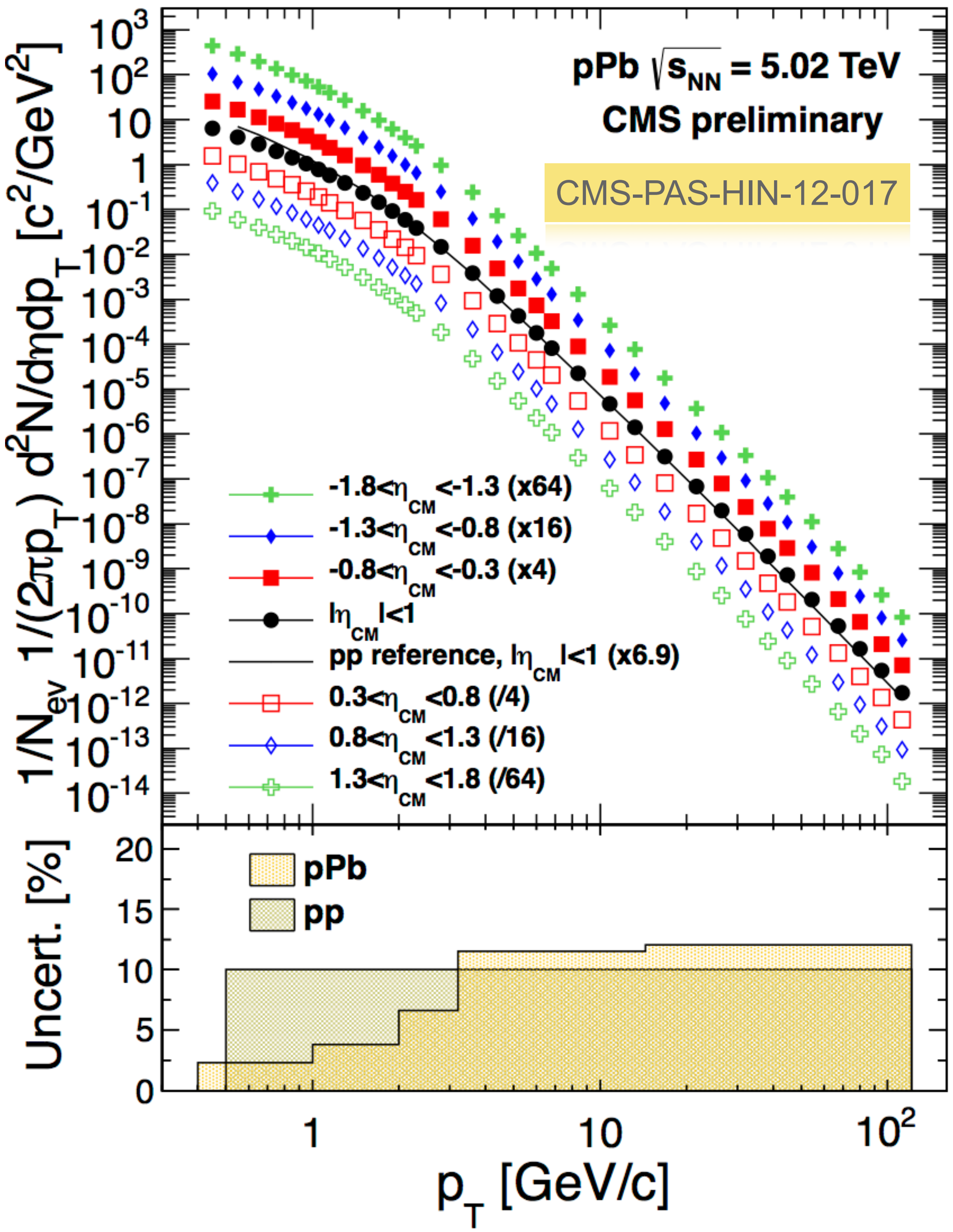
jet reconstruction: anti-k_T, R = 0.3, 0.5

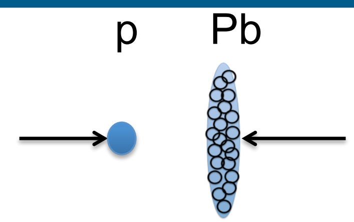
PYTHIA based data extrapolation method

- Only two datasets from published papers with R=0.5 and R=0.7 at the same $\sqrt{s}$ = 7 TeV
- PYTHIA Z2 correctly describes ratio of R=0.7/R=0.5, used to scale CMS jet cross section to R=0.3
- PYTHIA Z2 ratio of 5.02/7 TeV used to scale cross section to lower energy
- Systematic uncertainties taken from use of different PYTHIA tunes, shifting underlying measured spectra, changing the underlying data set used.
- Total uncertainty range: 14-20%

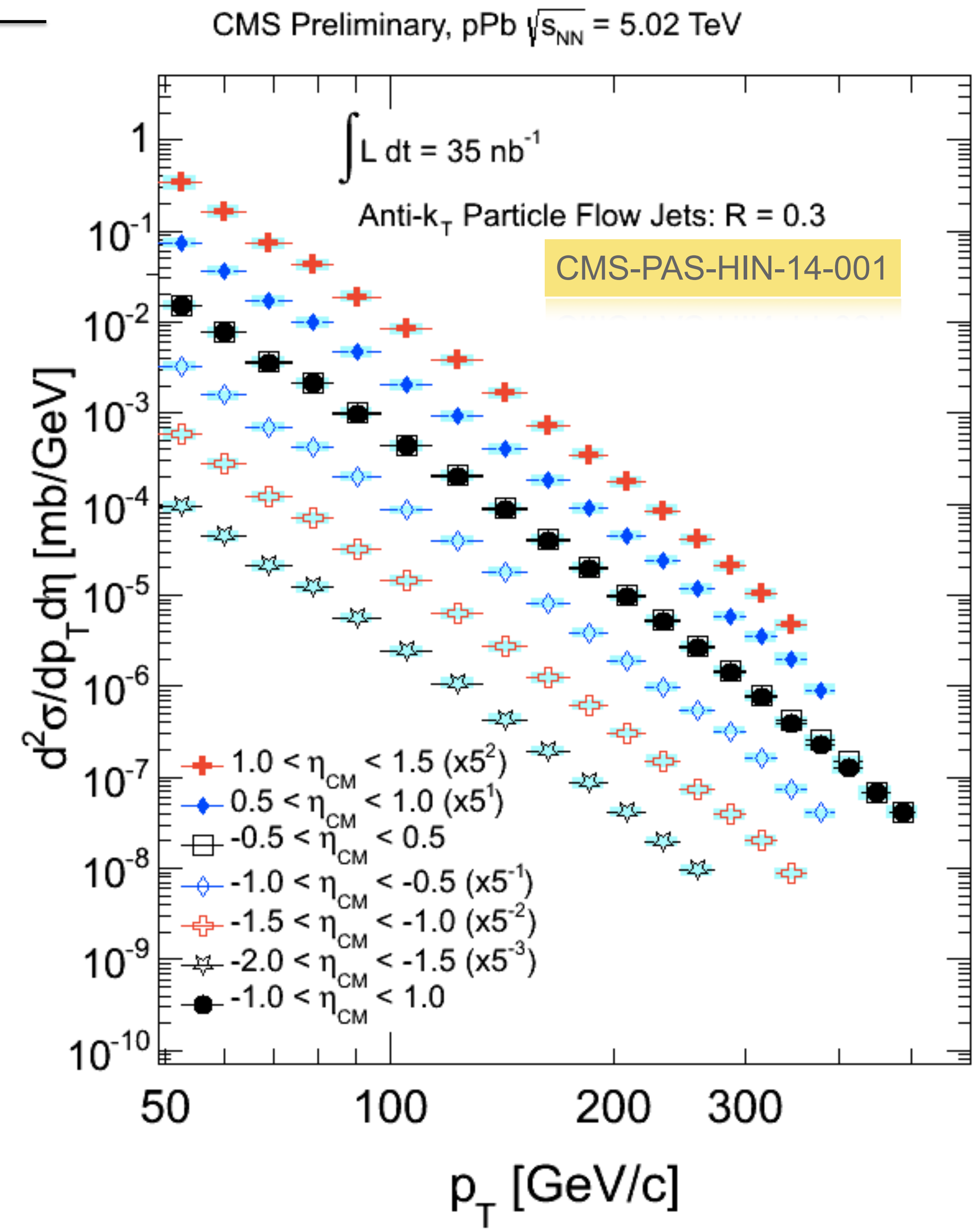
Measured spectrum in pPb collisions

Charged particles



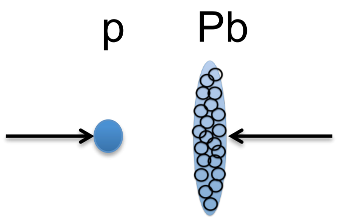


Inclusive jets

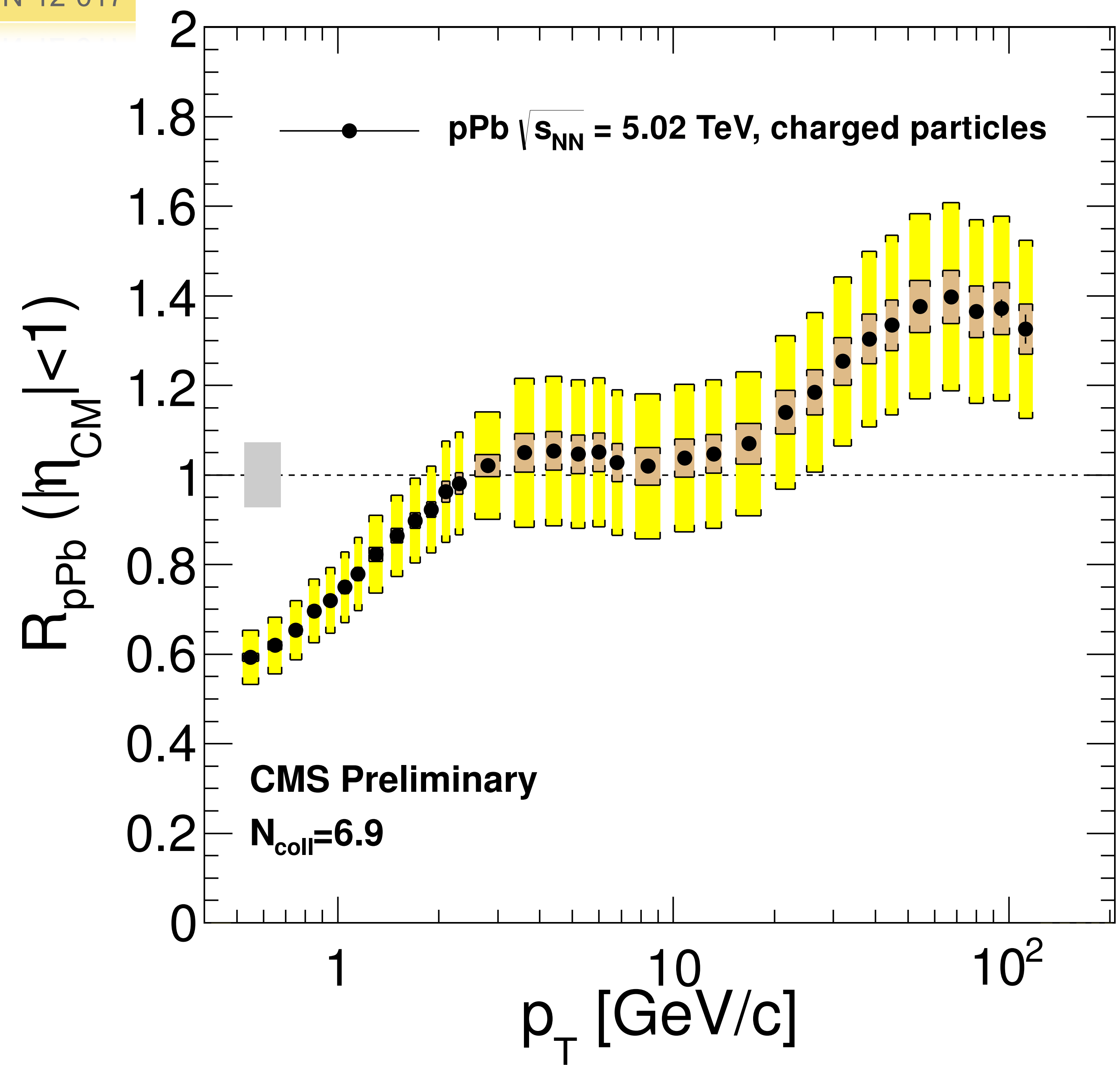


- Charged particle spectrum fully corrected, total uncertainty on cross section ~12%
- Inclusive jets unfolded, total uncertainty on jet cross section ~15%

Charged particle nuclear modification factor: R_{pA}

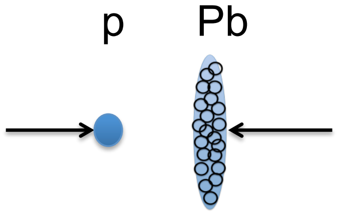


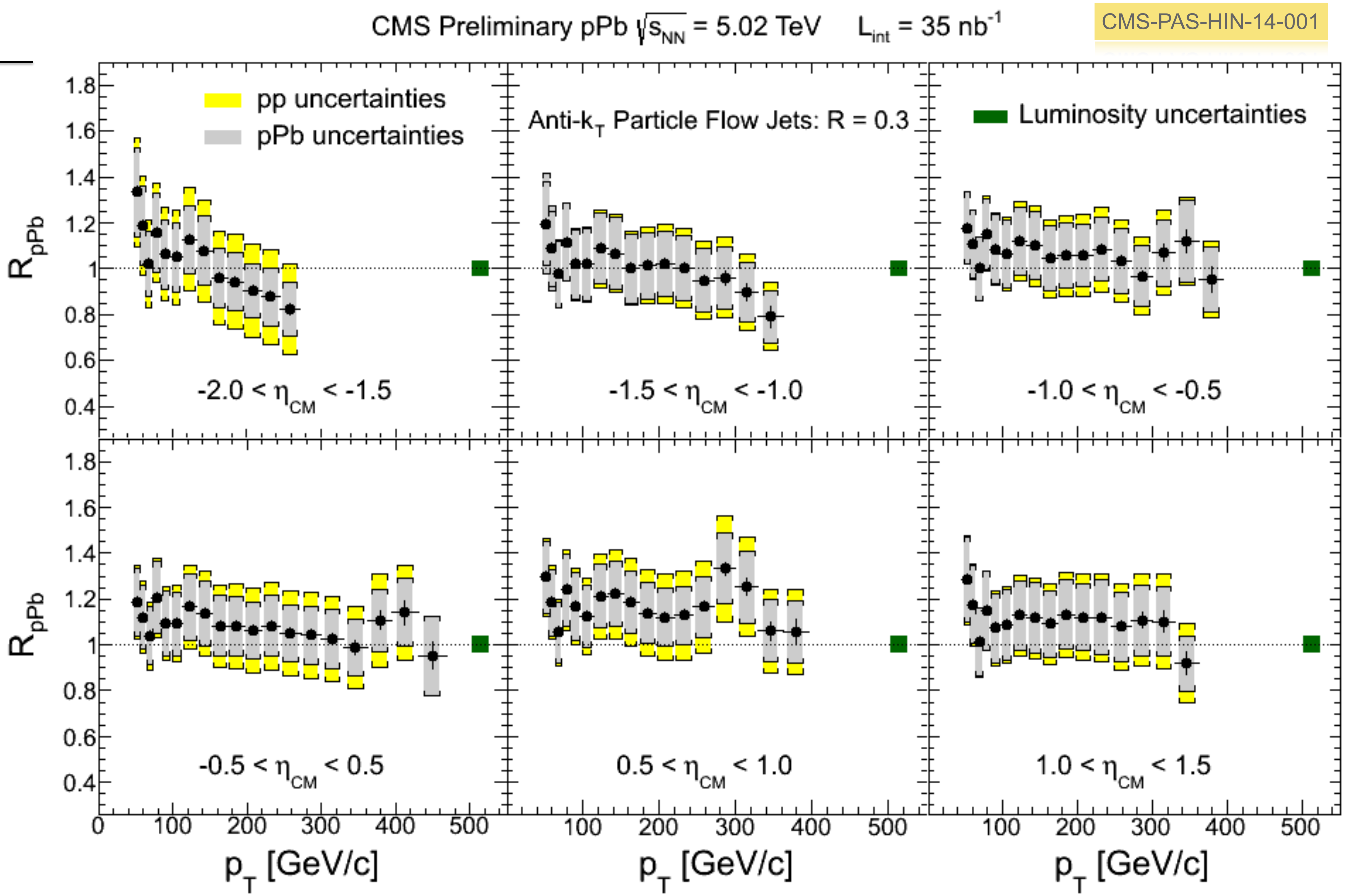
CMS-PAS-HIN-12-017



- High p_T charged particles ($50 < p_T < 100$) R_{pPb} approximately at 1.38 ± 0.22

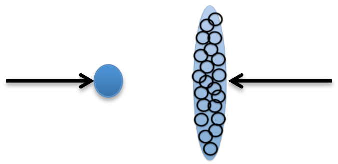
Jet nuclear modification factor: R_{pA}



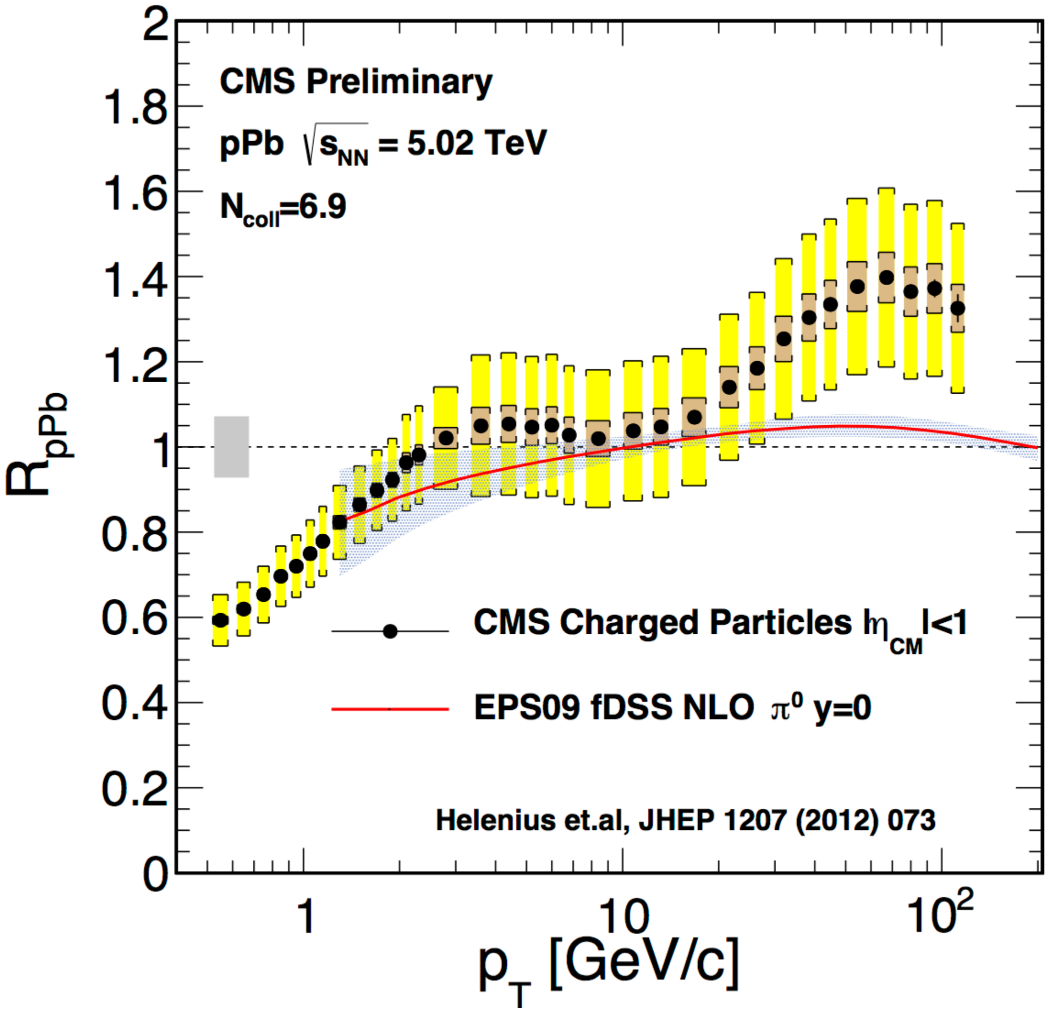


- No strong jet p_T dependence observed
- High p_T jets ($100 < p_T < 200$) R_{pPb} approximately at 1.11 ± 0.23

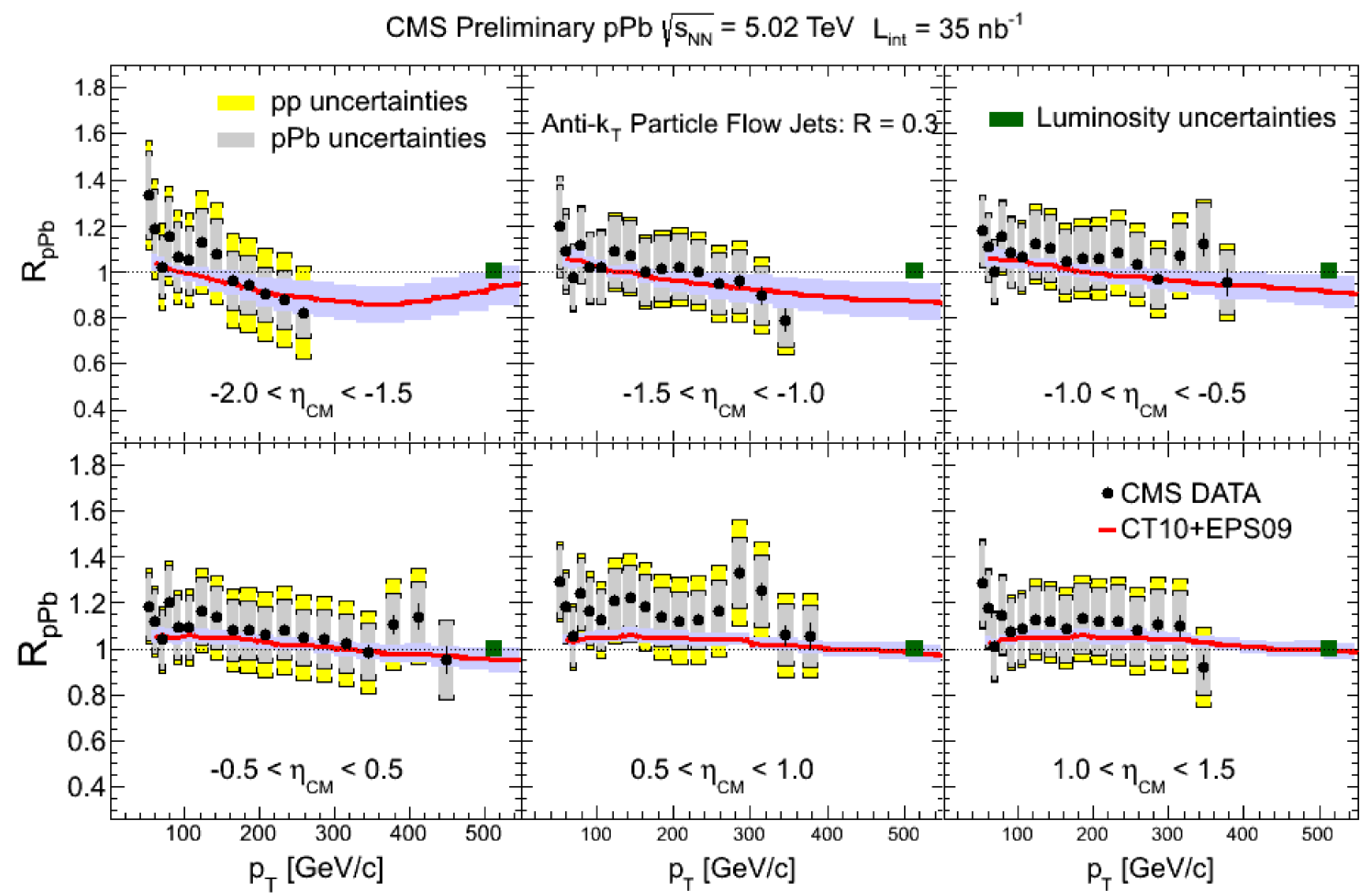
Jet and hadron R_{pA}: compare with EPS09 calculation



Charged particles



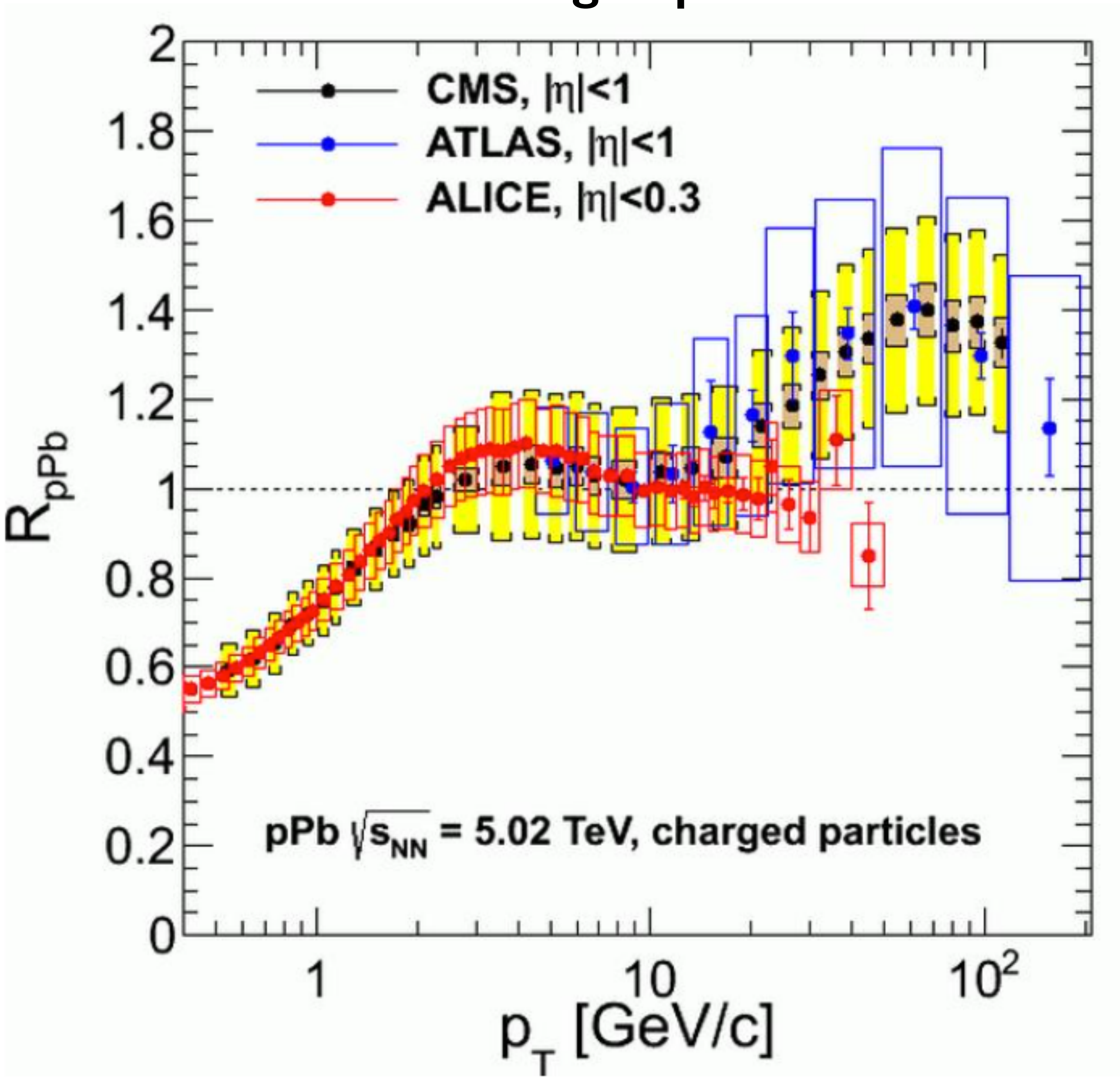
Inclusive jets



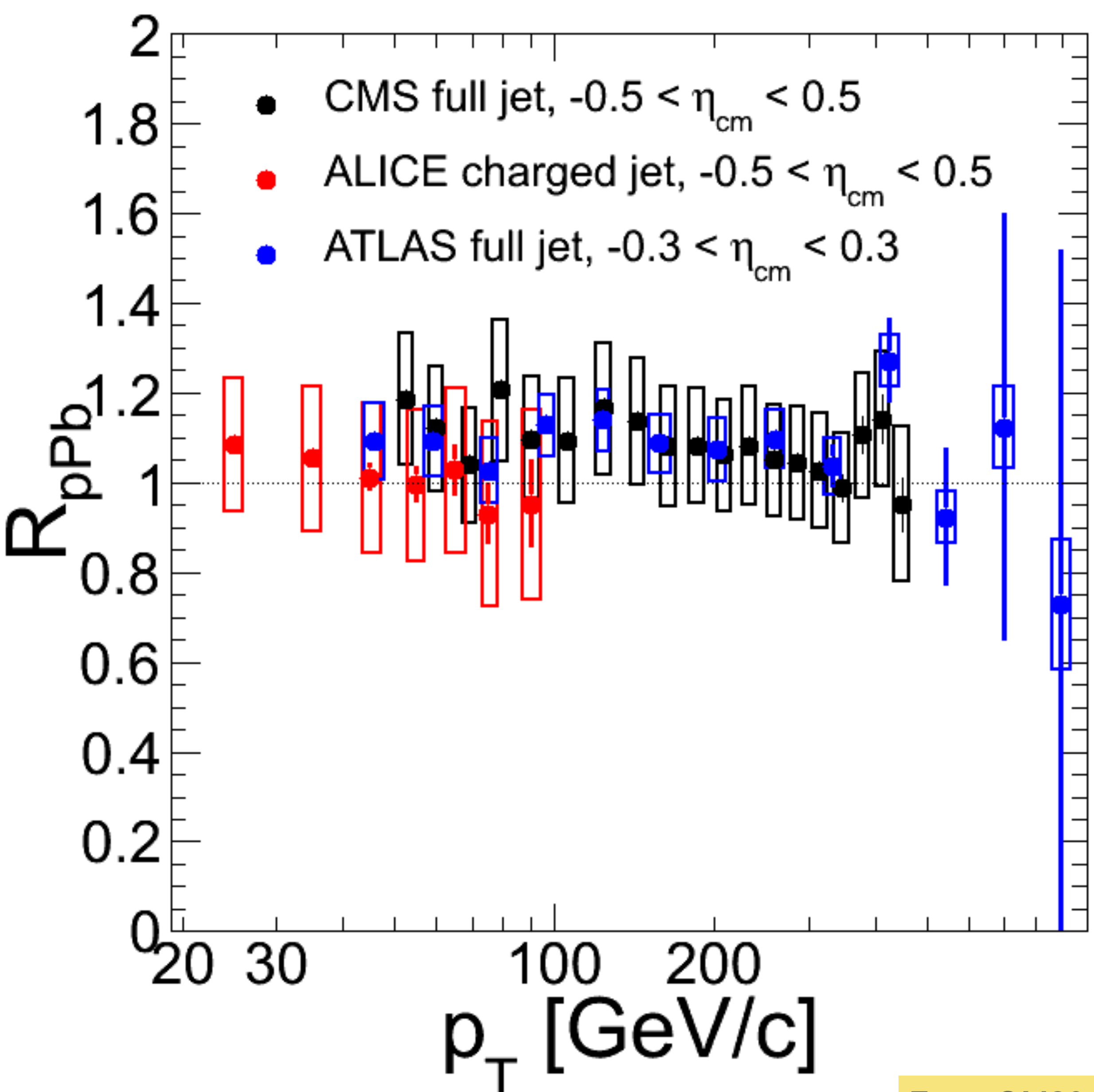
- EPS09 for π^0 calculation shows smaller R_{pPb} value than inclusive charged hadrons
- Theory curve for inclusive jets from Hannu Paukkunen (private communication)
- Jet results consistent with CT10+EPS09 calculation

Compare with other experiments

Charged particles



Inclusive jets

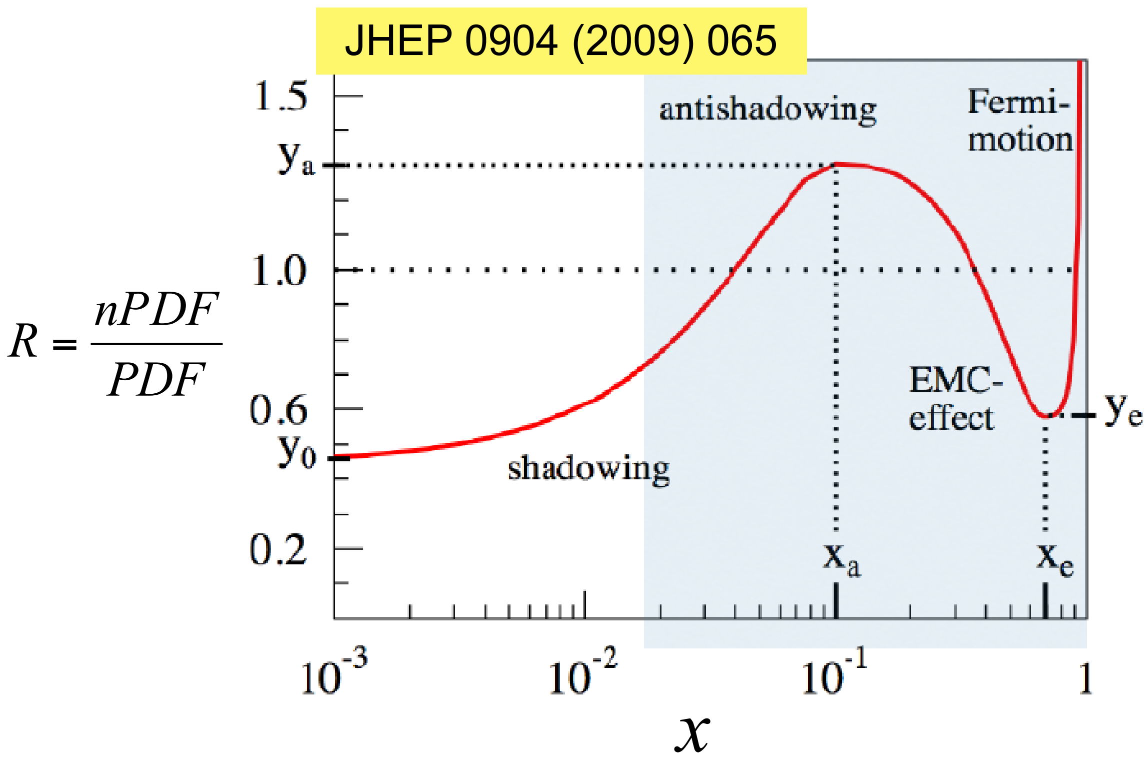


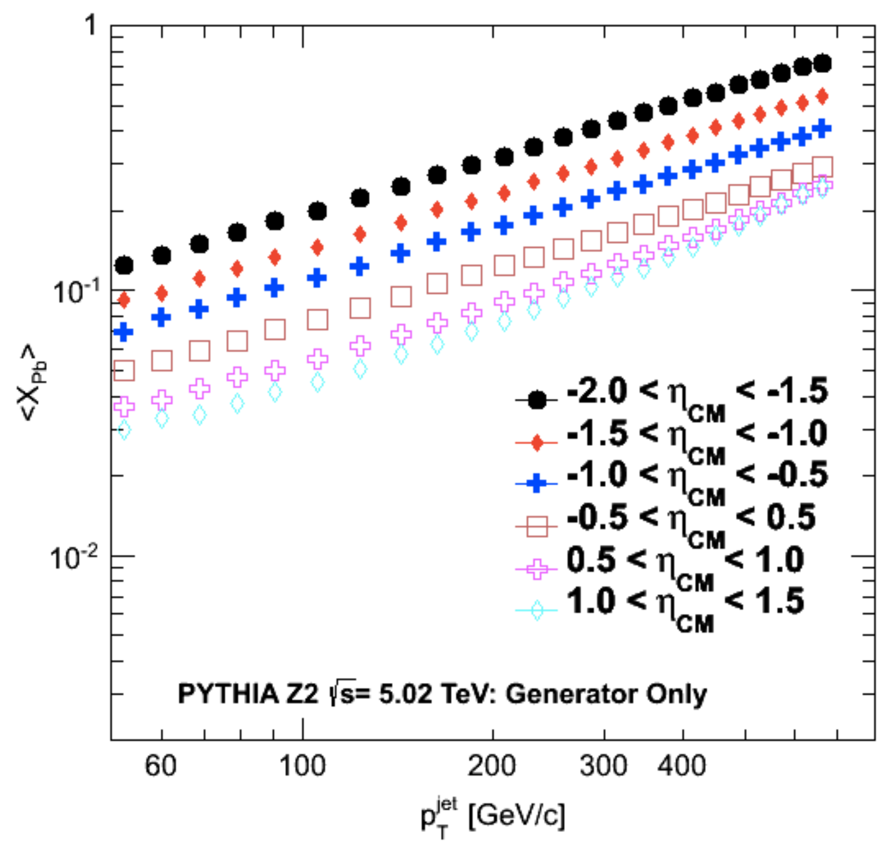
From QM2014

- Charged hadron results at high p_T are consistent between ATLAS and CMS, but not with ALICE
- Consistent with different experimental measurements for inclusive jets

Probing nPDF with jets and hadrons

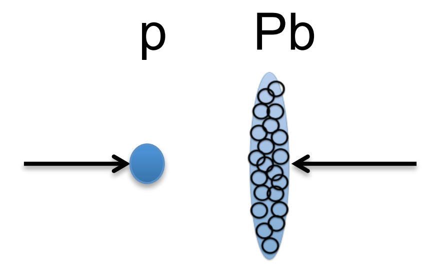
x - fractional momentum from a colliding nucleon carried by the parton





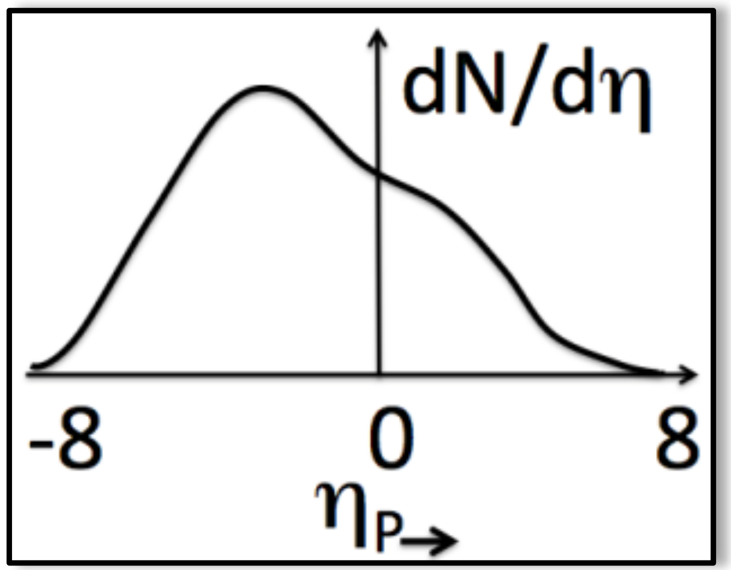
"backward"

large x from Pb



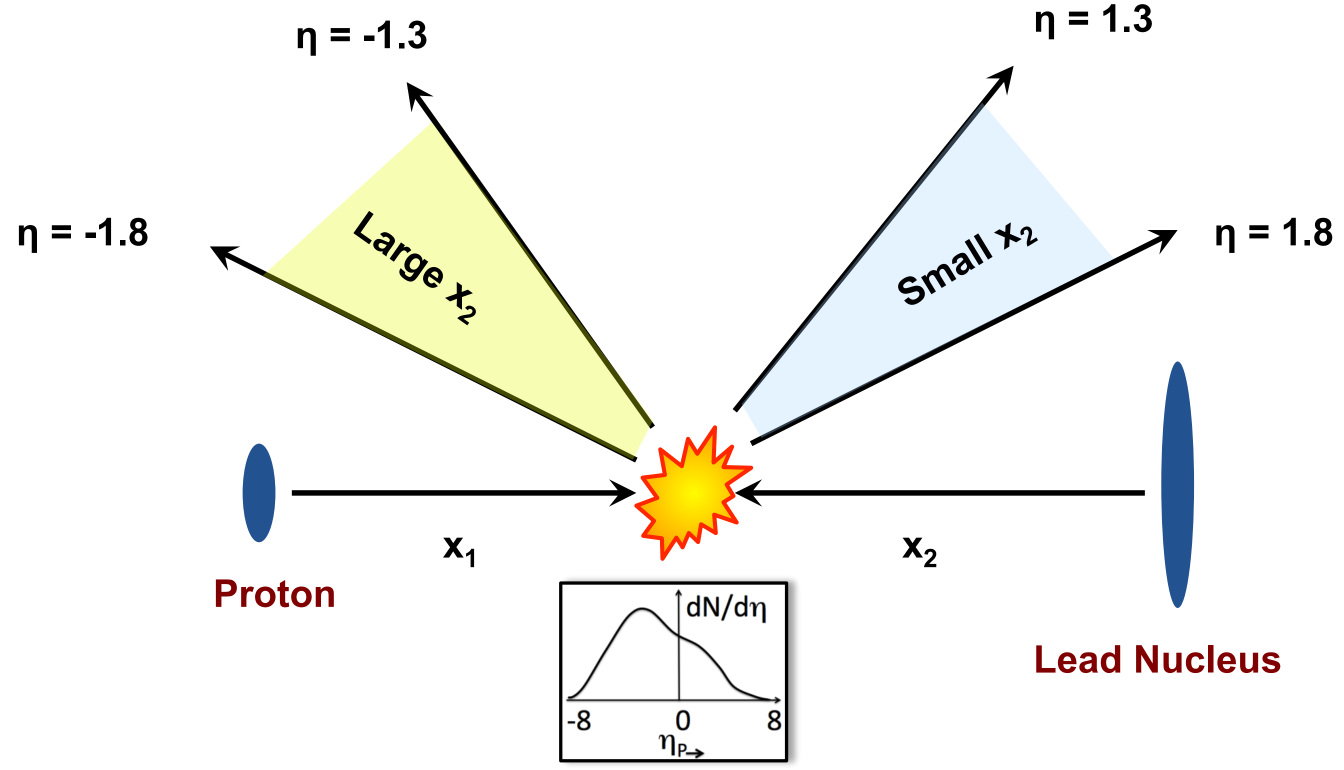
"forward"

small x from Pb

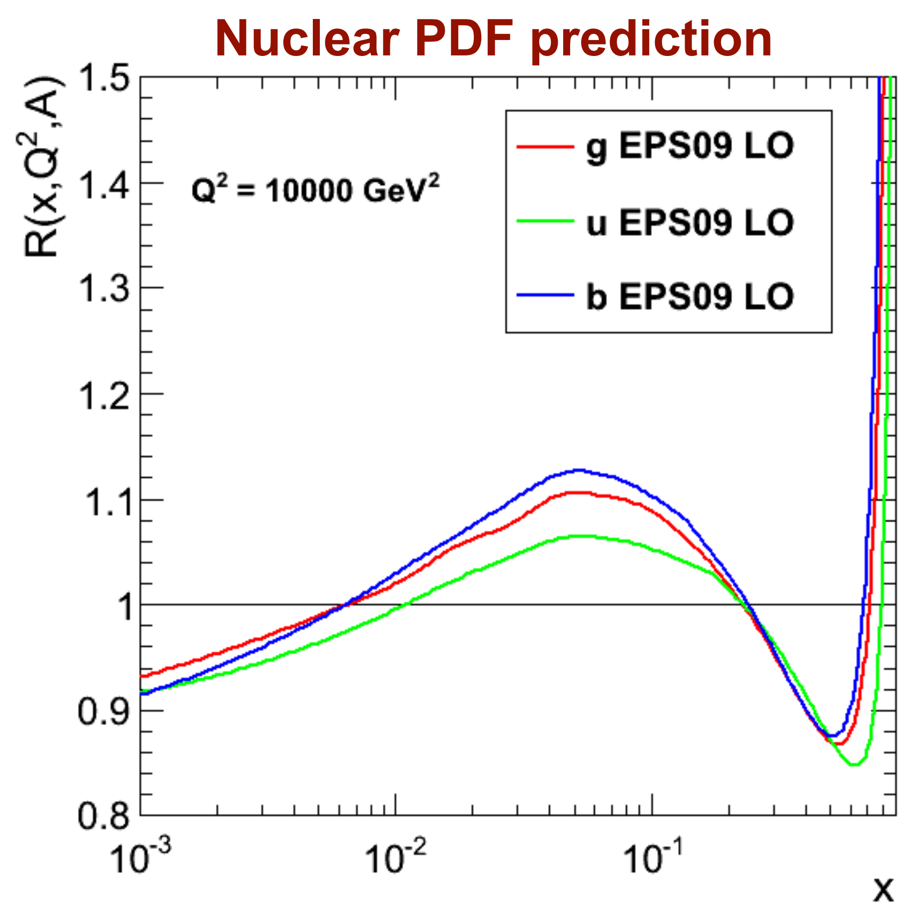


- Different p_T and η region can probe different x-range

Forward-backward asymmetry



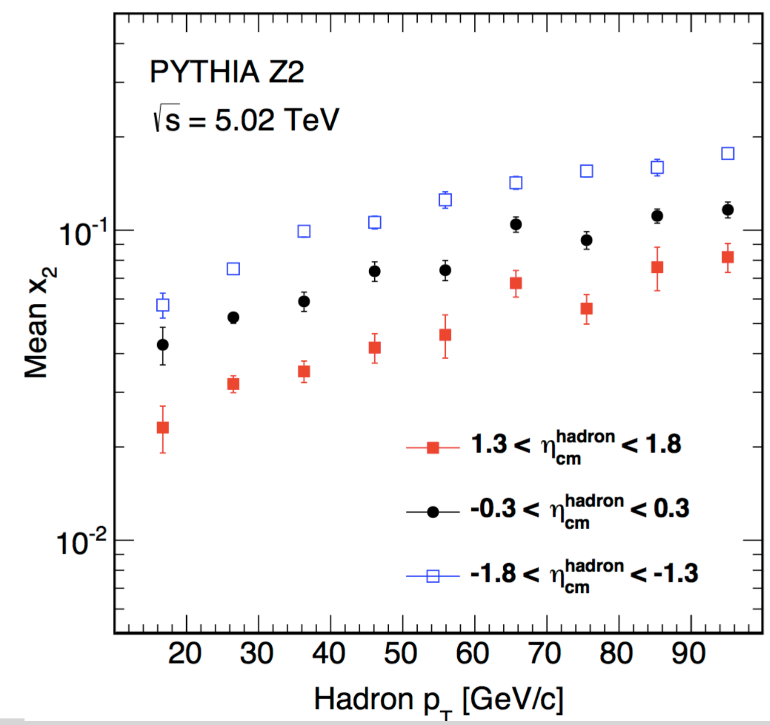
François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/



$$Y_{\rm asym}(p_{\rm T}) = \frac{d^2N_{ch}(p_{\rm T})/d\eta dp_{\rm T}|_{\eta_{\rm CM}\in[-b,-a]}}{d^2N_{ch}(p_{\rm T})/d\eta dp_{\rm T}|_{\eta_{\rm CM}\in[a,b]}}$$

PARTICLE YIELD LEAD GOING SIDE

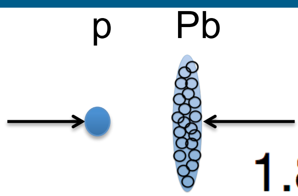
PARTICLE YIELD PROTON GOING SIDE



Naive expectations:

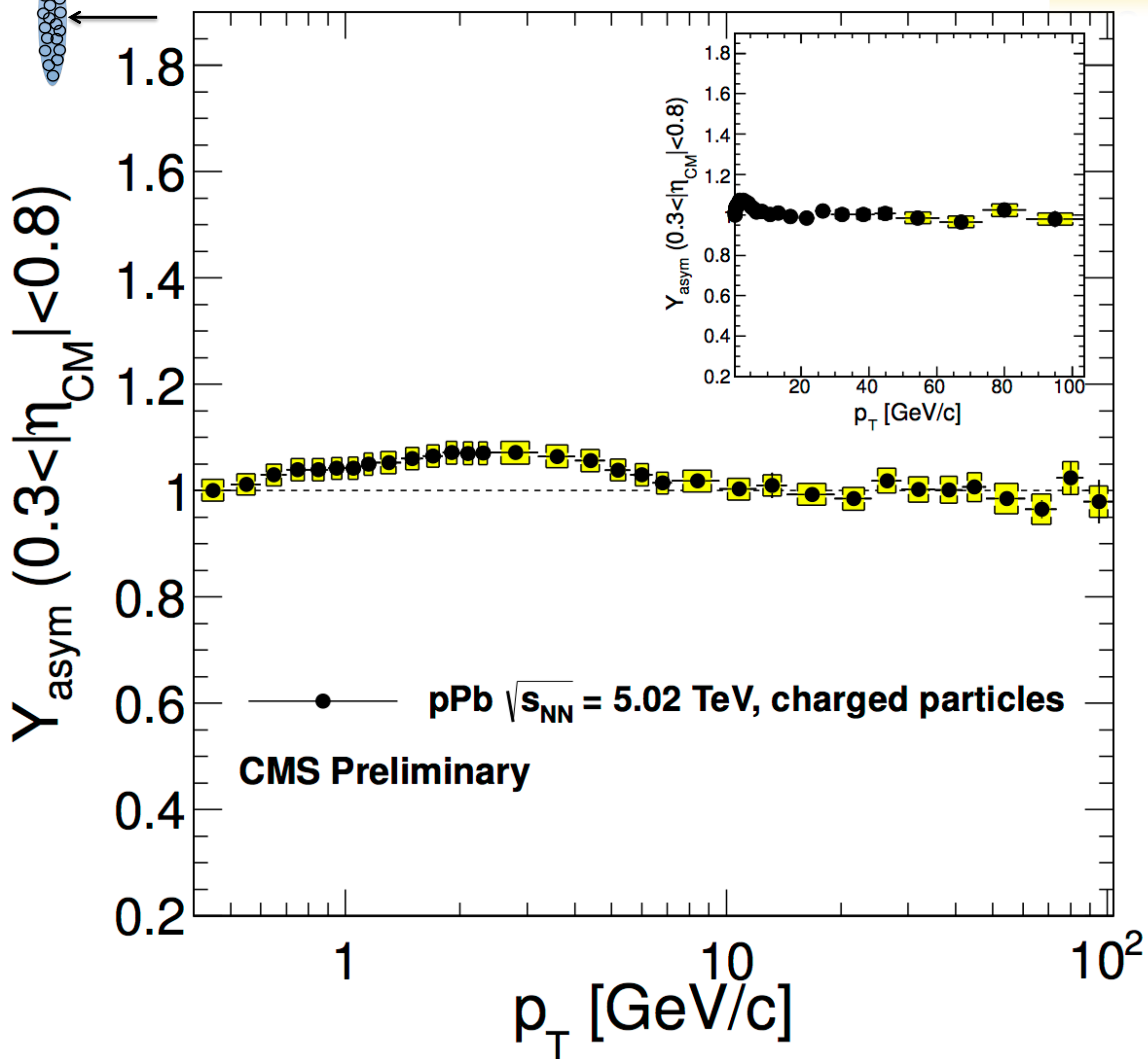
- $Y_{\rm asym}$ > 1 at low $p_{\rm T}$
- $Y_{\rm asym}$ < 1 at very high $p_{\rm T}$

Charged particle yield asymmetry

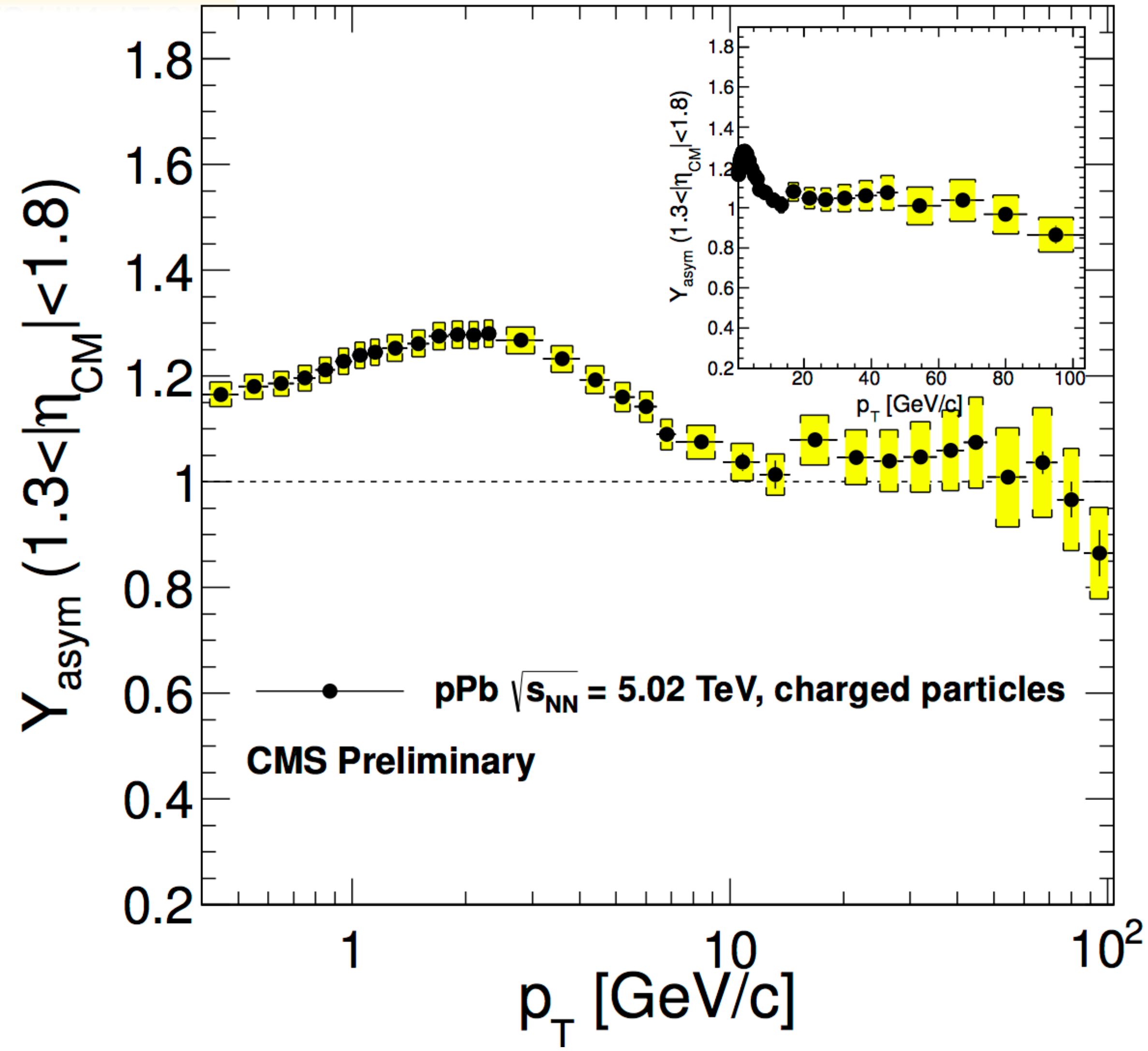


CMS-PAS-HIN-12-017

$0.3 < |\eta_{CM}| < 0.8$



$1.3 < |\eta_{CM}| < 1.8$

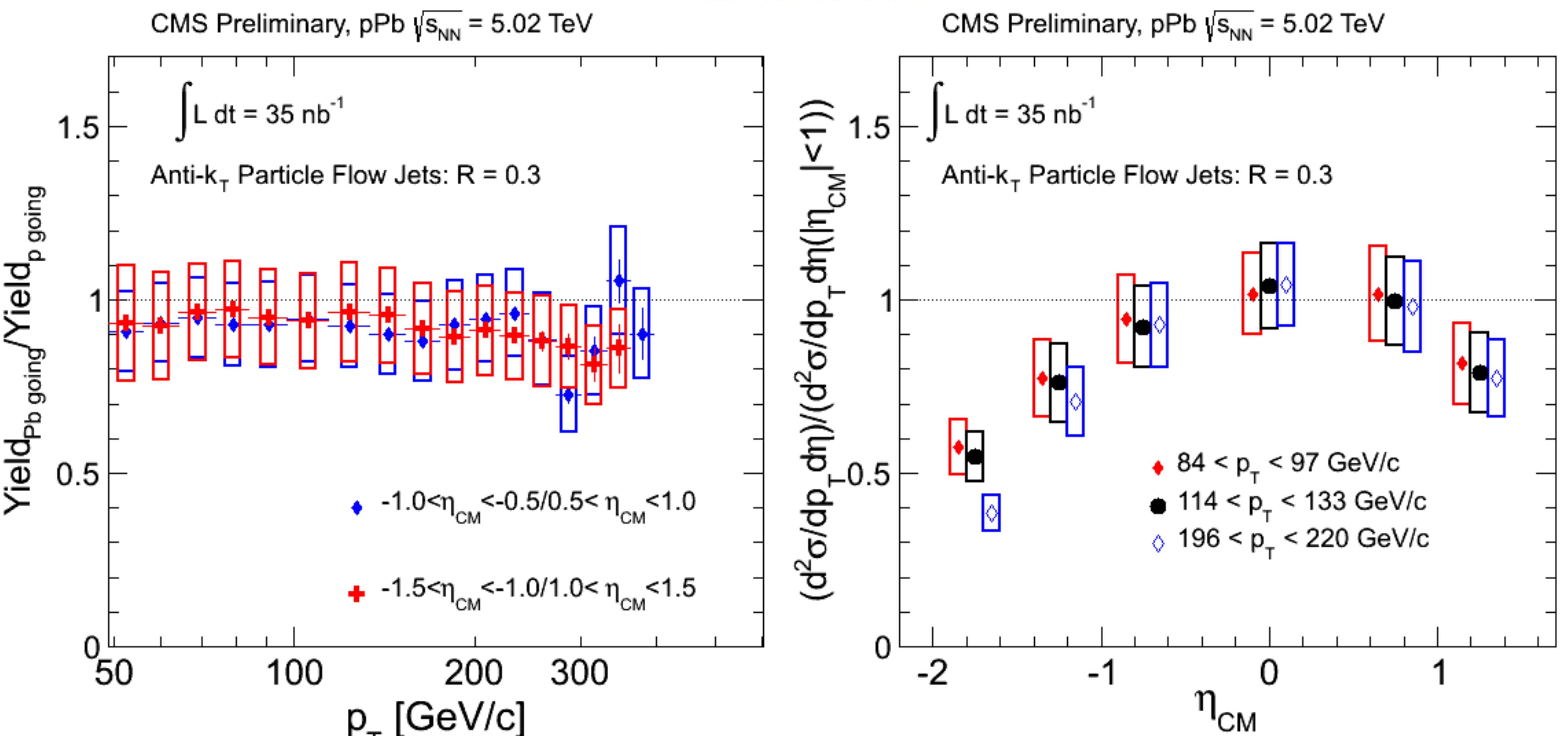


- Y_{asym} above 1 for p_T < 10 GeV/c for both η bins
- Y_{asym} close to unity for p_T > 10 GeV/c within systematics uncertainty
- A decreasing trend of Y_{asym} at very high p_T for most backward range

Inclusive jet yield asymmetry

Pb going/proton going

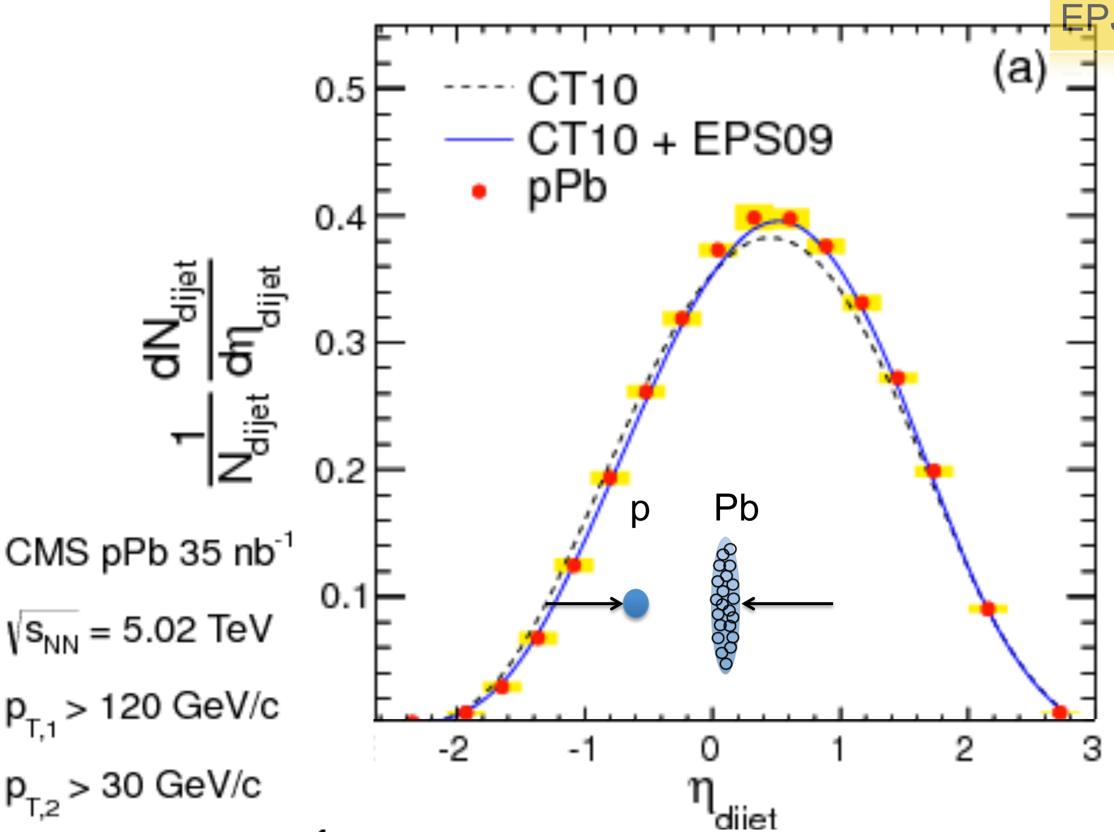
CMS-PAS-HIN-14-001

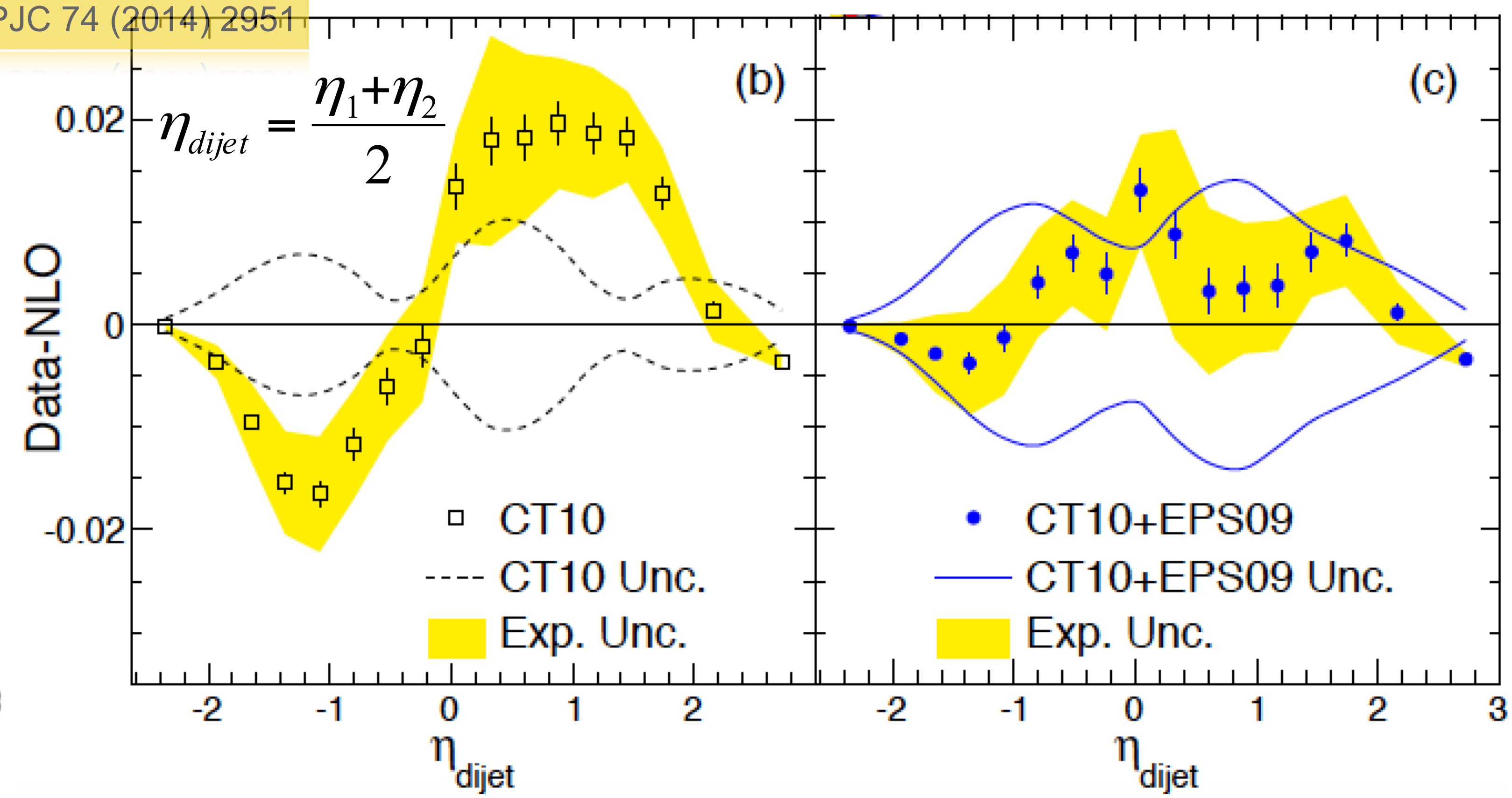


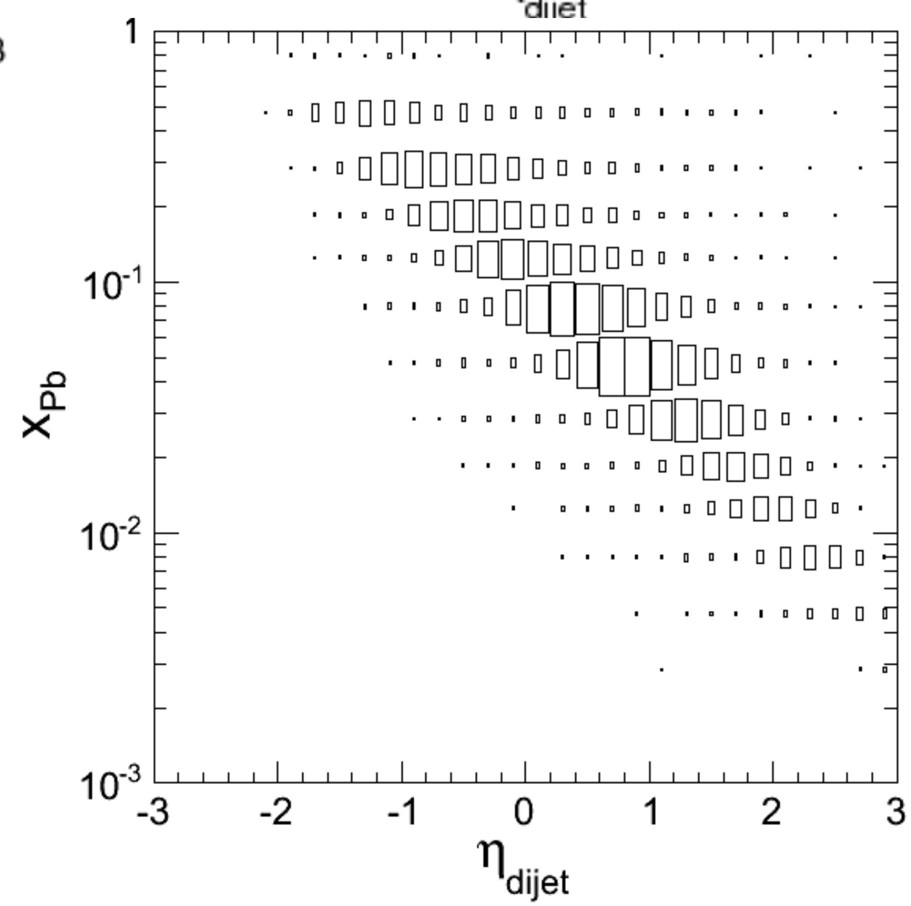
- Jet production yield in Pb going direction compared to proton going direction or to middle rapidity
  - close to unity for the jet p_T range measured within uncertainty
  - No strong η dependence observed within systematics

Dijet η asymmetry

EPJC 74 (2014) 2951

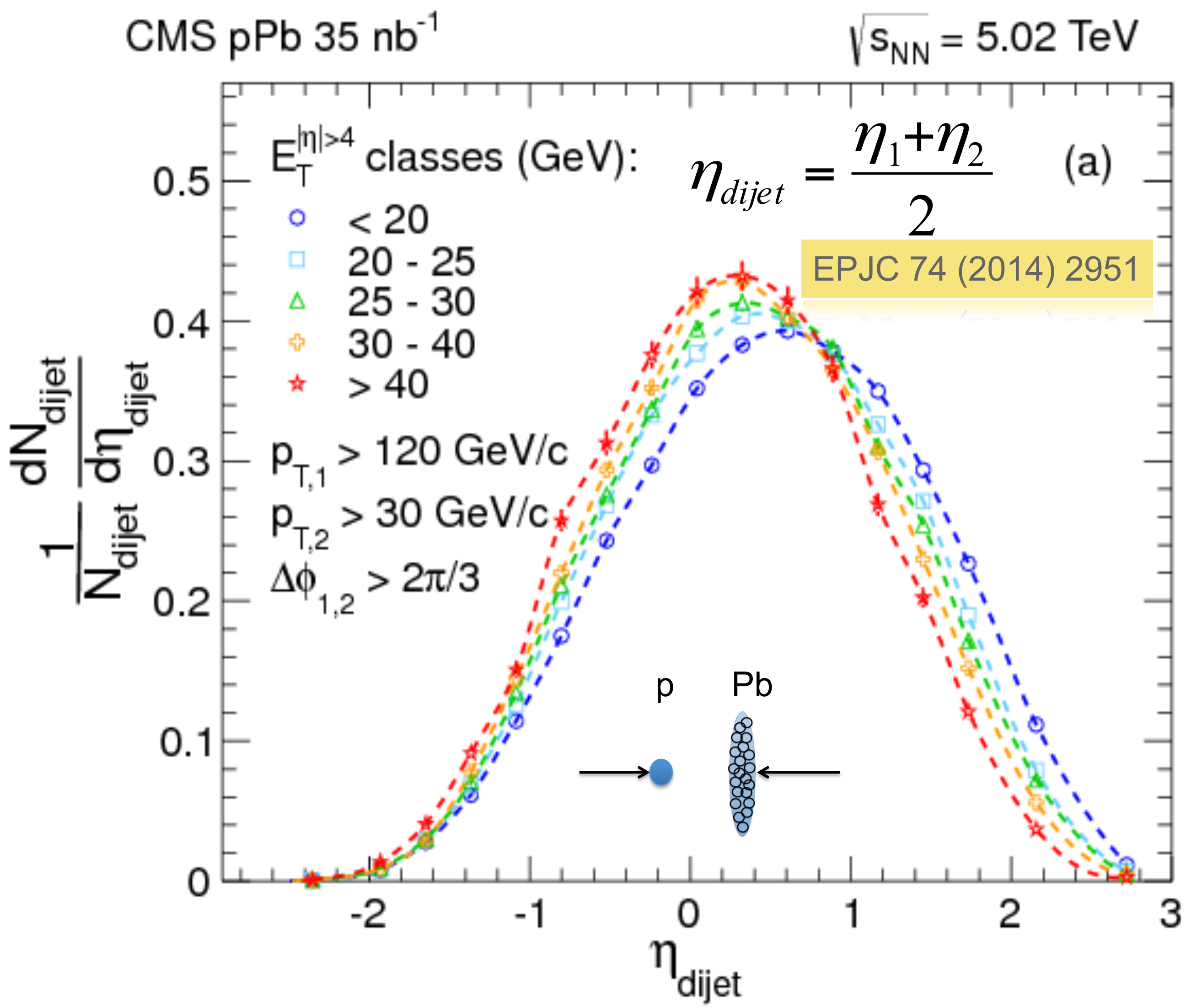


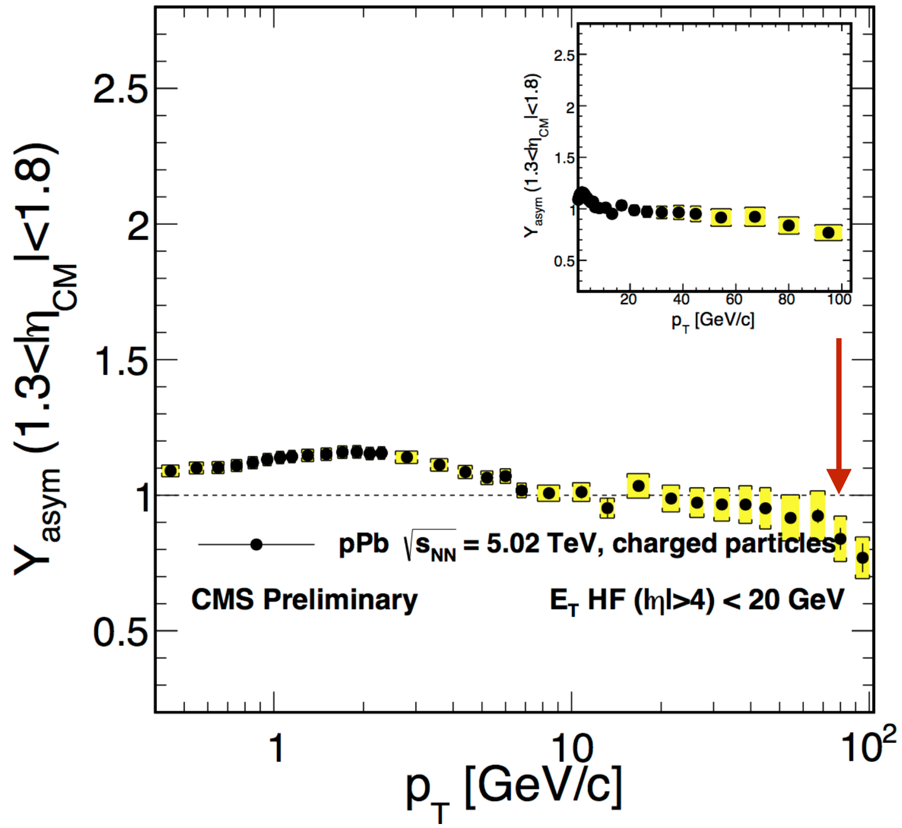


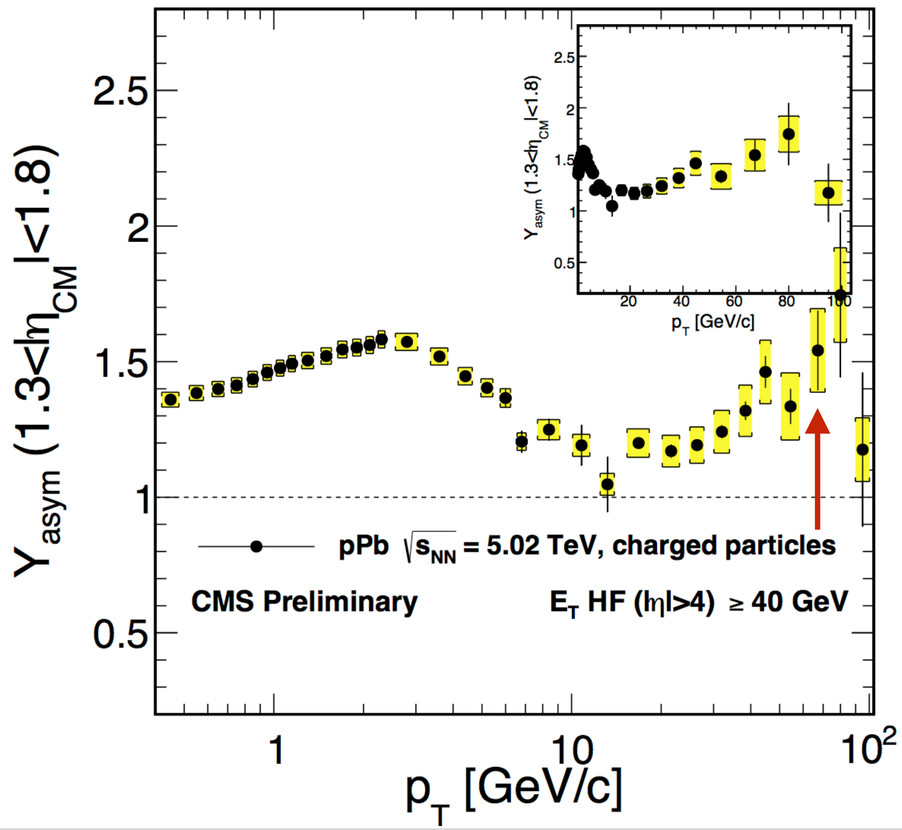


- Discrepancy between data and CT10 NLO pp calculation
- Agreement between data and EPS09 calculation with systematics

Consistency between dijet η and charged hadron asymmetry







- "Peripheral" events with low HF activity: dijets shifted to p-going side, expect $Y_{asym} < 1$
- "Central" events with high HF activity: dijets shifted to Pb-going side, expect $Y_{asym} > 1$

Summary

- CMS has performed both jet and charged hadron measurements in pPb collisions
  - Inclusive jet and charged hadron cross section measured to high p_T region
  - Asymmetry of jets and charged hadrons are studied
    - inclusive jet asymmetry consistent with unity and no strong η dependence
    - charged hadron asymmetry shows larger yield in Pb going direction at low p_T, while high p_T yields consistent with 1
    - η shift observed in dijet asymmetry results, and the asymmetry is consistent with charged hadron asymmetry in event activity classes
  - Nuclear modification factor R_{pPb} are presented
    - inclusive jets R_{pPb} using extrapolated pp reference is approximately 1.11 ± 0.23
    - charged particles R_{pPb} using interpolated pp reference at high p_T is approximately 1.38 ± 0.22
    - results for jet R_{pPb} consistent with EPS09 calculation

      ➡ need 5.02 TeV pp reference data to precise R_{pPb} measurements!
- More analysis are ongoing to understand how the initial-state effects influences the quenching interpretations in PbPb

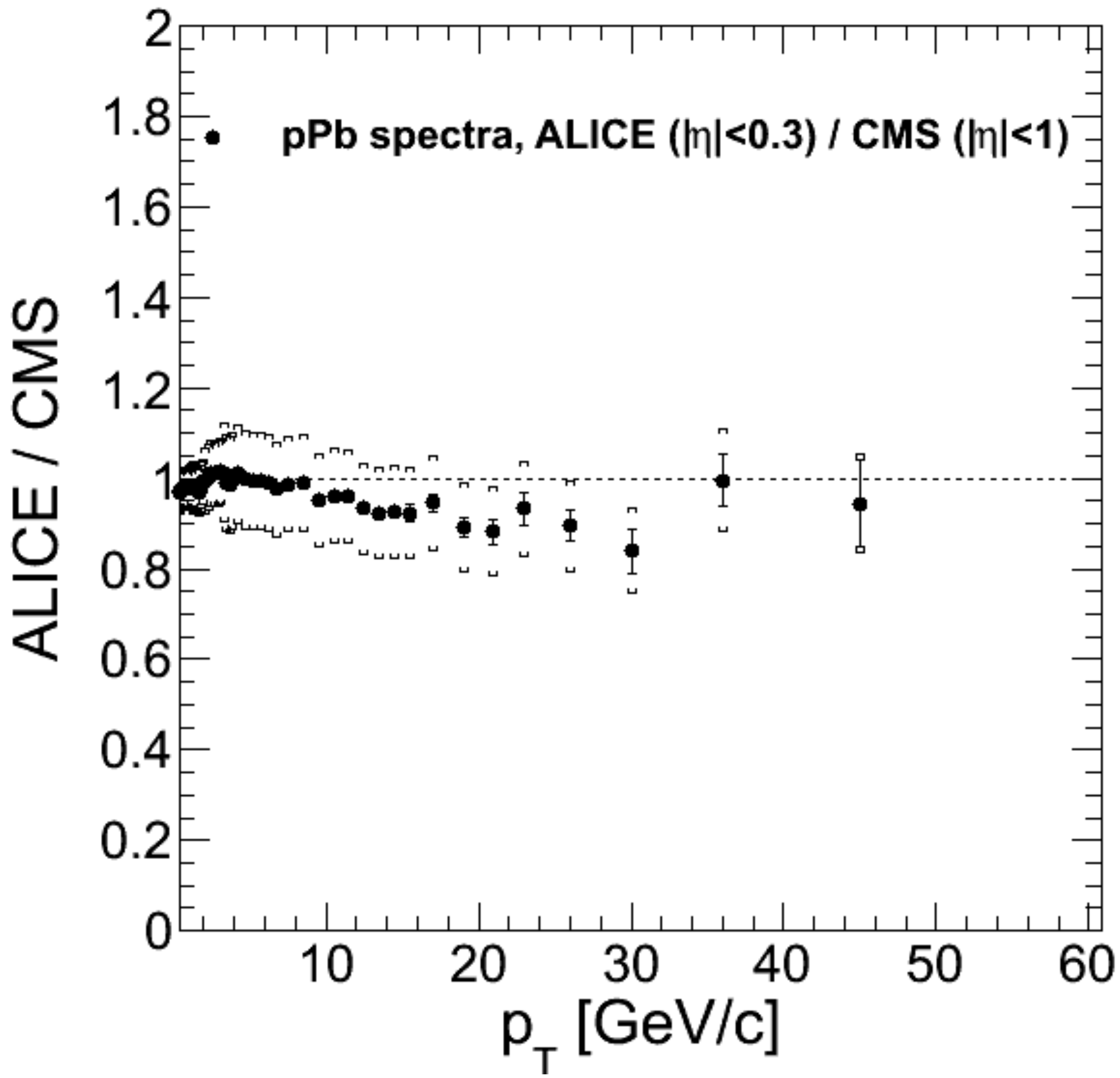
Thanks for your attention!

backup

Comparison to ALICE Charged Particles

pPb Measured Spectra

- ALICE and CMS results generally consistent within combined systematic uncertainty.
- CMS results ~5-10% higher
- Measured pPb spectra account for ~ 1/3 of the tension

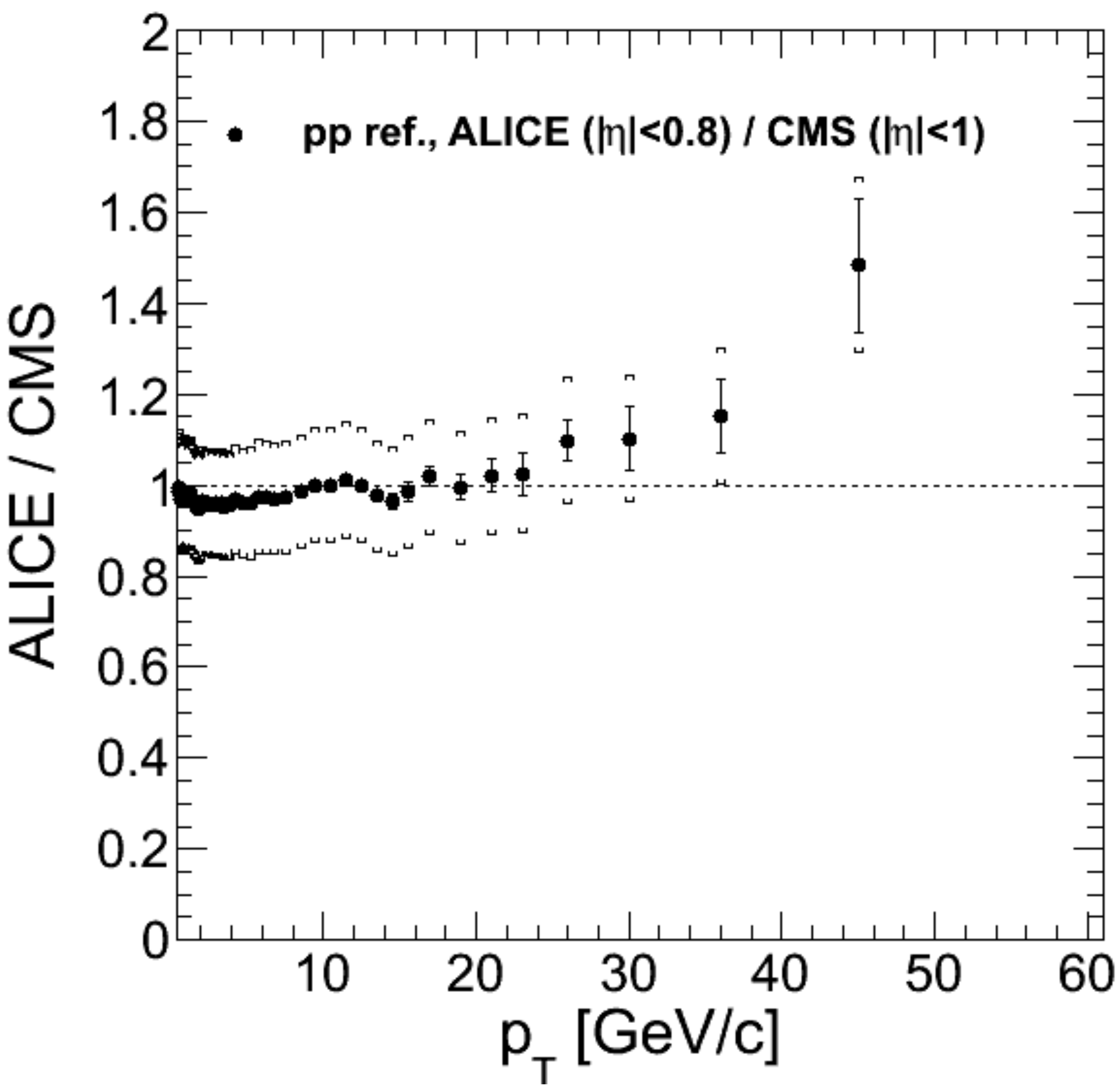


ALICE: arXiv:1405.2737
CMS: HIN-12-017

Comparison to ALICE Charged Particles

Artificial pp Reference Spectra

- ALICE and CMS references diverge at high-p_T
- Accounts for ~ 2/3 of the tension
- Different methods used
  - NLO-scaling (ALICE)
  - Direct Interpolation (CMS)
- Different underlying data used for ALICE and CMS

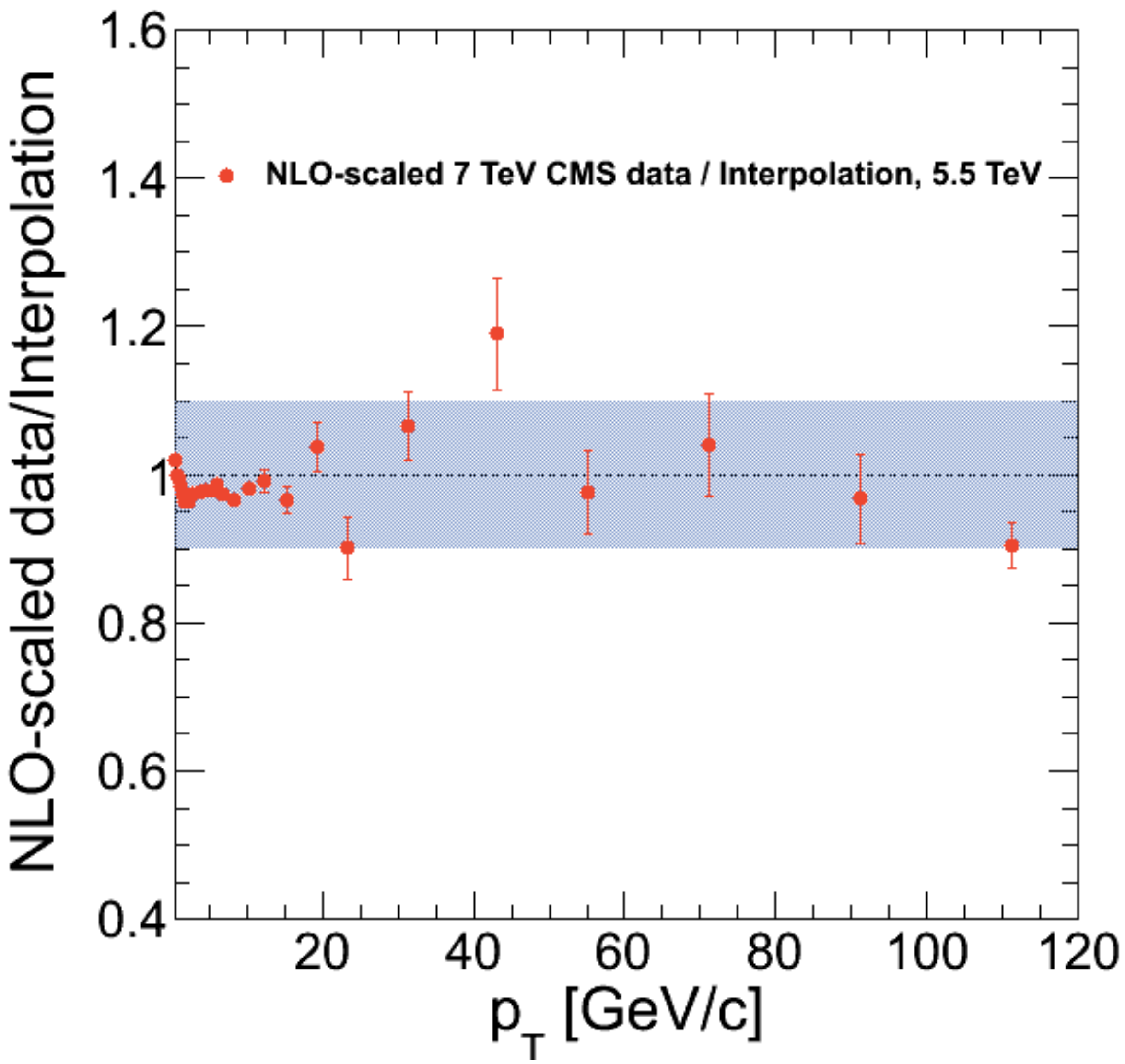


ALICE: arXiv:1405.2737
CMS: HIN-12-017

Comparison to ALICE Charged Particles

Comparison of Methods

- Perform NLO Scaling on CMS data to 5.5 TeV and
- Compare with interpolation to 5.5 TeV
- Two methods generally agree within 10%
- No clear systematic trend above or below unity

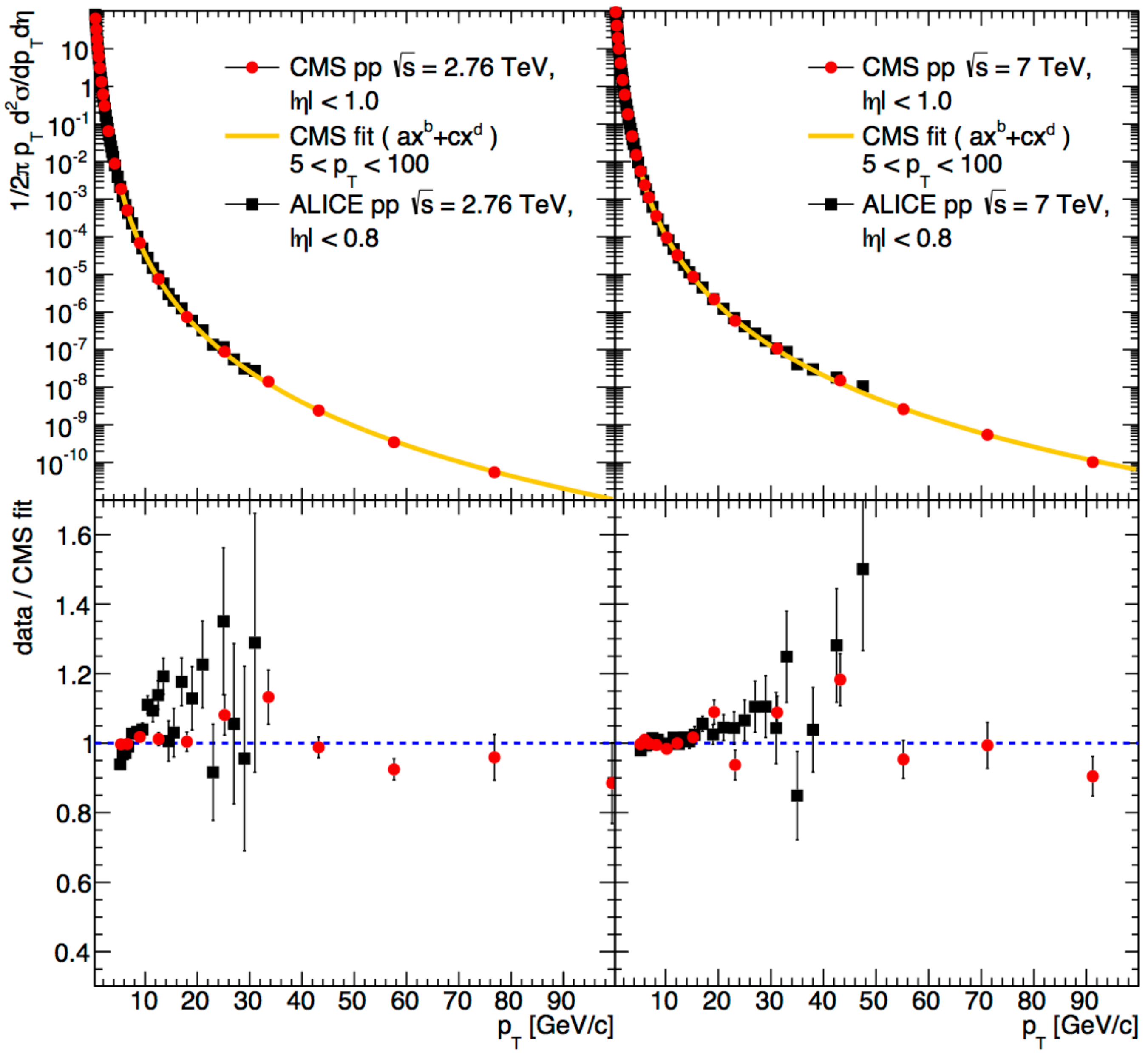


NLO – F. Arleo, D. d'Enterria, A. Yoon: JHEP 06 (2010) 035
CMS: HIN-12-017

Comparison to ALICE Charged Particles

Comparison pp Data from CMS and ALICE

- 7 TeV and 2.76 TeV datasets compared
- Larger statistical uncertainty on high-p_T ALICE data



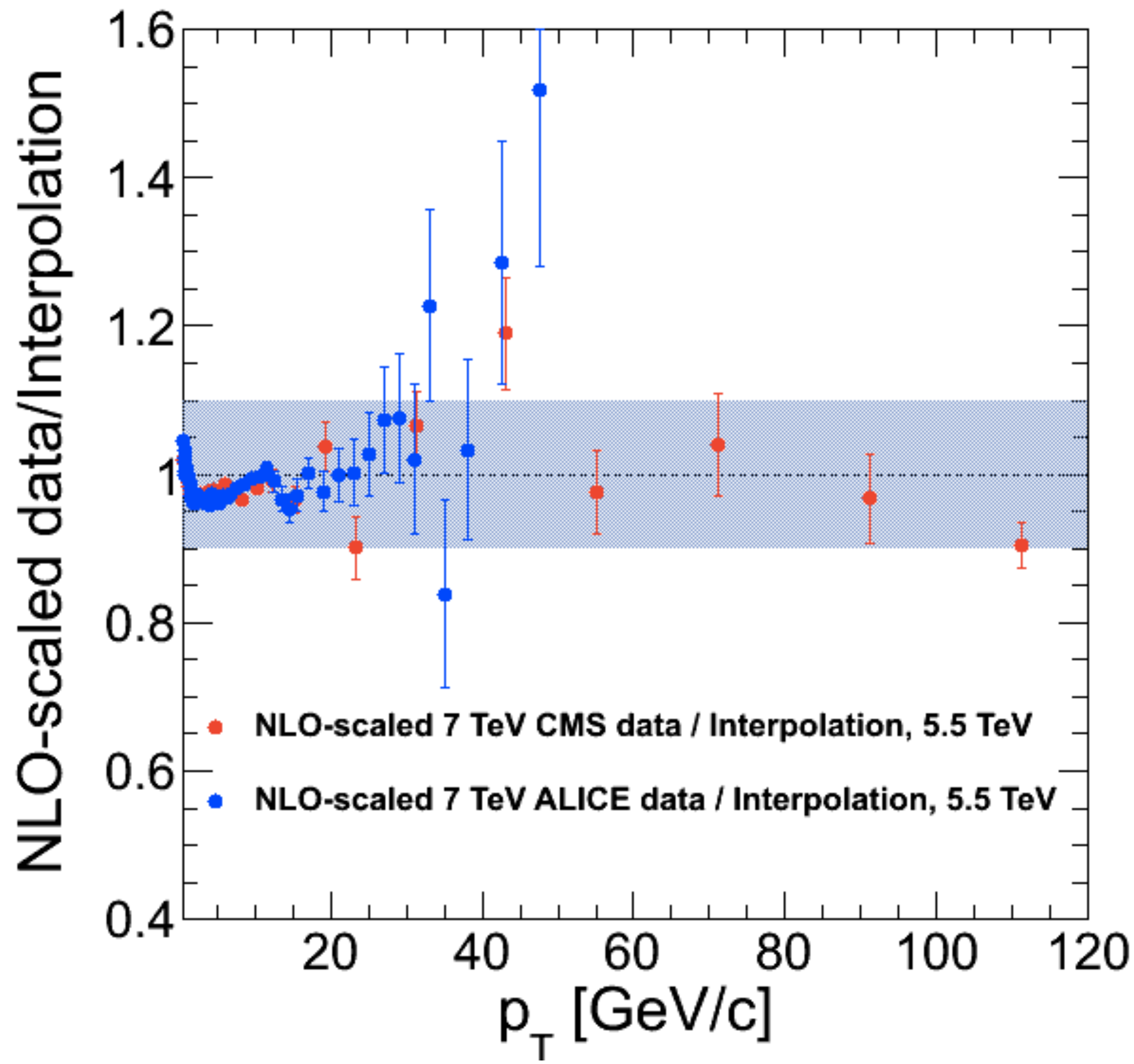
ALICE: EPJC 73 (2013) 2662
CMS: HIN-12-017

Comparison to ALICE Charged Particles

Comparison of NLO-Scaling with ALICE and CMS

- Perform NLO-Scaling on both ALICE and CMS data to 5.5 TeV and

- Compare with CMS interpolation to 5.5 TeV



NLO – F. Arleo, D. d'Enterria, A. Yoon: JHEP 06 (2010) 035
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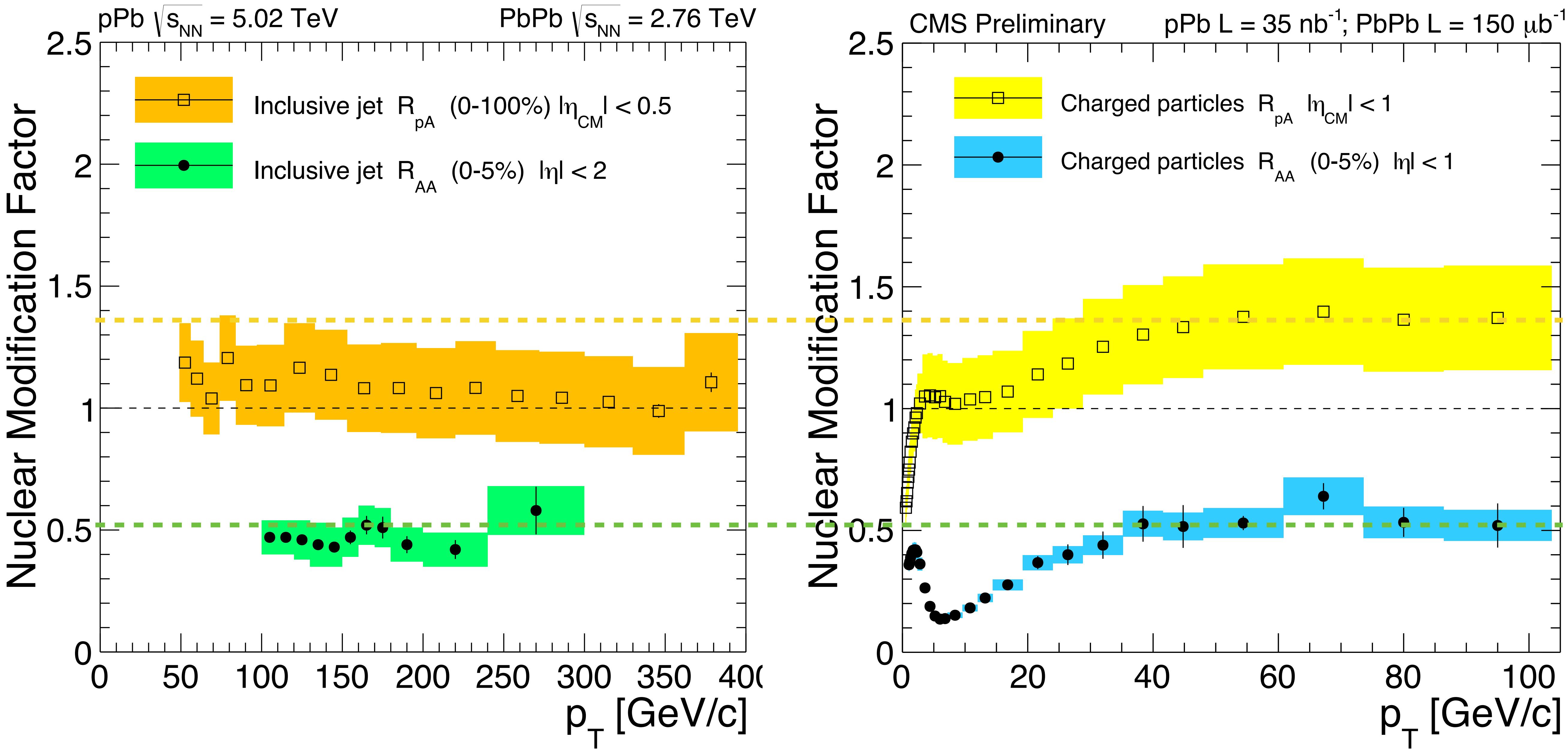
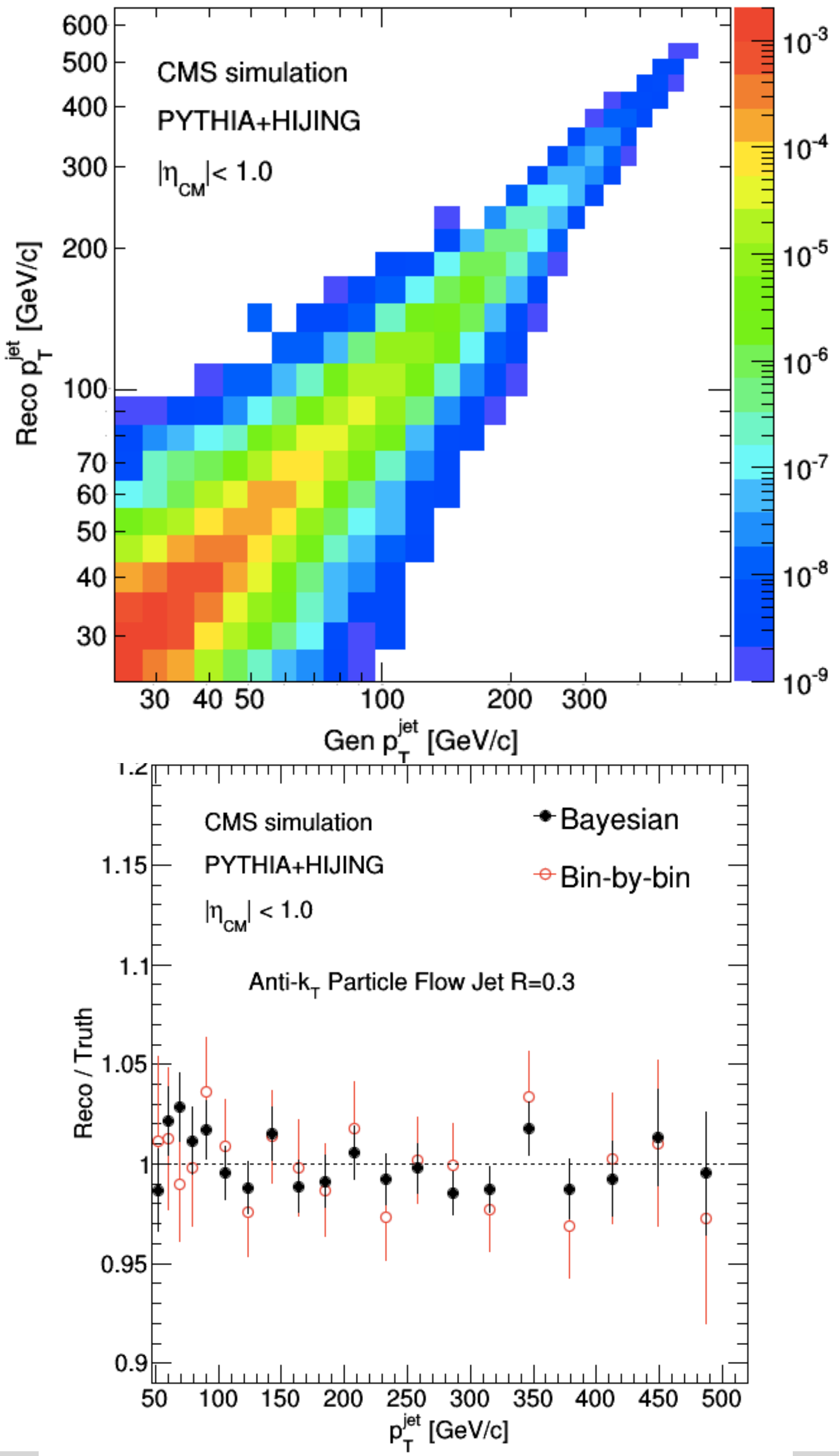
Jet/hadron R_{pA} vs. R_{AA}



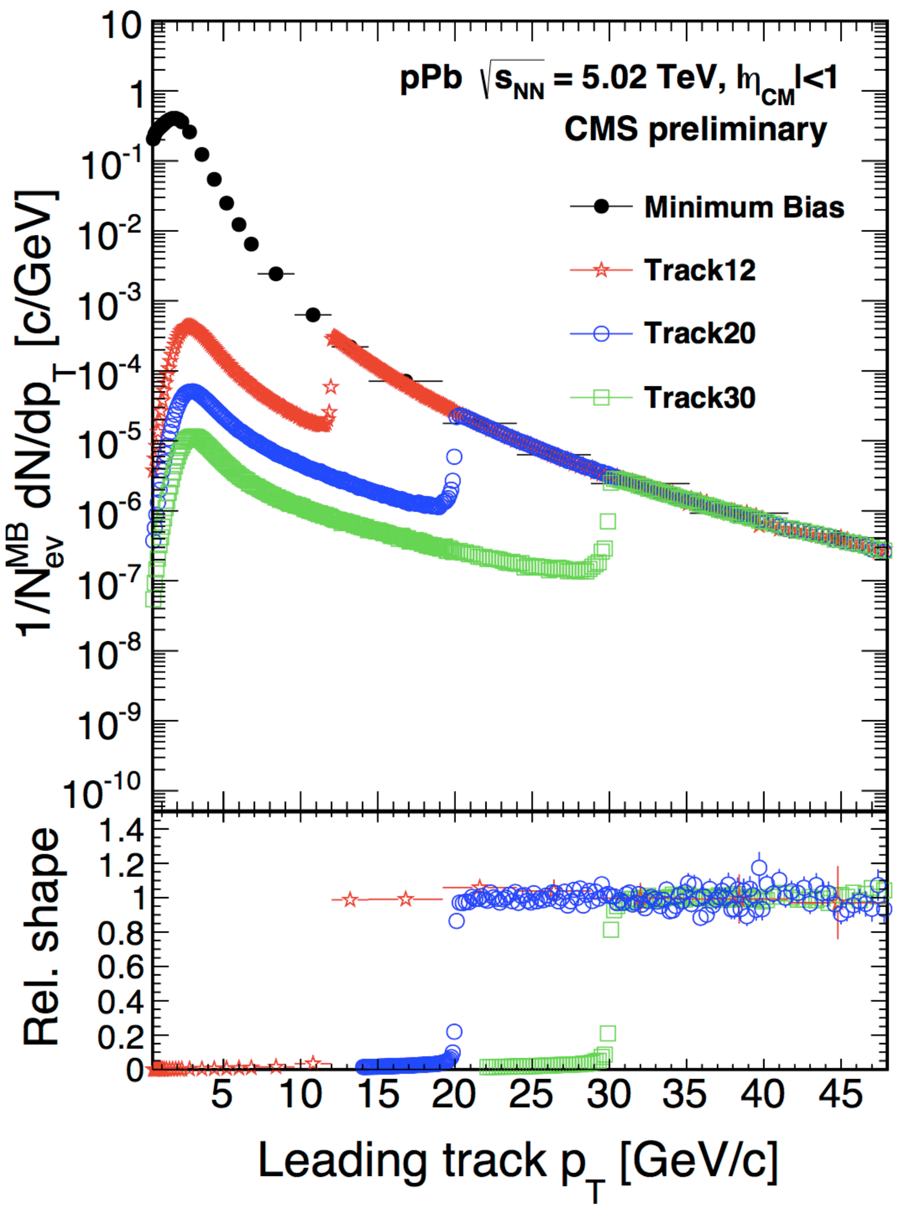
Jet reconstruction



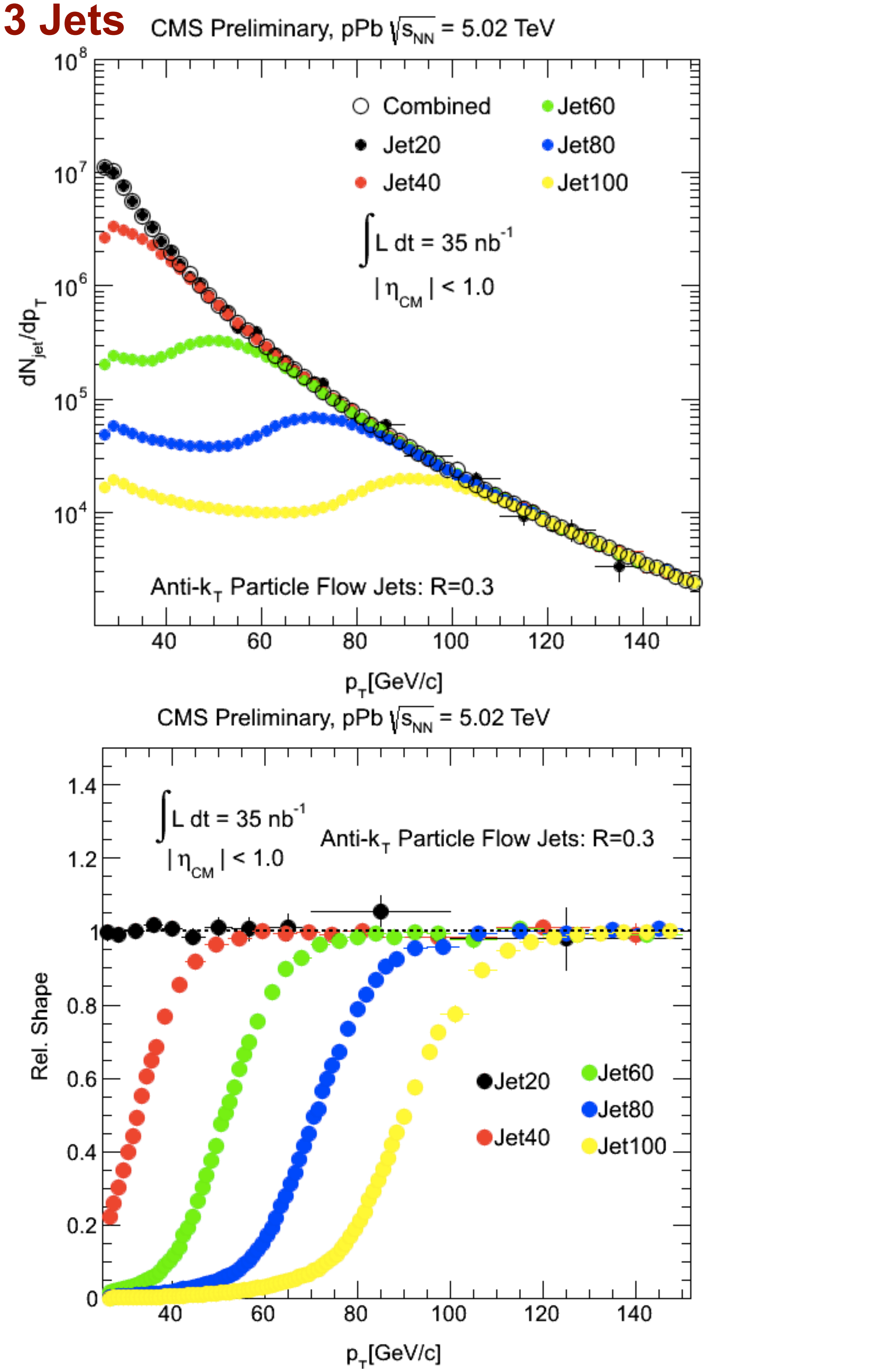
- Anti-k_T algorithm with R=0.3 cone size applied to projections from particle-flow candidate objects
- Iterative Pileup subtraction method applied to remove background.
- Jet energies corrected to final state particle jets
- Smearing effects of the finite-p_T resolution on the spectrum are corrected using an "unfolding" procedure with MC-derived response matrix.

Trigger combination

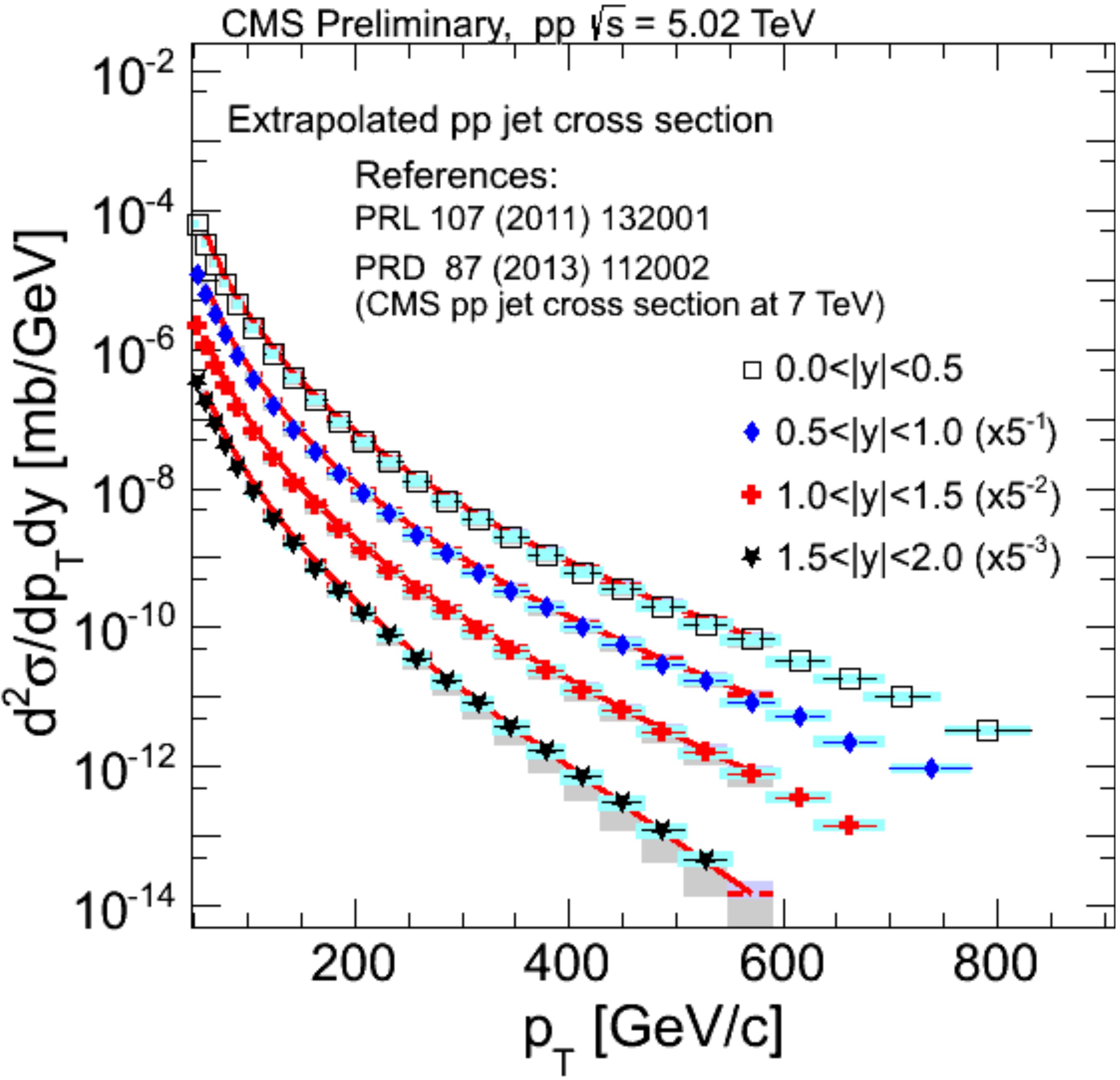
Charged Particles

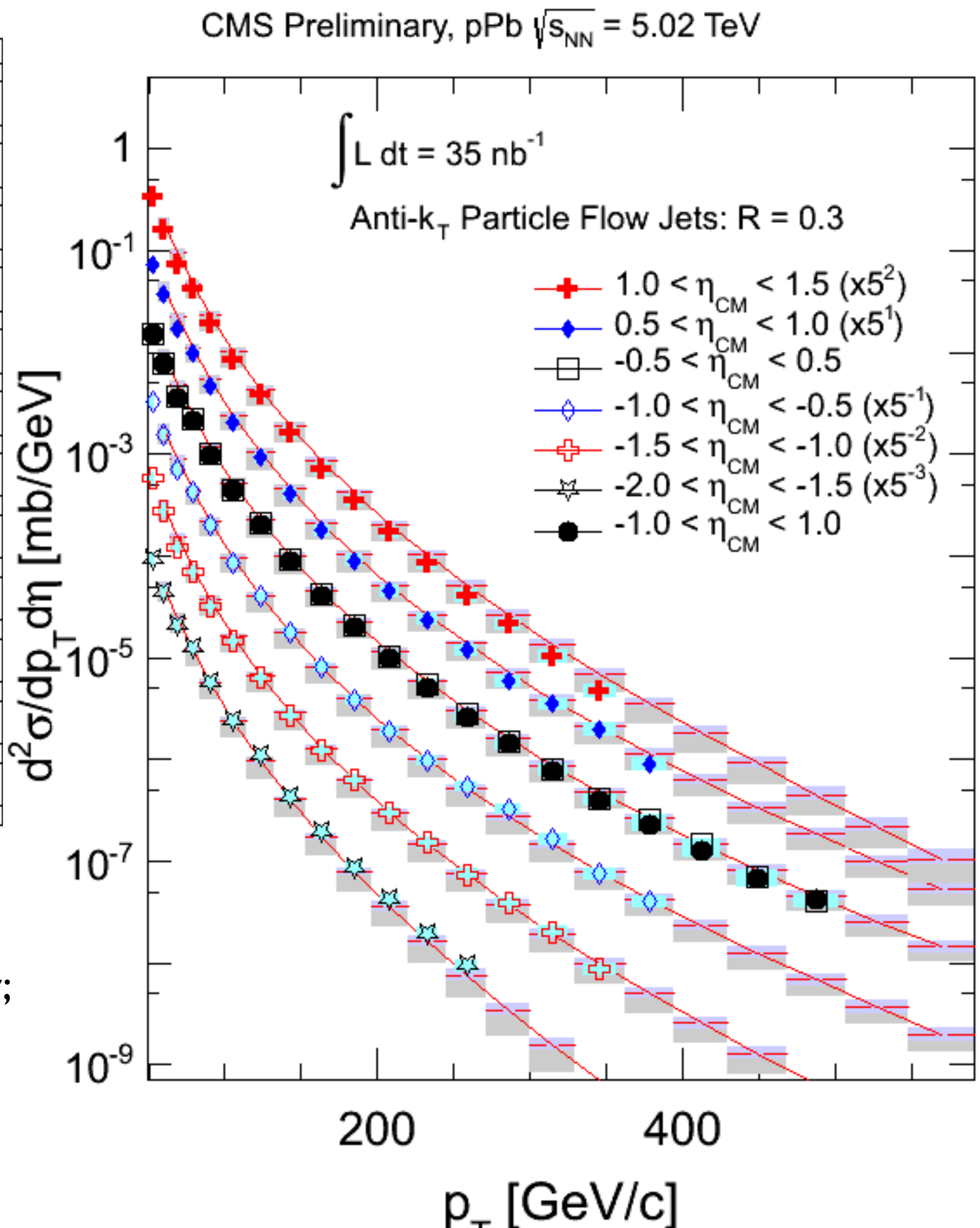


Anti-k$_T$ R=0.3 Jets



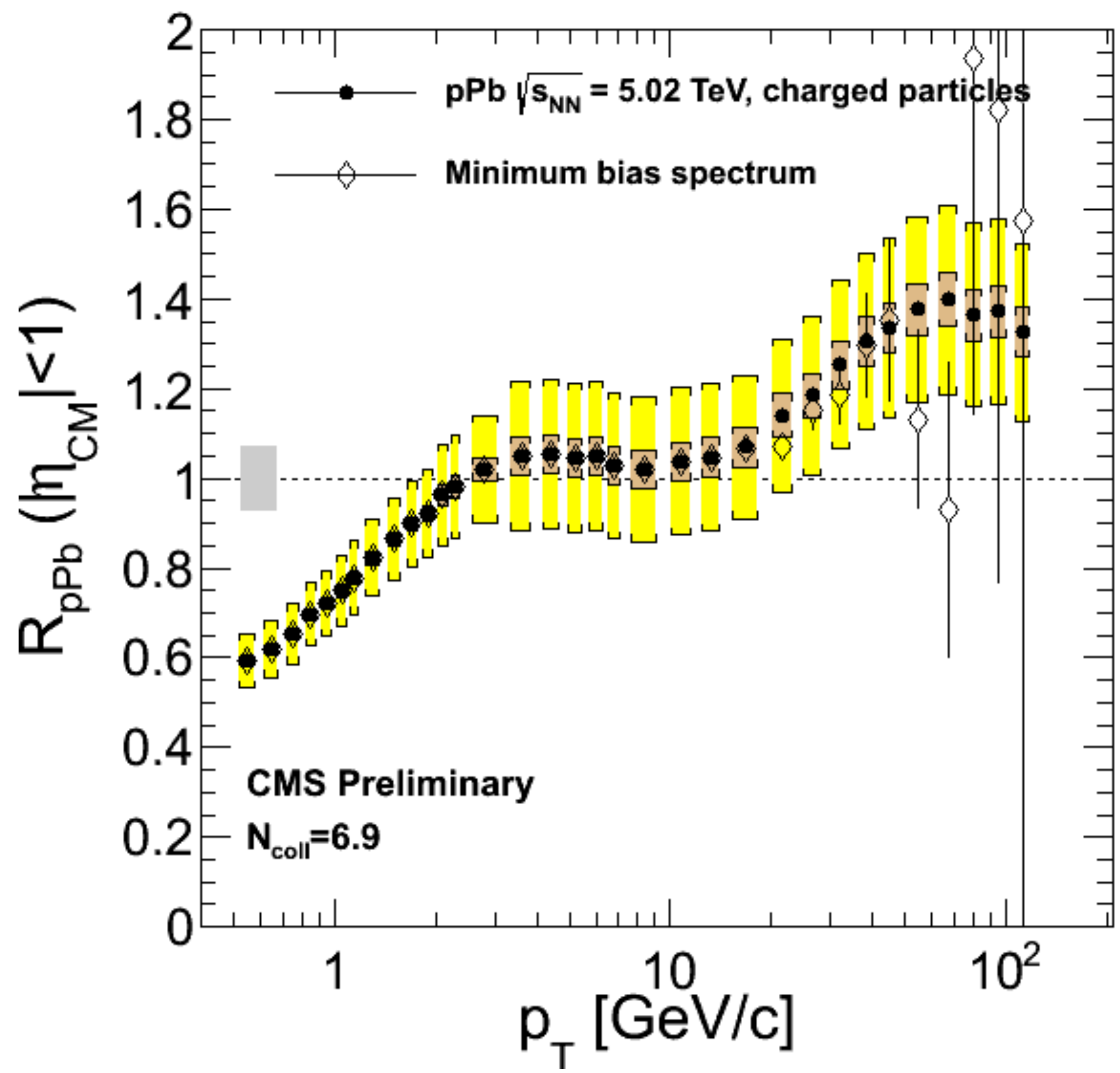
Jet Spectrum



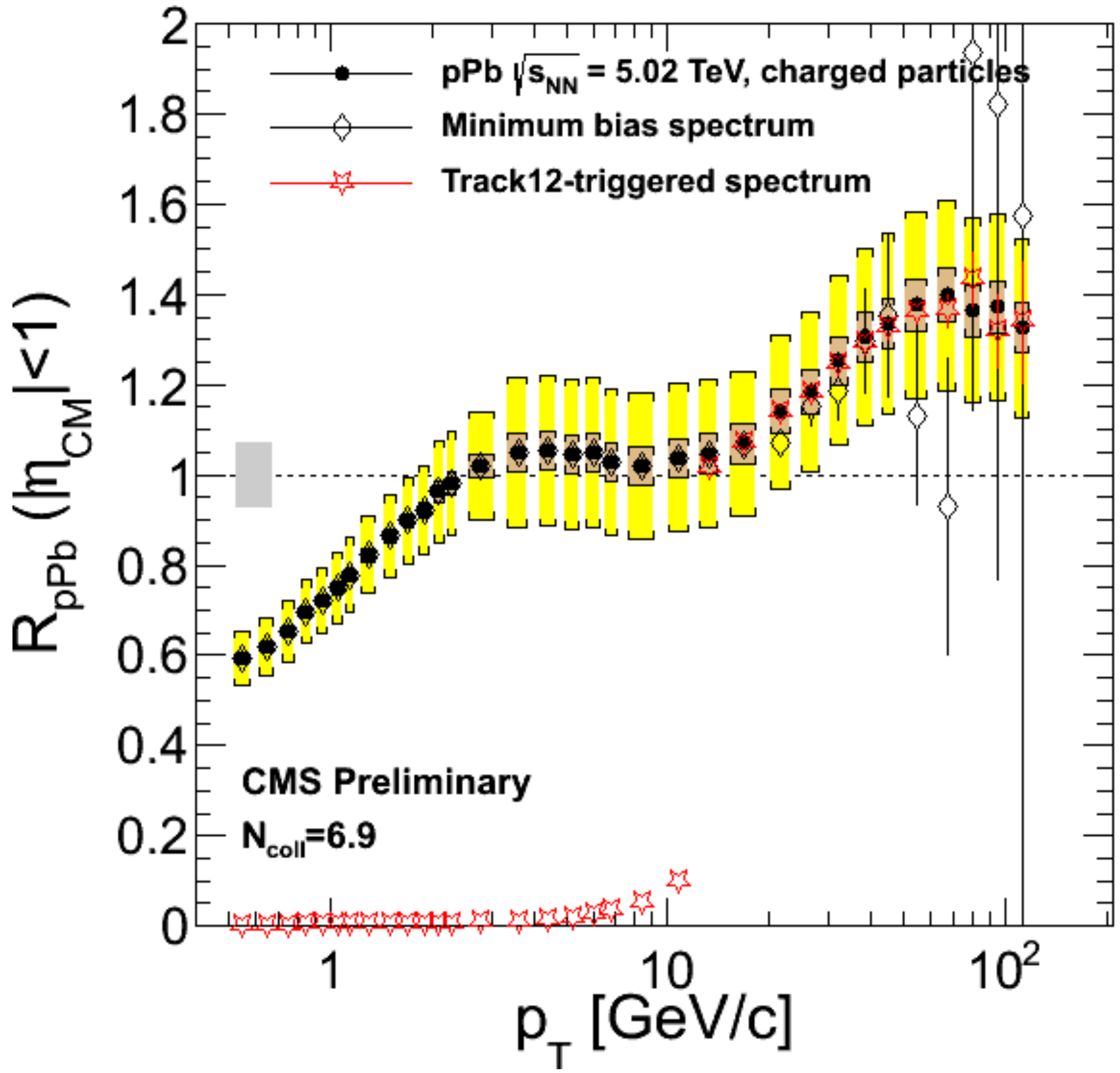


- The curve is from Hannu (gray: scale uncertainty; blue: PDF uncertainty):
  - pp: CT10
  - pPB: CT10++EPS09

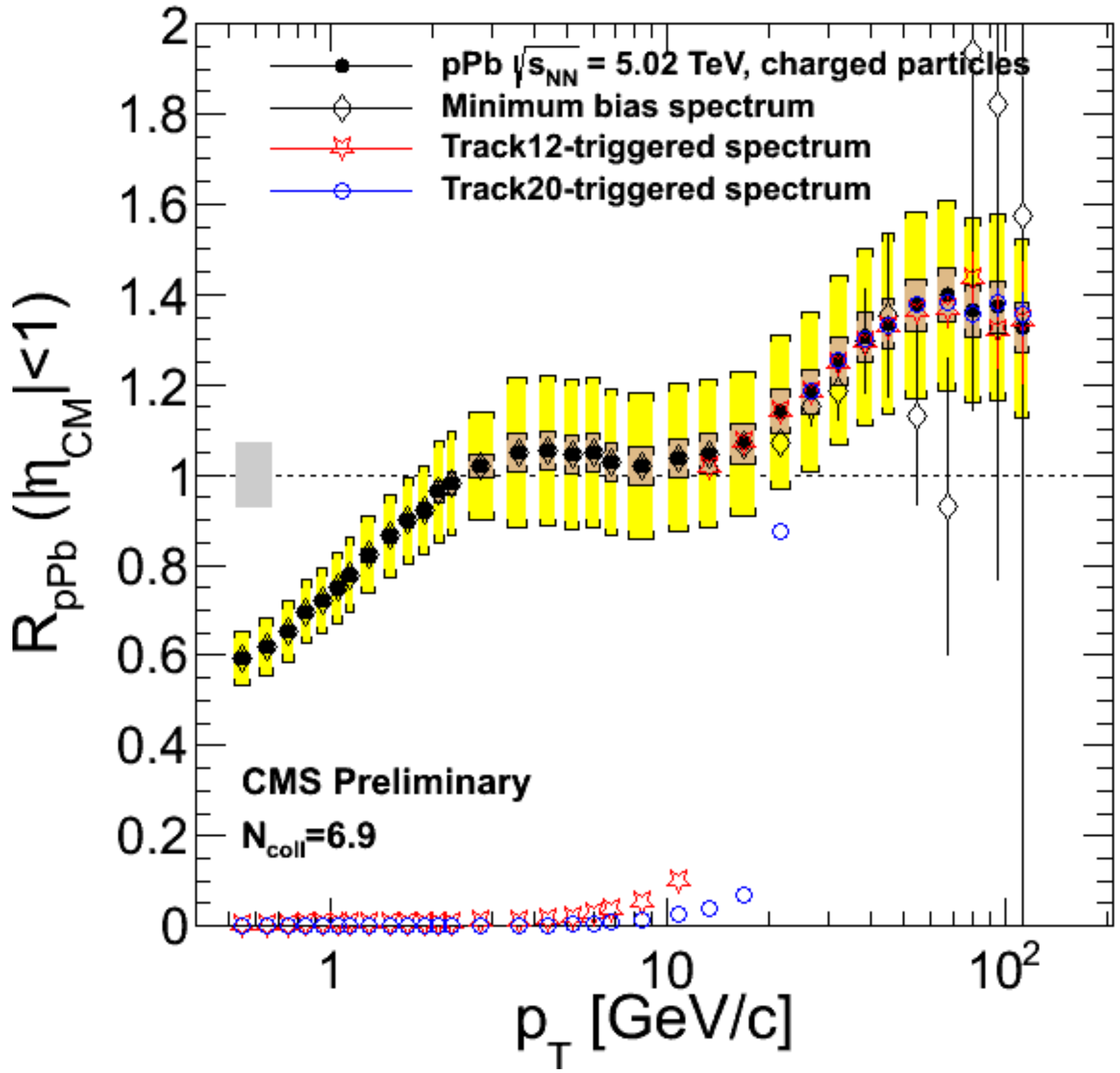
Charged R_{pPb} from individual triggers



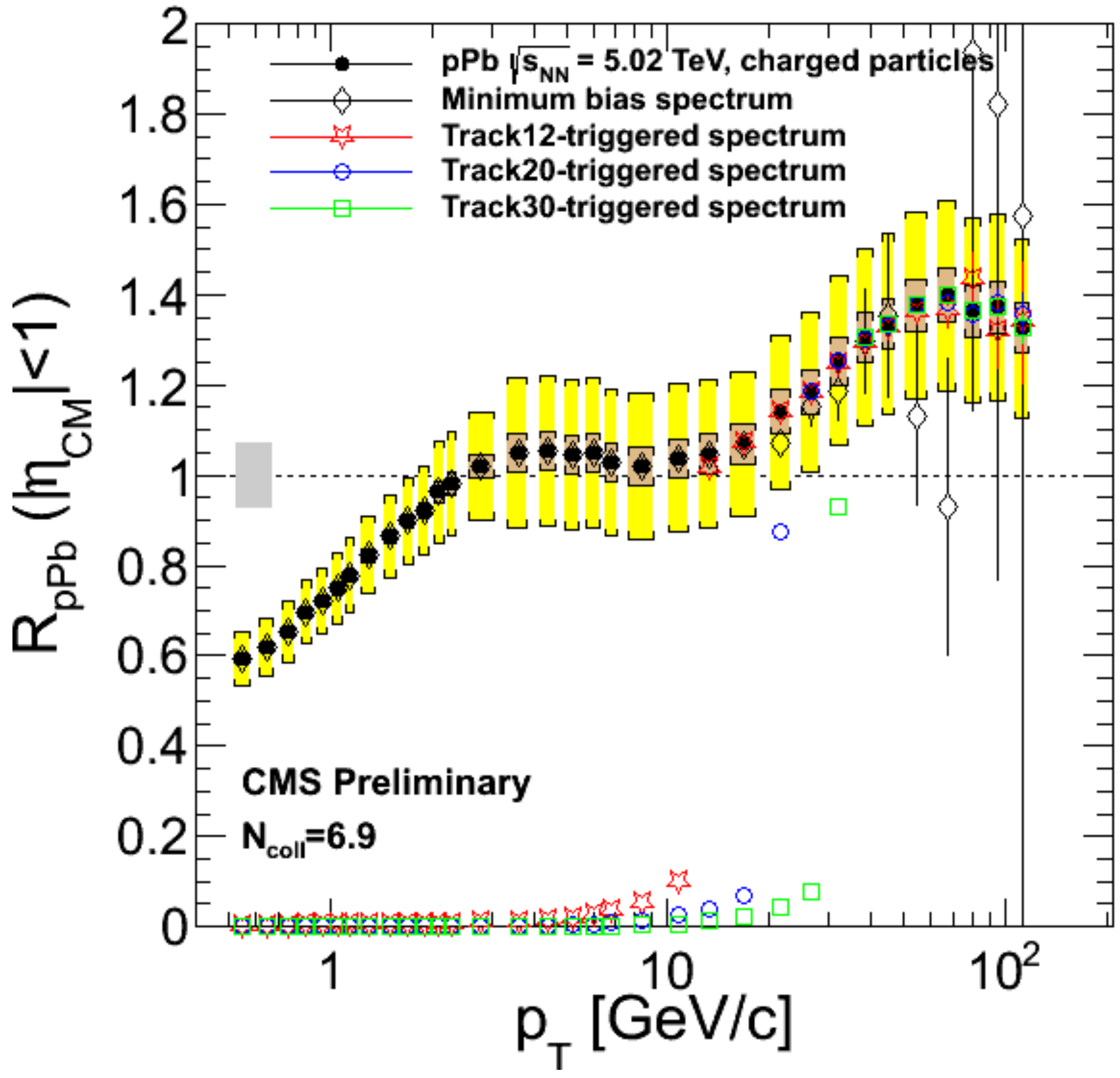
Charged R_{pPb} from individual triggers



Charged R_{pPb} from individual triggers

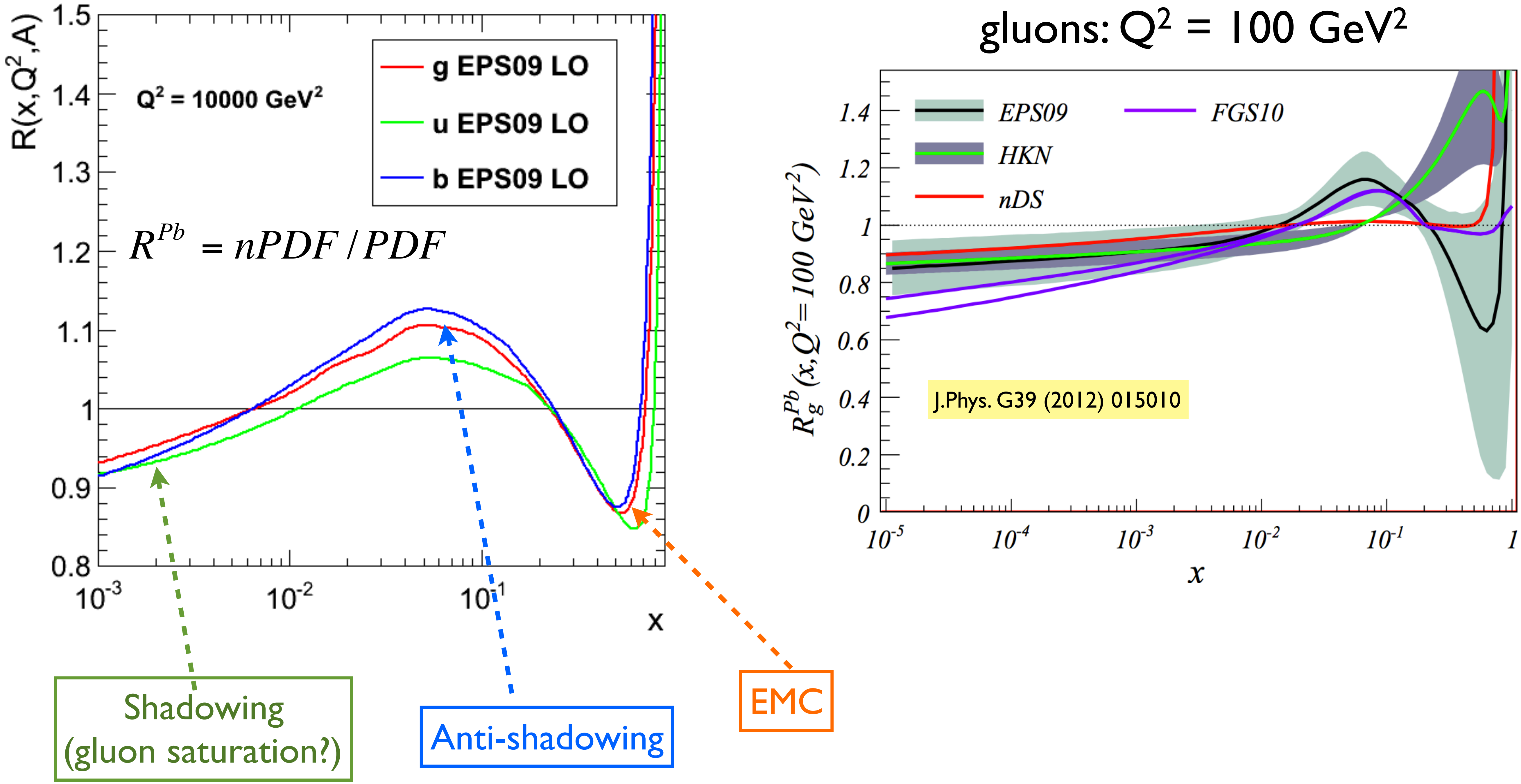


Charged R_{pPb} from individual triggers



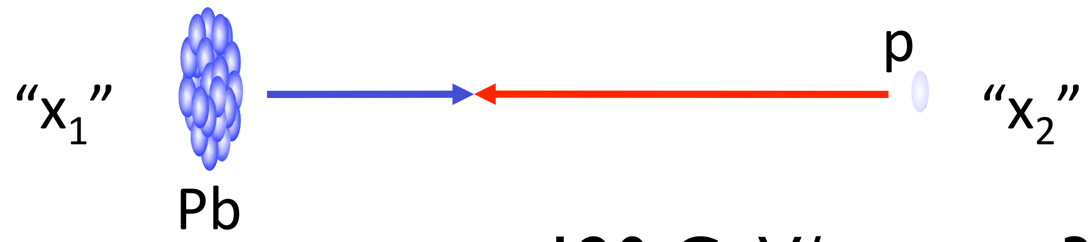
Nuclear PDF Predictions at LHC

François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/



- At LHC energies, the R^{Pb} is expected to have significant shadowing/anti-shadowing effects

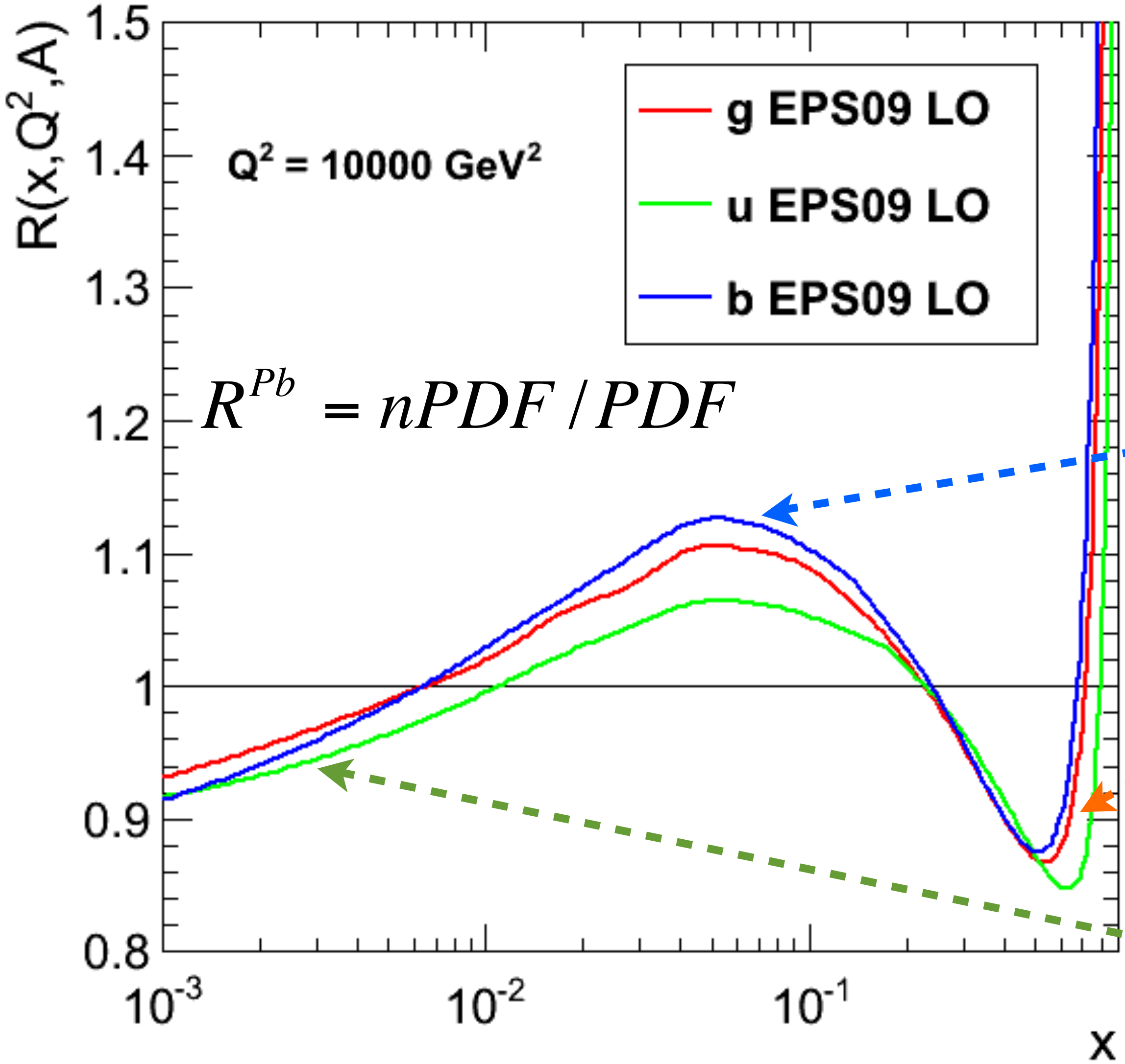
$x_1 \leftrightarrow \eta_{dijet}$

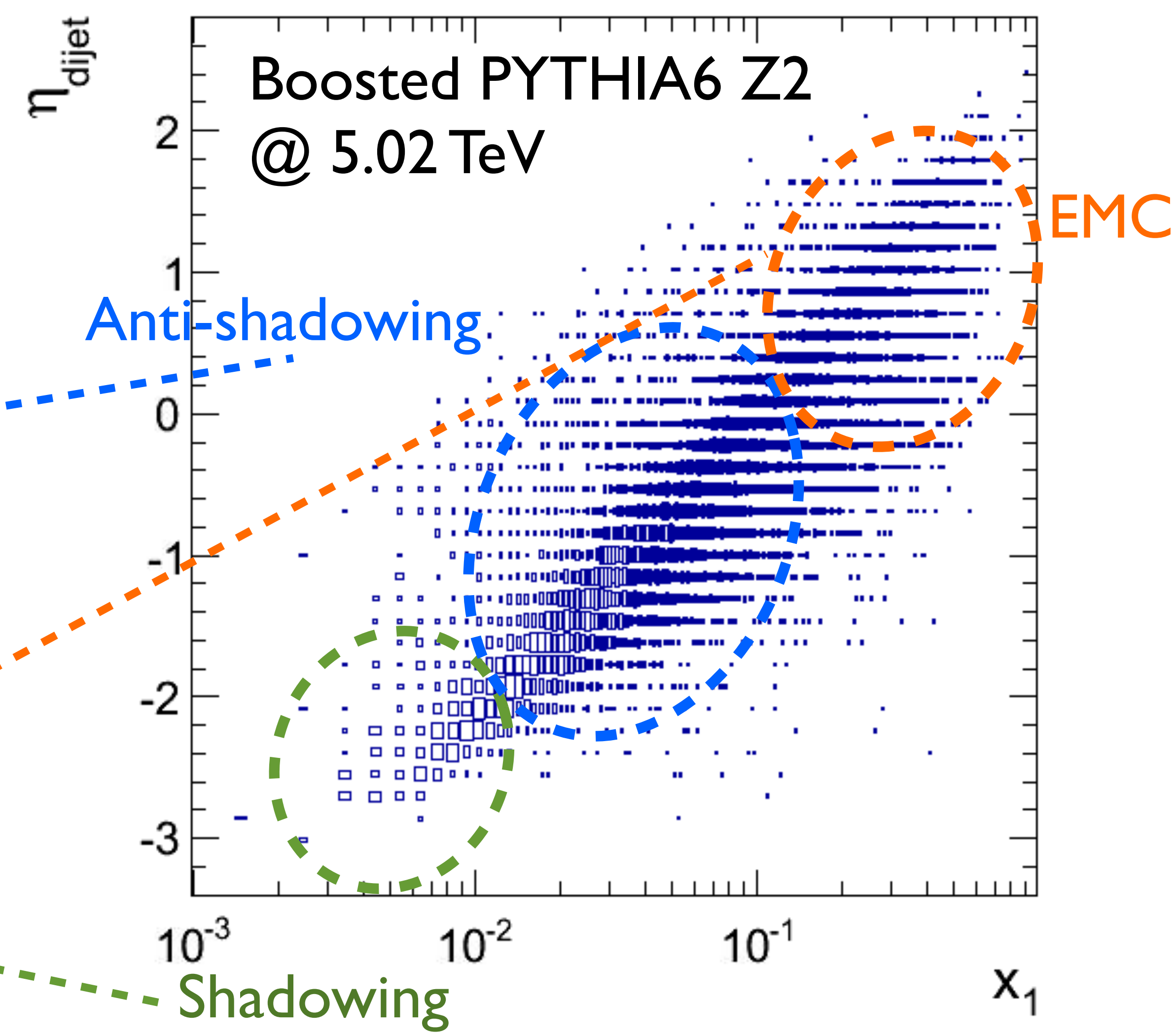


$p_{T,1} > 120$ GeV/c, $p_{T,2} > 30$ GeV/c, $\Delta\varphi_{12} > 2\pi/3$

$$\eta_{dijet} = \frac{\eta_1+\eta_2}{2}$$

Translation from η_{dijet} to x_1



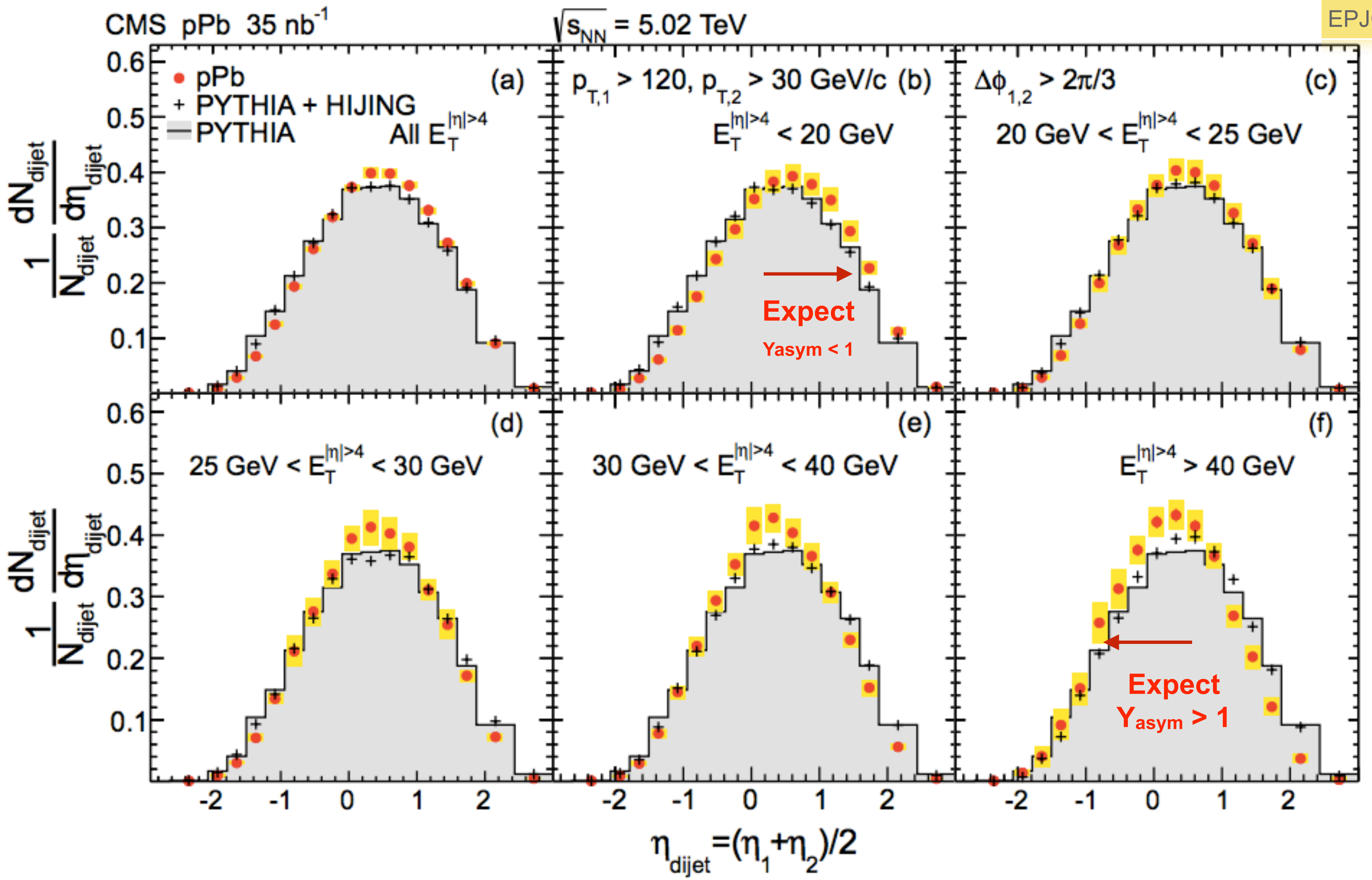


François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/

- Different η_{dijet} probes different effects with different x

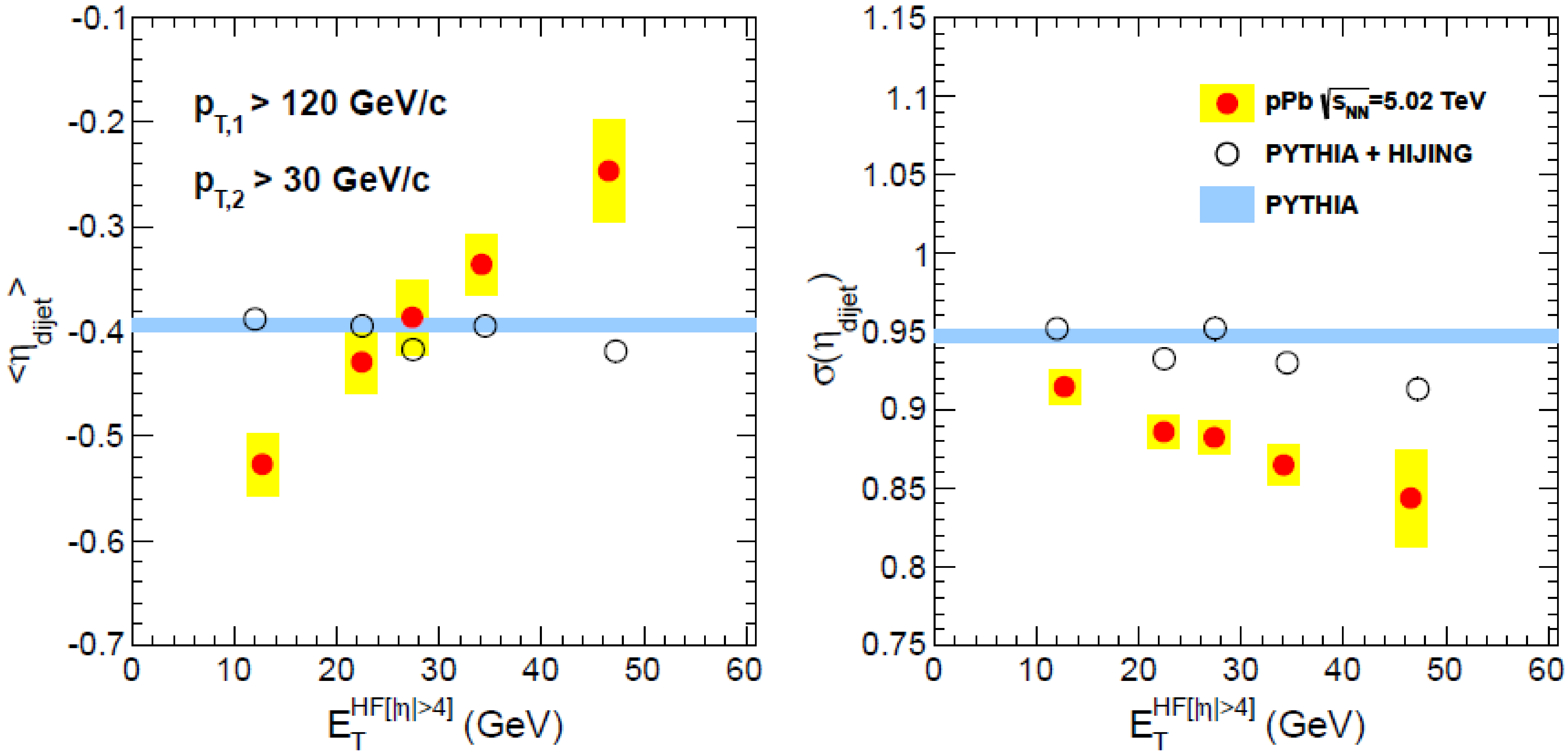
Dijet asymmetry comparison

EPJC 74 (2014) 2951



Summary from dijet η

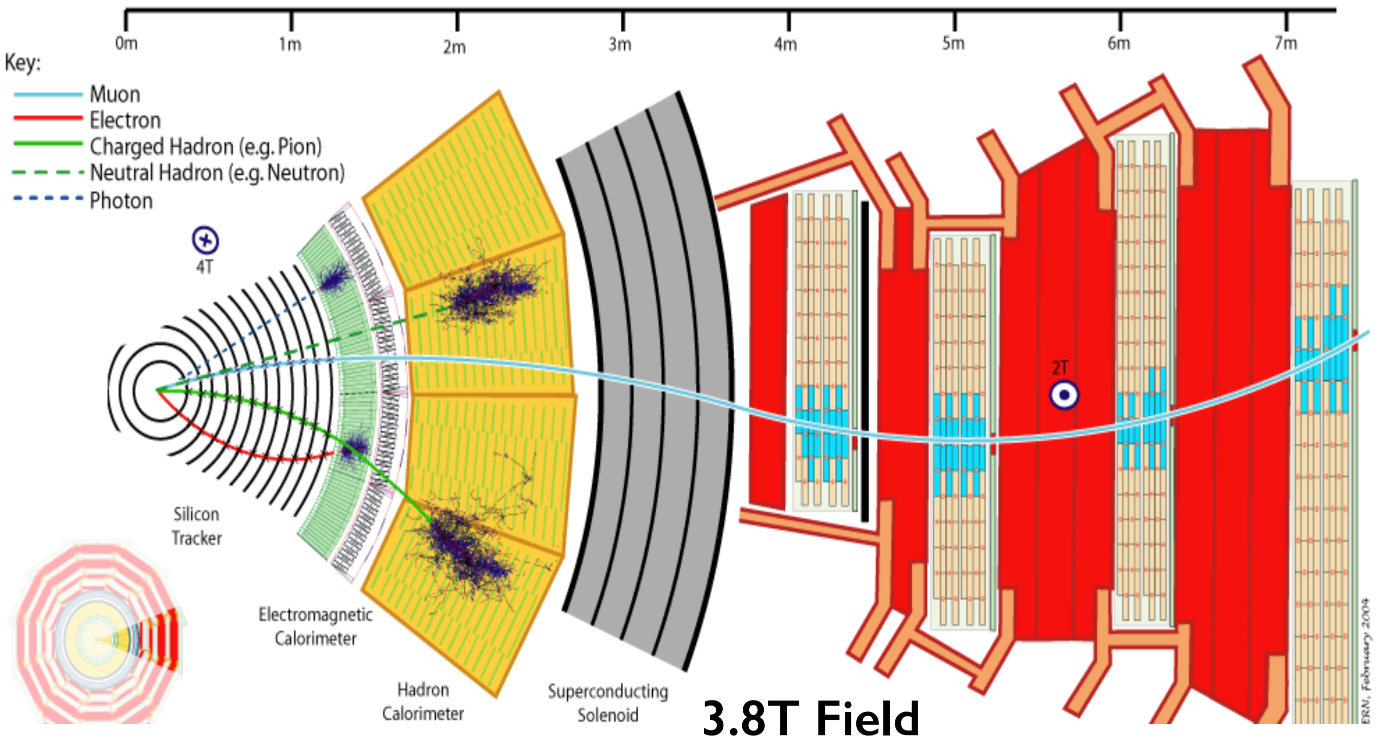
CMS PAS HIN-13-001

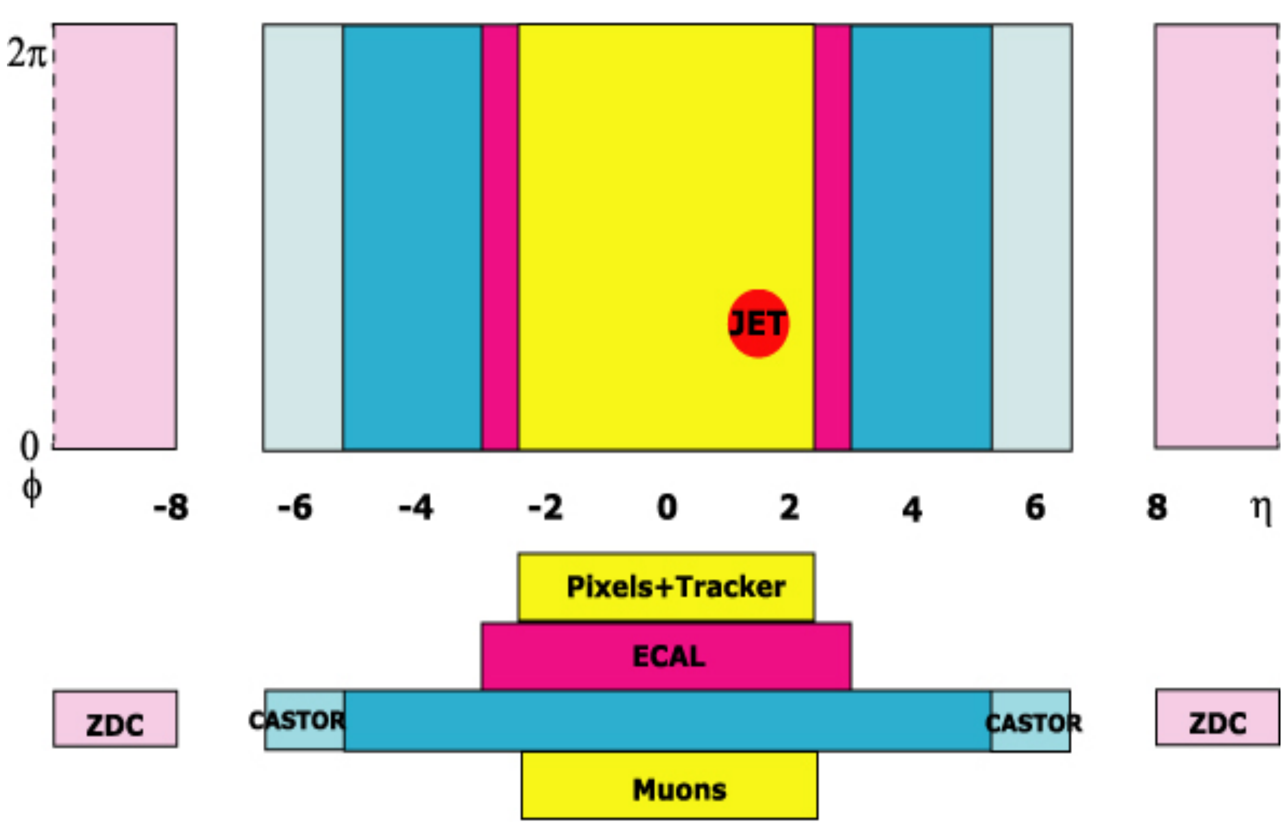


$$\eta_{dijet} = \frac{\eta_1+\eta_2}{2}$$

- Mean of η_{dijet} increases v.s. forward calorimeter energy
- Width of η_{dijet} decreases v.s. forward calorimeter energy

CMS Detector capabilities

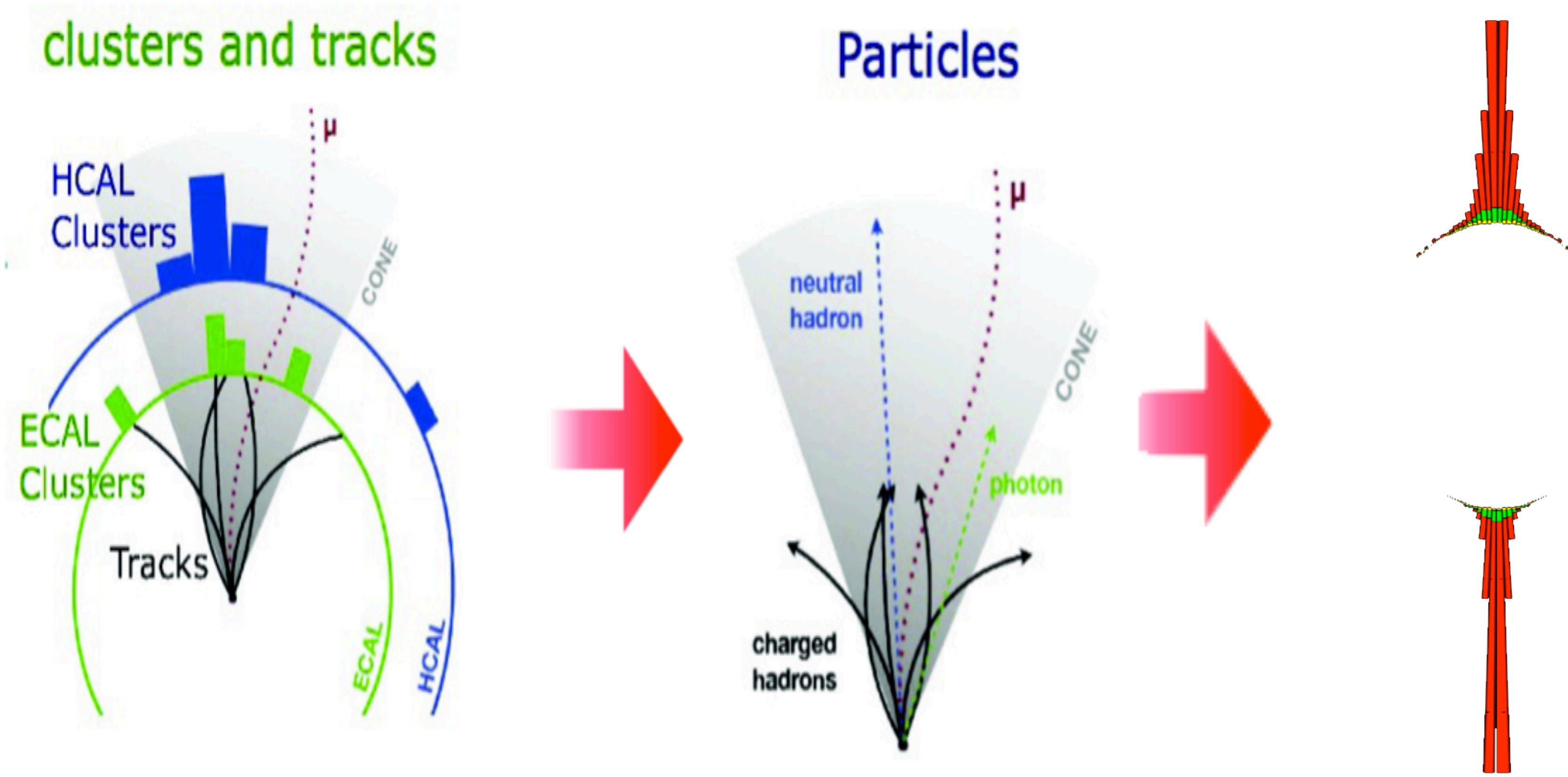




CMS is a multi-layer detector

- Excellent tracking capabilities
  - Momentum resolution of 1-2% to 100GeV/c
  - Displaced vertices for heavy flavor
- High-granularity calorimetry
  - Directly identifiable jets
  - γ-jet studies
- High Level Trigger
  - Higher energy reach
  - Ultra-central events
  - Improved J/ψ, Z^0, ϒ

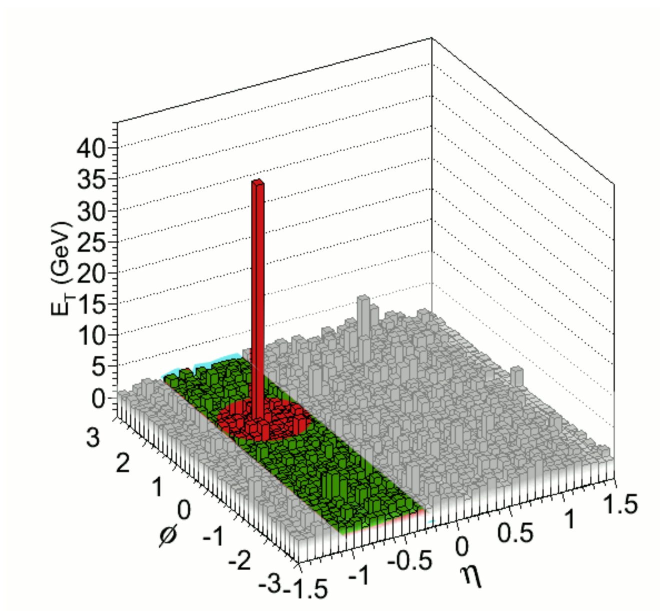
Jet reconstruction

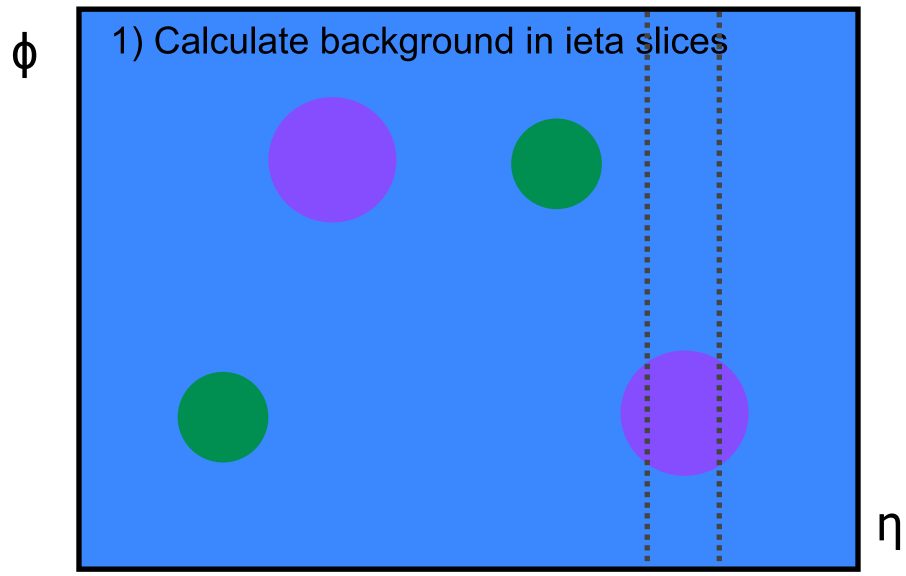


[1] arXiv:1107.0179
[2] CMS-PAS-PFT-09-001

- Information from all sub-detectors are combined into particle candidates "Particle flow" event reconstruction method[1-2]
  - Allows us to exploit the excellent resolution of the tracker for the charged hadron component of the jet
  - Also includes a fully consistent treatment of electron and muons inside jets

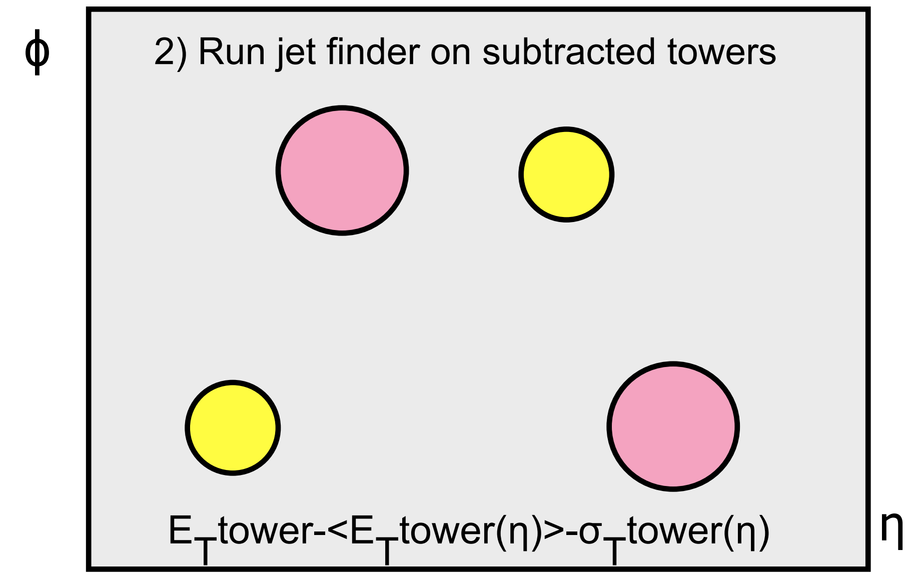
Jet underlying event subtraction



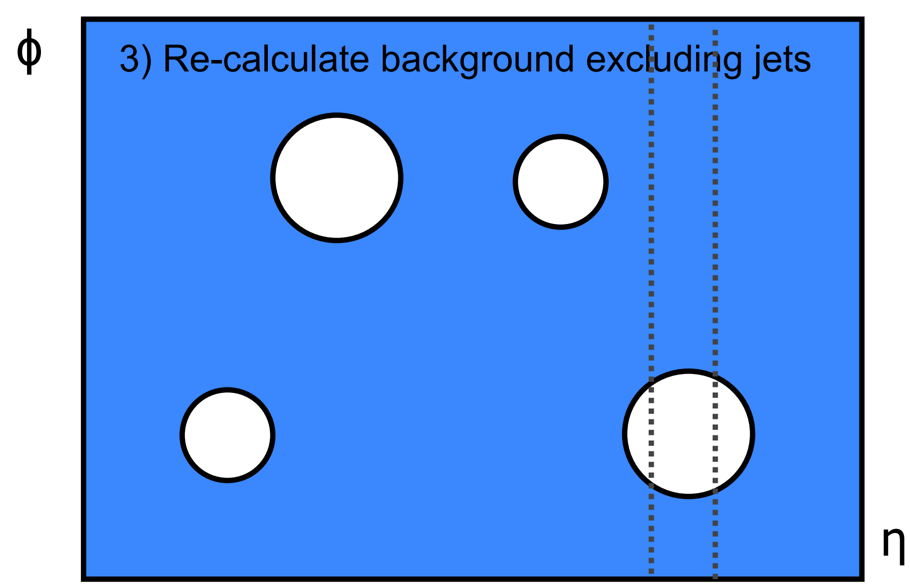


1. $\langle E_T \rangle$ calculated in strips of η. Subtract $\langle E_T \rangle + \sigma$

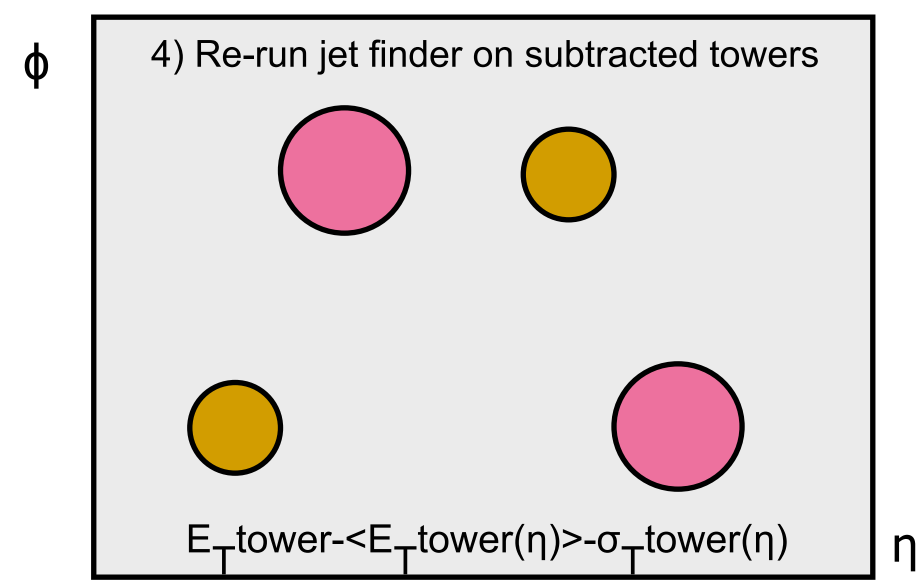
Original towers



2. Run anti-k_T algorithm on background-subtracted towers



3. Exclude reconstructed jets and re-estimate background



4. Re-run anti-k_T algorithm to get final jets

- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117