# Jet quenching and heavy flavor production with the ATLAS detector

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Hard Probes 2012
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Plenary 1A
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# Jets in Heavy Ion Collisions

‣ Jets provide a powerful tool for determining medium properties via **jet quenching**

‣ Results from the RHIC program show that high p_T particle production is suppressed and that usual factorization of hard processes is broken in nuclear collisions

- q^2 not single dominant scale

- Indirect observation of jet quenching

‣ Single particle suppression doesn't tell us:

- Is energy being transferred to the medium?

- Or simply redistributed among w/in jet?

‣ Need to go beyond single particles, look at **full jets**

- Kinematics of jet directly related to parton suffering energy loss

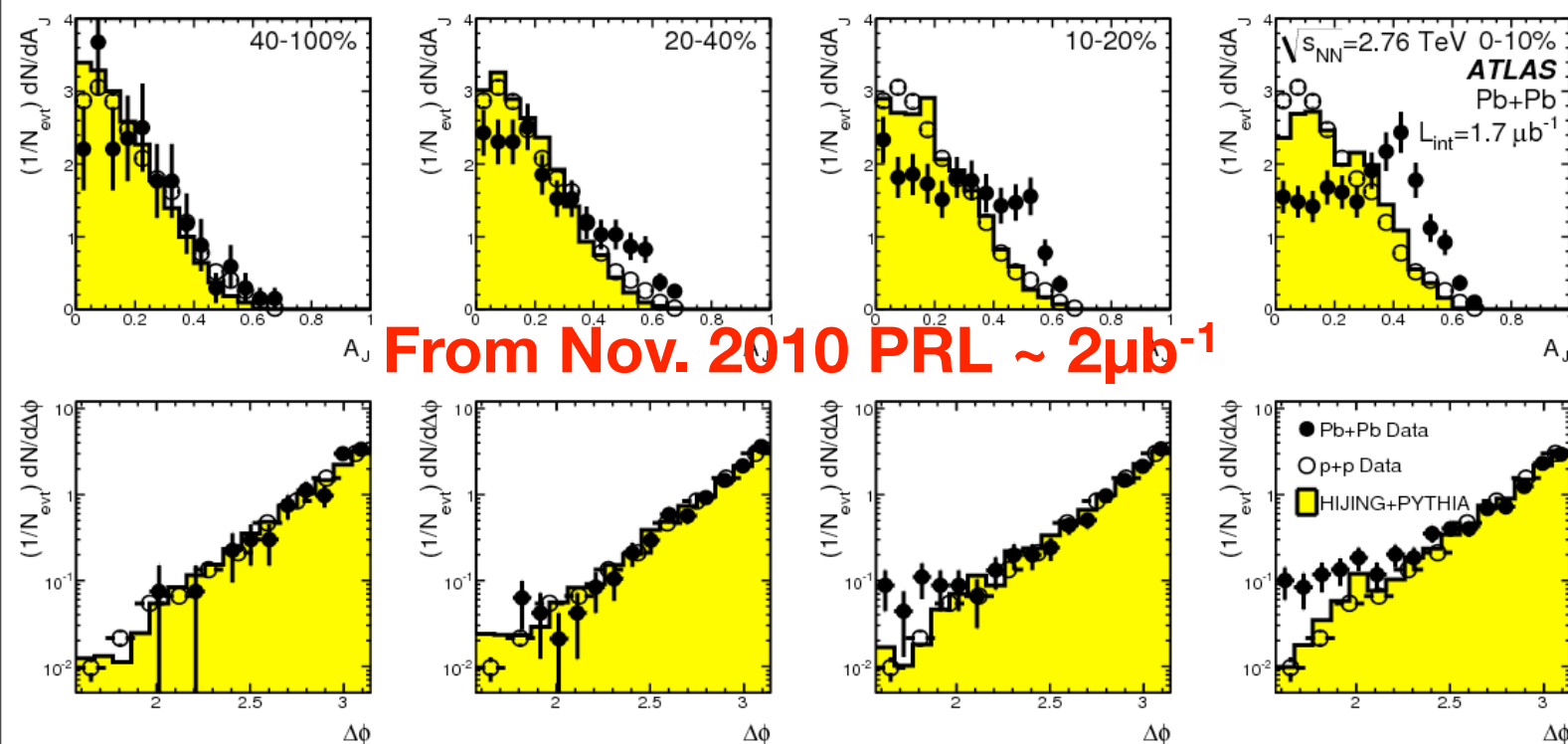- Sensitive to full angular pattern of medium-induced radiation

Dijet Asymmetry: Original Result

Calorimeter Towers
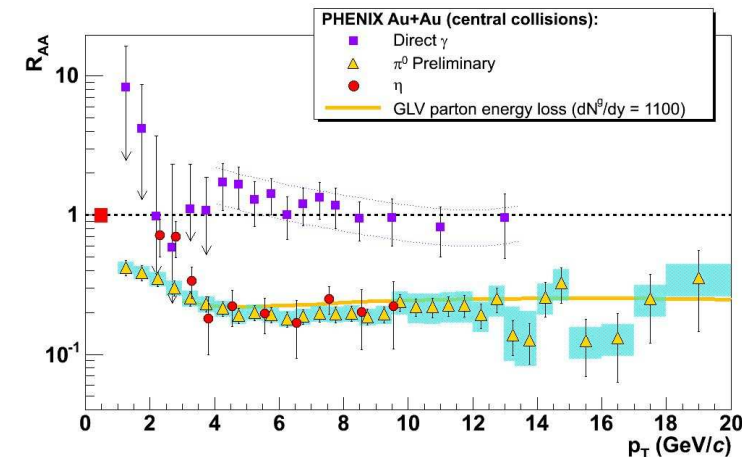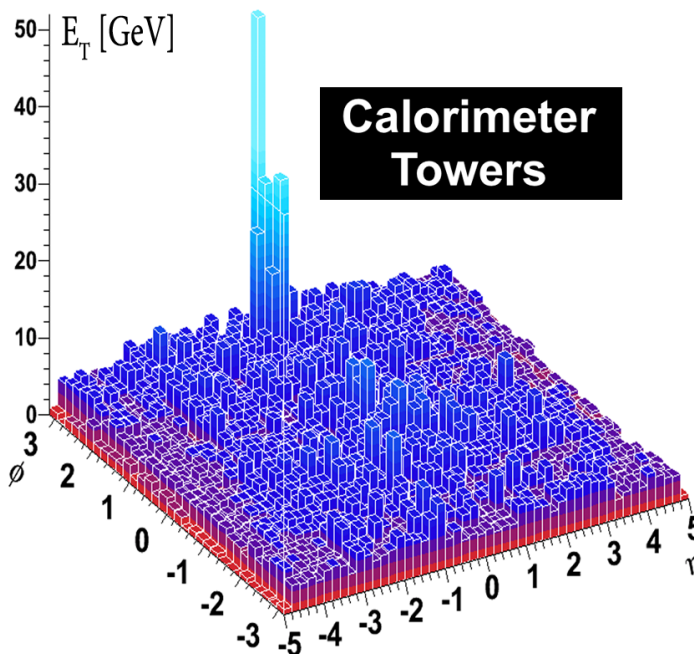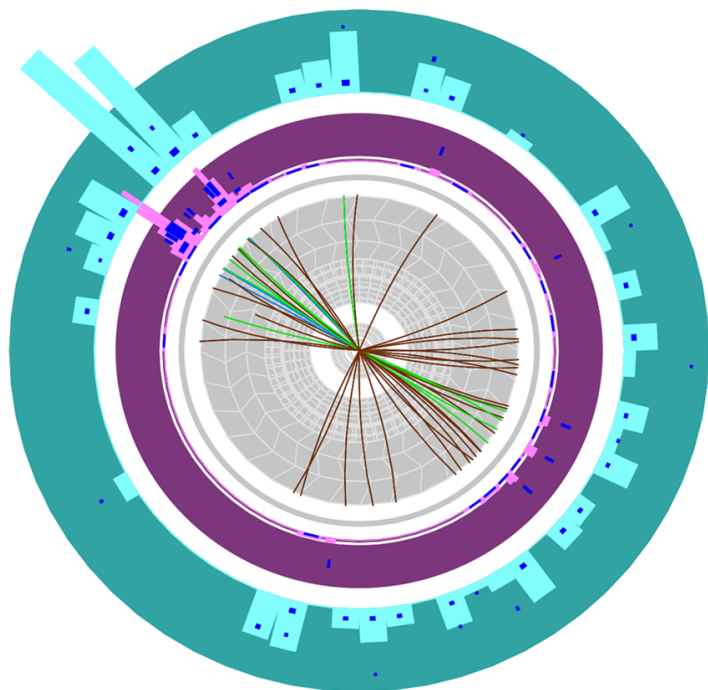
ATLAS
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET

Tracks
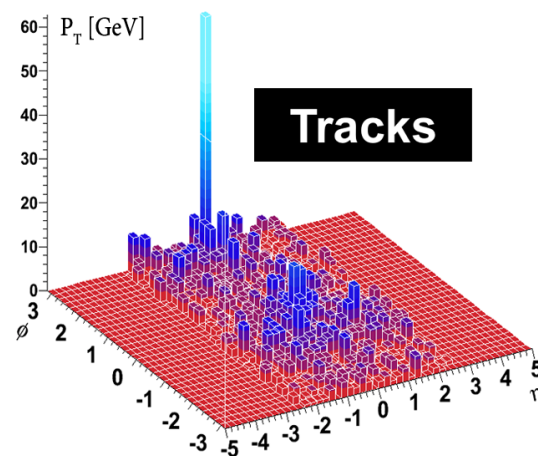
Dijet Asymmetry: Original Result

$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

$$E_{T1} > 100 \; GeV$$

$$E_{T2} > 25 \; GeV$$

From Nov. 2010 PRL ~ 2μb⁻¹

**First direct observation of jet quenching**

Momentum balance from hard process not fully contained in dijets

Beyond Asymmetry

‣ Asymmetry sensitive to **differential** energy loss

‣ Can gain additional insight by considering **inclusive** energy loss

- Single inclusive jet spectra and central to peripheral ratio R_{CP}

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Beyond Asymmetry

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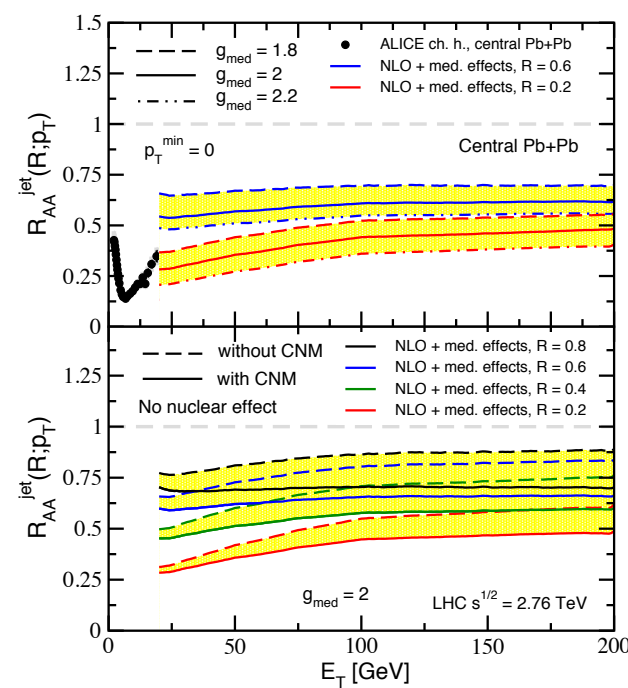 • Single inclusive jet spectra and central to peripheral ratio R_{CP}

‣ Medium-induced radiation can distribute jet's energy outside cone
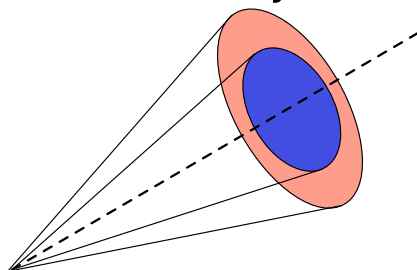
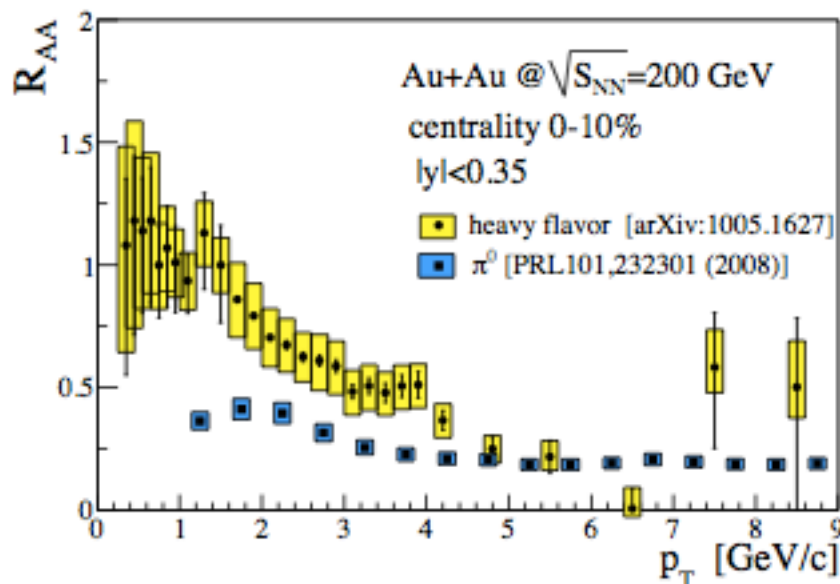

‣ Can lost energy due to recovered by expanding jet size?

**Measure single jet suppression
with multiple jet sizes**

He, Vitev, and Zhang hep-ph/1105.2566

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Heavy Flavor

‣ c/b quarks much heavier do they experience same degree of quenching as light quarks?

Au+Au @ $\sqrt{S_{NN}}$=200 GeV
centrality 0-10%
|y|<0.35

☐ heavy flavor [arXiv:1005.1627]
☐ π^0 [PRL101,232301 (2008)]
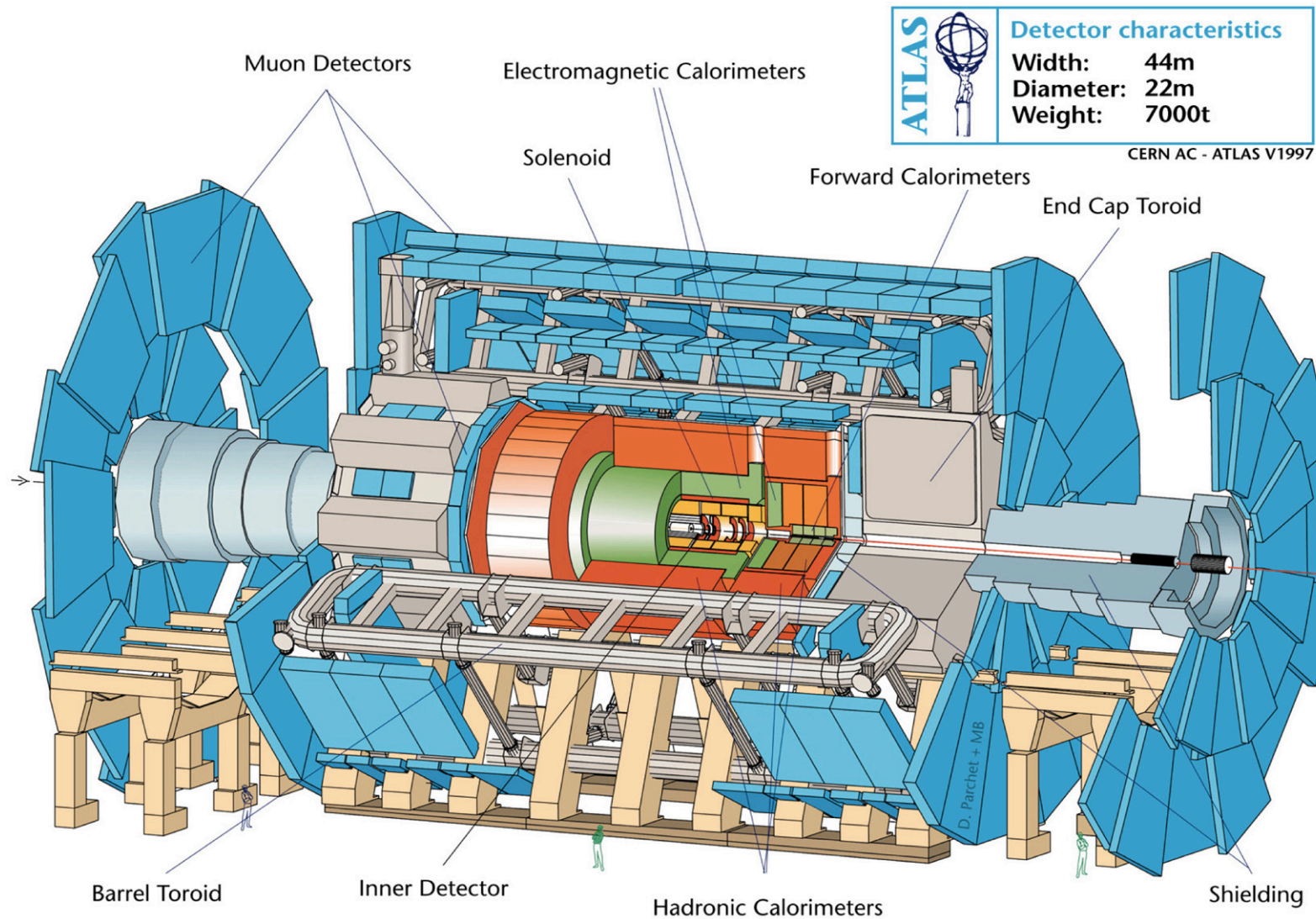
• RHIC results indicate:

  ✦ heavy and light quarks show similar suppression for $p_T > 4$ GeV

  ✦ R_{AA}~0.3

‣ Additional measurements may help to resolve outstanding theoretical issues on heavy quark energy loss

Measure single inclusive muon spectrum at intermediate p_T, which is dominated by semi-leptonic decay of heavy flavor

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The ATLAS Detector

Muon Detectors

Electromagnetic Calorimeters

Solenoid

Forward Calorimeters

End Cap Toroid

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

Barrel Toroid

Inner Detector

Hadronic Calorimeters

Shielding

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8

Jet Reconstruction

- ‣ Use anti-k_t, R=0.2, 0.3, 0.4 and 0.5

- ‣ Perform **event-by-event subtraction** per calorimeter cell in jet

$$E_{\mathrm{T}j}^{\mathrm{sub}} = E_{\mathrm{T}j} - A_j\ \rho_i(\eta_j)\left(1 + 2v_{2i}\cos\left[2\left(\phi_j - \Psi_2\right)\right]\right)$$

indices:
j for cell
j for layer

- • Average, η-dependent background E_T density: ρ

- • Elliptic flow modulation: η and p_T averaged v_2

- ‣ Two-step procedure to prevent jets from biasing subtraction

- • Define jet "seeds" and exclude from ρ and v_2 determination

Perceived Problems with Jet Measurements

☐ Uncorrelated UE fluctuations present under jet even after subtraction

☐ UE fluctuations from soft particles can be reconstructed as jets (fakes)

☐ Quenched jets may have different particle composition and fragmentation than unquenched jets in MC

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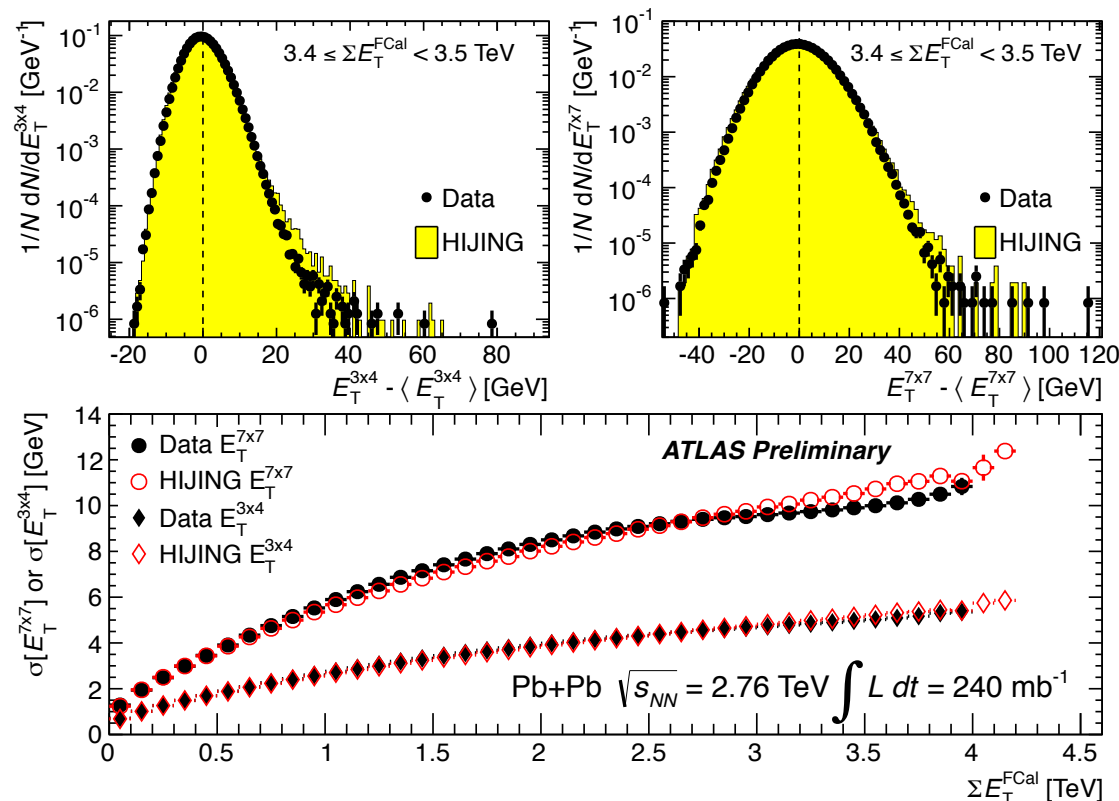## Uncorrelated UE fluctuations present under jet even after subtraction

- 🔴 Need accurate MC description (HIJING) to:

  - 🔴 Provide asymmetry baseline

  - 🔴 Correct for JER/unfolding in jet spectrum

Uncorrelated UE fluctuations present under jet even after subtraction

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  - 🔵 Use groups of towers approximately the same size as jets (e.g. Area R=0.4 jet ~ Area 7x7 tower group)
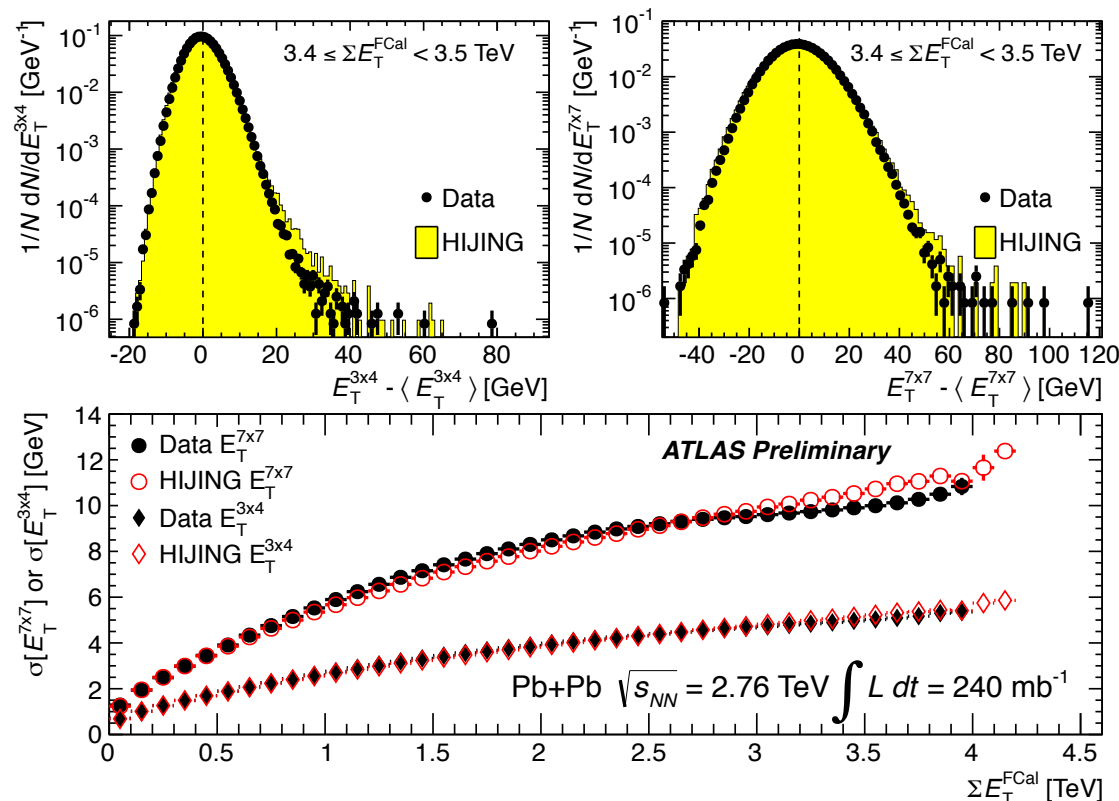 - 🔵 Sum E_T in each window and look at distribution

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- Require additional signal of **hard particle** production
  - Reject fakes by requiring jet to match:
    - Track jets or EM clusters with $p_T > 7$ GeV
  - Residual fake rate estimated to be ~3% at 50 GeV

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- 🔵 Track jet energy scale independent of centrality

- 🔵 Use track jet/calo jet matching to provide data-driven check by comparing relative energy scale

  - 🔵 $<E_T^{calo}>$ as function of $E_T^{trackjet}$

- 🔵 Differences in JES < 3%, included in systematic uncertainties

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Performance
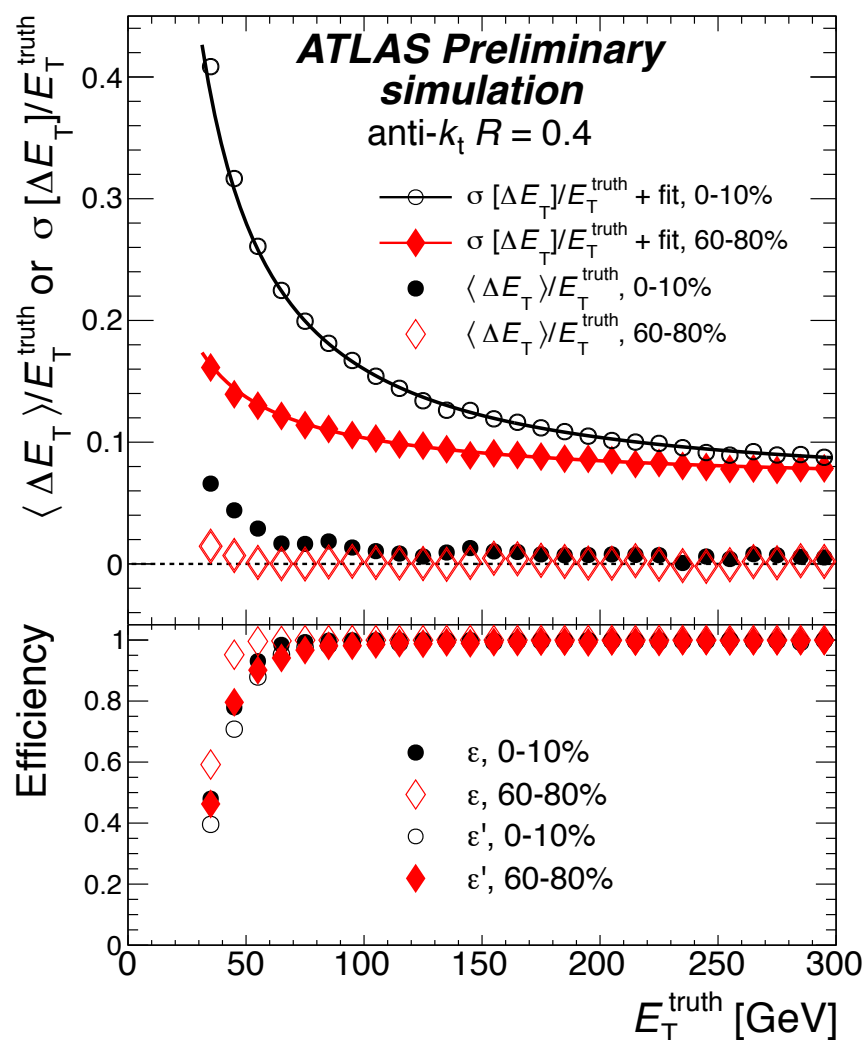
▸ Reconstruction capabilities evaluated using MC

- Use PYTHIA dijets embedded into HIJING events

▸ Validated using data, extract systematics

Unfolding
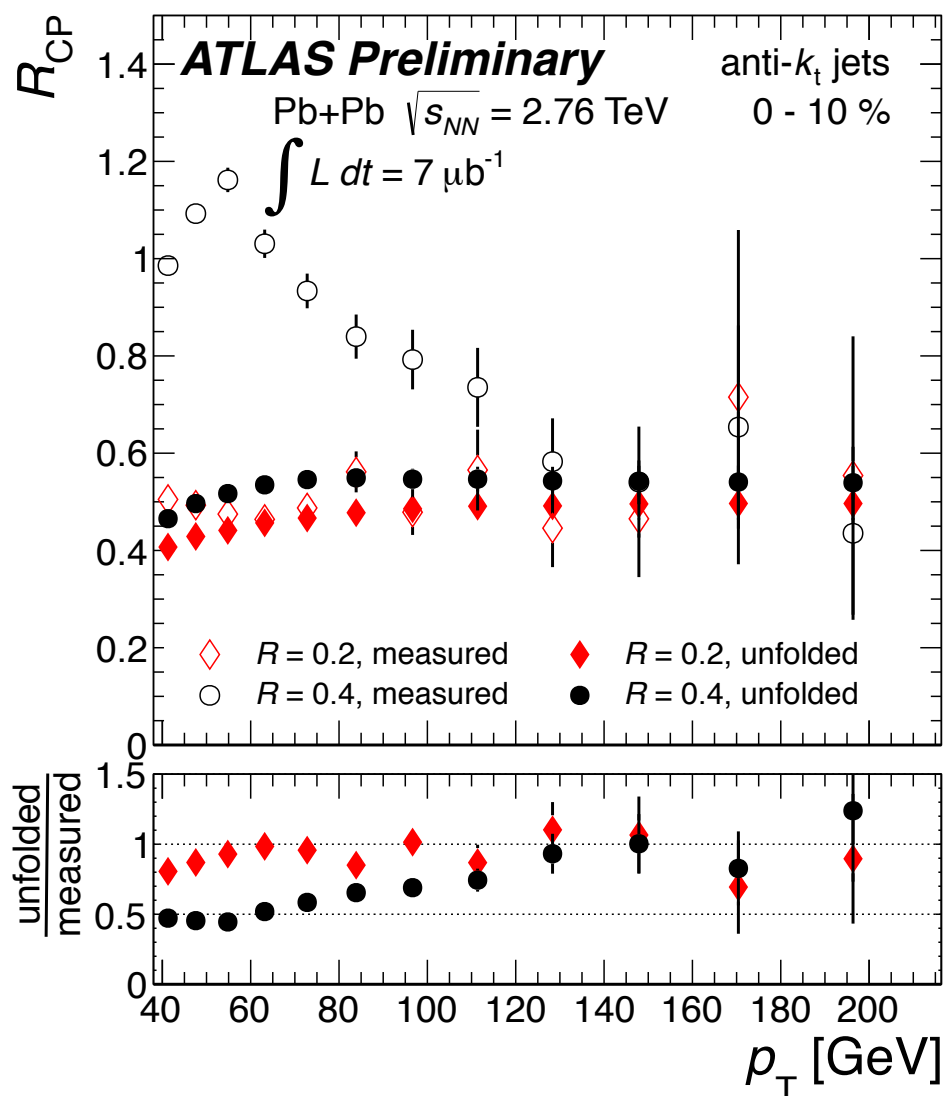
- ▸ UE and detector effects result in finite JER
  - Jet spectrum is steeply falling
  - Result is significant bin migration
- ▸ Use MC to generate response matrix
  - Contains information about bin migration
- ▸ SVD unfolding
  - Invert response using curvature constraint on result to regularize unfolding
- ▸ Unfolding checks
  - Apply to MC, look for bias
  - "Refold" data, check refolded looks like input

Hocker and Kartvelishvili: hep-ph/9509307

Results: R_{CP} vs p_T in Centrality Bins

▸ Systematic errors

- **Black band**: fully correlated systematics

  ✦ all points move up/down together

  ✦ JES, JER, efficiency, x_{ini}, R_{coll}

- **Red boxes**: partially correlated systematics

  ✦ regularization

▸ Error bars: sqrt of diagonal elements of cov matrix

▸ No significance to horizontal width of error bars

$$R_{CP} = \frac{\left.\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\right|_{cent}}{\left.\frac{1}{N_{coll}}\frac{1}{N_{evt}}\frac{dN}{dp_T}\right|_{60-80}}$$
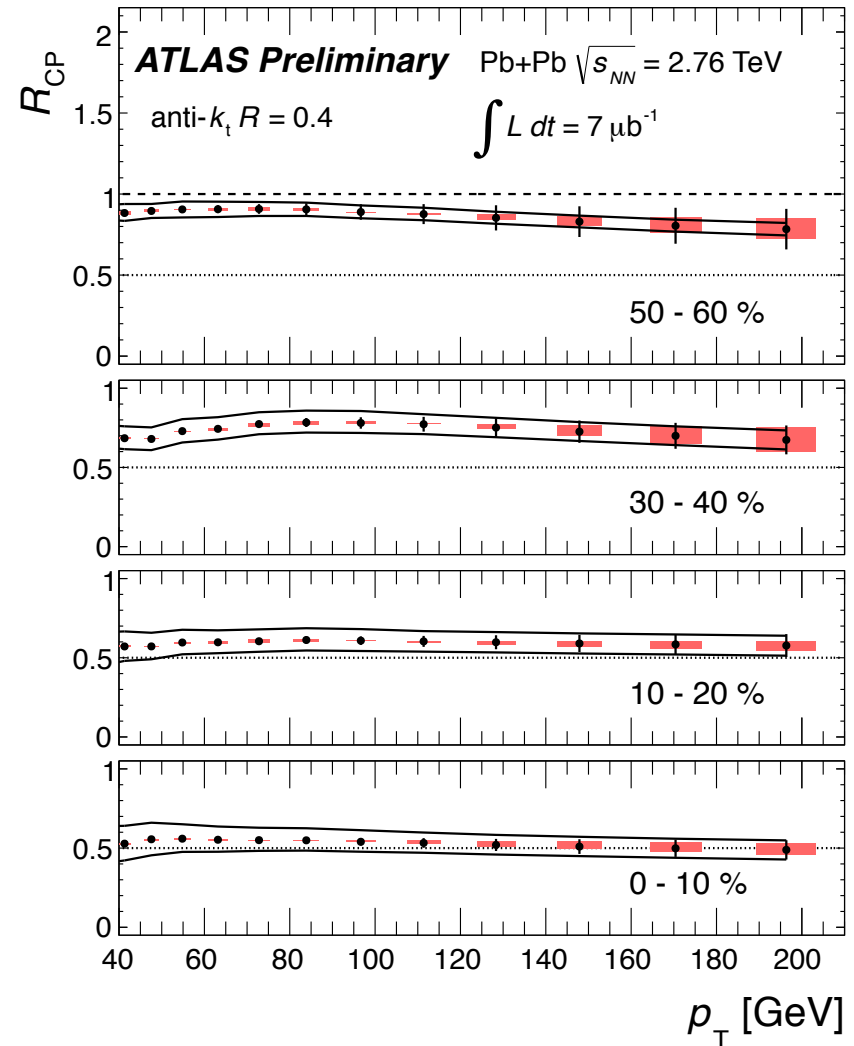
Results: R_{CP} vs p_T in Centrality Bins
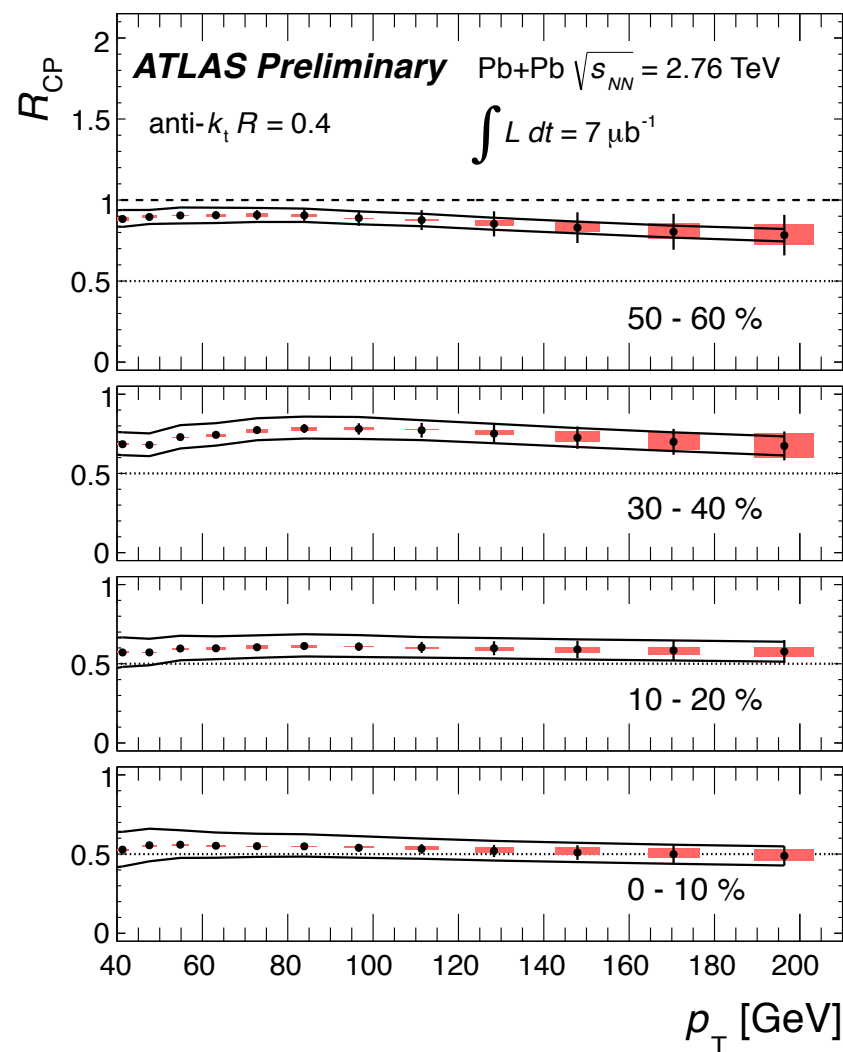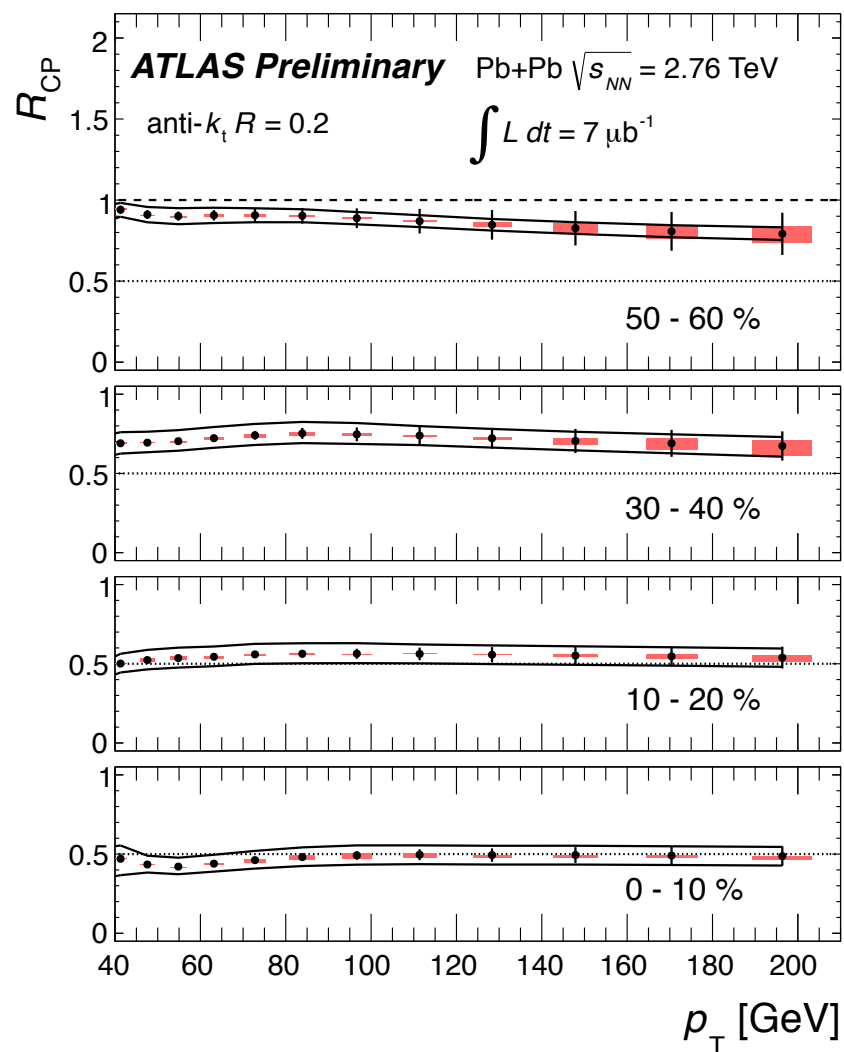
Results: R_{CP} vs N_{part} in p_T Bins
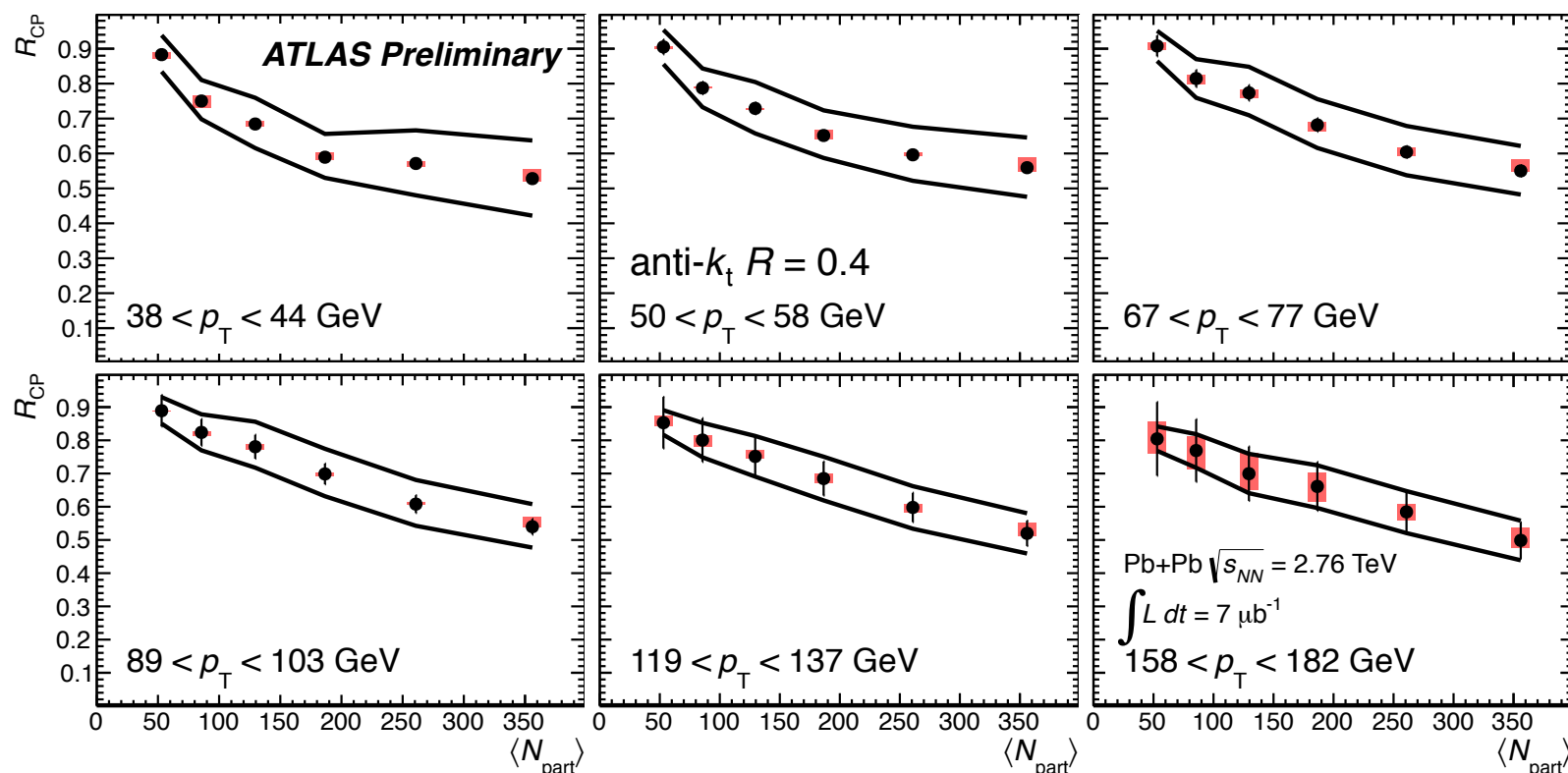
- **Correlated**: JES, efficiency, x_{ini}, R_{coll}

- **partially correlated**: regularization, JER

- Error bars: sqrt of diagonal elements of covariance matrix

- Horizontal width of boxes, N_{part} uncertainty

Results: R_{CP} vs R
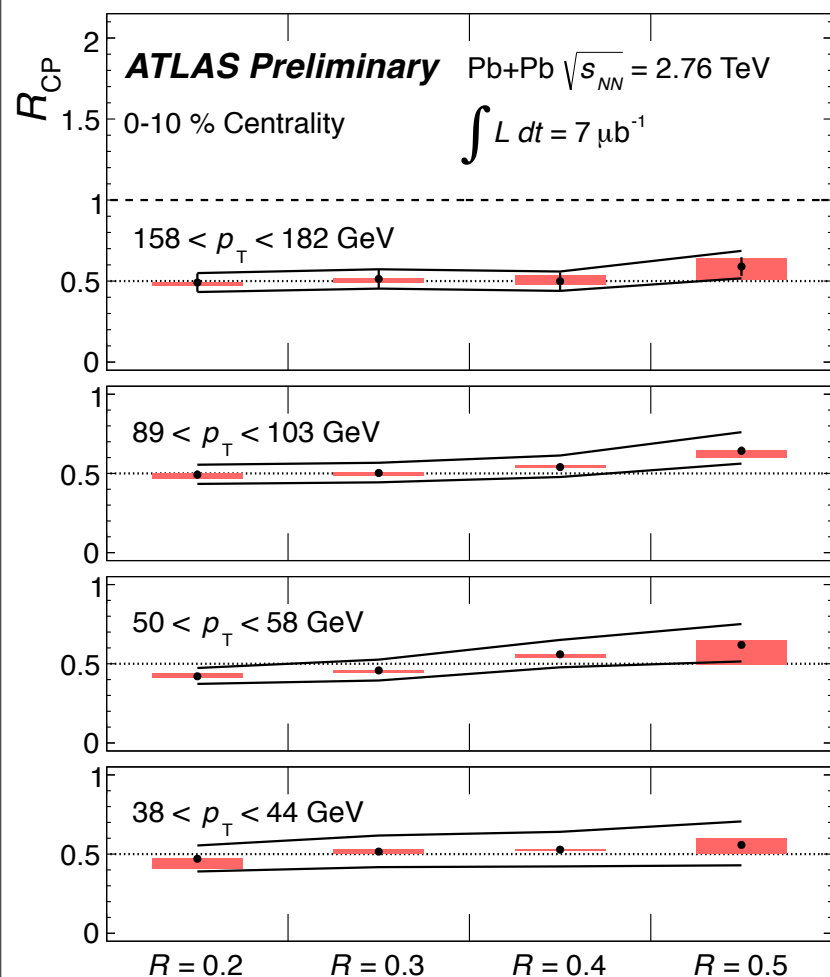
- Systematic errors
  - **Correlated**: JES, JER, efficiency, R_{coll}
  - **Partially correlated**: regularization, x_{ini}, efficiency
- Error bars: sqrt of diagonal elements of cov matrix
- No significance to horizontal width of error bars

Results: R_{CP} vs R
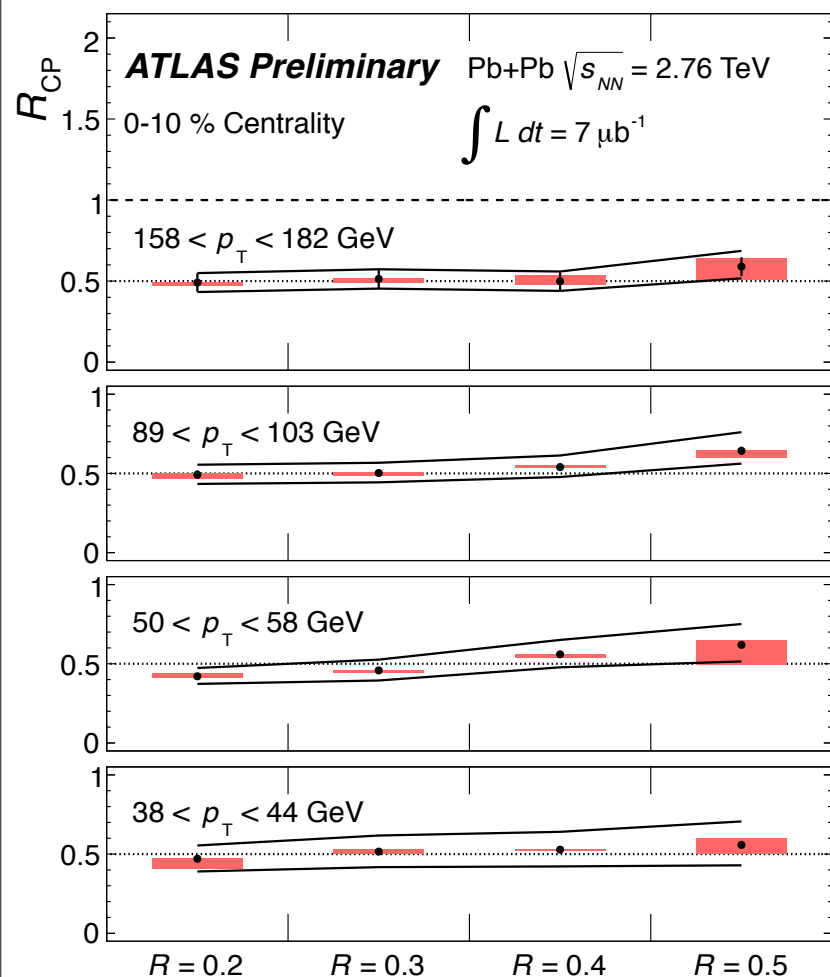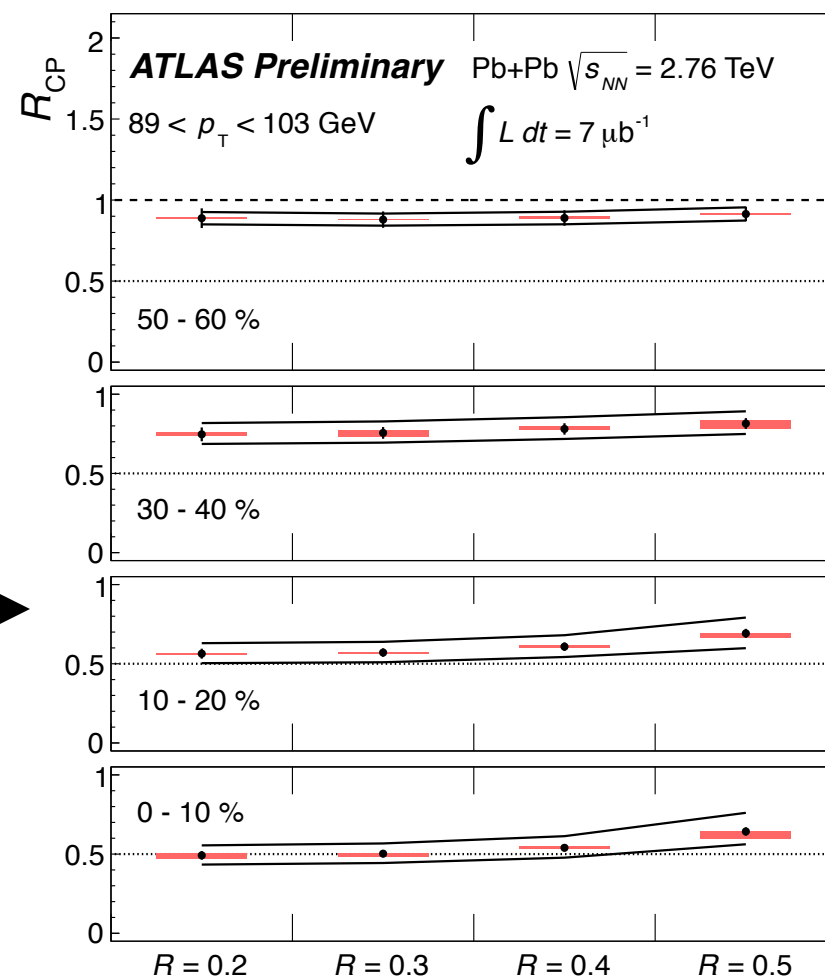
Quantitative Statement of *R* Dependence
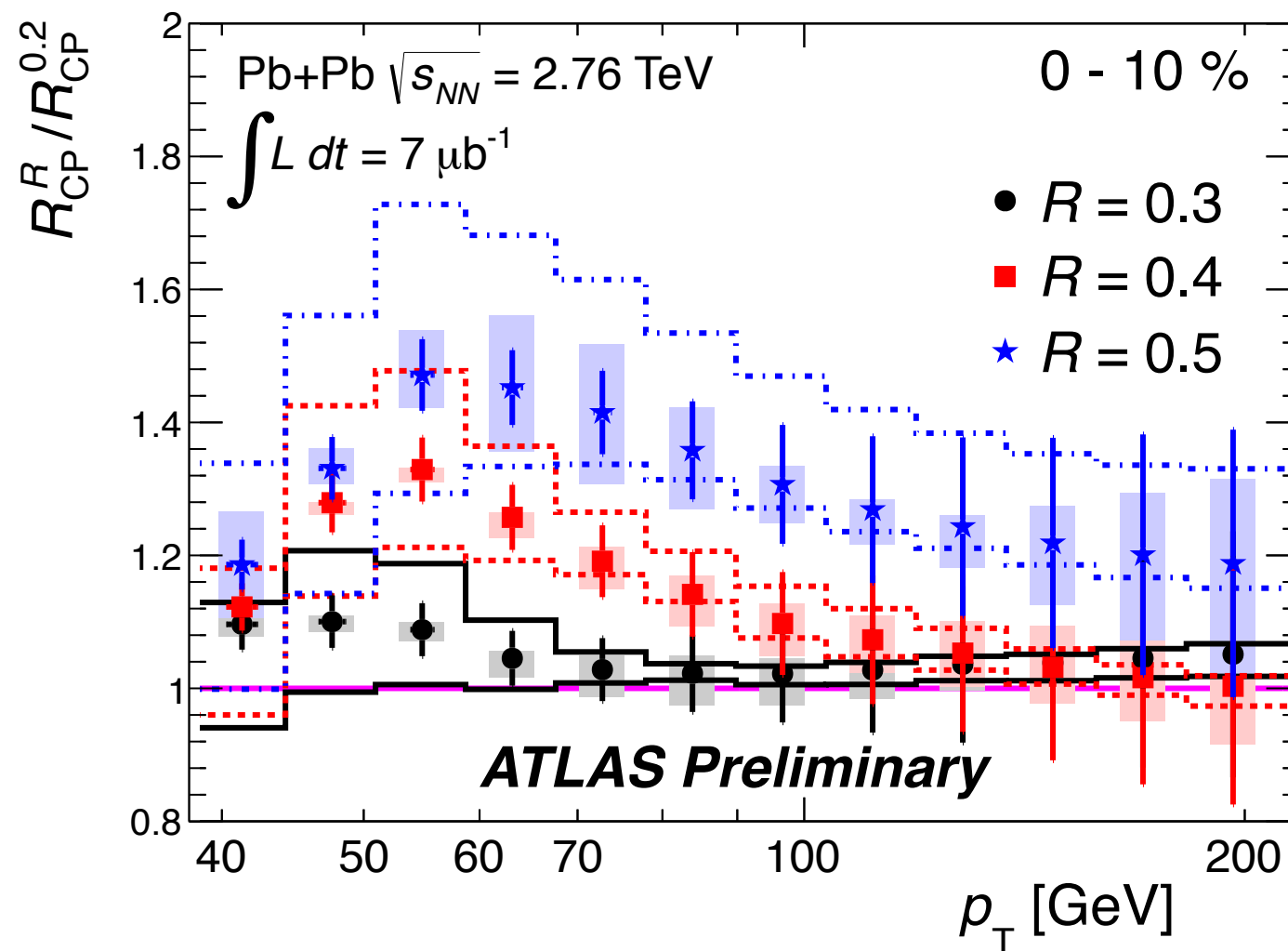
Measuring Heavy Quarks with Muons

▸ Single inclusive muon spectrum dominated by semi-leptonic decay of heavy quarks at intermediate p_T

▸ Measurements presented here: $4 < p_T < 14$ GeV, $|\eta| < 1.05$

▸ Match tracks from inner detector (ID) and muon spectrometer (MS)

▸ Background to prompt muon signal

- π/K decays in flight

- muons produced in hadronic showers in calorimeter

- fakes

▸ Use discriminant variables which have different distributions for signal and background and separate statistically

Composite Distribution

$$C = \left| \frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}} \right| + rS$$

Composite of two discriminants
r=0.07 chosen for optimal separation

Composite Distribution

$$\frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} = \frac{p_{\text{ID}} - p_{\text{MS}} - \Delta p_{\text{calo}}(p, \eta, \phi)}{p_{\text{ID}}}$$

Fraction of momentum lost in detector compared to expectation

$$C = \left| \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} \right| + rS$$

Composite of two discriminants
r=0.07 chosen for optimal separation

$S \equiv$ Scattering significance
Measure of angular deflection compared to expectation from multiple scattering
Identifies muons from decay in flight

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Composite Distribution
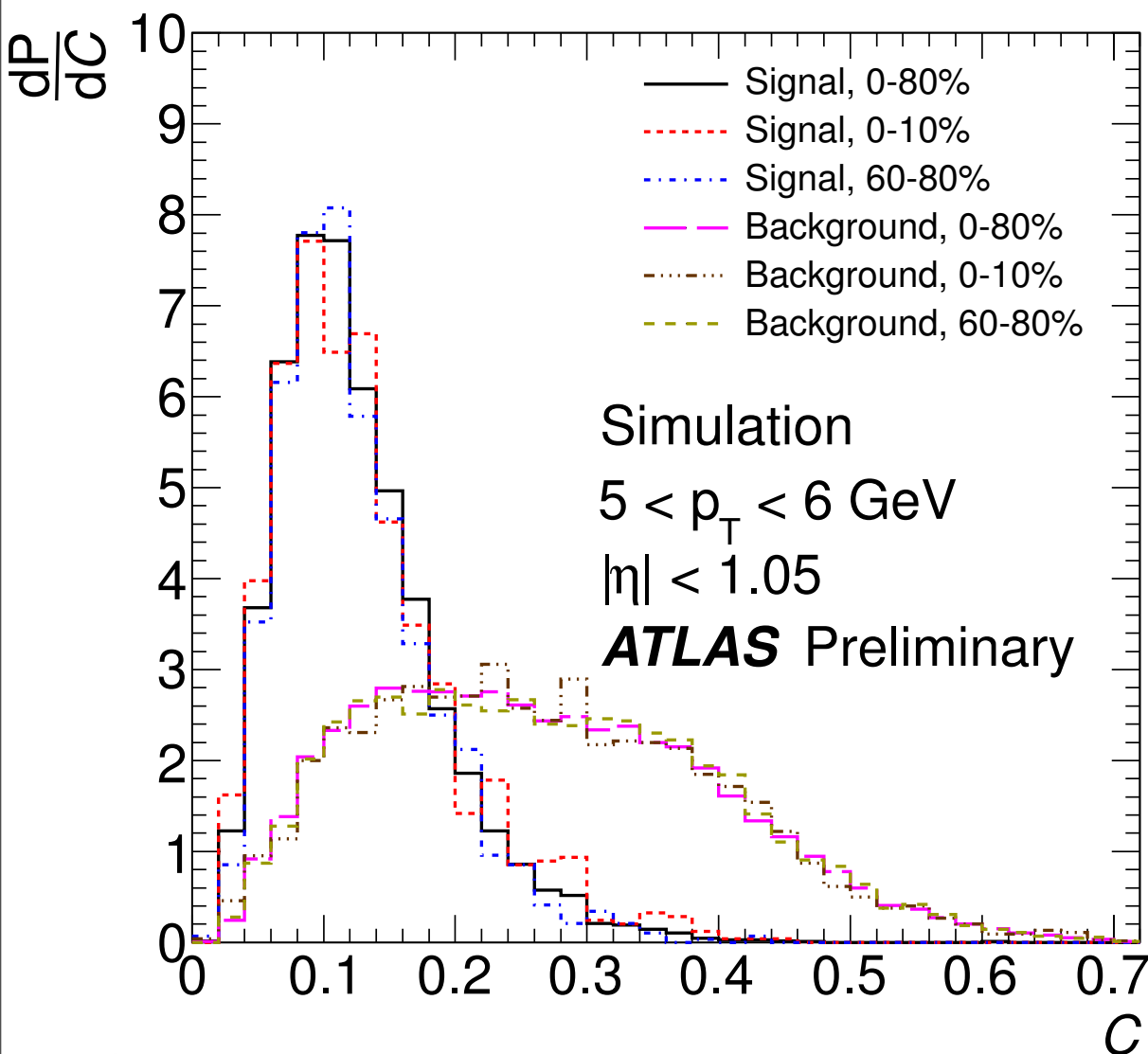
$$C = \left| \frac{\Delta p_{\text{loss}}}{p_{\text{ID}}} \right| + rS$$

‣ Shapes independent of centrality

Template Fitting
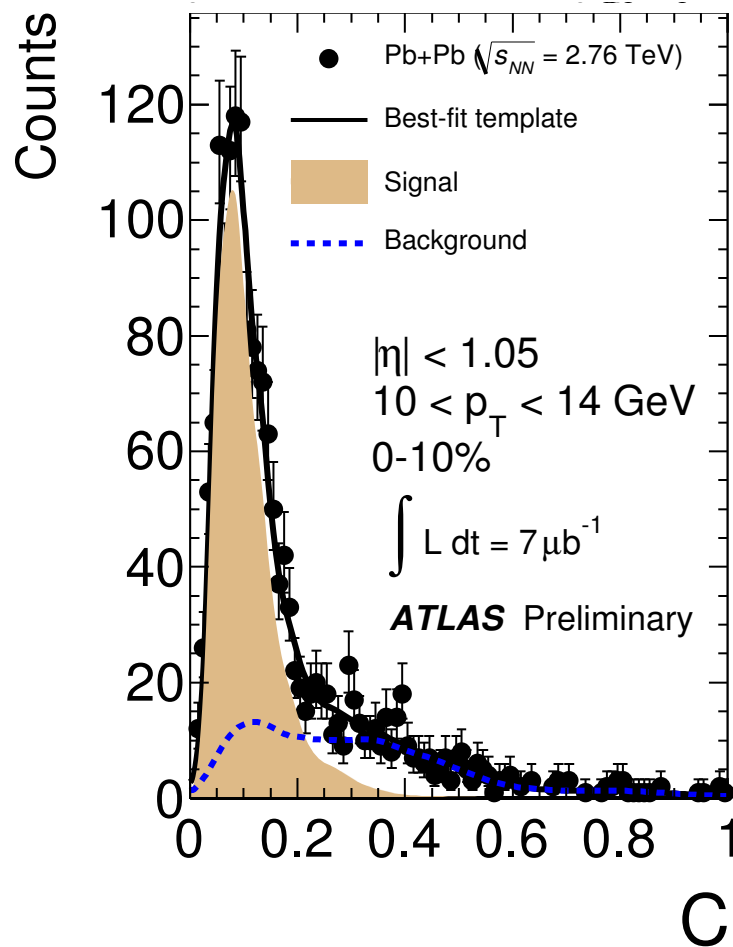
▸ Fit composite distribution in data with template

$$\frac{dP}{dC} = f_{\mathrm{s}} \left.\frac{dP}{dC}\right|_{\mathrm{S}} + (1 - f_{\mathrm{s}}) \left.\frac{dP}{dC}\right|_{\mathrm{B}}$$

▸ Extract signal fraction

▸ Build into fitting procedure ability to account for:

- MC inaccuracies in describing shape of dP/dC
- Momentum resolution effects
- Included in systematic error

Signal Fractions
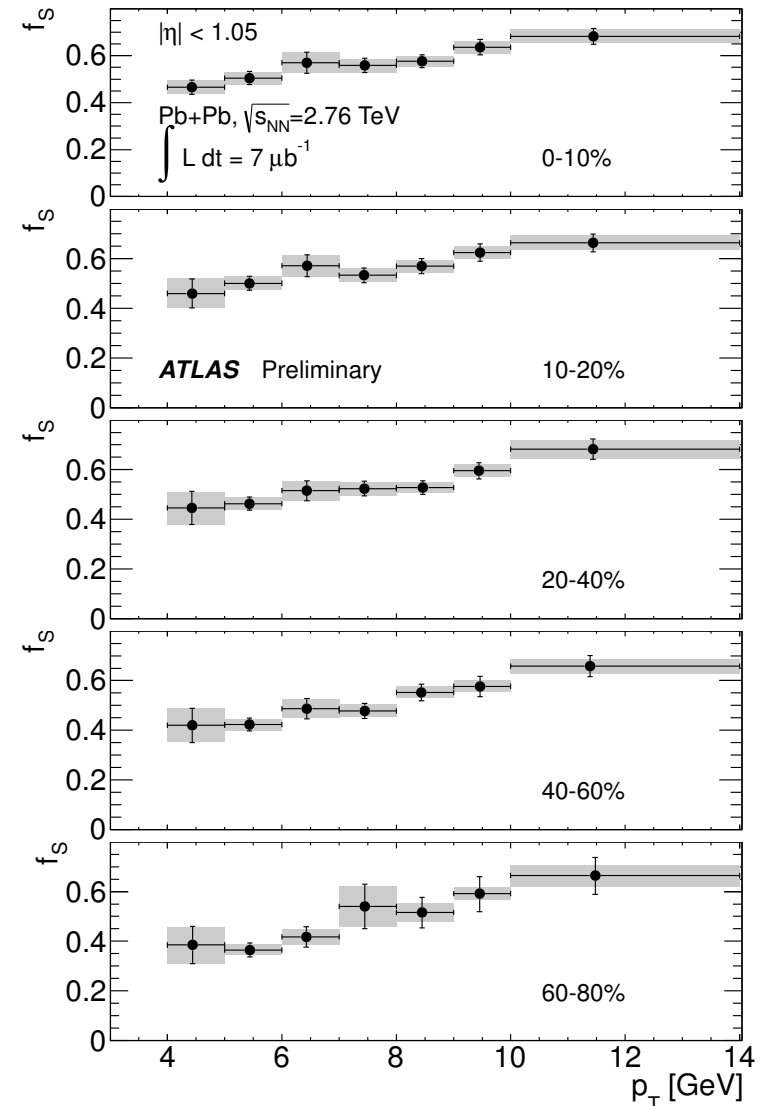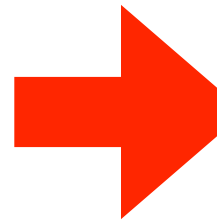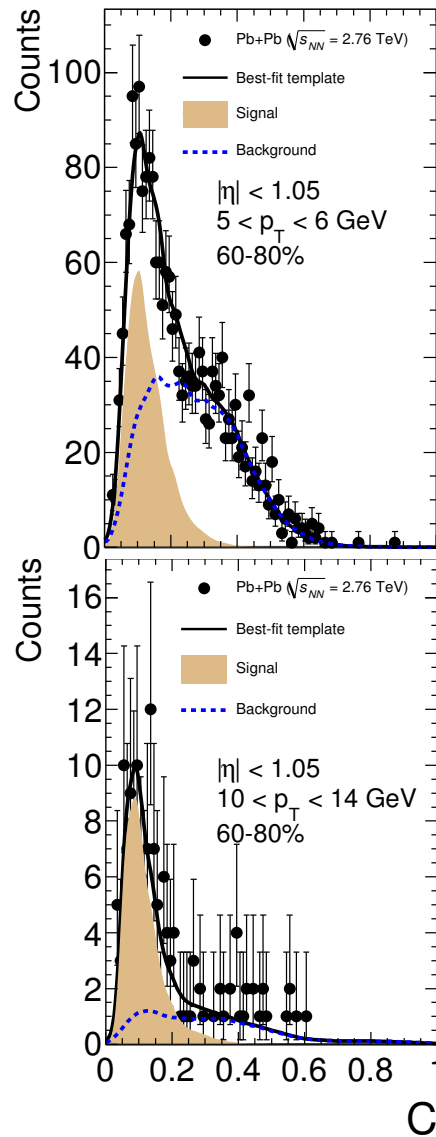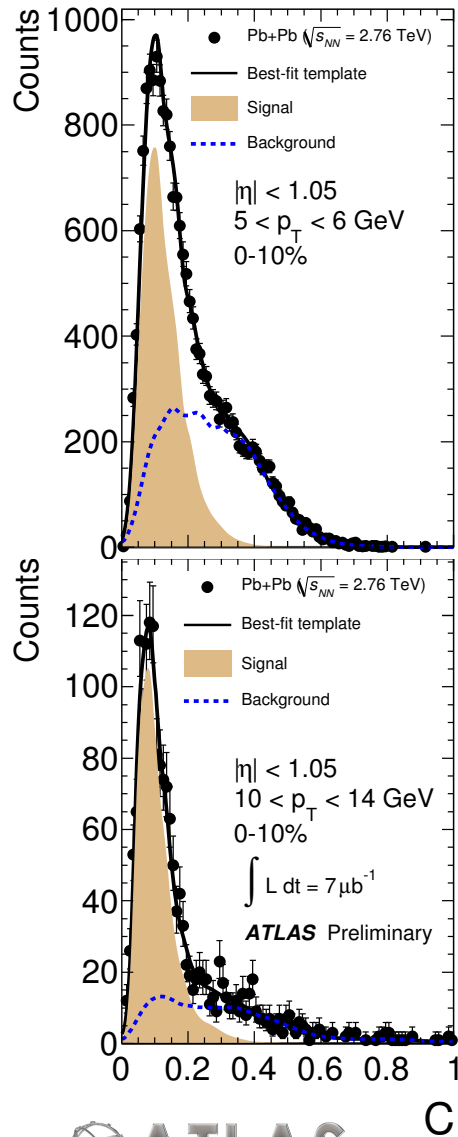
Invariant Yield: Prompt Muons
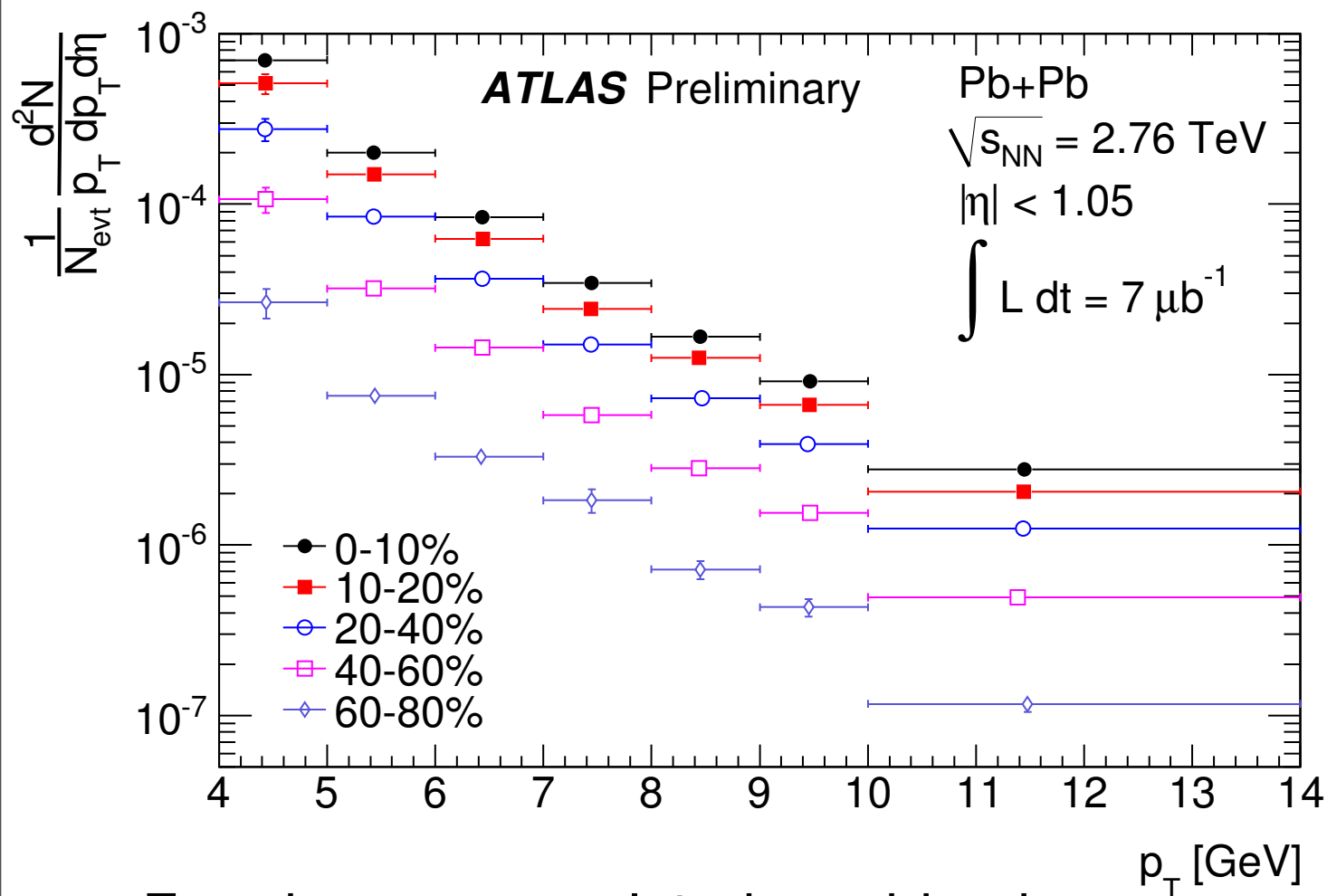
- Use signal fraction to extract spectrum

- Muon reconstruction efficiency correction applied

Error bars: uncorrelated combined statistical+systematic

Muon R_{CP} vs p_T

- Generally flat with p_T however statistical fluctuation in peripheral bin makes trend difficult to evaluate
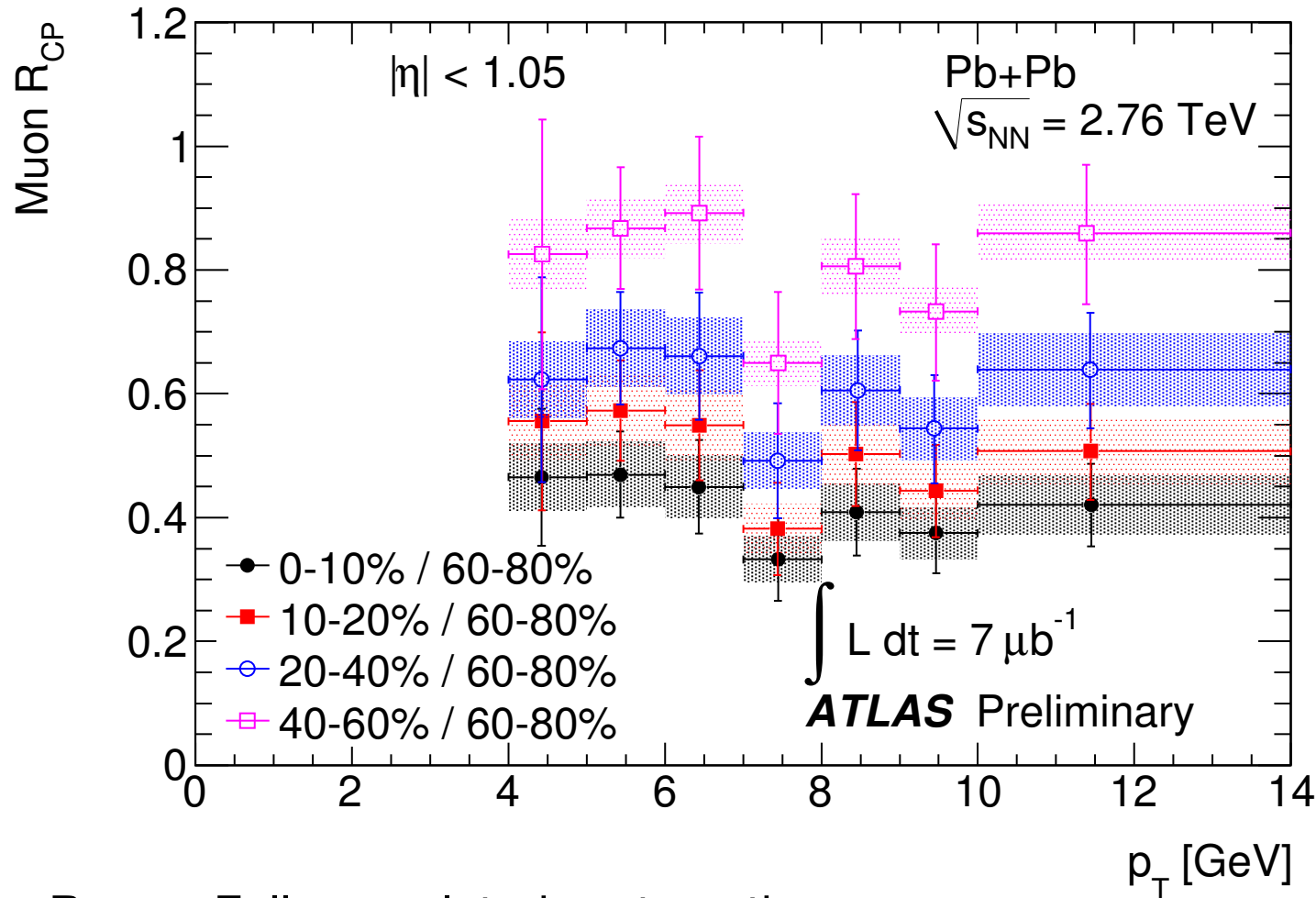
Boxes: Fully correlated systematics
Error bars: uncorrelated combined statistical+systematic

Muon R_{PC} vs p_T

- Can evaluate R_{PC} instead

- Easier to see very flat p_T dependence
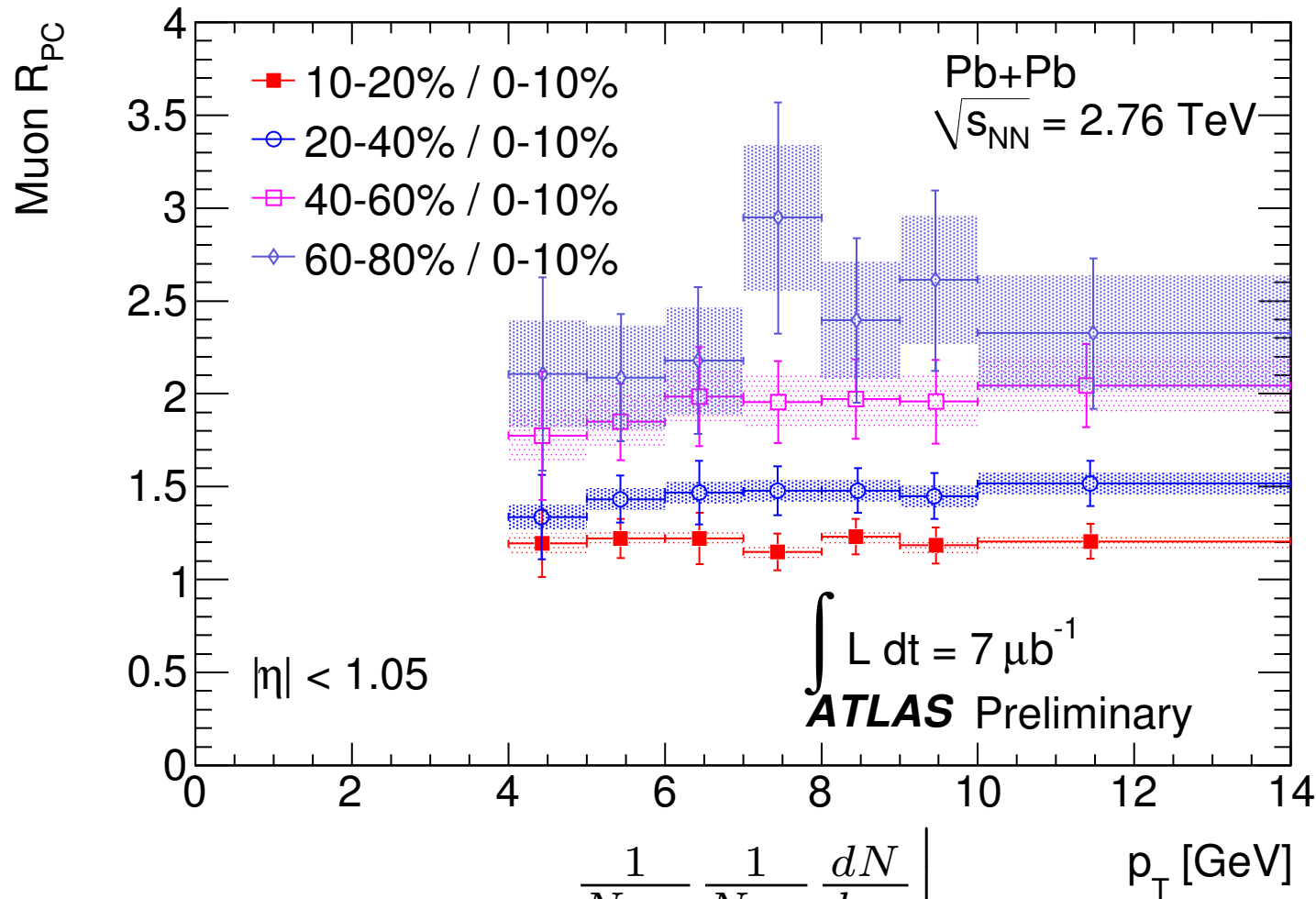
$$R_{PC} = \frac{\left.\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}\right|_{periph}}{\left.\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}\right|_{0-10}}$$

Muon R_{CP} vs N_{part}
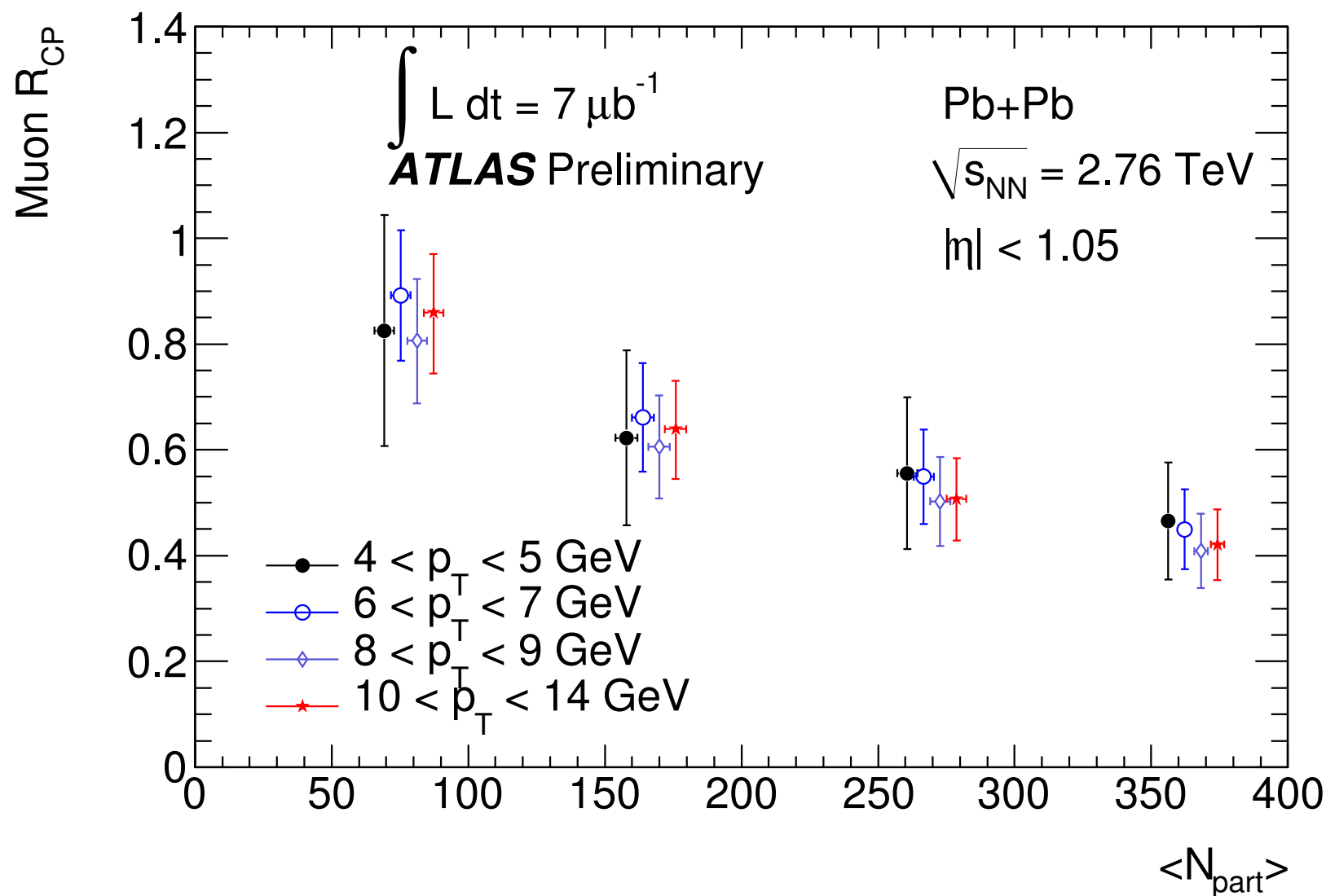
Conclusions: Inclusive Jet Measurements

‣ In central collisions, jets suppressed by factor of two relative to peripheral

- Flat in p_T, RCP~0.5 for $38 < p_T < 210$ GeV

- Roughly same as single particle R_{AA} for $p_T > 30$ GeV

‣ R dependence

- Effect significant beyond systematic errors

- More R dependence at lower p_T

  ✦ Qualitatively consistent w/ existing calculation (Vitev et al.)

‣ Centrality/N_{part} dependence

- Suppression turns on differently for high and low p_T jets

Conclusions: Heavy Flavor

‣ Heavy flavor suppression flat in p_T, plateau at 0.45

‣ Relative to single hadron R_{CP} heavy flavor shows:

- Less suppression by factor of ~2 at comparable p_T

- Less variation with p_T

  ✦ Different than at RHIC where heavy flavor and single hadron R_{AA} had same magnitude and p_T dependence

‣ Centrality (N_{part}) dependence

- Smooth decrease from peripheral to central collisions

- N_{part} dependence similar for all p_T

For the Future

- Jet fragmentation measurement presented at QM2011

$$z = \frac{p_T}{E_T^{jet}} \cos \Delta R$$

Plot labels: $1/N_{jets}\ dN/dz$ (y-axis), z (x-axis)

$E_{T,jet} > 100$ GeV
○ R = 0.4, 0-10%, $p_T > 2$ GeV
● R = 0.4, 40-80%, $p_T > 2$ GeV

R=0.4

ATLAS Preliminary
Pb+Pb$\sqrt{s_{NN}}$= 2.76 TeV
L_{int}=7 μb^{-1}
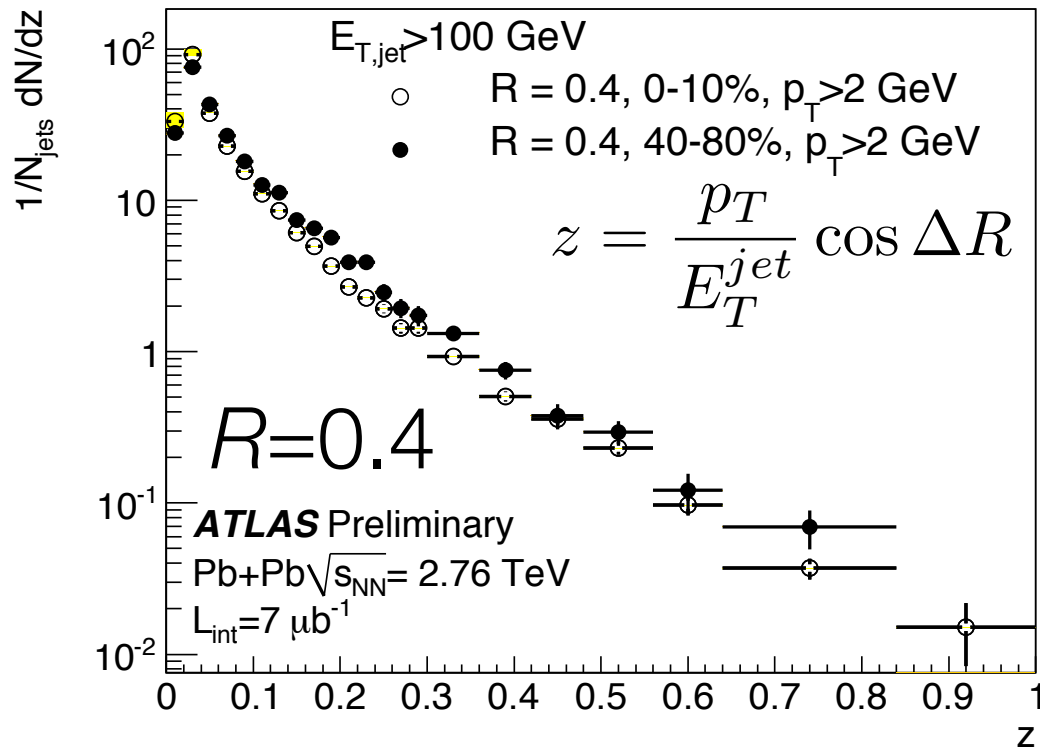
- Working to update this measurement using 2011 data

- Also preparing update to asymmetry using this larger data sample

Additional Slides

Detecting Particles

ATLAS Calorimeter

$|\eta| < 1.0$

Tile barrel

Tile extended barrel $\quad 0.8 < |\eta| < 1.7$

$1.5 < |\eta| < 3.2$

LAr hadronic
end-cap (HEC)

LAr electromagnetic
end-cap (EMEC)

$1.5 < |\eta| < 3.2$

LAr electromagnetic
barrel
$|\eta| < 1.5$

LAr forward (FCal)

$3.2 < |\eta| < 4.9$
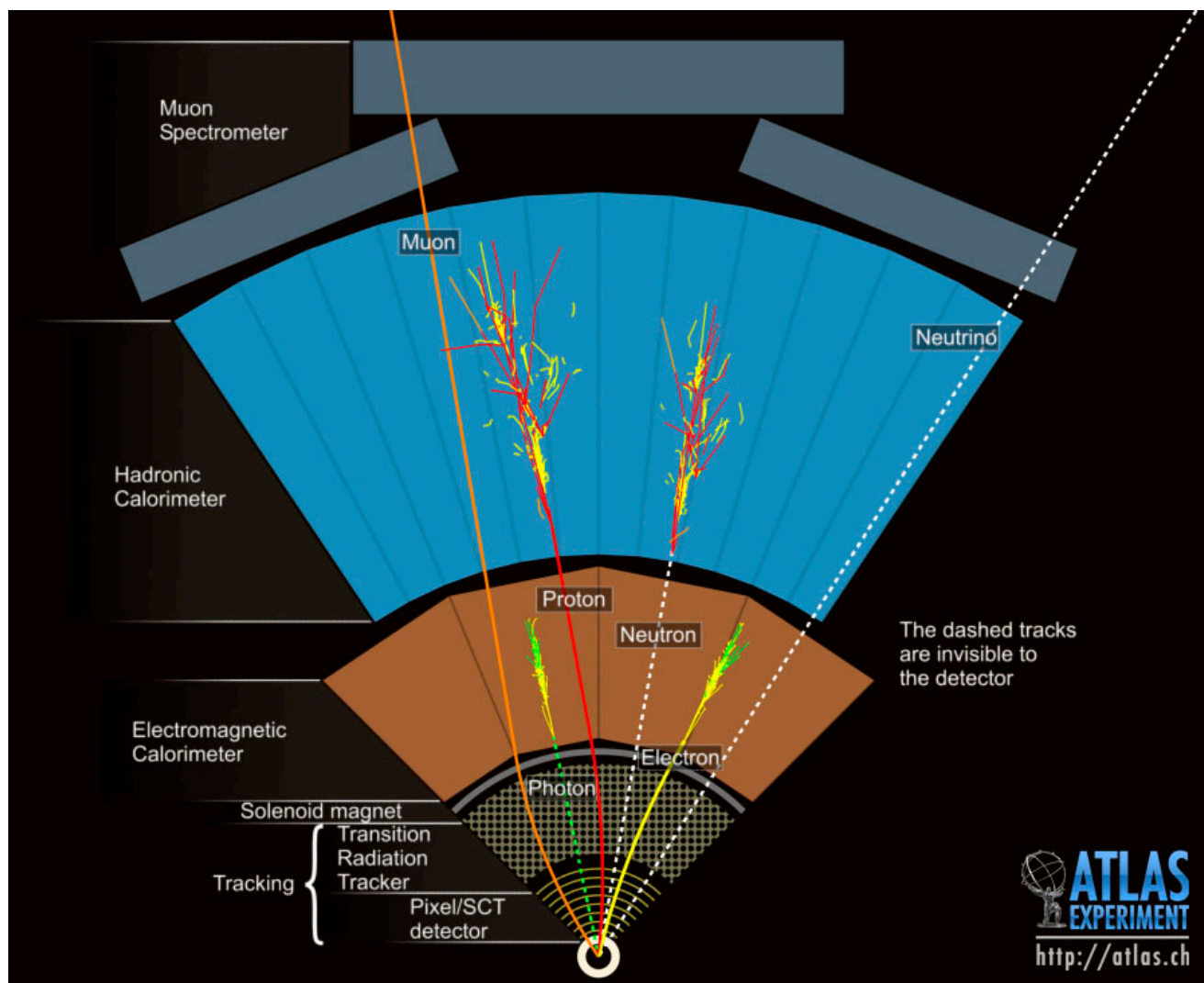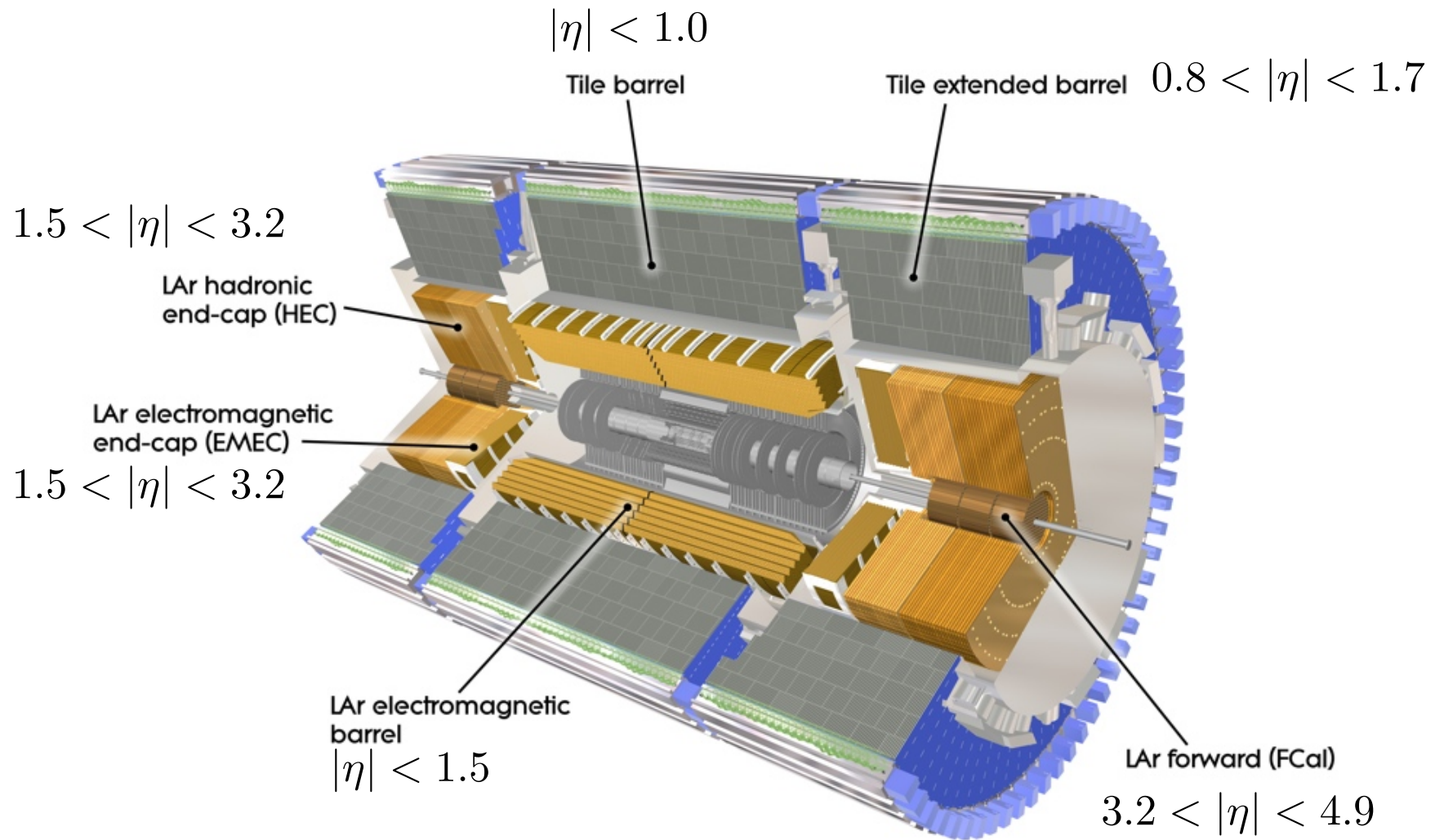
ATLAS Muon Spectrometer
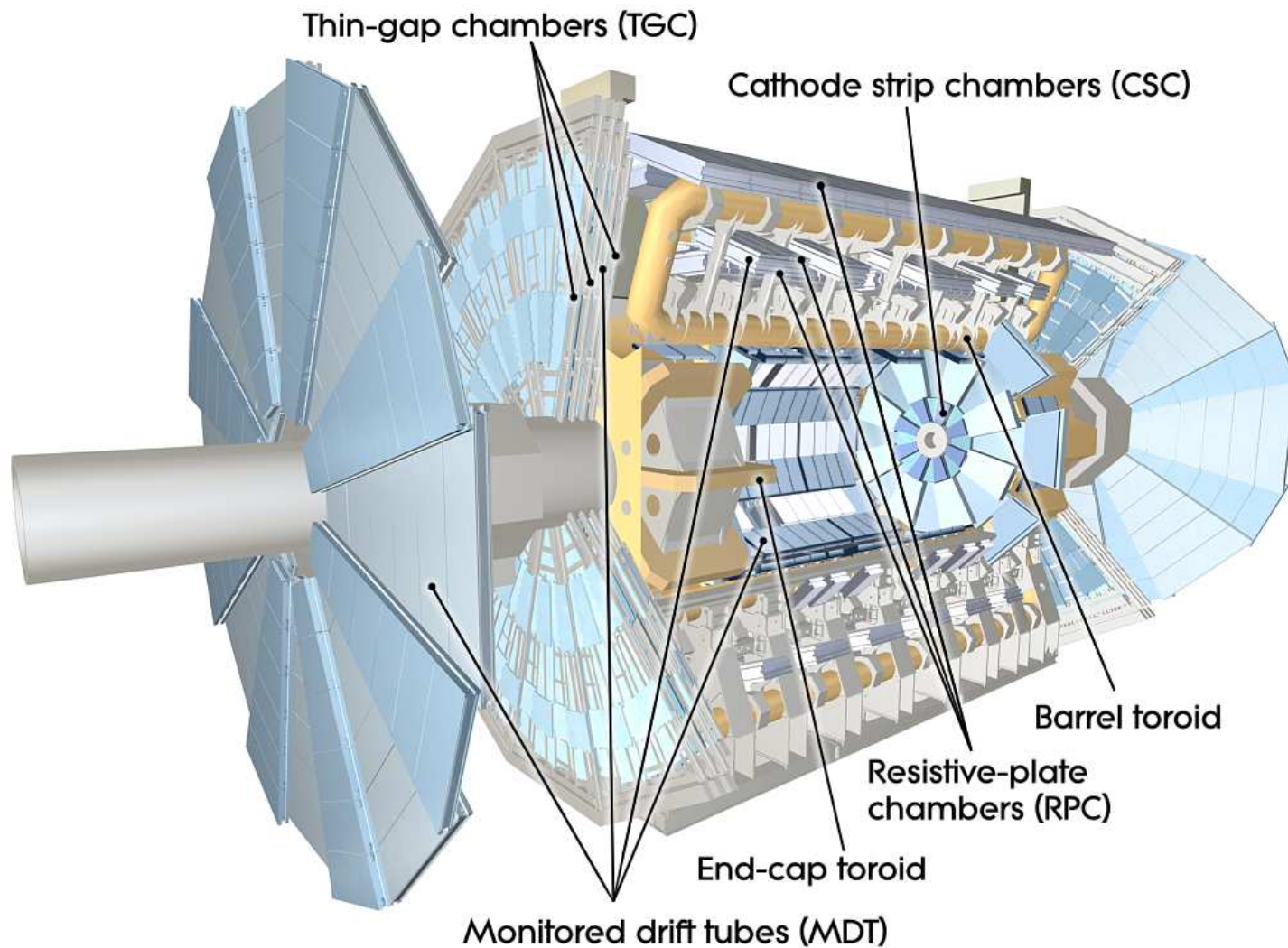
Event Selection

- 2010 Pb Pb 2.76 TeV data

- All good runs/lumi blocks with solenoidal field on

- Minimum bias event selection:

  - ZDC coincidence trigger

    - `L1_ZDC_AND` or `L1_ZCD_A_C`

  - MBTS timing: $\Delta t_{\mathrm{MBTS}} < 3\,\mathrm{ns}$

  - Good reconstructed vertex

- After selection: 51 million events, $\int \mathcal{L}\,dt = 7\mu b^{-1}$

- Event selection cuts estimated to be 2% inefficient

  - Included in centrality determination

- Solenoidal field off data not used $\sim 1\mu\mathrm{b}^{-1}$
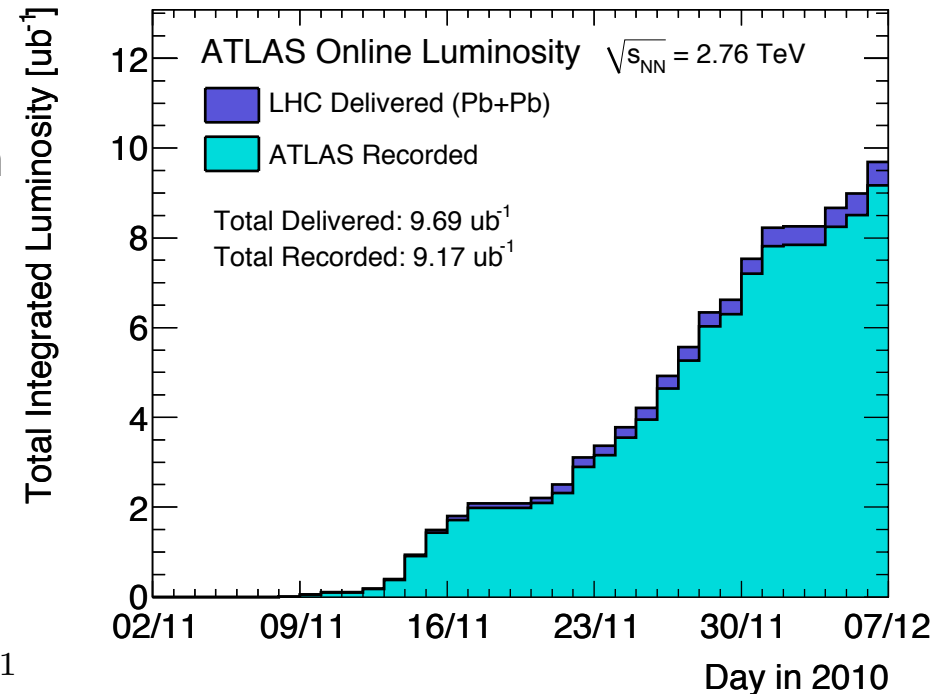
Centrality

- Determined from FCal E_T distribution, which is well correlated with total event activity
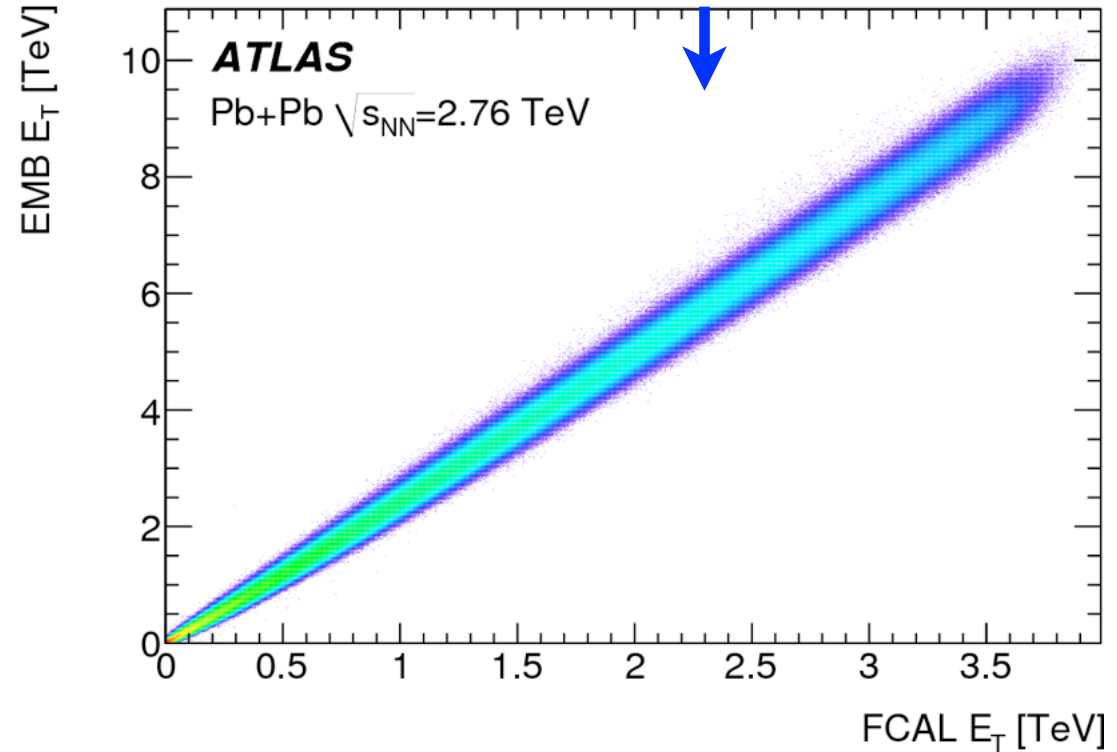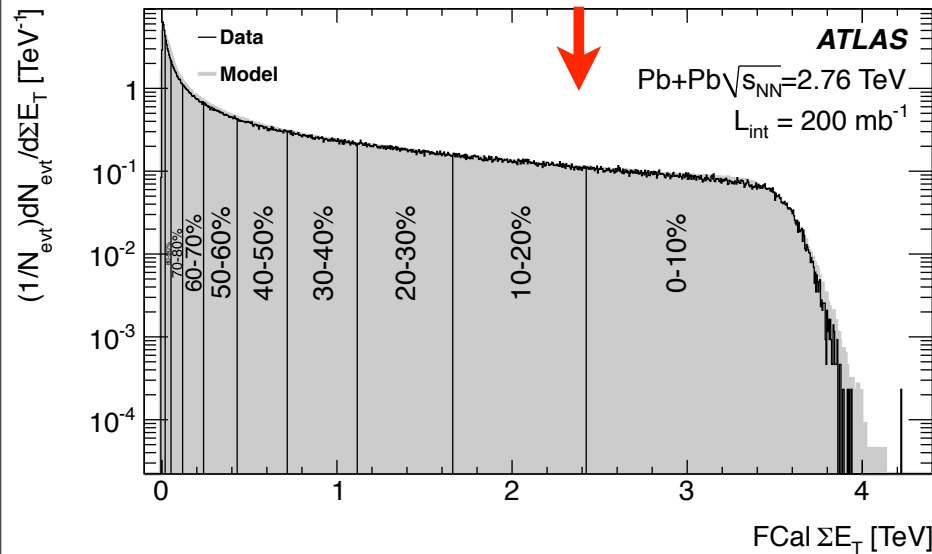
- Standard centrality definitions:

  - "central" : 0-60% divided into 6 10%

  - "peripheral" 60-80%

- N_{coll}, N_{part} and uncertainties from Glauber

  - R$_{CP}$ uses ratio: $R_{coll}^{cent} = \dfrac{\langle N_{coll}^{cent} \rangle}{\langle N_{coll}^{60-80} \rangle}$

Centrality

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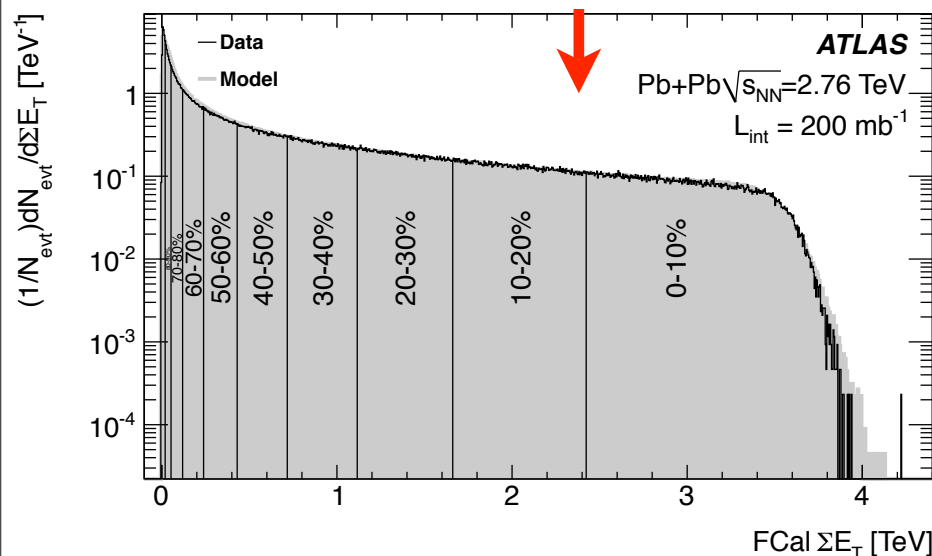
Centrality [%]		$\Sigma E_T^{\mathrm{FCal}}$[TeV]		N_{coll}		$R_{\mathrm{coll}}^{\mathrm{cent}}$		N_{part}	
low	high	low	high	$\langle N_{\mathrm{coll}} \rangle$	δN_{coll}	$R_{\mathrm{coll}}^{\mathrm{cent}}$	$\delta R_{\mathrm{coll}}^{\mathrm{cent}}$ [%]	$\langle N_{\mathrm{part}} \rangle$	δN_{part}
0	10	2.423	∞	1500.63	114.8	56.7	11.4	356.2	2.5
10	20	1.661	2.423	923.29	68.0	34.9	10.5	261.4	3.6
20	30	1.116	1.661	559.02	40.5	21.1	9.4	186.7	3.8
30	40	0.716	1.116	322.26	23.9	12.2	7.9	129.3	3.8
40	50	0.430	0.716	173.11	14.1	6.5	6.1	85.6	3.6
50	60	0.239	0.430	85.07	8.4	3.2	3.8	53.0	3.1
60	80	0.053	0.239	26.47	3.5	–	–	22.6	2.1

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  - "central" : 0-60% divided into 6 10% bins
  - "peripheral" 60-80%
- N_{coll}, N_{part} and uncertainties from Glauber
  - R_{CP} uses ratio: $R_{\mathrm{coll}}^{\mathrm{cent}} = \dfrac{\langle N_{\mathrm{coll}}^{\mathrm{cent}} \rangle}{\langle N_{\mathrm{coll}}^{60-80} \rangle}$

- Sources of uncertainty
  - Woods-Saxon parameters
  - Inefficiency in event selection
  - nucleon-nucleon cross section $\sigma_{\mathrm{inel}}^{NN}$

Jets In Heavy Ion Collisions

- Apply IRC safe jet definition to measured E_T distribution in calorimeter

- In addition to jet signal, also have contribution from underlying event (UE)

- **Define** jet measurement as energy **correlated** with single QCD hard scattering, need to separate from **uncorrelated** UE contribution

$$\frac{dE_T^{\text{total}}}{d\eta d\phi} = \frac{dE_T^{\text{UE}}}{d\eta d\phi} + \frac{dE_T^{\text{jet}}}{d\eta d\phi}$$

- Construct estimate of UE background, subtract and run jet finding

  - Average depends strongly on centrality, must determine event-by-event

  - Must be modulated to include flow effects $1 + 2v_2 \cos\left[2\left(\phi - \Psi_2\right)\right]$

- Jets must be excluded from the estimate of the background

Jet Reconstruction: First Step

- Calculate v_2

- Run anti-k_t with R=0.4 on tracks $p_T > 4$ GeV

- Run anti-k_t with R=0.2 on unsubtracted E_T distribution

- Define initial seeds as all jets with:

  - D=max(tower E_T)/mean(tower E_T) > 4

  - At least one tower $E_T > 3$ GeV

- Exclude from average background all cells within jet seeds

- Define a background, modulate by v_2, to build subtracted jets

- Apply jet energy scale calibration to subtracted jets

Jet Reconstruction

- Define average background excluding cells $\Delta R < 0.4$ from jet

- Calculate event plane angle from FCal

$$\Psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{\sum\limits_{k} w_k E_{\mathrm{T}k}\sin\left(2\phi_k\right)}{\sum\limits_{k} w_k E_{\mathrm{T}k}\cos\left(2\phi_k\right)}\right)$$

- Calculate v_2 per sampling layer:

$$v_{2i} = \frac{\sum\limits_{j\in i} E_{\mathrm{T}j}\cos\left[2\left(\phi_j - \Psi_2\right)\right]}{\sum\limits_{j\in i} E_{\mathrm{T}j}}$$

  - Average over η excluding bins within 0.4 of seeds

- Also reconstruct **track jets**, run anti-k_t R=0.4 on particles $p_\mathrm{T} > 4$ GeV
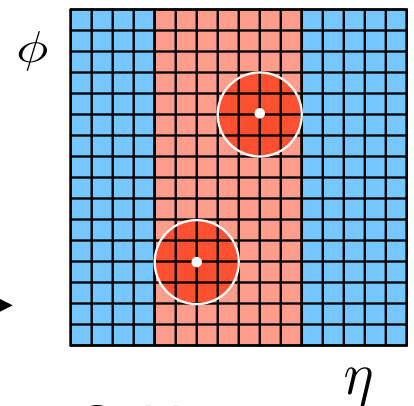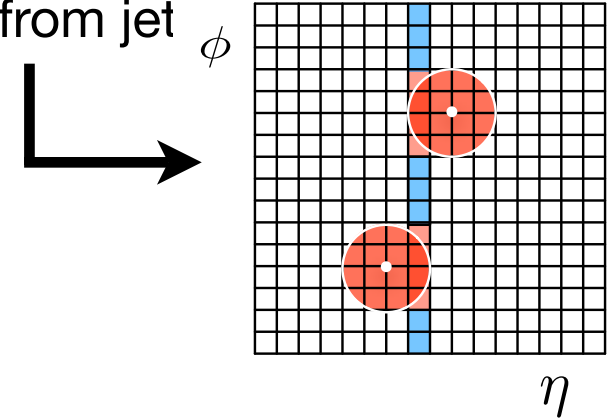
Jet Reconstruction: Second Step

- Use output of previous step to define new seeds:

  - Jets with E_T > 25 GeV

  - Track jets p_T > 10 GeV

- Define new background excluding cells ΔR < 0.4 from jets

- Define new v_2:

  - Calculate v_2 in each η bin (0.1)

  - Average over η excluding bins within 0.4 of seeds

- Run anti-k_t R=0.2, 0.3, 0.4 and 0.5 on subtracted background

- Calibrate jet energy scale
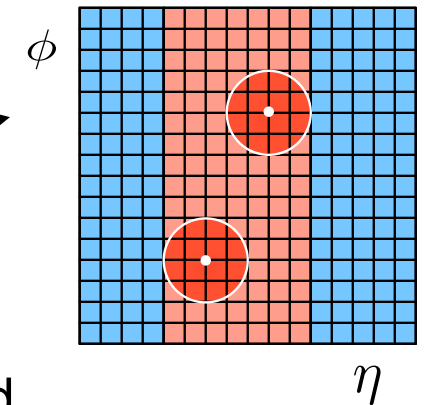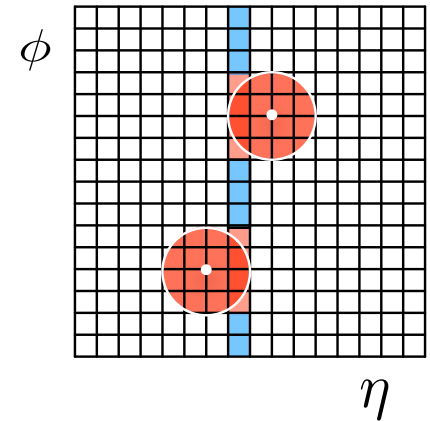
Monte Carlo Sample

- Truth jets: run anti-k_t on particles from MC event generators

- Reconstructed jets: apply GEANT detector simulation, reconstruct as in data

- Jet performance studies and corrections derived from three samples

  - HIJING only: used in estimates of fake rate

  - HIJING+PYTHIA: Jet performance, response matrices

    - HIJING events with a PYTHIA jet event embedded per event

    - For each truth jet, find nearest reconstructed jet within $\Delta R < 0.2$

    - If truth jet is near a HIJING jet ($\Delta R < 0.8$, $E_T > 10$ GeV), exclude from sample

  - Data+PYTHIA: Used to validate performance etc.,

- HIJING is v1.38b, quenching off, flow applied using parameterization from data

Analysis Details: Single Inclusive Jets

- UE fluctuations of soft particles can be reconstructed as jets

  - Worse for larger R, contribute up to $p_T \sim 80$ GeV

    - Remove by requiring additional signal consistent with hard particles

    - **Reject fakes** by requiring jet match ($\Delta R < 0.2$):

      - track jet or an EM cluster with $p_T > 7$ GeV

    - Rate for fake jets after rejection estimated to be ~2% at 50 GeV

- For the spectrum analysis require jets to have $|\eta| < 2.1$

  - Measurement performed on range $38 < p_T < 210$ GeV

  - Total number of jets in sample:

R	$p_T > 40$ GeV		$p_T > 100$ GeV	
	0-10%	60-80%	0-10%	60-80%
0.2	112,333	8,068	2,308	162
0.3	287,153	12,629	3,534	222
0.4	543,444	15,964	4,974	277
0.5	710,158	18,573	7,586	307

ATLAS EXPERIMENT

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

JES Validation: Track Jet Matching

- Matching between track jets and calo jets to study calorimetric response in MC and data

- Limits effects of possible medium-modified fragmentation on JES

- All values not shown 0.5%

R	0 - 10 %	10 - 20 %	20 - 30 %
0.2	0.5 %	0.5 %	0.5 %
0.3	1.0 %	0.5 %	0.5 %
0.4	1.5 %	1.0 %	0.5 %
0.5	2.5 %	1.5 %	1.0 %

- JES uncertainty constant above 70 GeV (table)

- Grows linearly, doubling from its nominal value at 30 GeV
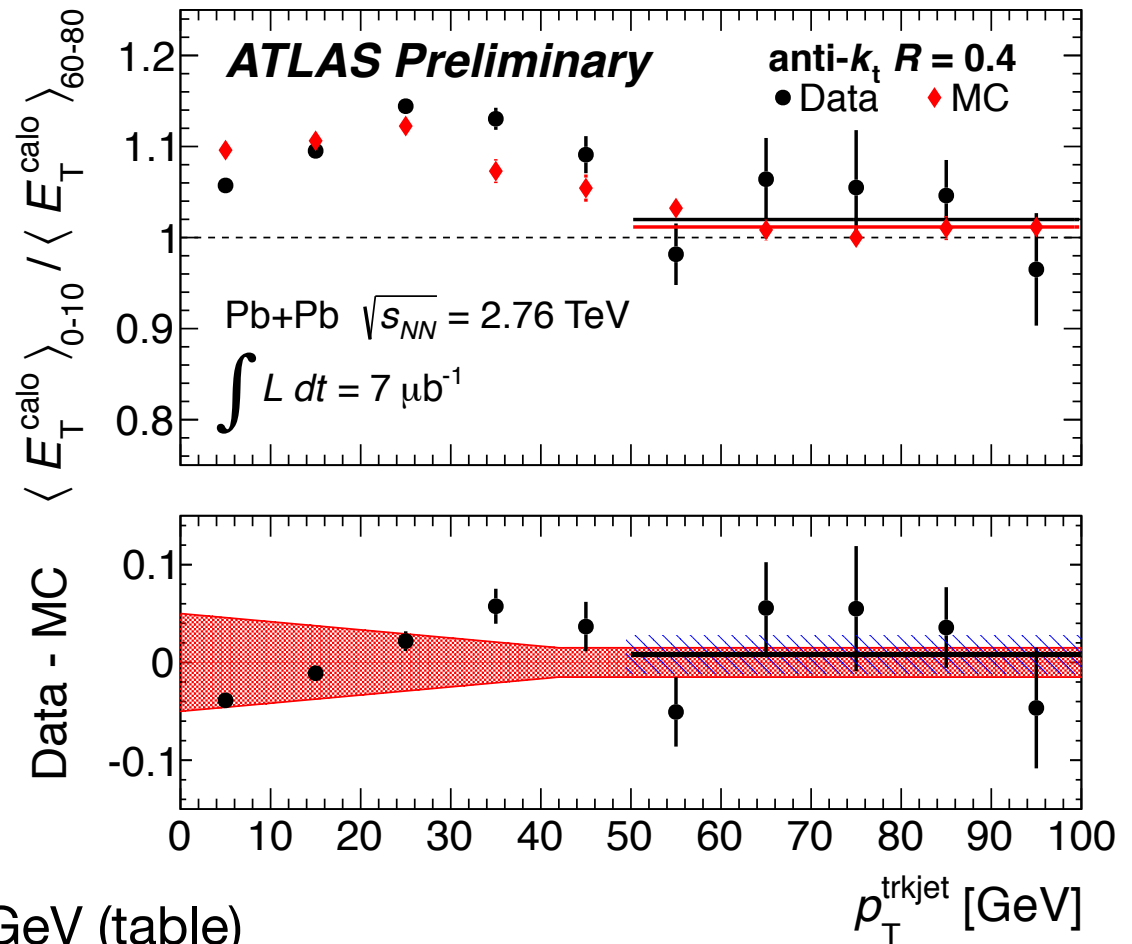
JES Uncertainty

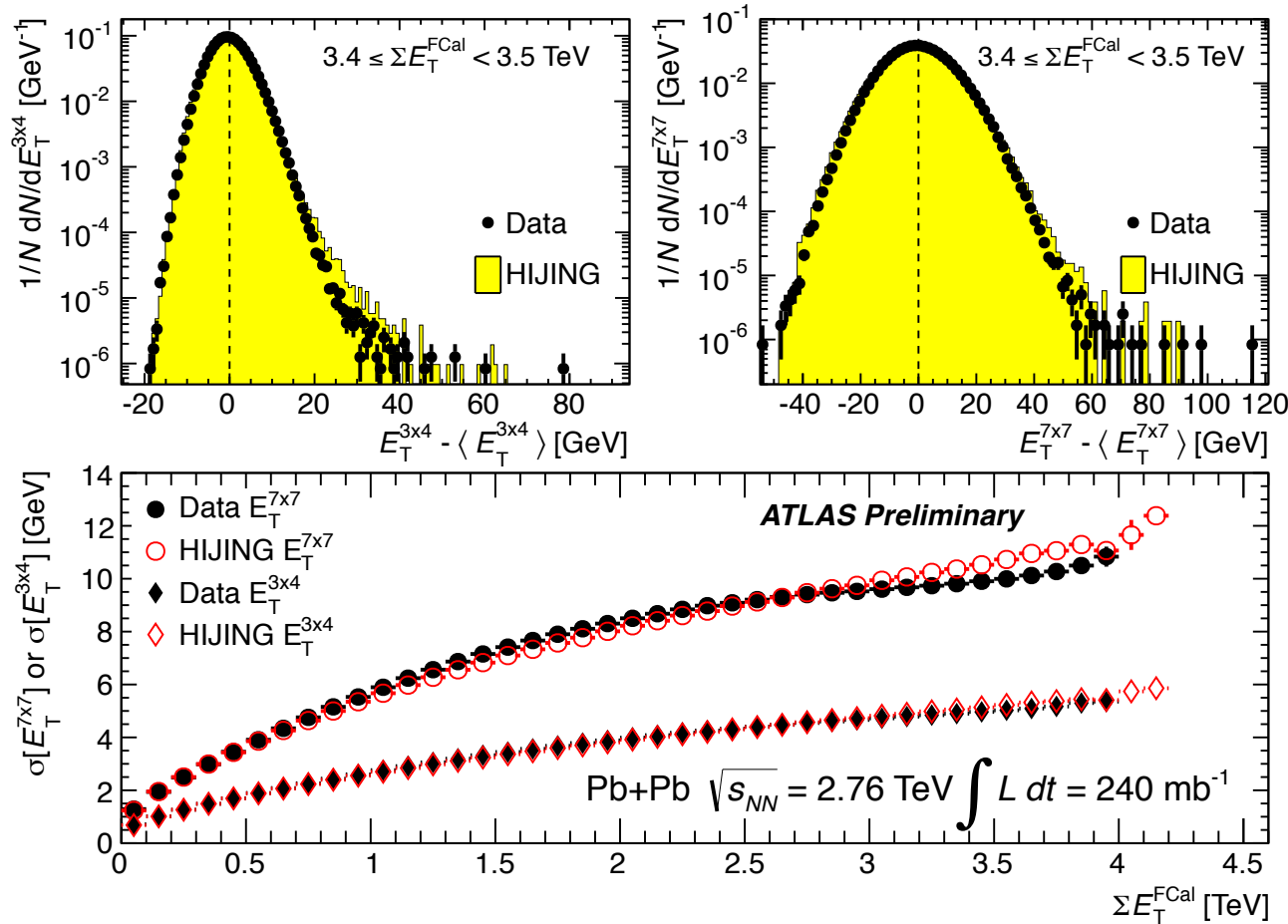| R	0.2	0.3	0.4	0.5
0-10	0.5%	0.5%	0.5%	0.5%
10-20	0.5%	0.5%	0.5%	0.5%
20-30	0.5%	0.5%	0.5%	0.5%
30-40	0.5%	0.5%	0.5%	0.5%
40-50	0.5%	0.5%	0.5%	0.5%
50-60	0.5%	0.5%	0.5%	0.5%

Performance: Jet Energy Resolution

- Extract "σ" through statistical RMS or Gaussian fit

- Low E_T: dominated by UE fluctuations

- High E_T: limited by intrinsic detector resolution

- Described by functional form:

$$\frac{\sigma(\Delta E_T)}{E_T} = \frac{1}{E_T}\left(a\sqrt{E_T} \oplus b \oplus cE_T\right)$$

➡ **a**: sampling fluctuations

➡ **c**: proportional to energy e.g. holes

} centrality independent

➡ **b**: UE fluctuations — centrality dependent

ATLAS Preliminary simulation
anti-k_t $R = 0.4$

— ○ — σ [ΔE_T]/E_T^{truth} + fit, 0-10%
— ◆ — σ [ΔE_T]/E_T^{truth} + fit, 60-80%
● ⟨ ΔE_T ⟩/E_T^{truth}, 0-10%
◇ ⟨ ΔE_T ⟩/E_T^{truth}, 60-80%

● ε, 0-10%
◇ ε, 60-80%
○ ε', 0-10%
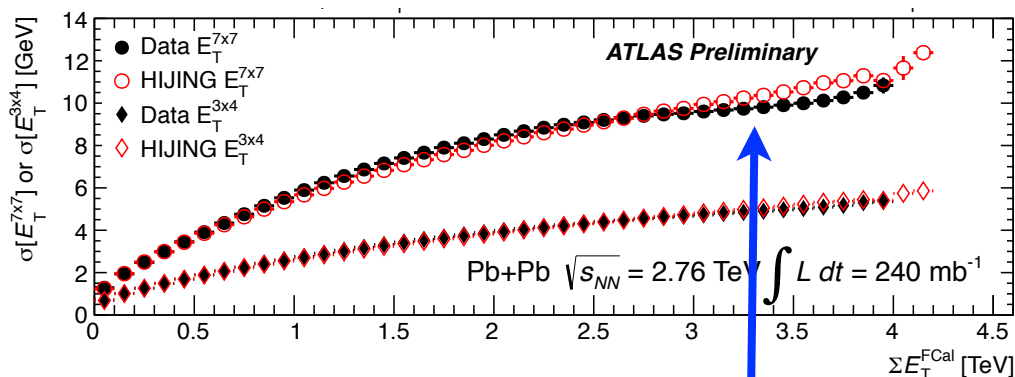◆ ε', 60-80%

E_T^{truth} [GeV]
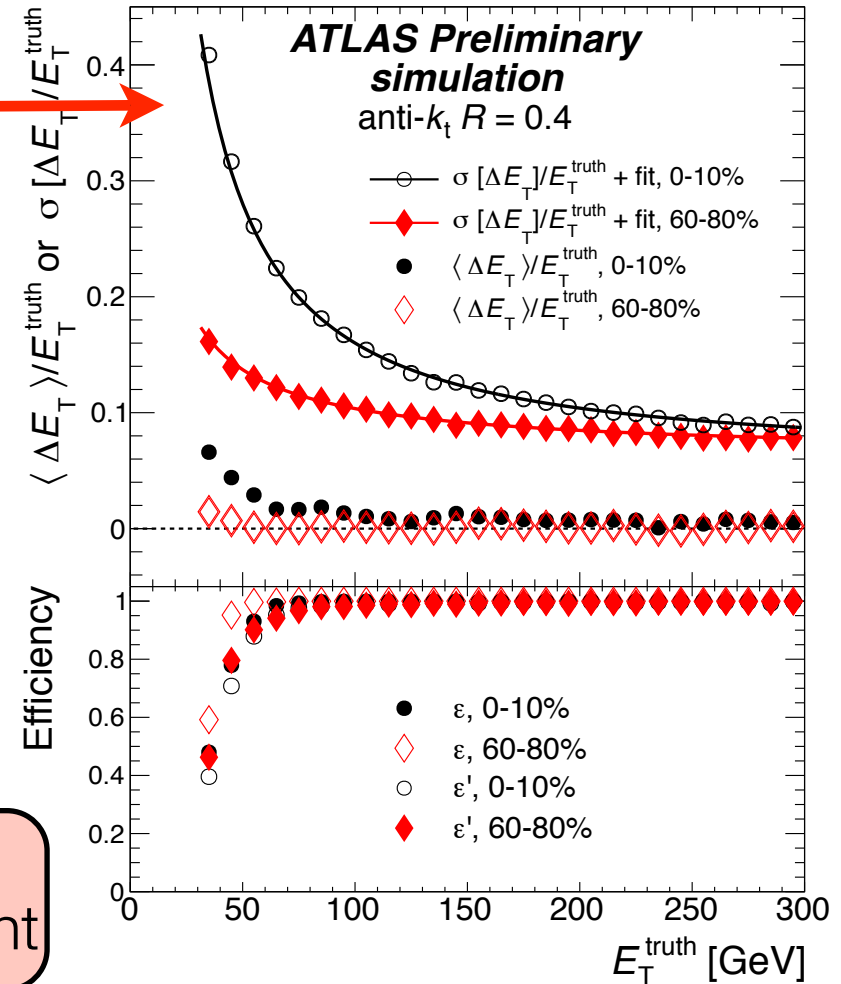
Fluctuations Analysis

- Uncorrelated UE fluctuations underneath jet not subtracted

- Effect on jet spectrum corrected by unfolding
  - MC must provide accurate description of UE fluctuations

- Study distributions of E_T sum in groups of rectangular groups of towers approximately same size as jets (e.g. 7x7 ↔ R=0.4)

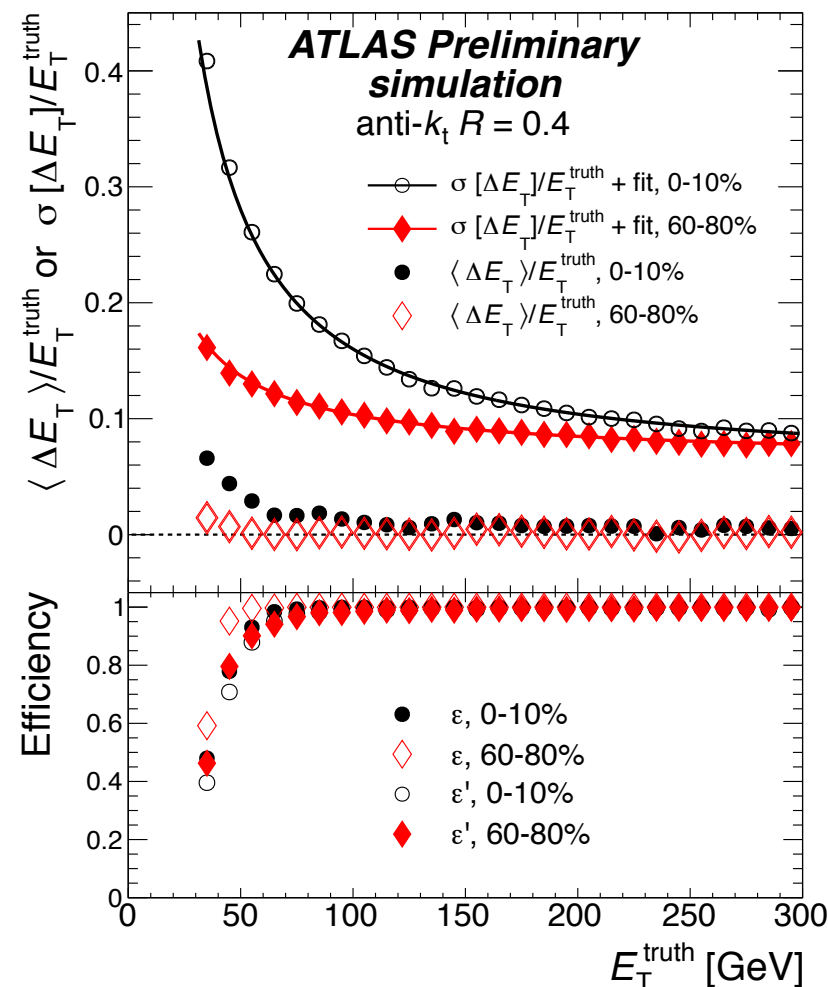# Performance: Jet Energy Resolution

Fixed by fluctuation analysis

$$\frac{\sigma(\Delta E_T)}{E_T} = \frac{1}{E_T}\left(a\sqrt{E_T} \oplus b \oplus cE_T\right)$$

Free parameters in fit

- Fit results give a and c values in agreement for all centralities

- Establishes quantitative relationship between UE fluctuations and ΔE_T fluctuations (JER)

Jet Reconstruction : Corrections

- Jet energy scale calibration factors obtained specifically for HI reconstruction

    - Cell energies are at "EM" scale

    - Response calibrated to EM deposition only

    - Apply multiplicative (p_T, η, R dependent) JES factor

    - Derive using "Numerical Inversion" procedure, MC based

- Energy bias

    - If cells in final jets were not excluded by seeds, some (or all) of the jet's energy will have biased the background

    - After selecting "good" jets (fake rejection) apply correction removing any biases these jets may have on background
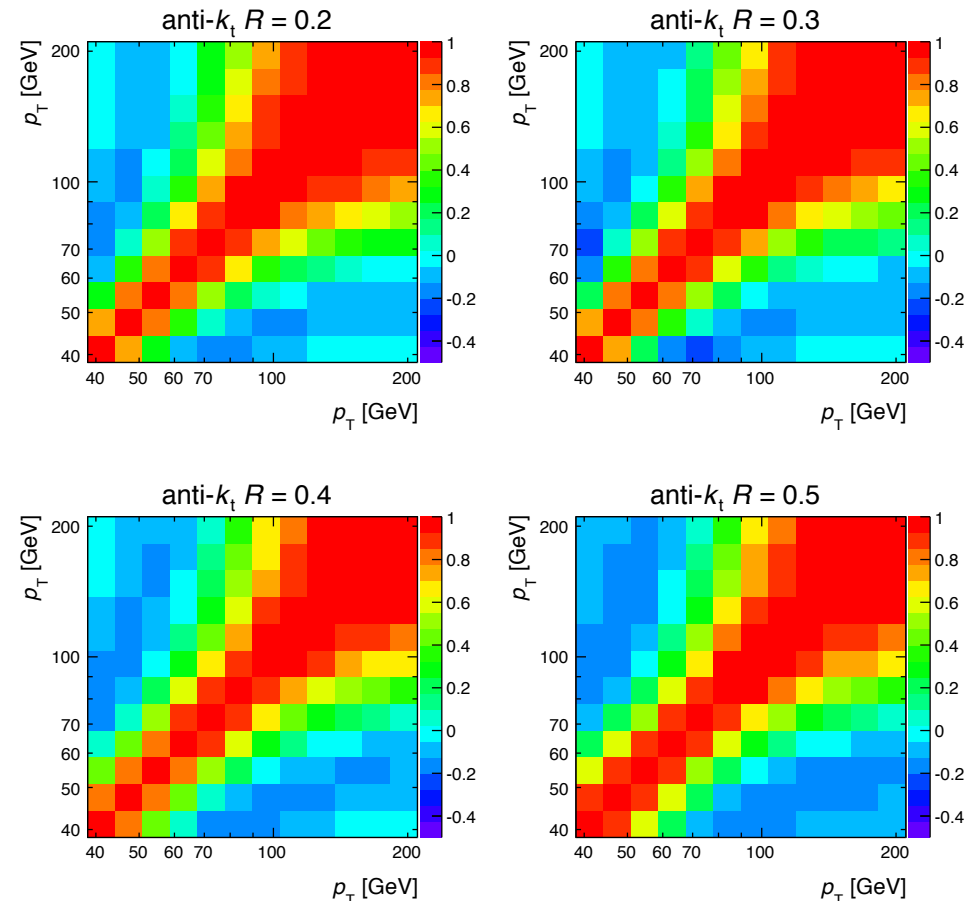
Error Analysis: Statistical Errors

- Since unfolding involves bin migration there is non-trivial covariance matrix

- Use toy method to estimate statistical uncertainty

- Construct fluctuation of data using measured covariance

- Unfold "pseudo experiment"

- Repeat many times, calculate statistical covariance

- Apply same method to include statistical uncertainty in response matrix from MC

- Combine two covariance matrices as independent sources

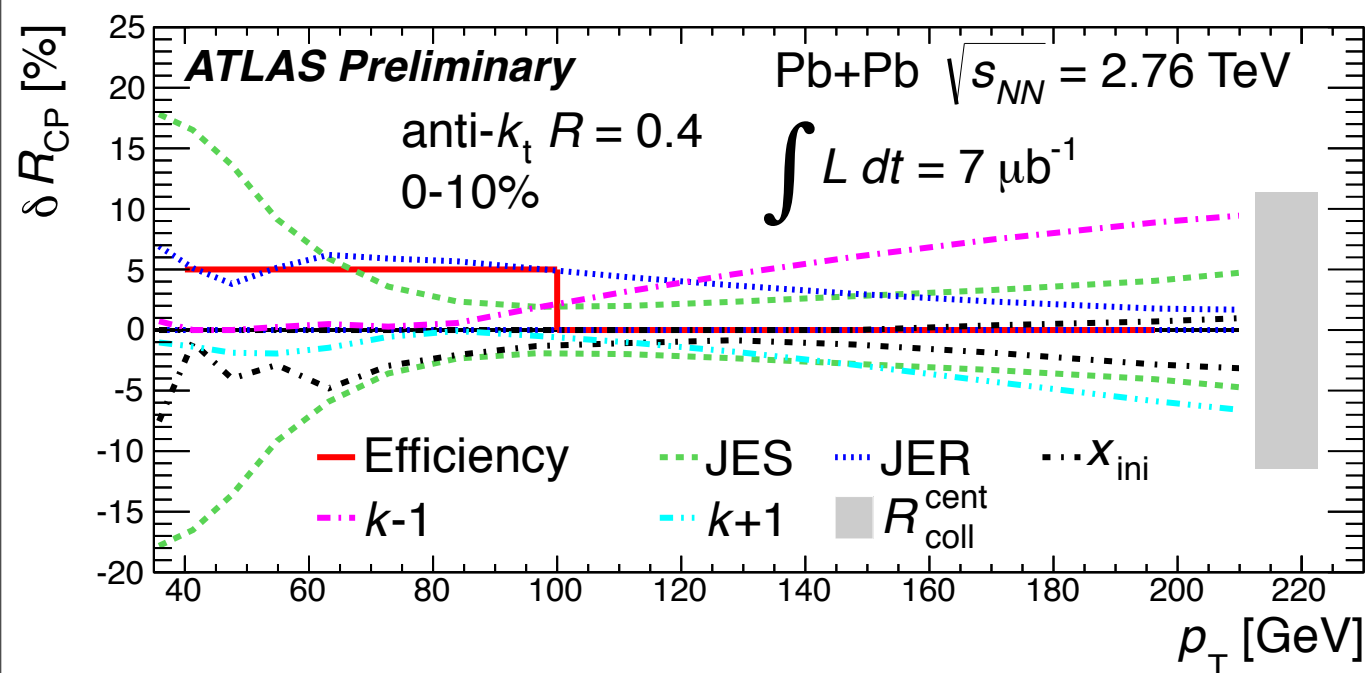$$\rho_{ij} = \frac{\mathrm{Cov}(Y_i, Y_j)}{\sqrt{\mathrm{Var}(Y_i)}\sqrt{\mathrm{Var}(Y_j)}}$$

ATLAS Preliminary

Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV

$\int L\, dt = 7\ \mu b^{-1}$

0 - 10 % Centrality

anti-k_t R = 0.2

anti-k_t R = 0.3

anti-k_t R = 0.4

anti-k_t R = 0.5

Overview of Systematic Uncertainties

JES: Relative energy scale differences central and peripheral

JER: Possible disagreement between data and MC in UE fluctuations

- **Efficiency:** cover possible MC/data differences, 5% for $p_T < 100$ GeV
- **X^{ini}**: Sensitivity to power in power law: **+0.5**, **-0.5**
- **R_{coll}**: sensitive to centrality determination, σ_{NN}
- **Regularization:** Sensitivity to choice of k:+/-1

Systematic Uncertainties

- Both JER and JES uncertainties, fill response matrix with modified $(p_T^{\text{reco}}, p_T^{\text{truth}})$

- Unfold with new response matrix, use difference from nominal result as error

- **JES**: used MC closure, overlay and in-situ study

  - Includes background subtraction effects and differences in fragmentation

  - Change $p_T^{\text{reco}} \to p_T^{\text{reco}}(1 + f(p_T^{\text{true}}))$, *f* constant p_T > 70 GeV, increases linearly with lower p_T such that $f(p_T = 40) = 2f(p_T = 70)$

- **JER**: use fluctuation analysis, vary *b*→*b'=b(1+g)* to cover data/MC difference

  - *g*=2.5%, 2.5%, 5%, 7.5% for R=0.2, 0.3, 0.4 and 0.5

  - Use *b'* to calculate a new JER σ(*b'*), rescale $\Delta p_T = (p_T^{\text{truth}} - p_T^{\text{reco}})$

$$p_T^{\text{reco}} \to p_T^{\text{truth}} + (p_T^{\text{truth}} - p_T^{\text{reco}})\frac{\sigma(b')}{\sigma(b)}$$

Discriminants: Scattering Significance

- Evaluate deflection in each ID layer relative to expected contribution from multiple scattering

$$s_i \equiv q\Delta\phi_i/\phi^{\mathrm{msc}}$$

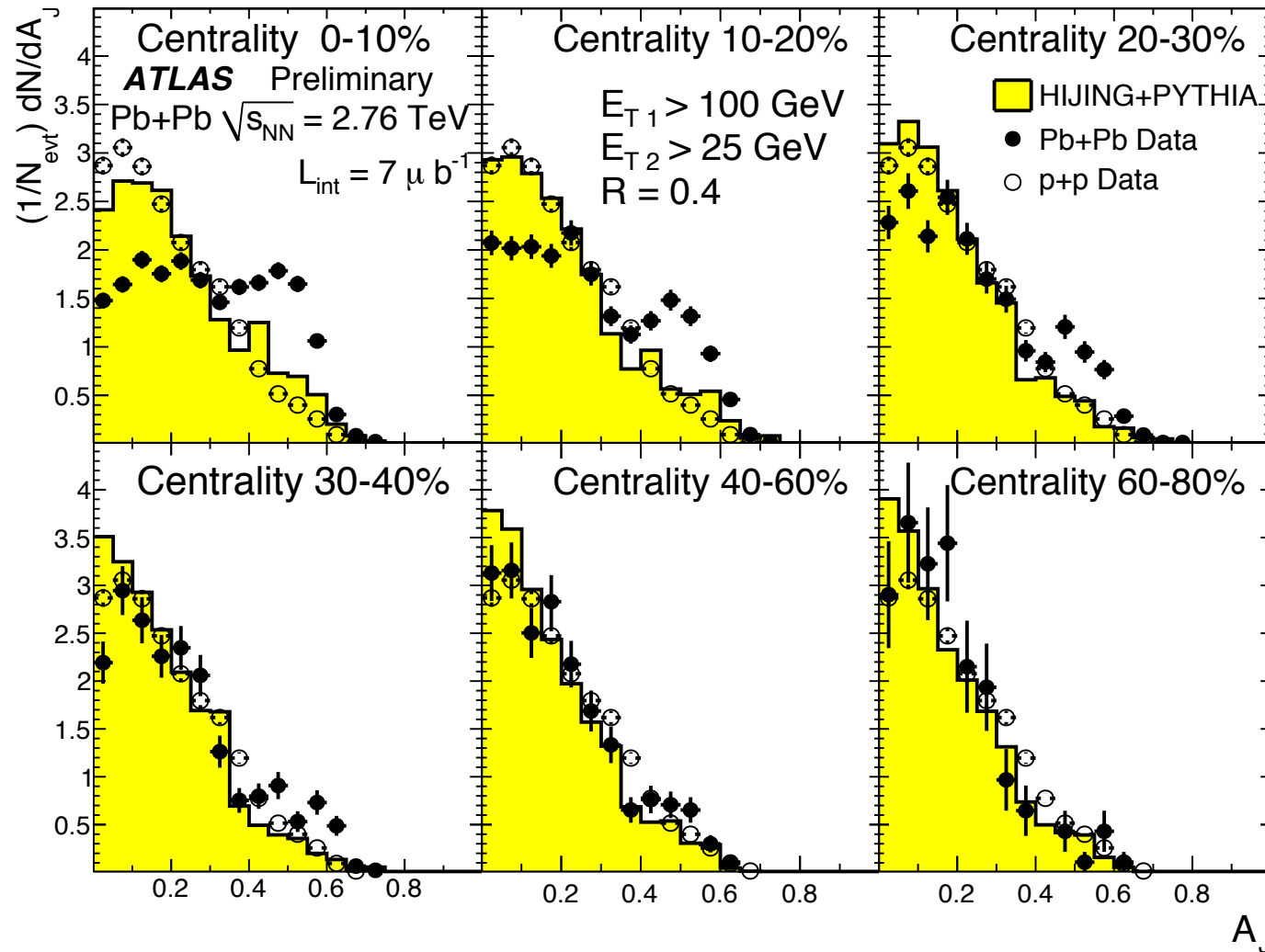- Calculate scattering significance for k$^{\text{th}}$ layer

$$S(k) = \frac{1}{\sqrt{n}}\left(\sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_k\right)$$

- Define total **significance** as maximum deflection between adjacent layers

$$S = \max\left\{|S(k)|, k = 1, 2, \cdots\right\}$$

- Effective at low p_{T}
  - Identifies in flight decays

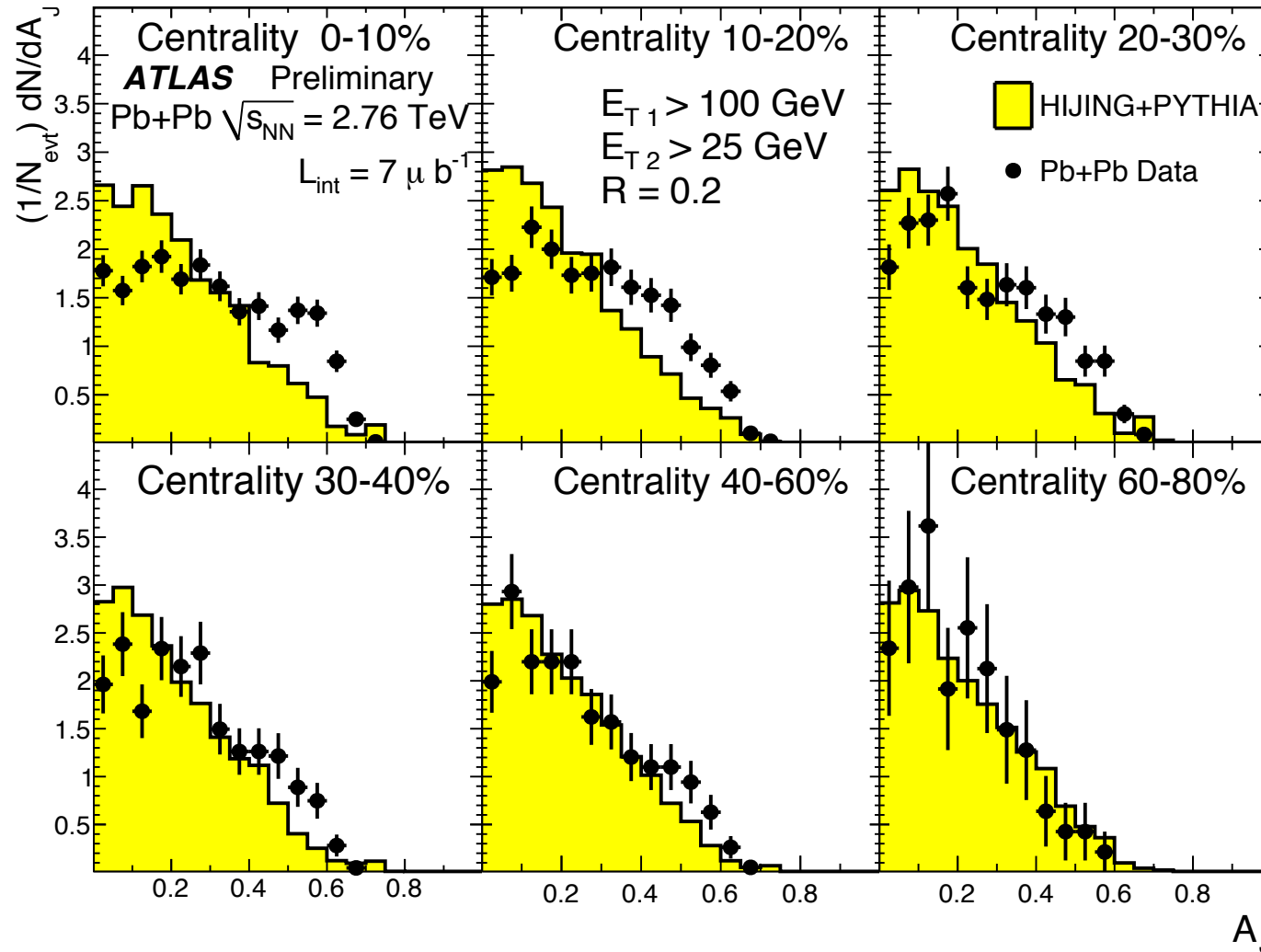# Two-Jet Observables: Dijet Asymmetry

$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

Updated from published result

Contributions to second peak mostly from events where second jet consistent with background level
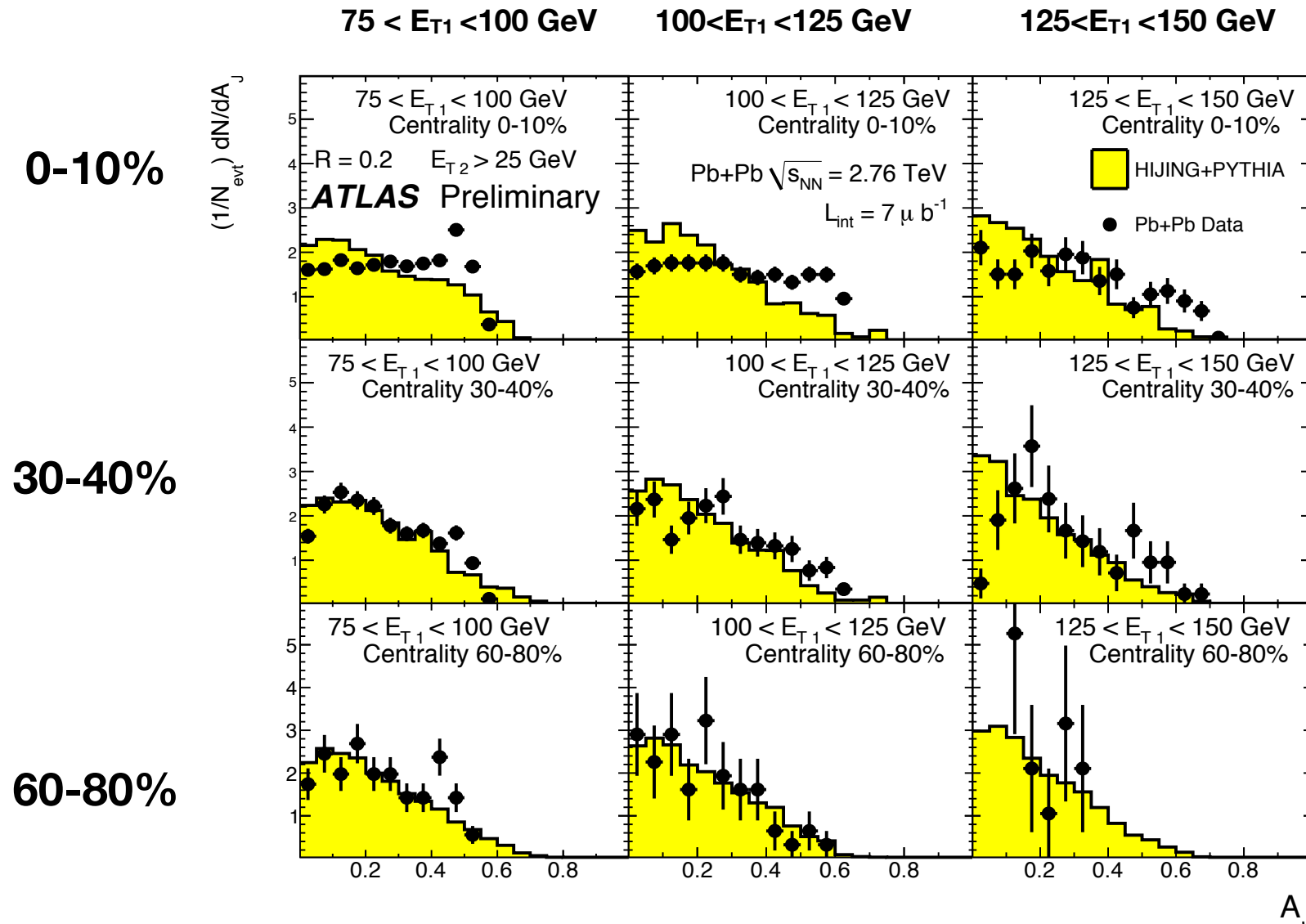
Dijet Asymmetry: *R*=0.2

$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

$$E_{T1} > 100 \; GeV$$

$$E_{T2} > 25 \; GeV$$

Smaller R is
Less sensitive to
background
fluctuations

Distribution flatter, peak smeared out

Asymmetry: Energy Dependence, *R*=0.2

Increasing jet energy stretches peak out

Peak at low values of A_J restored in peripheral collisions

Dijet Angular Correlation

- $\Delta\phi$ distributions show (almost) no modification

- Contribution in tail likely due to combinatoric match with uncorrelated or fake low energy jet

- Rate is reduced for smaller R value, consistent with lower fake rate for these jets