Photon-Jet Correlations

Alex Barbieri
MIT
For the CMS Collaboration

Jet Workshop in HI Collisions
UPMC, Paris
July 2nd 2013

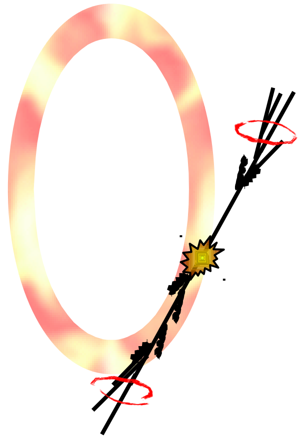
Outline

- Motivation for gamma-jet measurements
- Experimental Techniques
  - CMS
  - ATLAS
- Comparison of Experimental Results
- Comparison with Theory

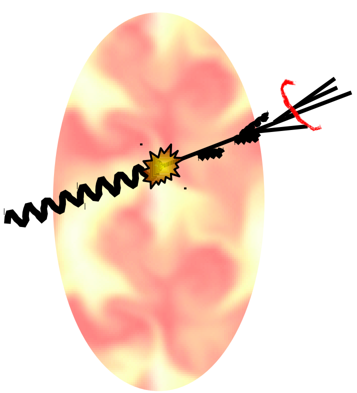
Motivation for Gamma-Jet Measurements

Strong Probes have surface bias

- Pure-strong probes (dijets) occur frequently (high statistics)
- Dijets have two drawbacks:
  - Surface bias of data sample
  - Loss of information about initial energy
- Solution: tag strong probe (jet) with EW probe (photon)



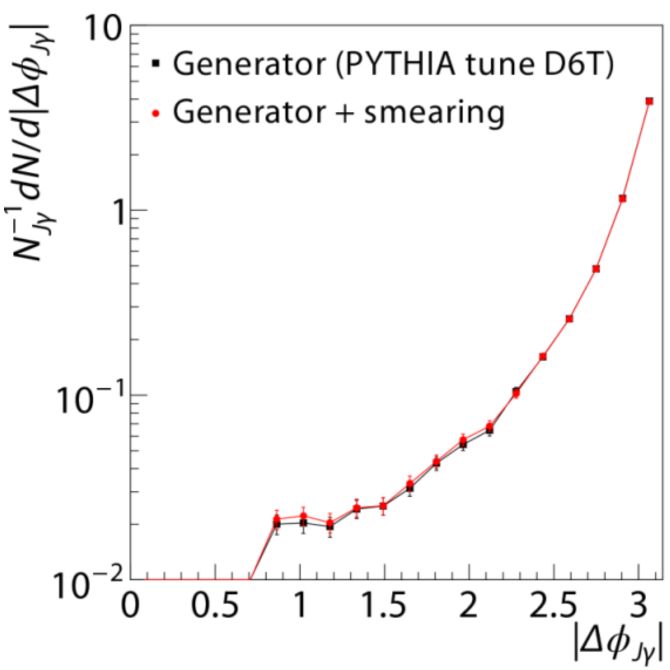
High statistics, with surface bias

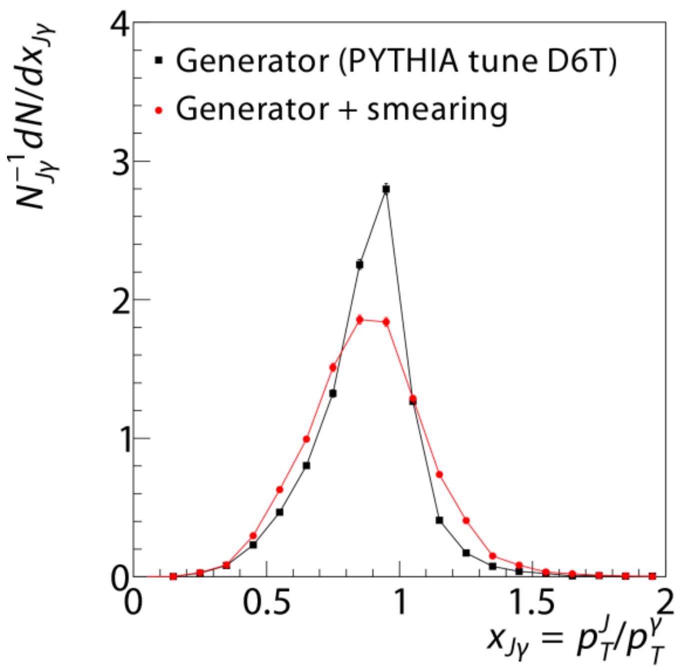


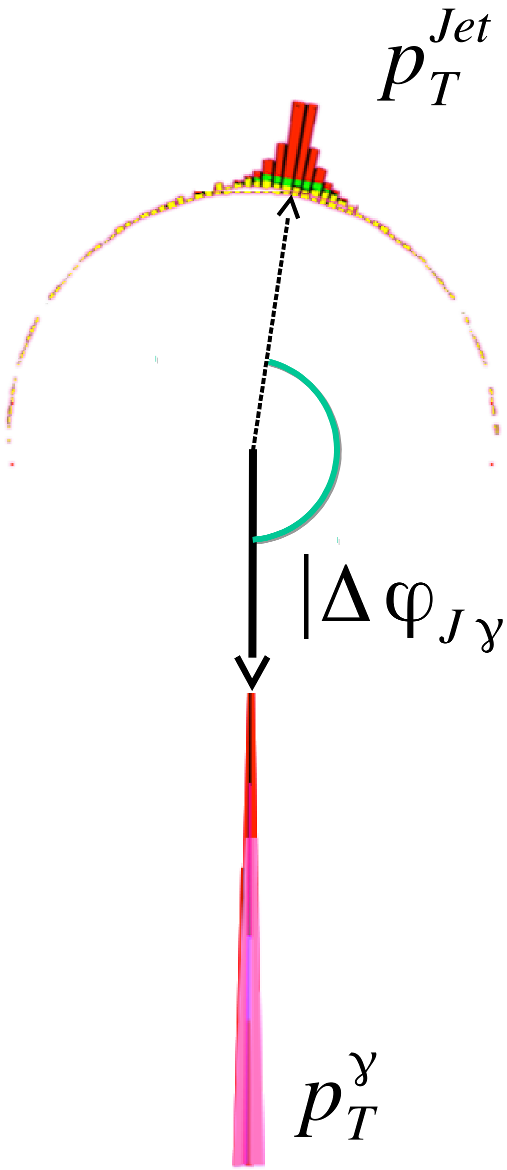
Lower statistics, without surface bias

Observables

- Azimuthal decorrelation: $|\Delta\varphi_{J\gamma}|$, and its parametrized width $\sigma(|\Delta\varphi_{J\gamma}|)$
- Transverse momentum ratio: $x_{J\gamma}=p_T^{Jet}/p_T^{\gamma}$, and its mean $<x_{J\gamma}>$
- Fraction of photons with associated jets: $R_{J\gamma}$

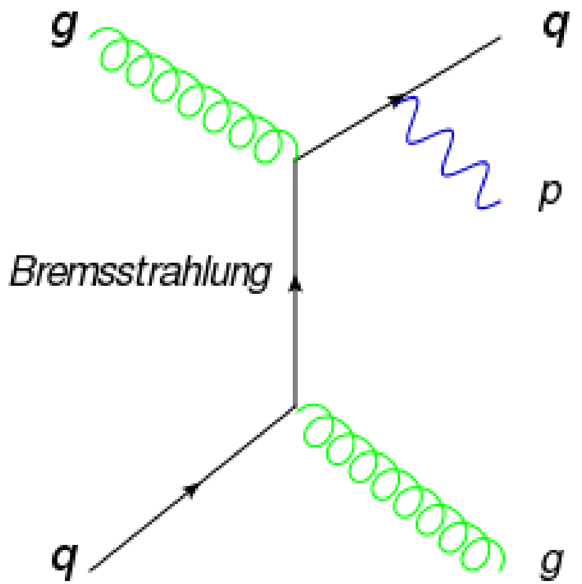


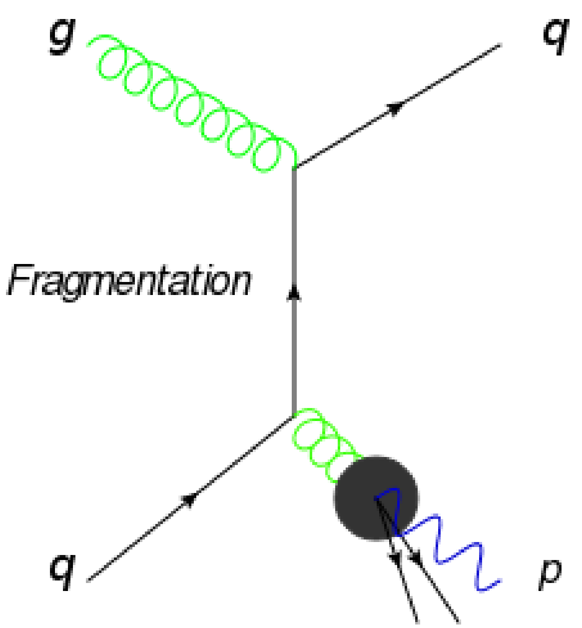




Background

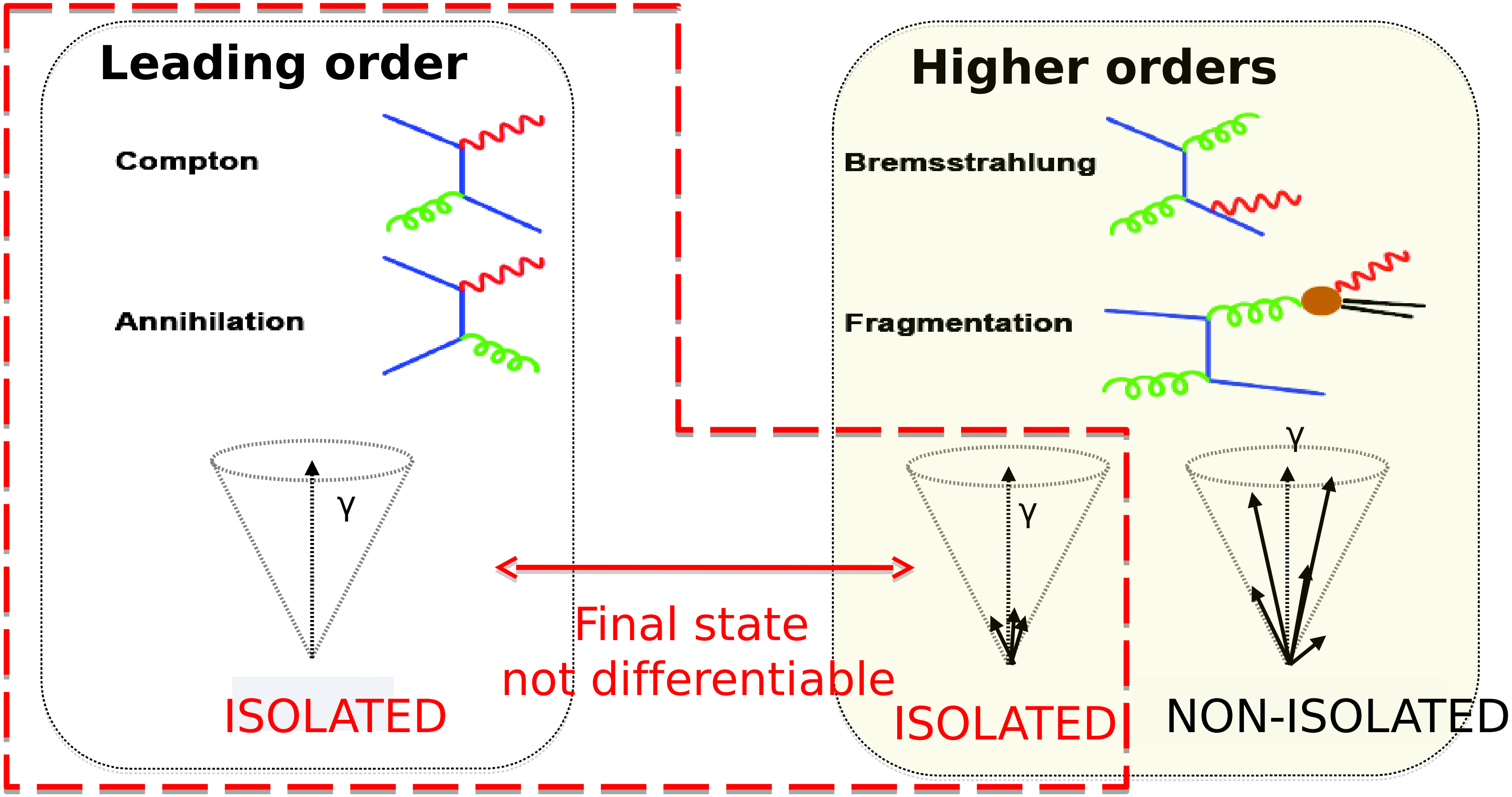
- Background from:
  - Underlying Event
  - Decay photons (*π^0*, *η*)
  - Higher order processes
    - Bremsstrahlung
    - Fragmentation
- Rejected using
  - underlying event subtraction
  - isolation requirement





Isolation

- Signal – isolated photons
- Background – suppressed by isolation requirement



Experimental Techniques

CMS: Phys. Lett. B 718 (2013) 773
ATLAS: ATLAS-CONF-2012-121

Kinematics Comparison

CMS

- Anti-k_T particle-flow jets, R=0.3, UE subtracted
- $p_T^{Jet} > 30$ GeV
- $|\eta^{Jet}| < 1.6$
- $\Delta\varphi > 7\pi/8$
- $p_T^{\gamma} > 60$ GeV
- $|\eta^{\gamma}| < 1.44$
- Centrality bins: [100-50], [50-30], [30-10], [10-0]%
- ALL jets in each event which meet criteria are included, not just leading.

ATLAS

- Anti-k_T jets, R=0.3, UE subtracted
- $p_T^{Jet} > 25$ GeV
- $|\eta^{Jet}| < 2.1$
- $\Delta\varphi > 7\pi/8$
- 60 GeV $< p_T^{\gamma} <$ 90 GeV
- $|\eta^{\gamma}| < 1.3$
- Centrality bins: [80-40], [40-20], [20-10], [10-0]%
- ***Only events with $(p_T^{Jet})/(p_T^{\gamma}) > 25/60$ considered**
- ***Only the leading jet in each event considered**

CMS UE Subtraction

Subtract energy mean+σ from towers, in const. η strips

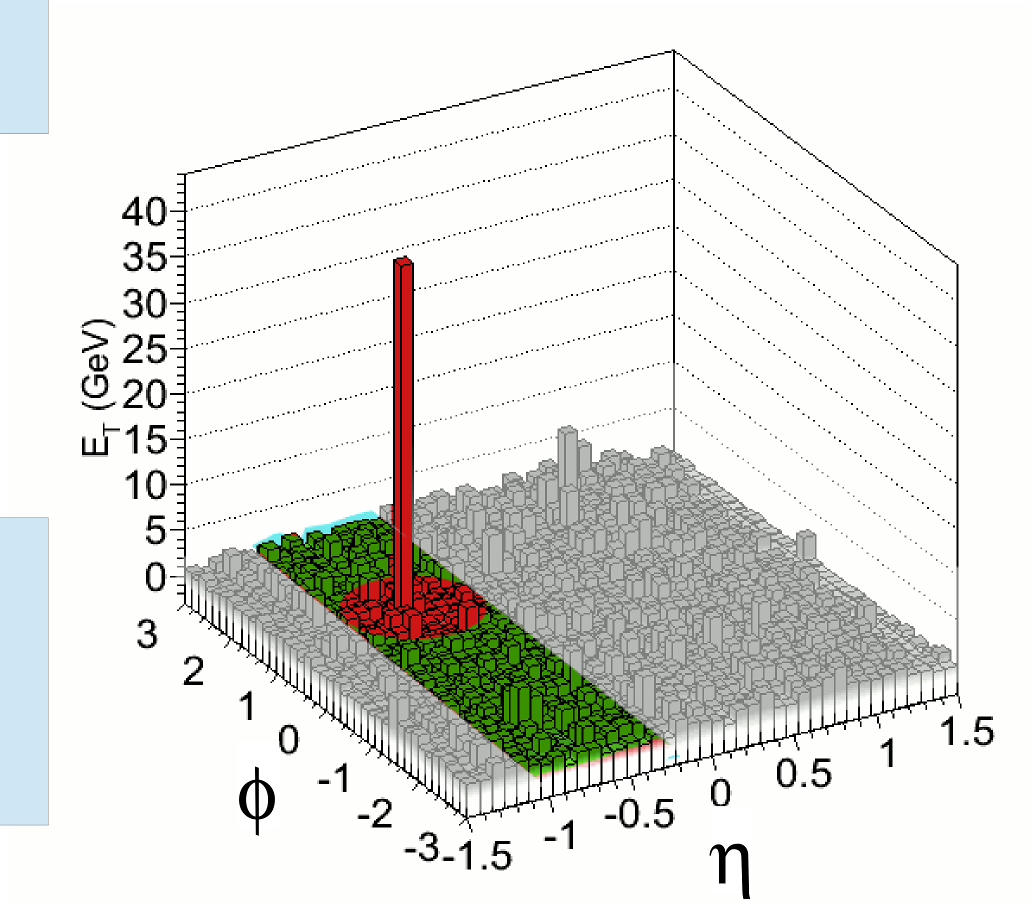
Remove Jets from event

1st pass

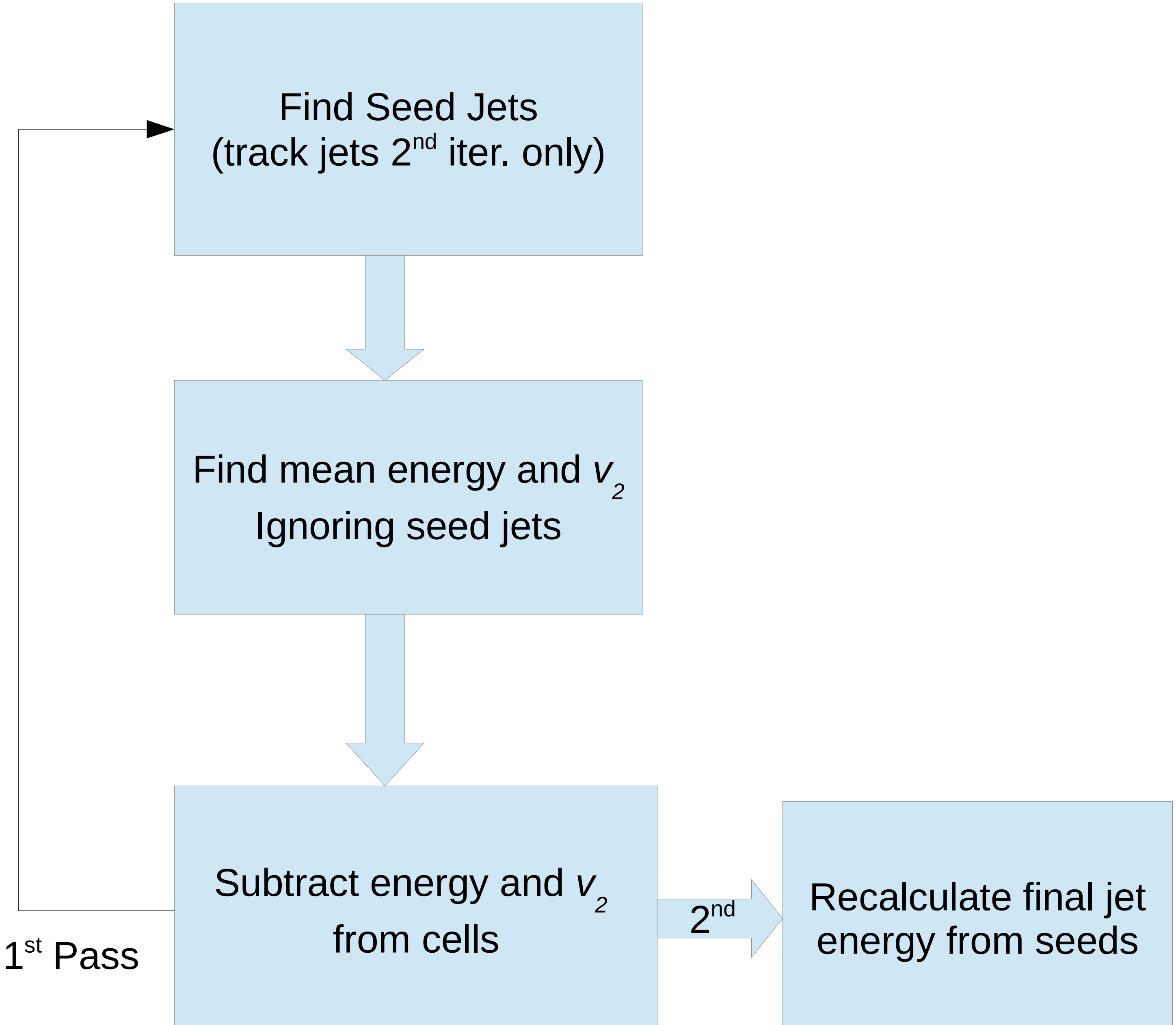
Find Jets

2nd

Final Jets



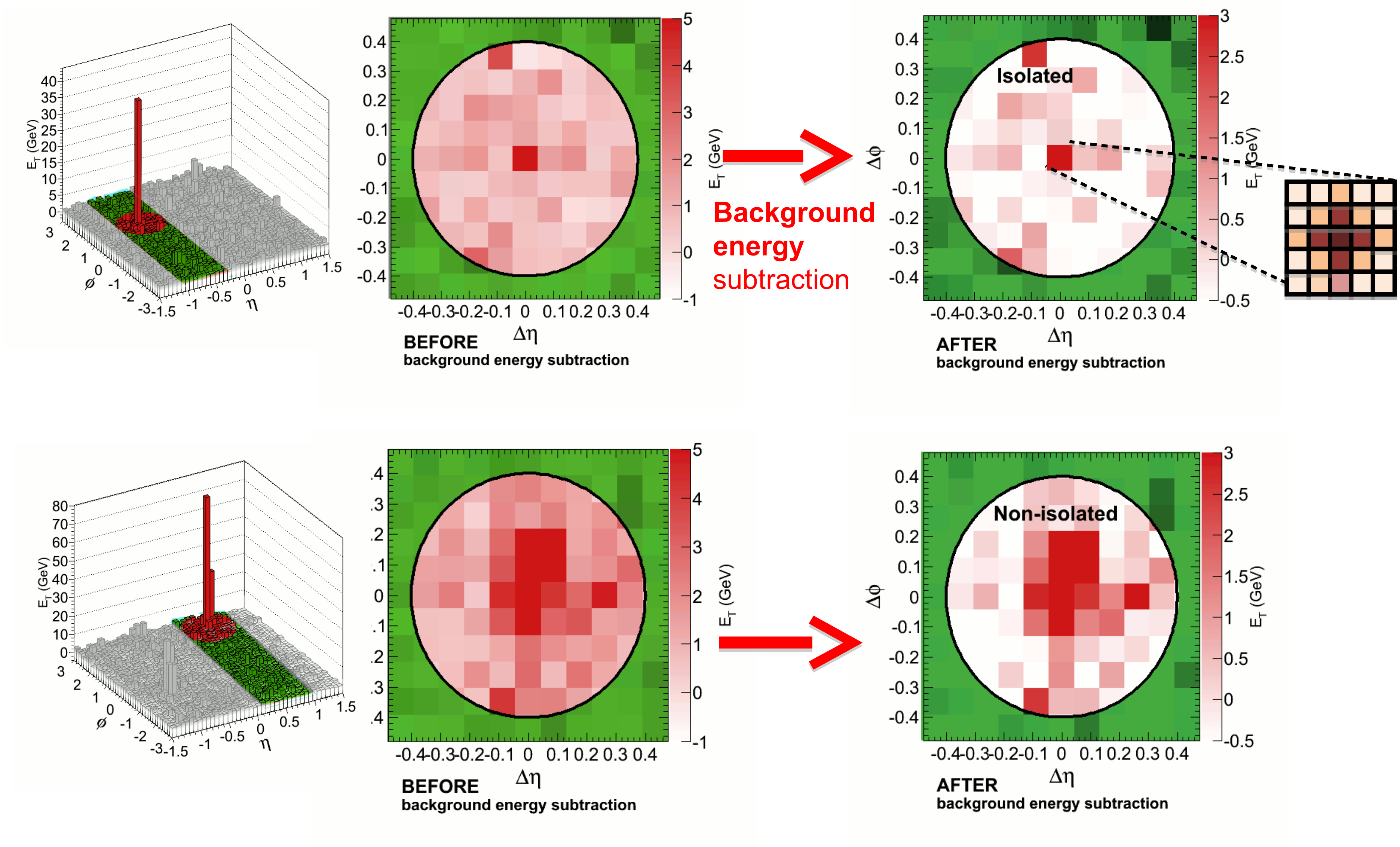
ATLAS UE Subtraction



CMS Isolation

- Photons associated with a track are rejected to reduce electrons
- Cut on the ratio of hadronic calorimeter energy to electromagnetic energy, $H/E < 0.1$
- After UE subtraction, the energy in R=0.4 cone around photon in tracker and calorimeters is
  - sumIso = tracker Et + ecal Et + hcal Et
- sumIso is required to be below threshold
  - Data: 1.0 GeV
  - MC: 5.0 GeV (particle level isolation, counting only energy from same hard interaction)

CMS Isolation



ATLAS Isolation and Shower Shapes

- Calorimeter energy in R=0.3 cone around photon < 6 GeV
- 9 shower shape variables used to reject jets and hadrons, broadly classified in three categories
  - Second sampling layer shape information
  - The ratio of hadronic energy to photon energy
  - High granularity strip layer shape information

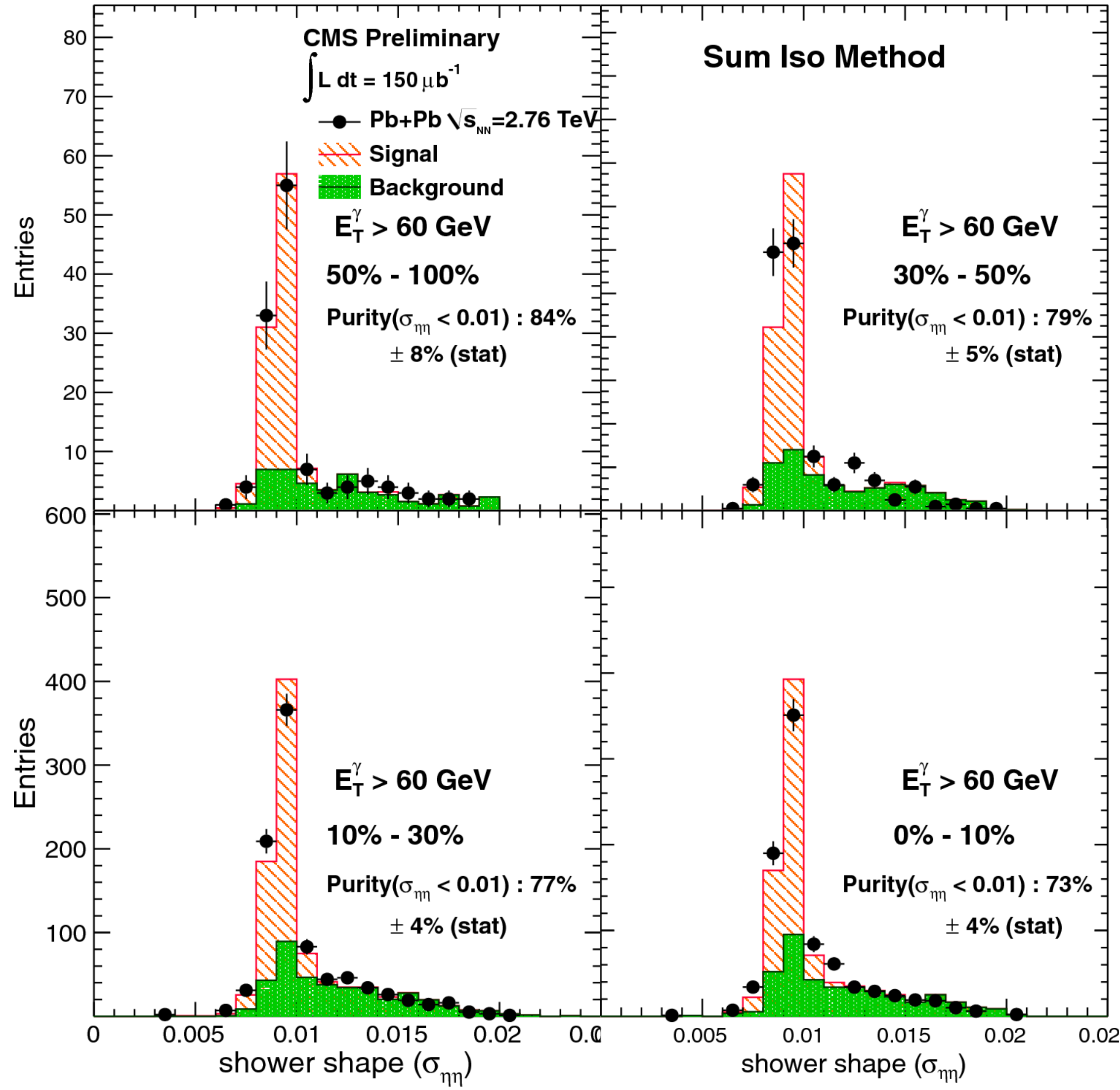
CMS Purity Measurement

- Template fitting method used to reduce decay background further
- Define Shower shape variable

$$\sigma_{\eta\eta} = \frac{\sum_i w_i (\eta_i - \langle \eta \rangle)^2}{\sum_i w_i}$$

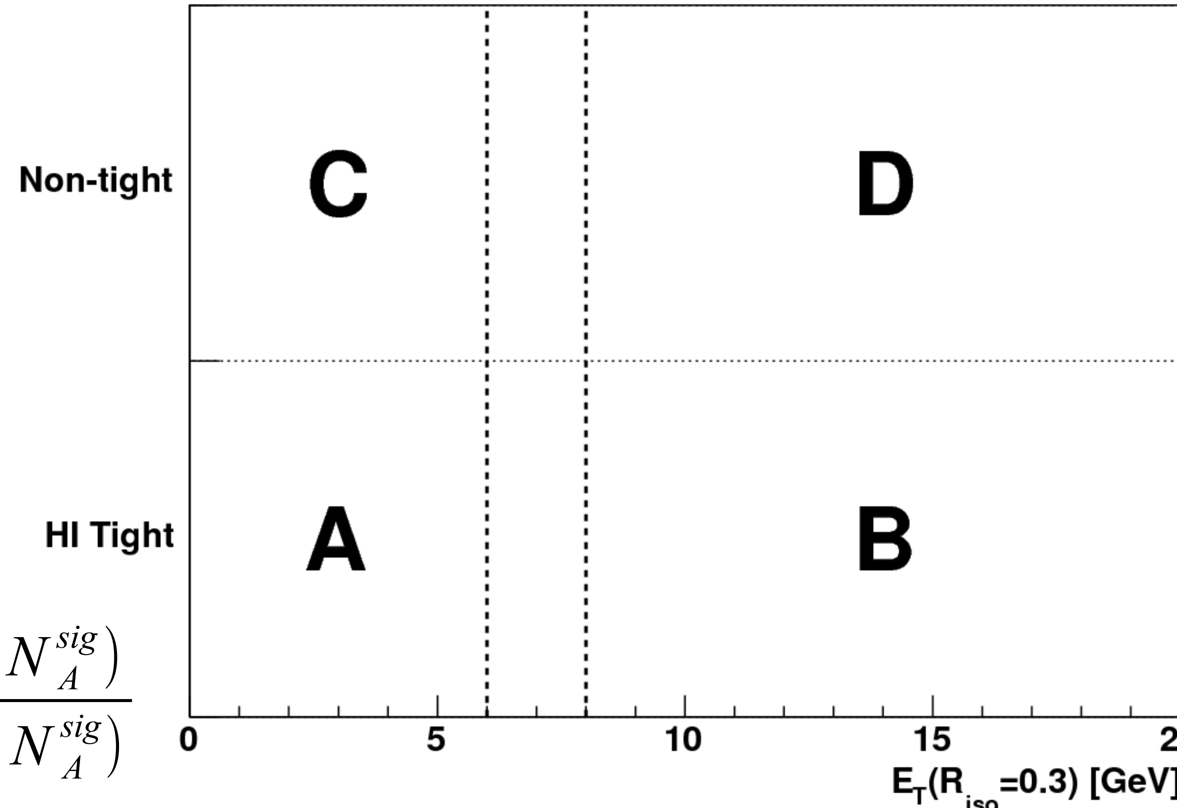
$$w_i = max\left(0, c + \ln \frac{E_i}{E_{5x5}}\right)$$

- Signal distribution comes from pythia+data
- Background distribution comes from data with 6<sumIso<11GeV
- Decay photons largely removed by cutting on $\sigma_{\eta\eta} < 0.01$
- Remaining contribution of decay photons removed using predicted purity value



ATLAS Purity Measurement

- Double Sideband Technique
- Photon candidates binned on two axes
  - Isolation energy
  - Tight or loose cut



$$N_A^{sig} = N_A^{obs} - \left(N_B^{obs} - c_B N_A^{sig}\right) \frac{\left(N_C^{obs} - c_C N_A^{sig}\right)}{\left(N_D^{obs} - c_D N_A^{sig}\right)}$$

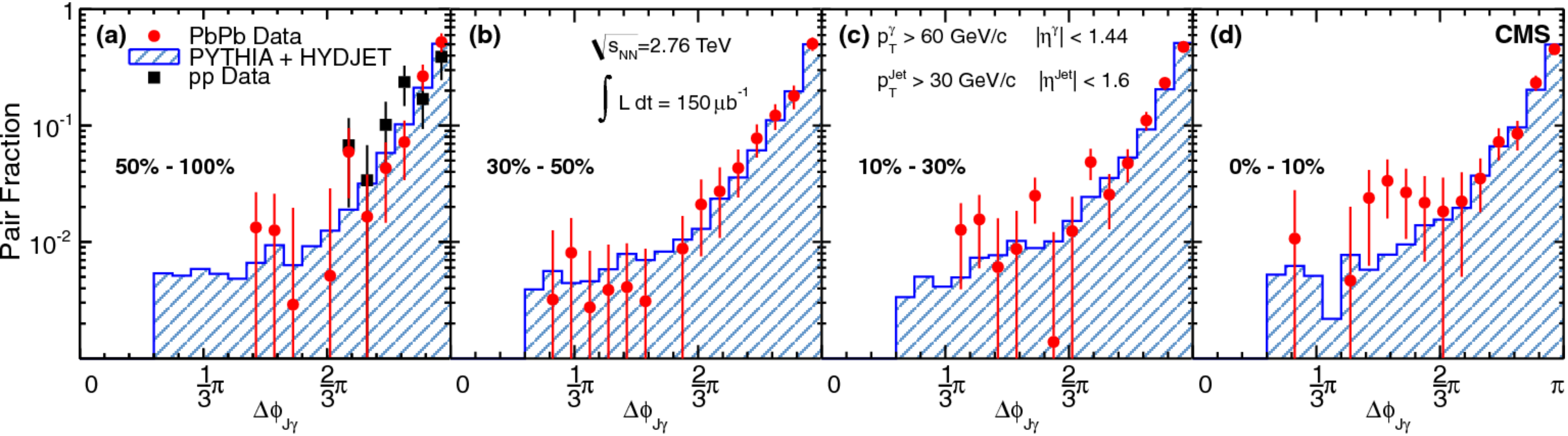
$$c_i = \frac{N_i^{sig}}{N_A^{sig}}$$

From pythia+data

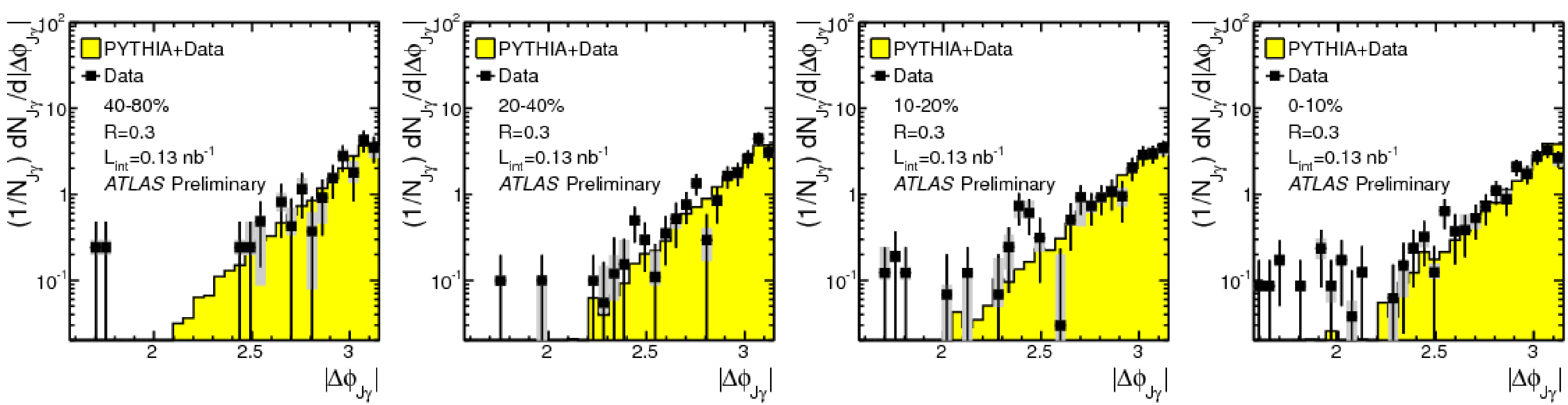
Centrality	1-P
0-10%	16 ± 6%
10-20%	21 ± 9%
20-40%	23 ± 8%
40-80%	25 ± 12%

Experimental Results

No jet deflection observed

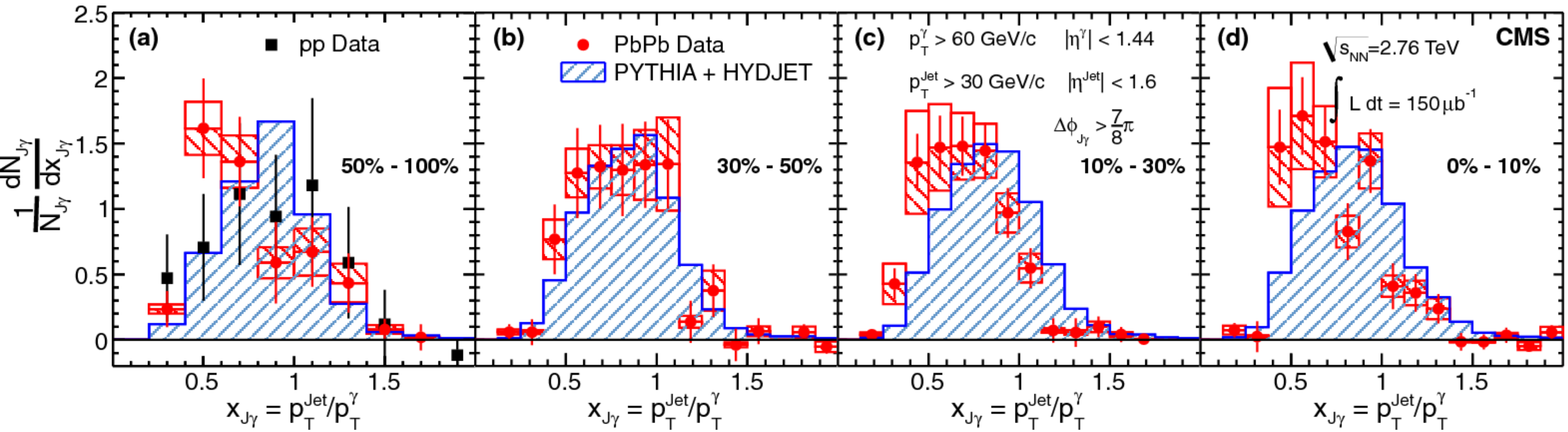


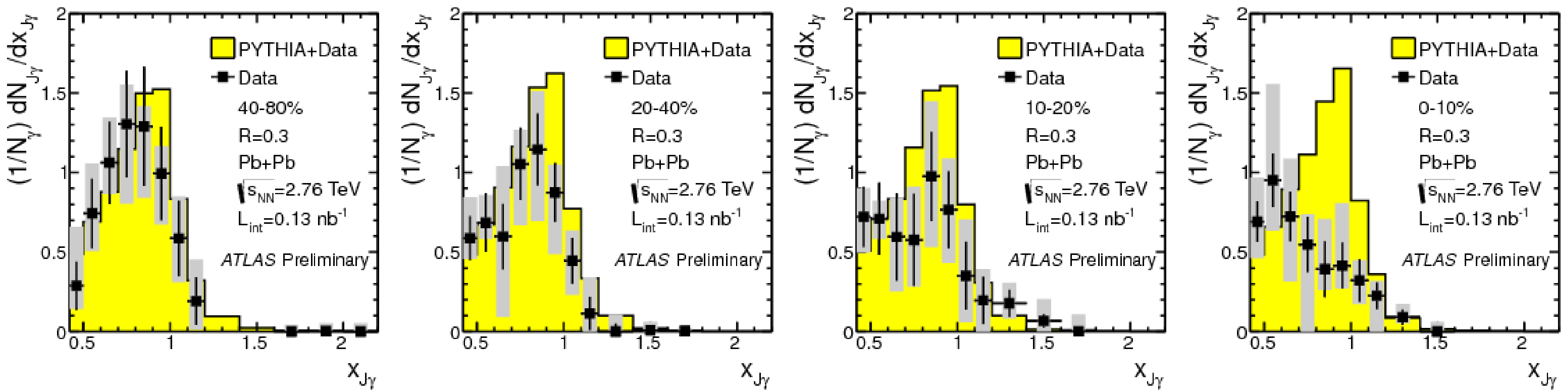
Phys. Lett. B 718 (2013) 773



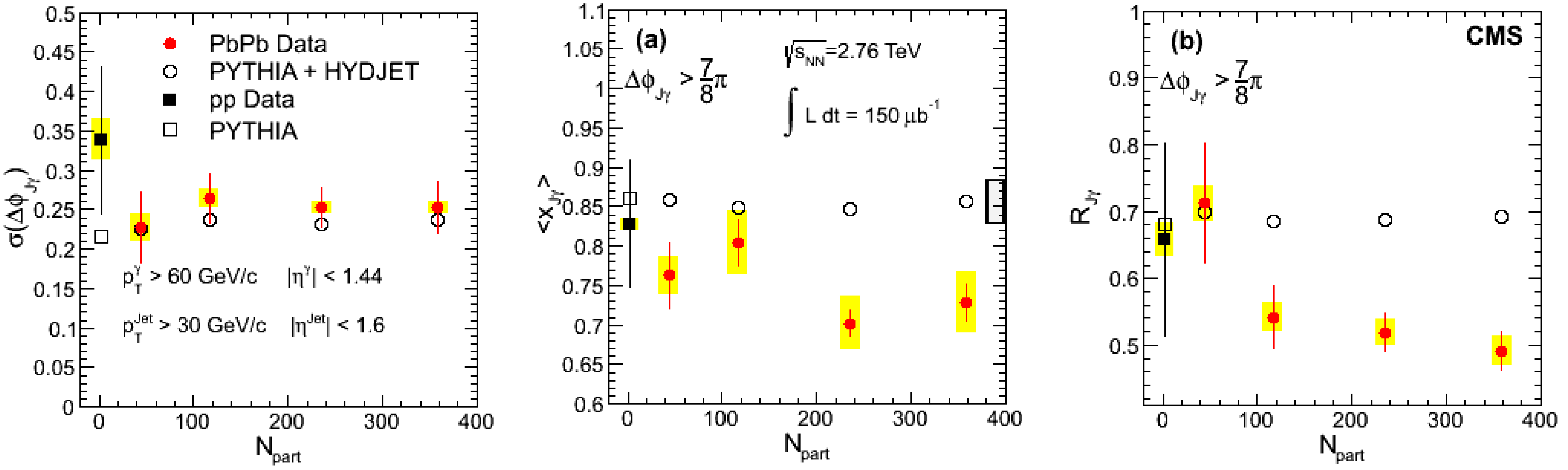
ATLAS-CONF-2012-121

Shift to lower $x_{J\gamma}$ with centrality

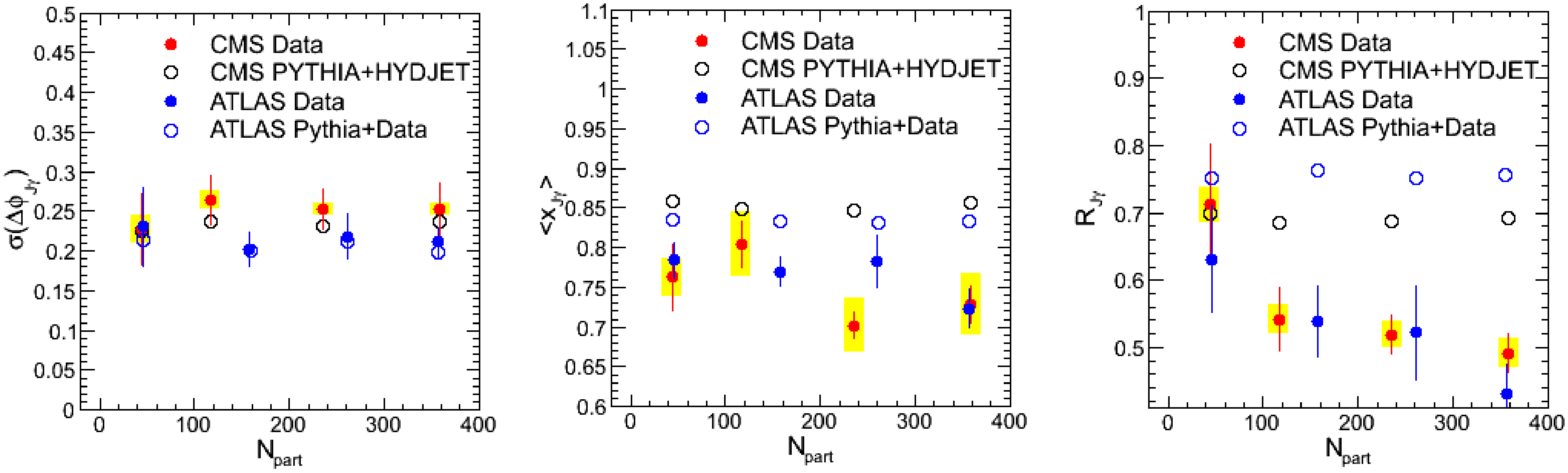




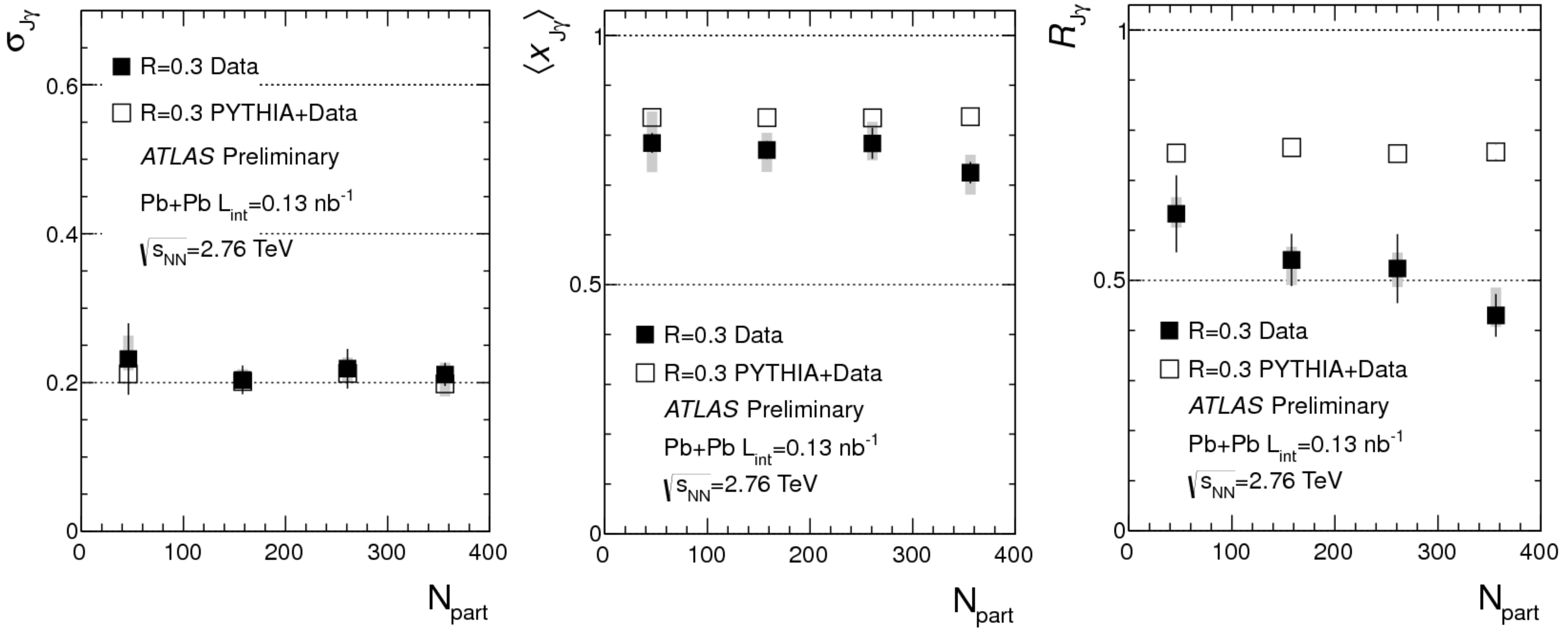
Significant loss of jet partners with centrality



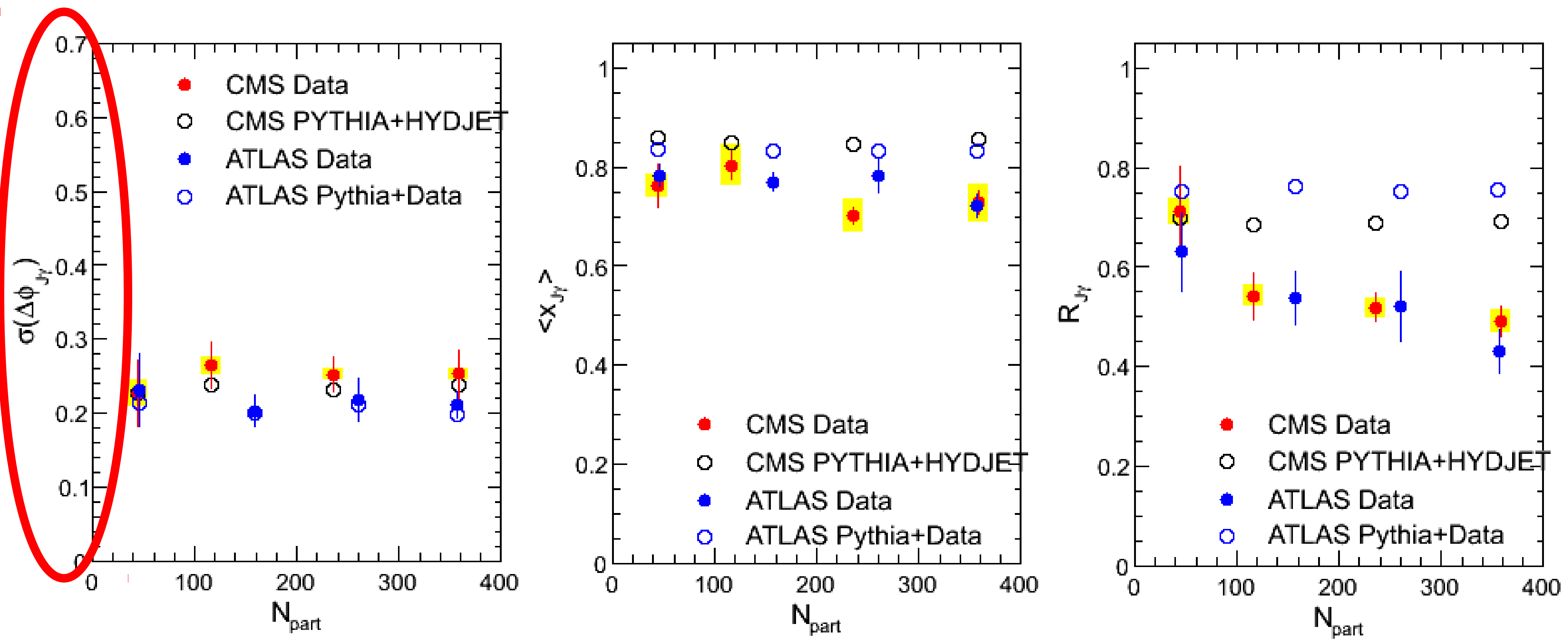
CMS and ATLAS consistent within uncertainties



ATLAS Results as made public



ATLAS-CMS Results on ATLAS axes

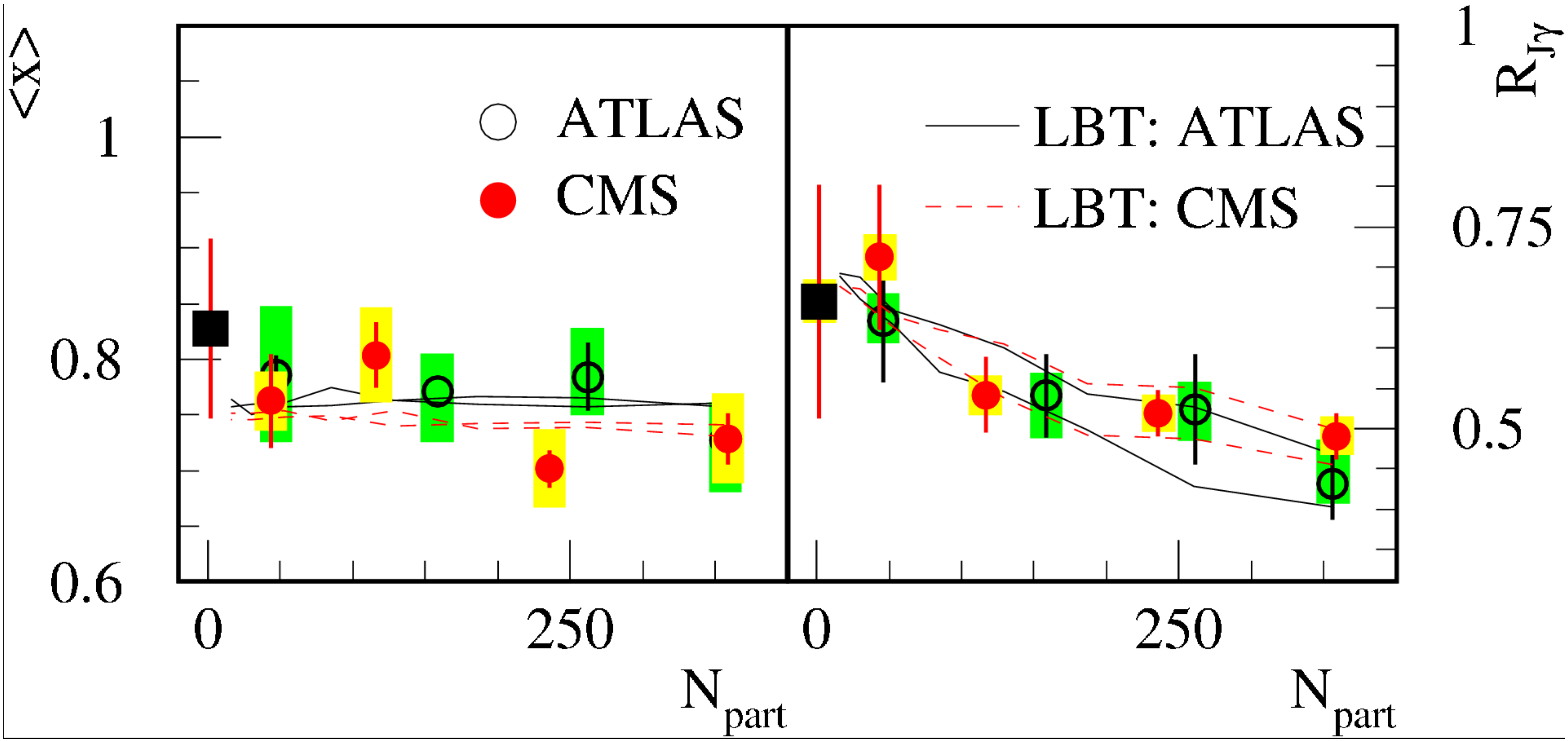


Theoretical Comparison

Theory: LBT

- arXiv:1302.5874 X-N Wang, Y. Zhu
- Linearized Boltzmann Transport model of jet propagation
- Includes
  - Elastic parton scattering
  - Induced gluon emission
  - recoiled medium partons

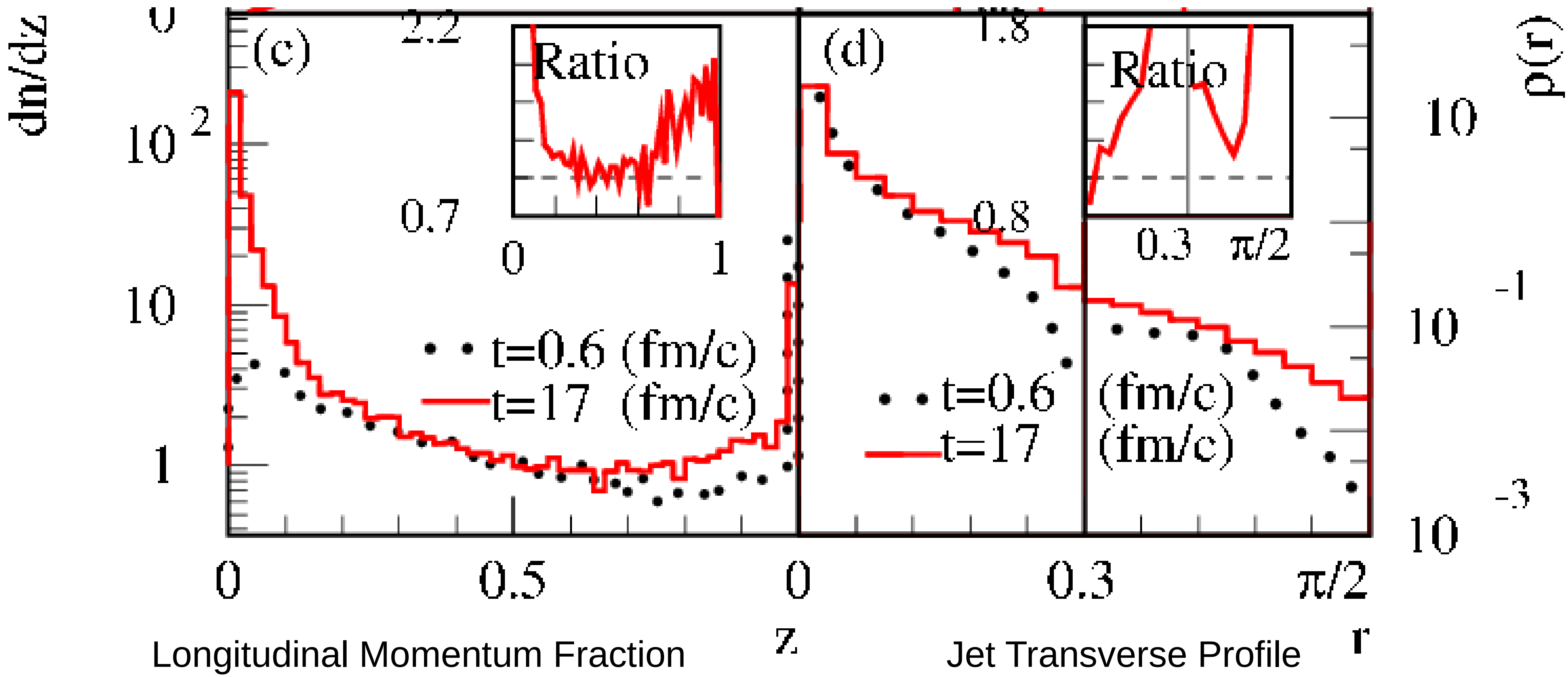
Reproduction of experimental data



Double lines correspond to different tunes of α_s

- ATLAS $0.2 < \alpha_s < 0.27$
- CMS $0.15 < \alpha_s < 0.23$

Fragmentation function and jet shape are sensitive to energy loss mechanism



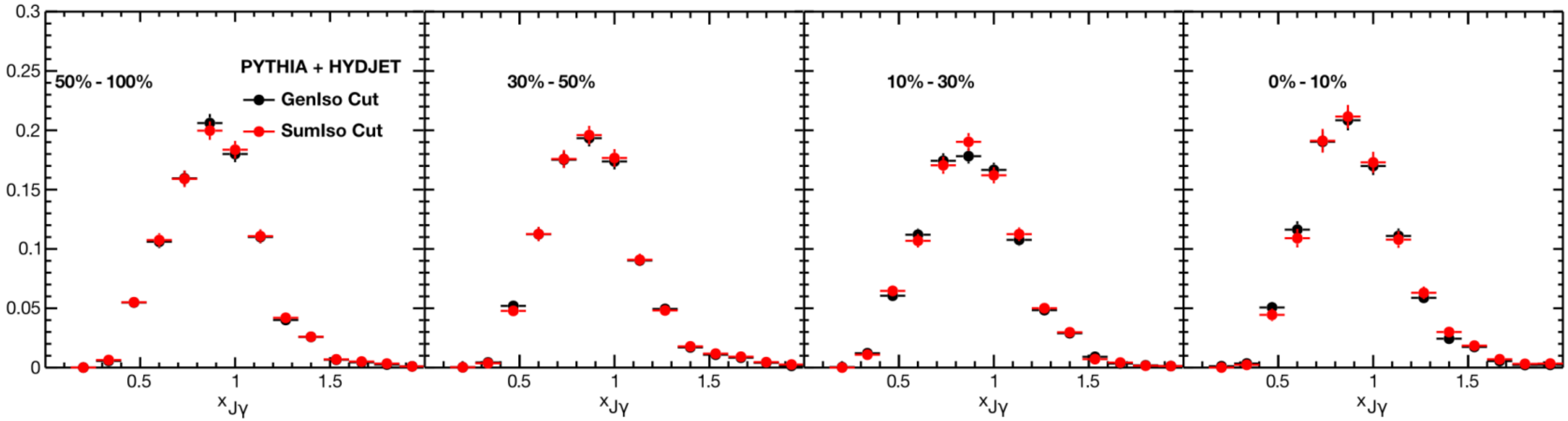
$$\rho(r)=\frac{1}{\Delta r}\frac{1}{N^{jet}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

Conclusion

- Within uncertainties
  - No deflection of jets
  - Decrease of p_T ratio with centrality
  - Decrease in number of partner jets with centrality
- Physics take-home
  - Quenching occurs
  - Lack of deflection => energy loss mechanism "soft"
- Future measurements
  - Fragmentation function and jet-shape in γ-jet

Backup

Isolated Photon Definition (Syst. Uncert.)

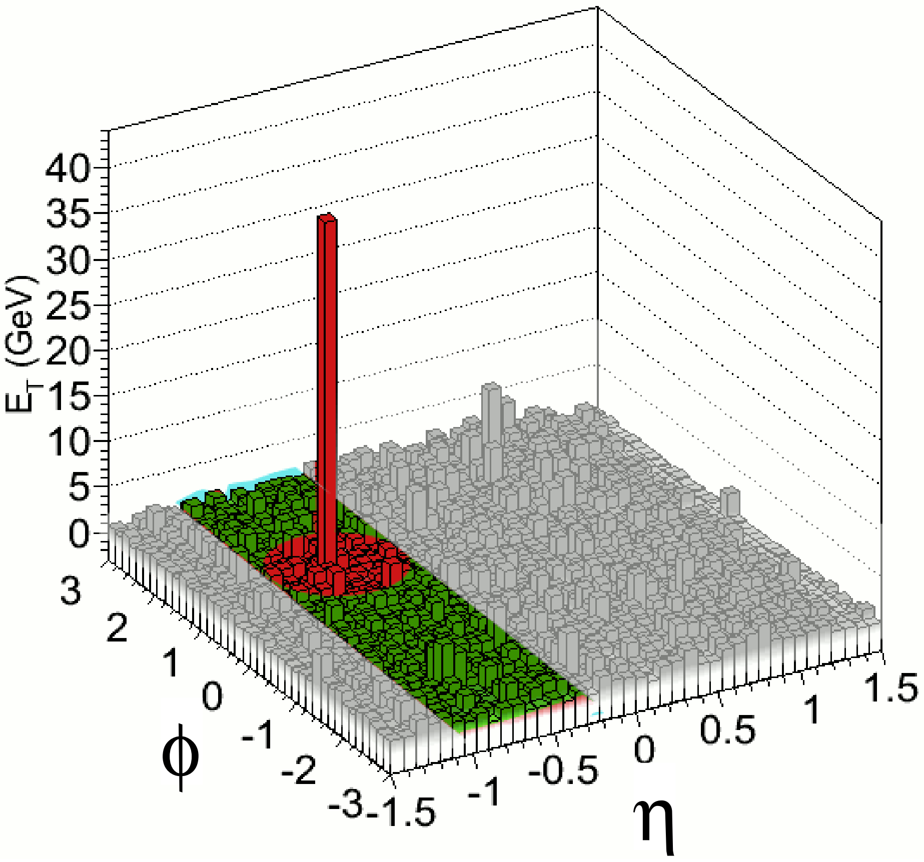


- Comparison of SumIso < 1 GeV reconstructed photon to GenIso < 5 GeV generator photon
- GenIso/SumIso difference quoted as a systematic uncertainty

Y. S. Lai QM 2012

CMS UE Subtraction

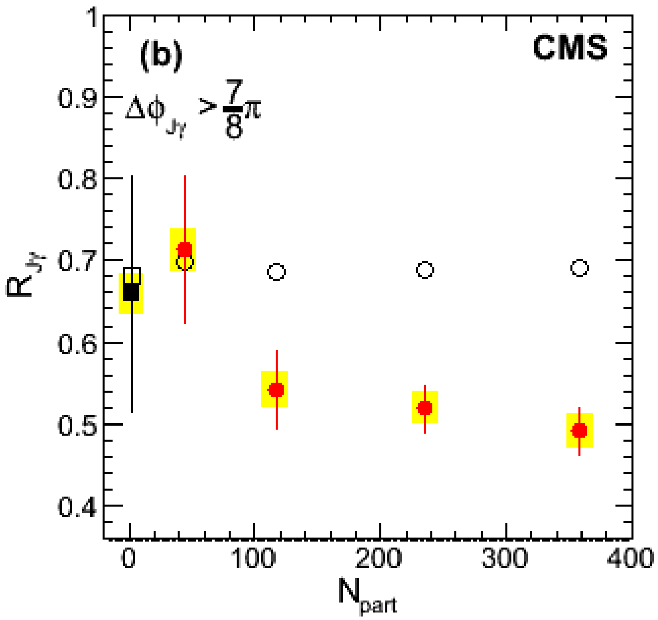
- Iterative subtraction
- 1st pass calculate average energy in eta rings and subtract mean + σ from all towers
- Find jets above 30GeV
- 2nd pass calculate average excluding jets found in 1st pass, subtract new mean + σ from towers.



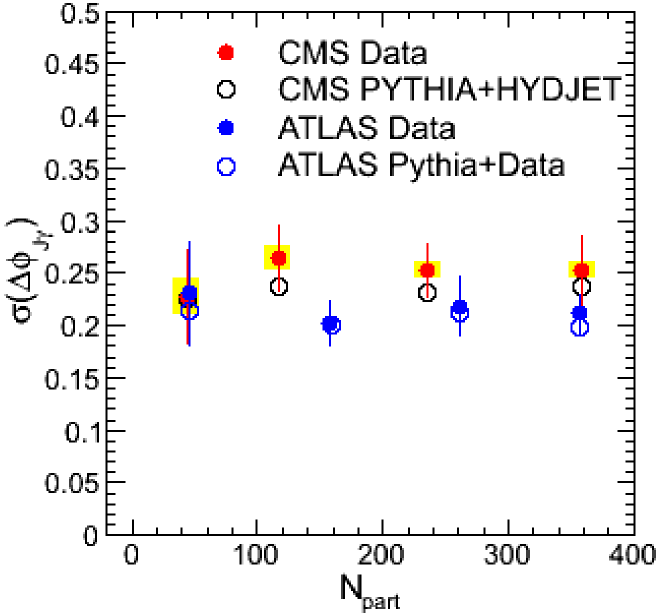
ATLAS UE Subtraction

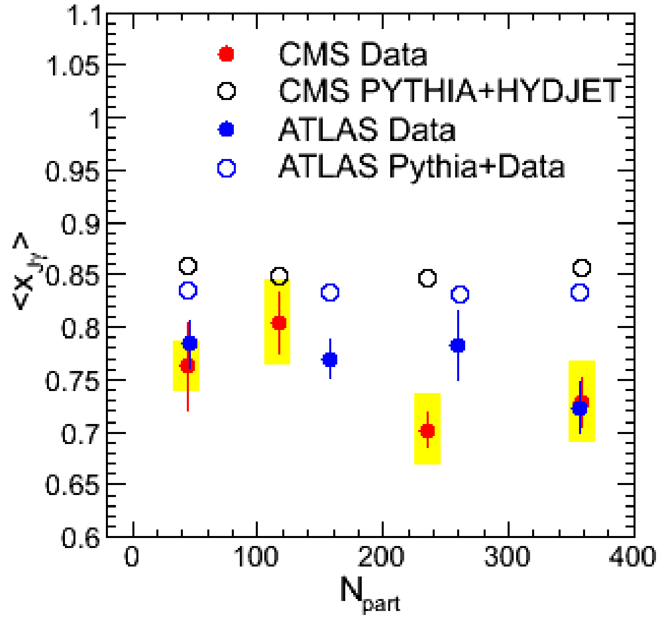
- Iterative Subtraction
- 1st pass: create seed R=0.2 anti-kT calorimeter jets, calculate mean ET in $\Delta\eta=0.1$ strips
- Subtract mean ET and v2 modulation
- 2nd pass: create seed R=0.2 anti-kT calorimeter and track jets, recalculate mean ET and v2
- Subtract new mean ET and v2, recalculate jet energy

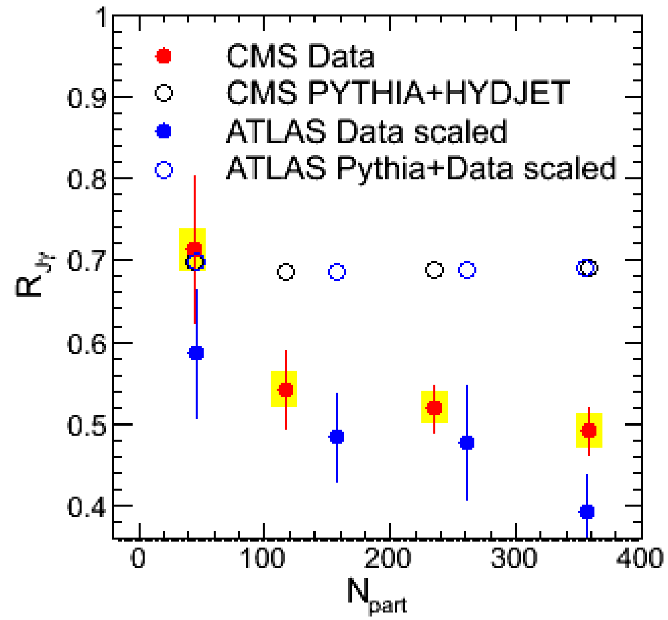
Significant loss of jet partners with centrality



CMS and ATLAS consistent within uncertainties



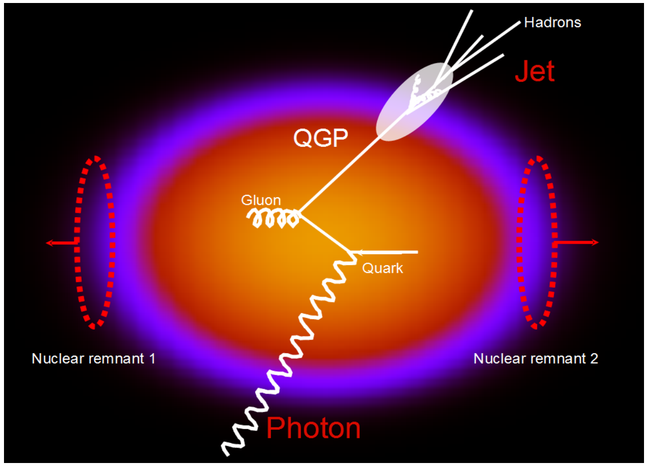




ATLAS reference scaled to CMS reference

Use probes to study new phase.

- A new phase of matter is expected in heavy ion collisions
- Use high-p_T probes to study new phase
- Possible probes can be:
  - Strongly interacting (jets, hadrons)
  - Non-Strongly interacting (photons, Z, W)



Different probes have different qualities

Strong Probe

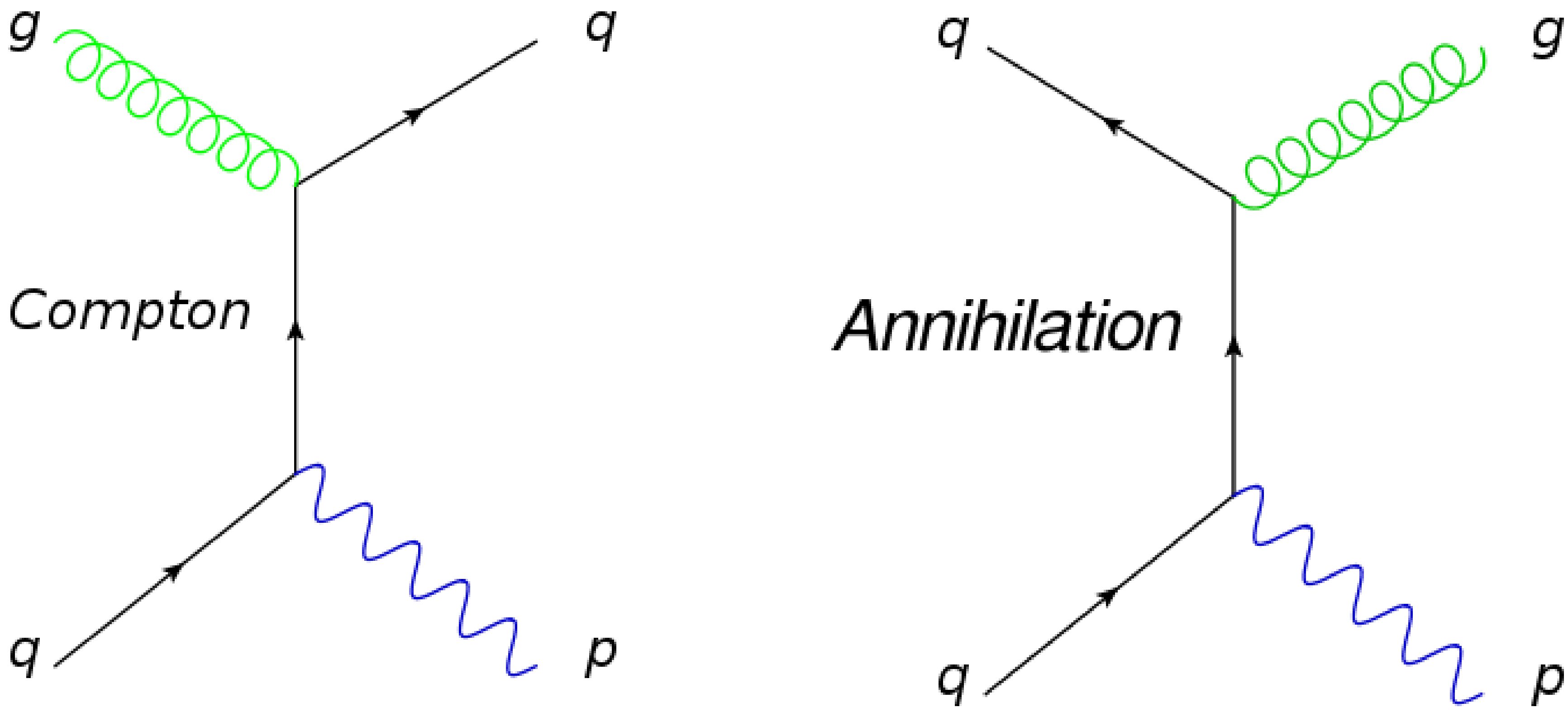
- Contains information about the medium
- Loses information about initial hard interaction

EW Probe

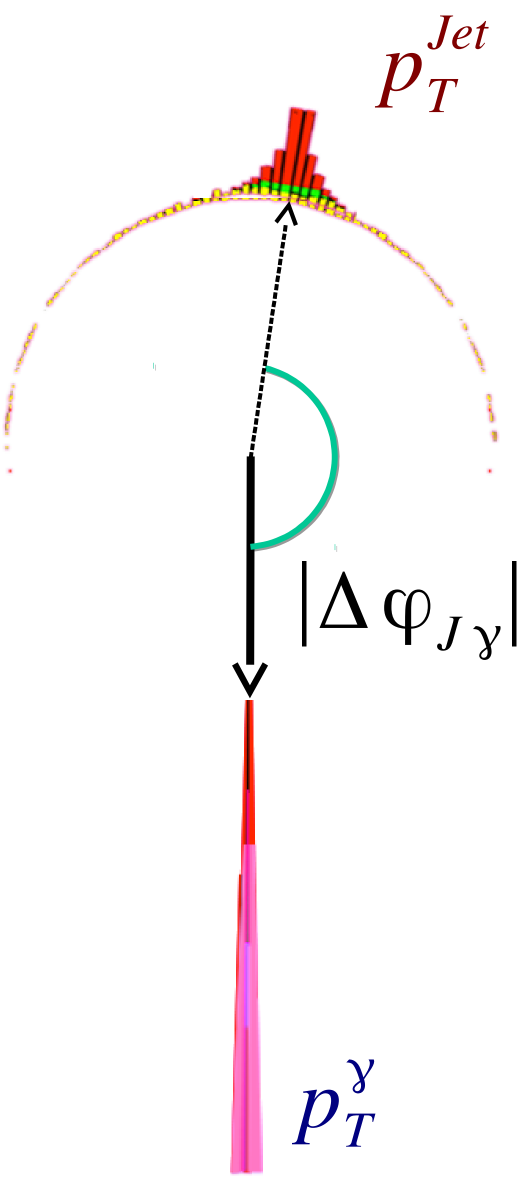
- No strong interaction with the medium
- Preserves information about the initial hard interaction

Combine Strong and EW Probes

- Tag stongly interacting probe (jets) with non-strongly interacting probe (photons)
  - Select very specific set of LO Feynman diagrams with high-p_T photon-jet pairs:

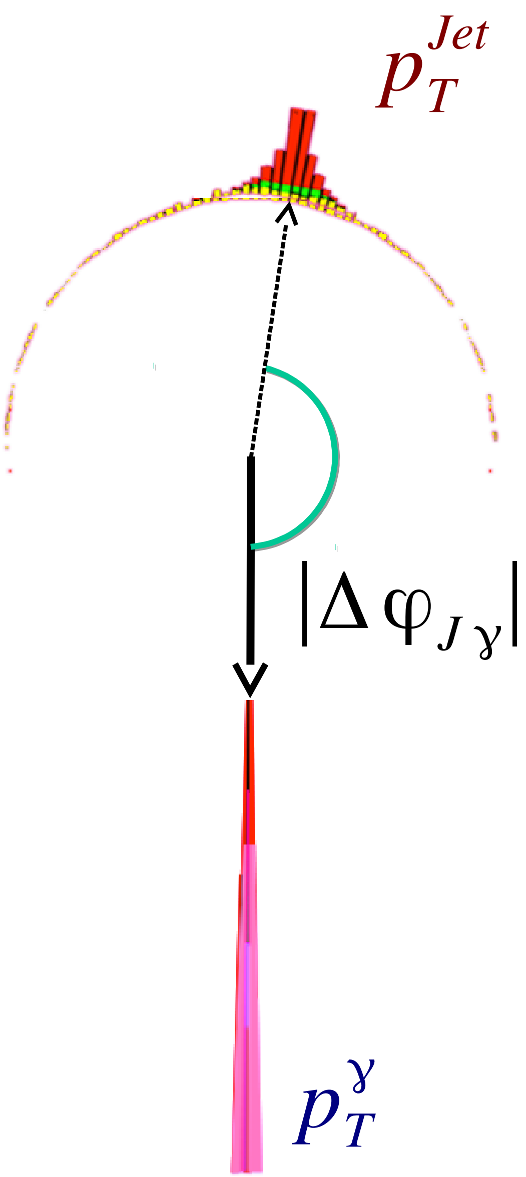


CMS Kinematics



- Anti-k_T particle-flow jets, R=0.3, UE subtracted
- $p_T^{Jet} > 30$ GeV
- $|\eta^{Jet}| < 1.6$
- $\Delta\varphi > 7\pi/8$
- $p_T^{\gamma} > 60$ GeV
- $|\eta^{\gamma}| < 1.44$
- Centrality bins: [100-50], [50-30], [30-10], [10-0]%
- ALL jets in each event which meet criteria are included, not just leading.

ATLAS Kinematics



- Anti-k_T jets, R=0.3, UE subtracted
- $p_T^{Jet} > 25$ GeV
- $|\eta^{Jet}| < 2.1$
- $\Delta\varphi > 7\pi/8$
- 60 GeV $< p_T^{\gamma} <$ 90 GeV
- $|\eta^{\gamma}| < 1.3$
- Centrality bins: [80-40], [40-20], [20-10], [10-0]%
- ***Only events with $(p_T^{Jet})/(p_T^{\gamma})$ > 25/60 considered**
- ***Only the leading jet in each event considered**

Summary of Systematic Uncert.: $\sigma(|\Delta\phi_{J\gamma}|)$

Source	pp	50–100%	30–50%	10–30%	0–10%
γ purity	6.8%	6.8%	2.7%	0.5%	0.9%
γ p_T threshold	3.0%	3.0%	3.0%	2.0%	1.2%
Jet p_T threshold	1.3%	1.3%	0.2%	0.5%	2.4%
Isolated γ definition	0.7%	0.7%	1.6%	2.0%	0.5%
Fake jet contamination	0.3%	0.3%	0.1%	0.2%	1.2%
γ efficiency	0.8%	0.8%	0.3%	0.3%	0.3%
Jet efficiency	0.6%	0.6%	0.7%	0.4%	0.3%
$e\pm$ contamination	0.5%	0.5%	0.5%	0.5%	0.5%
Jet ϕ resolution	0.5%	0.5%	0.5%	0.5%	0.5%
σ fitting	0.3%	0.3%	0.1%	0.1%	0.1%
Total	**7.7%**	**7.7%**	**4.5%**	**3.0%**	**3.2%**

- γ purity dominates due to different mixture of direct vs. fragmentation photon
- p_T threshold influences the selected kinematics

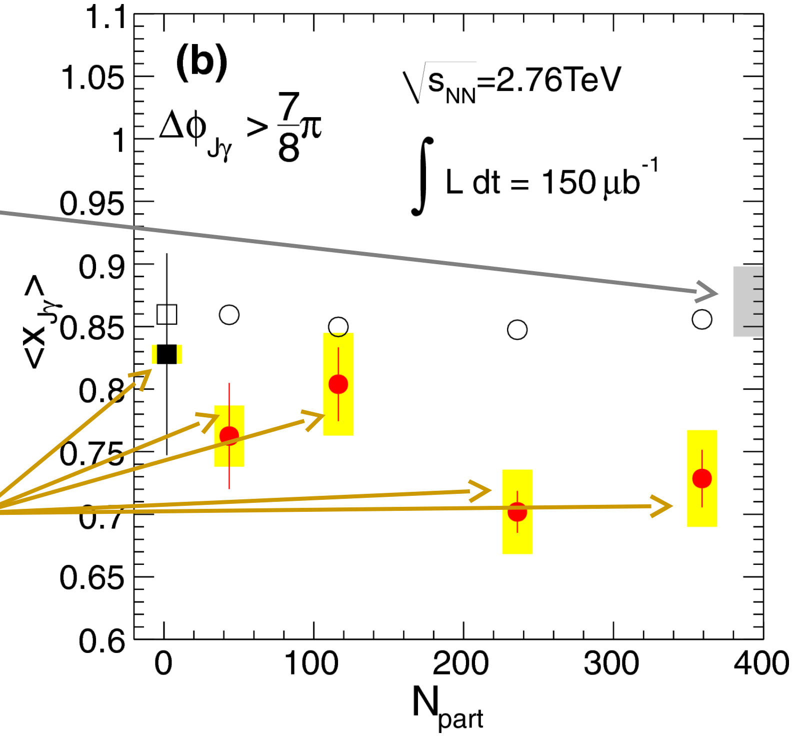
Summary of Systematic Uncertainty: $\langle x_{J\gamma} \rangle$

Source	pp	50–100%	30–50%	10–30%	0–10%
γ–jet rel. energy scale	2.8%	4.1%	5.4%	5.0%	4.9%
γ purity	2.2%	2.2%	1.9%	2.4%	2.7%
Jet pT threshold	0.7%	0.7%	1.9%	1.9%	2.0%
Isolated γ definition	0.1%	0.1%	0.7%	0.4%	2.0%
γ pT threshold	0.6%	0.6%	0.6%	0.6%	1.3%
Jet efficiency	0.5%	0.5%	0.6%	0.6%	0.5%
$e\pm$ contamination	0.5%	0.5%	0.5%	0.5%	0.5%
Fake jet contamination	0.1%	0.1%	0.1%	0.2%	0.1%
γ efficiency	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	0.1%	0.2%
Total	**3.7%**	**4.8%**	**6.2%**	**6.0%**	**6.4%**
Correlated	**3.6%**	**3.6%**	**3.6%**	**3.6%**	**3.6%**
Point-to-point	**0.9%**	**3.2%**	**5.1%**	**4.8%**	**5.3%**

Systematic Uncert.: Decorrelation for ⟨xJγ⟩

Source	pp	50–100%	30–50%	10–30%	0–10%
Total	**3.7%**	**4.8%**	**6.2%**	**6.0%**	**6.4%**
Correlated	**3.6%**	**3.6%**	**3.6%**	**3.6%**	**3.6%**
Point-to-point	**0.9%**	**3.2%**	**5.1%**	**4.8%**	**5.3%**

- Total = correlated ⊕ point-to-point, or Point-to-point = Total ⊖ correlated
- Correlated describes the overall ⟨xJγ⟩ sensitivity
  - shifts all ⟨xJγ⟩ points simultaneously
  - normalization-like
- Point-to-point describes pp and PbPb centrality dependence



Summary of Systematic Uncertainty: *RJγ*

Source	pp	50–100%	30–50%	10–30%	0–10%
Jet *p*T threshold	1.4%	1.4%	2.3%	2.6%	2.7%
γ purity	2.3%	2.3%	1.9%	0.2%	0.9%
γ *p*T threshold	2.0%	2.0%	1.9%	1.3%	2.1%
Jet efficiency	1.5%	1.5%	1.7%	1.8%	2.1%
Fake jet contamination	0.4%	0.4%	0.8%	1.0%	1.4%
Isolated *γ* definition	0.2%	0.2%	0.6%	1.3%	0.8%
e± contamination	0.5%	0.5%	0.5%	0.5%	0.5%
γ efficiency	0.2%	0.2%	0.2%	0.5%	0.5%
Total	**3.7%**	**3.7%**	**4.1%**	**3.9%**	**4.5%**

- Fully data driven, vary analysis by expected uncertainties
- Nonmonotonic centrality dependence due to statistical limitation
- *RJγ* is not unitary normalized, and therefore more sensitive to the jet/photon sample and jet efficiency

Jet/Photon Relative Energy Scale

Energy Scale Source	pp	30–100%	0–30%
pp jet–γ relative (missing ET projection fraction)	2%	2%	2%
pp data/MC difference	2%	2%	2%
Heavy ion UE on jet (PYTHIA + HYDJET 1.8)	—	3%	4%
Heavy ion UE on γ (PbPb ECAL $\ominus$ pp ECAL)	—	$< 1\%$	$< 1\%$
Total relative	**2.8%**	**4.1%**	**4.9%**
pp ECAL	—	1%	1%
Total absolute	**3.0%**	**4.2%**	**5.0%**

- Jet energy scale = jet–γ relative $\oplus$ ECAL absolute (next slide)
- Sampled jet pT range is well calibrated (no extrapolation)
- Relative energy scale directly shifts xJγ
- Absolute energy propagates into pT thresholds