Study of Jet Quenching Using Photon–Jet Events in PbPb Collisions at 2.76 TeV with CMS

Yue Shi Lai

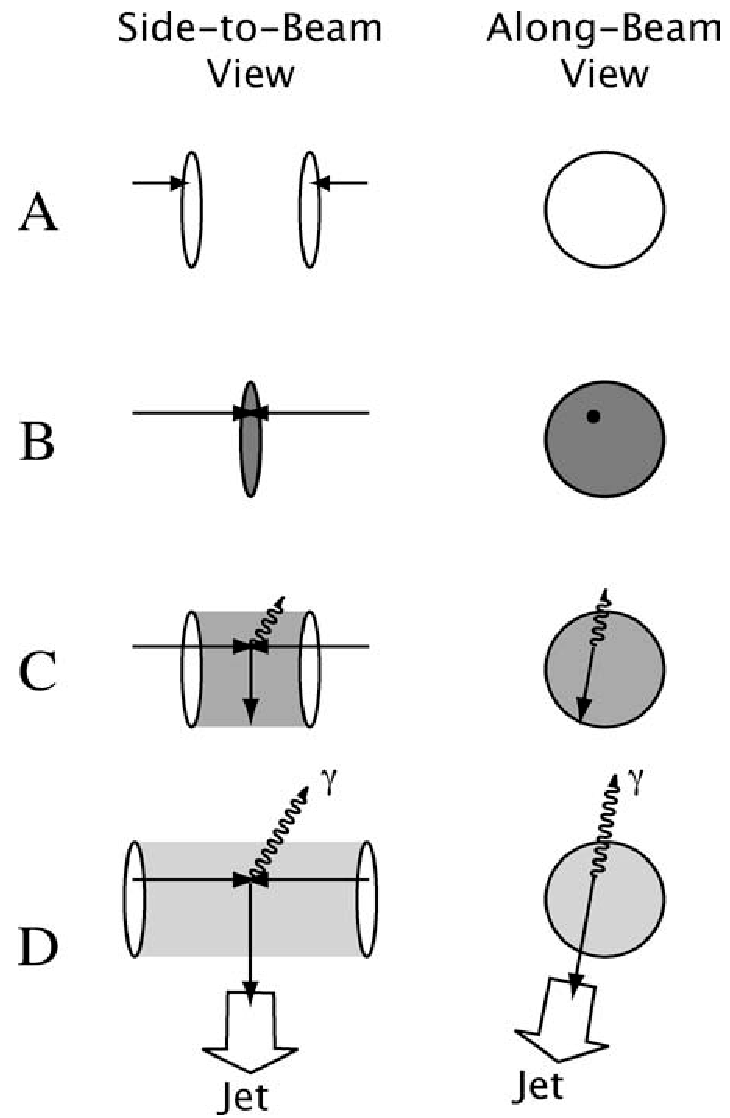
MIT

for the CMS Collaboration

Quark Matter 2012

Motivation

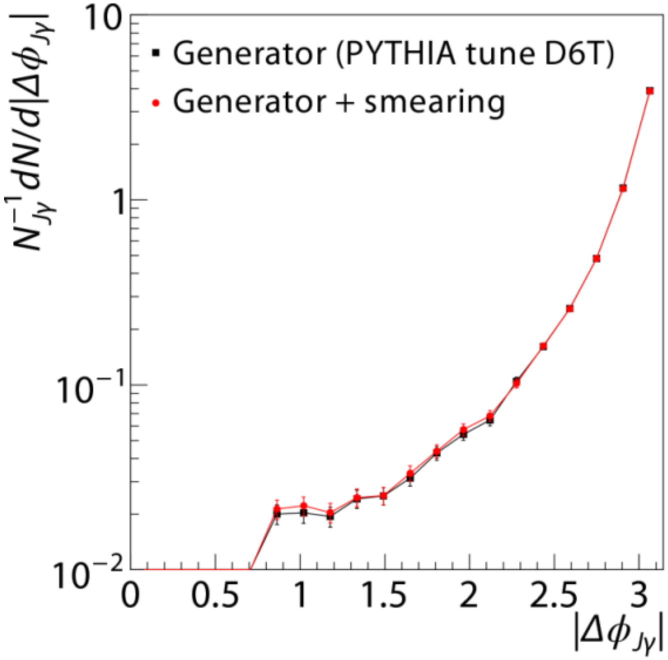
- Direct measurement of the parton energy loss in the QGP with photon–jet events.
- Isolated photons are unmodified
- Remove the "surface bias" which dijet events suffer
- Access to the initial parton energy via isolated photon
- Access to the final parton energy via jet reconstruction

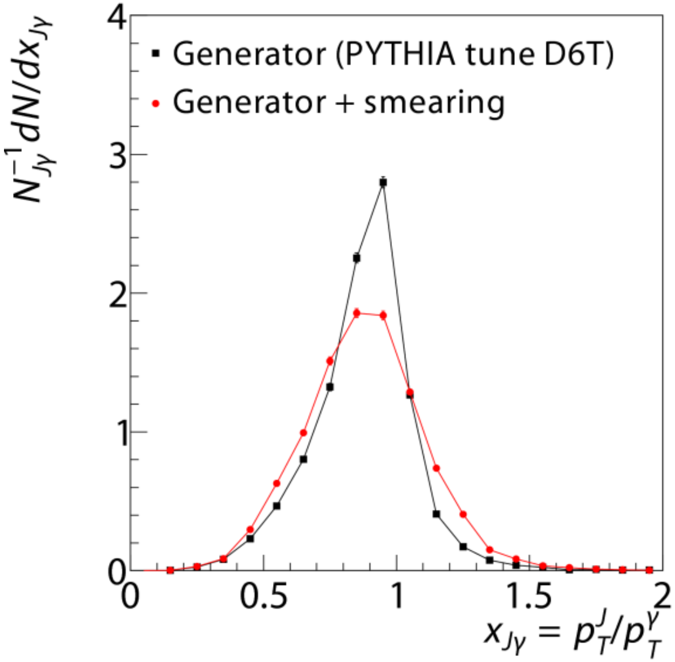


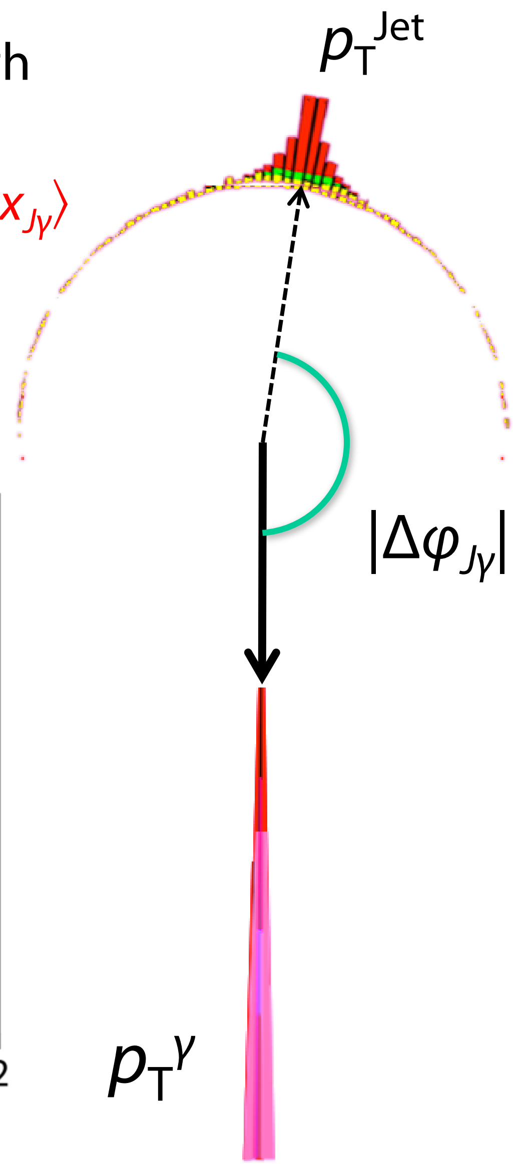
P. Stankus, Ann. Rev. Nucl. Part. Sci. 55, 517 (2005)

Observables

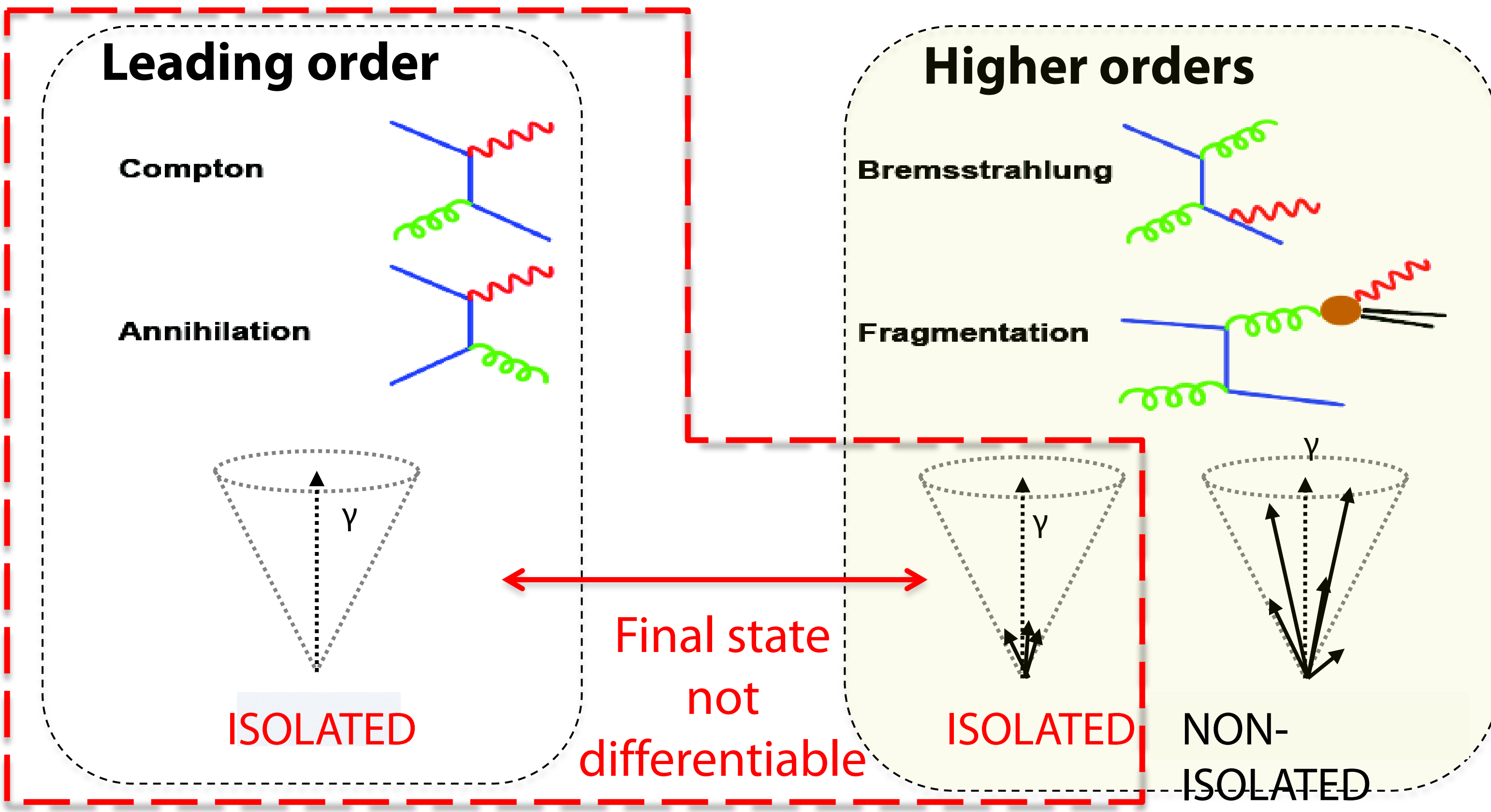
- Azimuthal decorrelation: $|\Delta\varphi_{J\gamma}|$, and its parametrized width $\sigma(|\Delta\varphi_{J\gamma}|)$
- Transverse momentum ratio: $x_{J\gamma} = p_T^{Jet}/p_T^{\gamma}$, and its mean $\langle x_{J\gamma} \rangle$
- Fraction of photons with associated jets: $R_{J\gamma}$
- $p_T^{\gamma} > 60$ GeV/c (to have sufficient $x_{J\gamma}$ phase space)
- $p_T^{Jet} > 30$ GeV/c (constrained by efficiency)





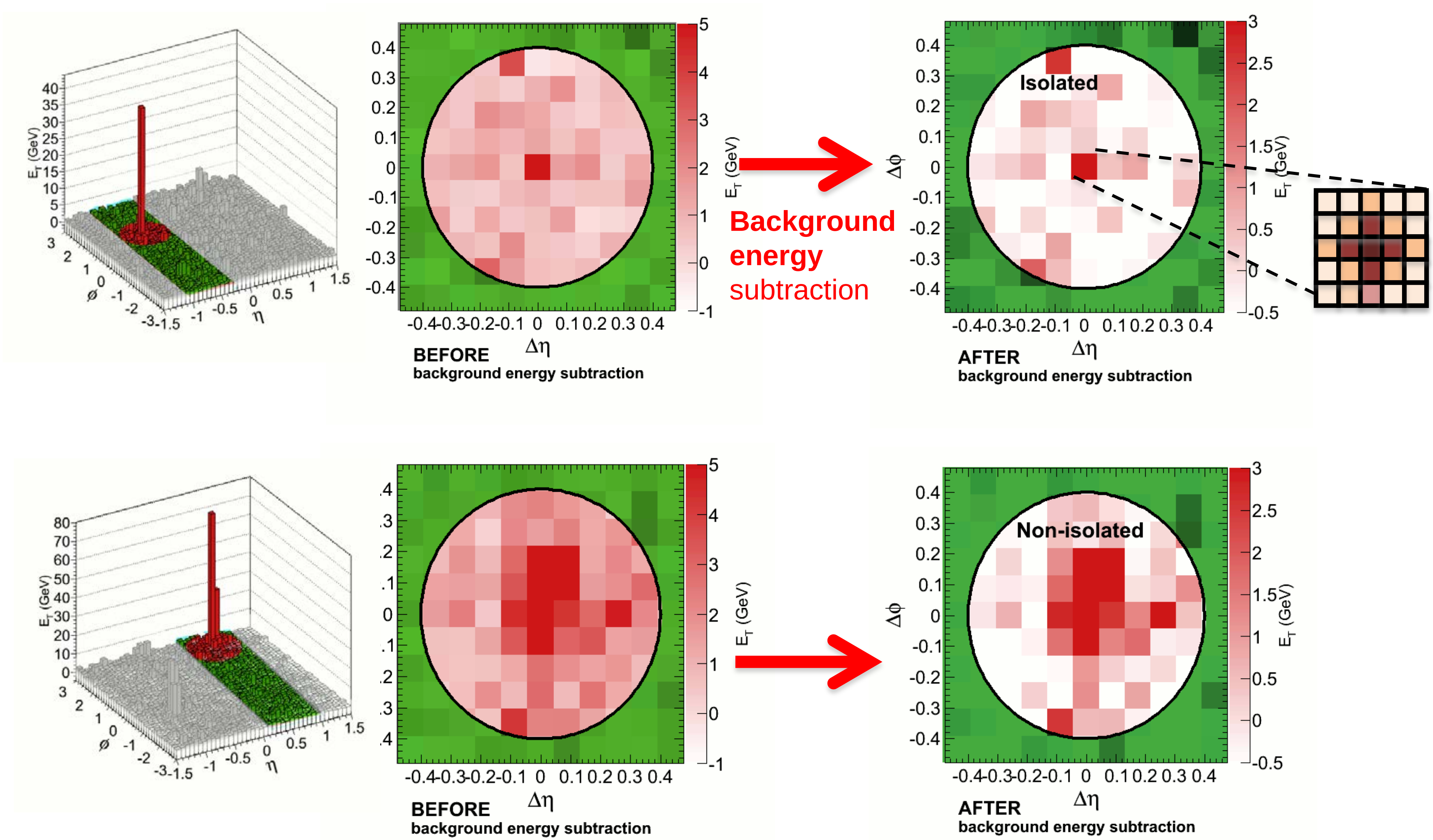


Signal Definition



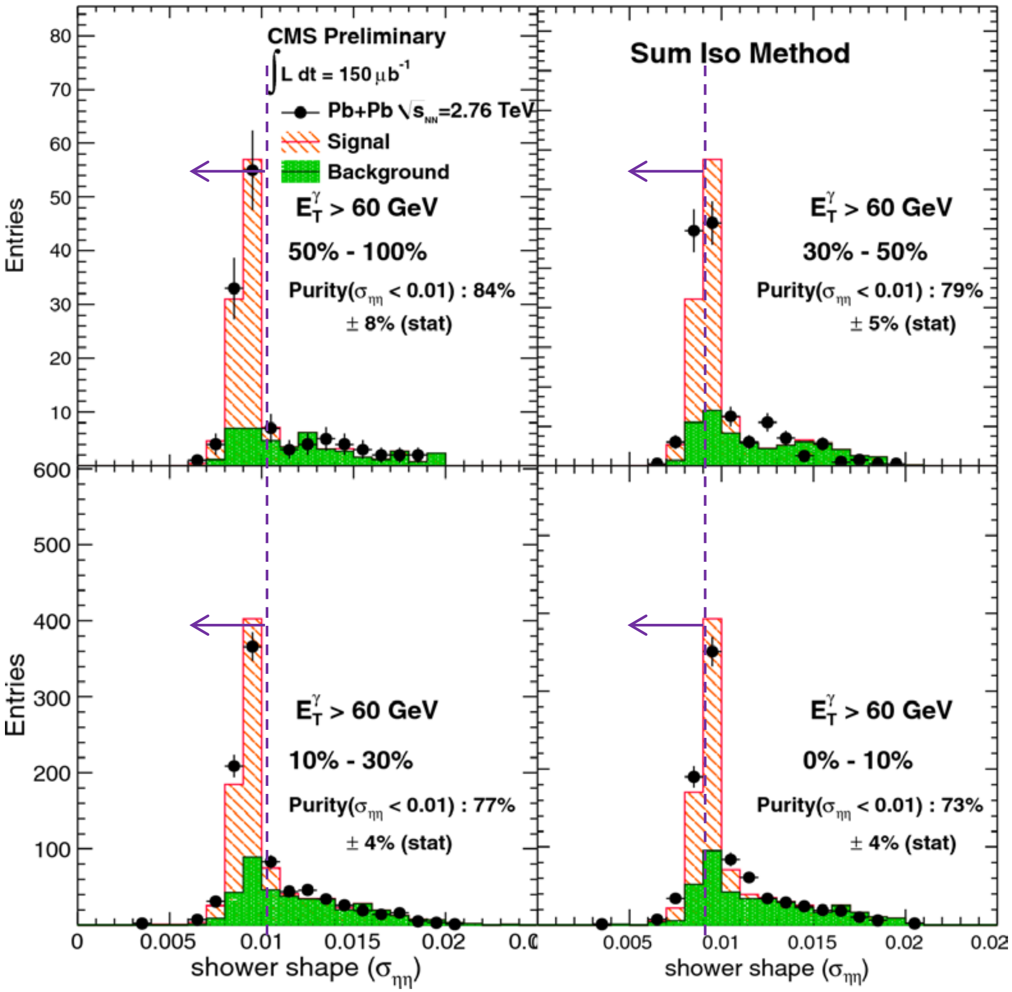
- SumIso = uncorrected Track + ECAL + HCAL E_T in $R < 0.4$
- GenIso = generator level particle energy in $R < 0.4$
- Isolated prompt (non-decay) photons with SumIso < 1 GeV
- Comparison to MC definition GenIso < 5 GeV
- SumIso ≠ GenIso due to PbPb underlying event fluctuation

Isolation in Data



Y. Kim, QM 2011

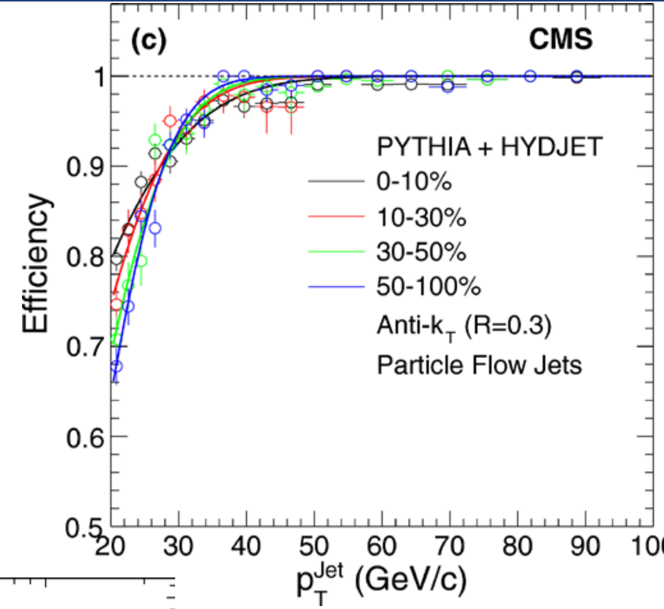
Statistical Subtraction of Decay Photons

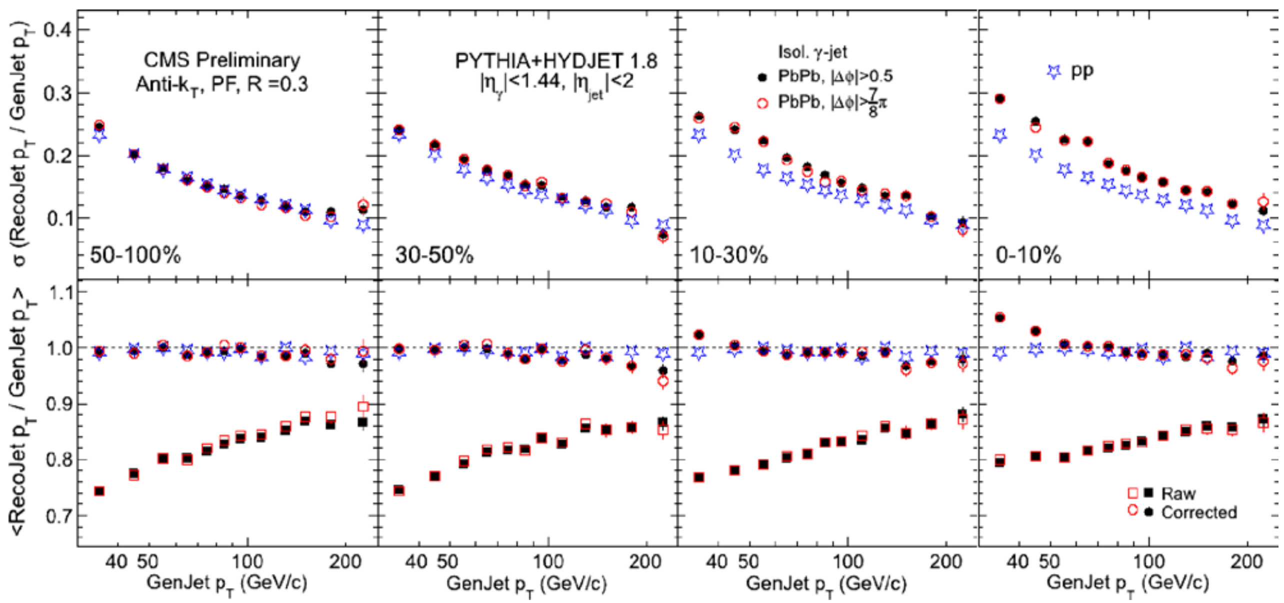


- Shower shape
  $\sigma_{\eta\eta} = \Sigma_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2 / \Sigma_i^{5\times5} w_i$
  $w_i = \max(0, c + \ln E_i/E_{5\times5})$
- Decay photons largely removed by cutting on $\sigma_{\eta\eta} < 0.01$
- Remaining contribution of decay photons removed using predicted $\sigma_{\eta\eta}$ distribution
- Shape of background $\sigma_{\eta\eta}$ found **data driven** using photons failing the SumIso cuts

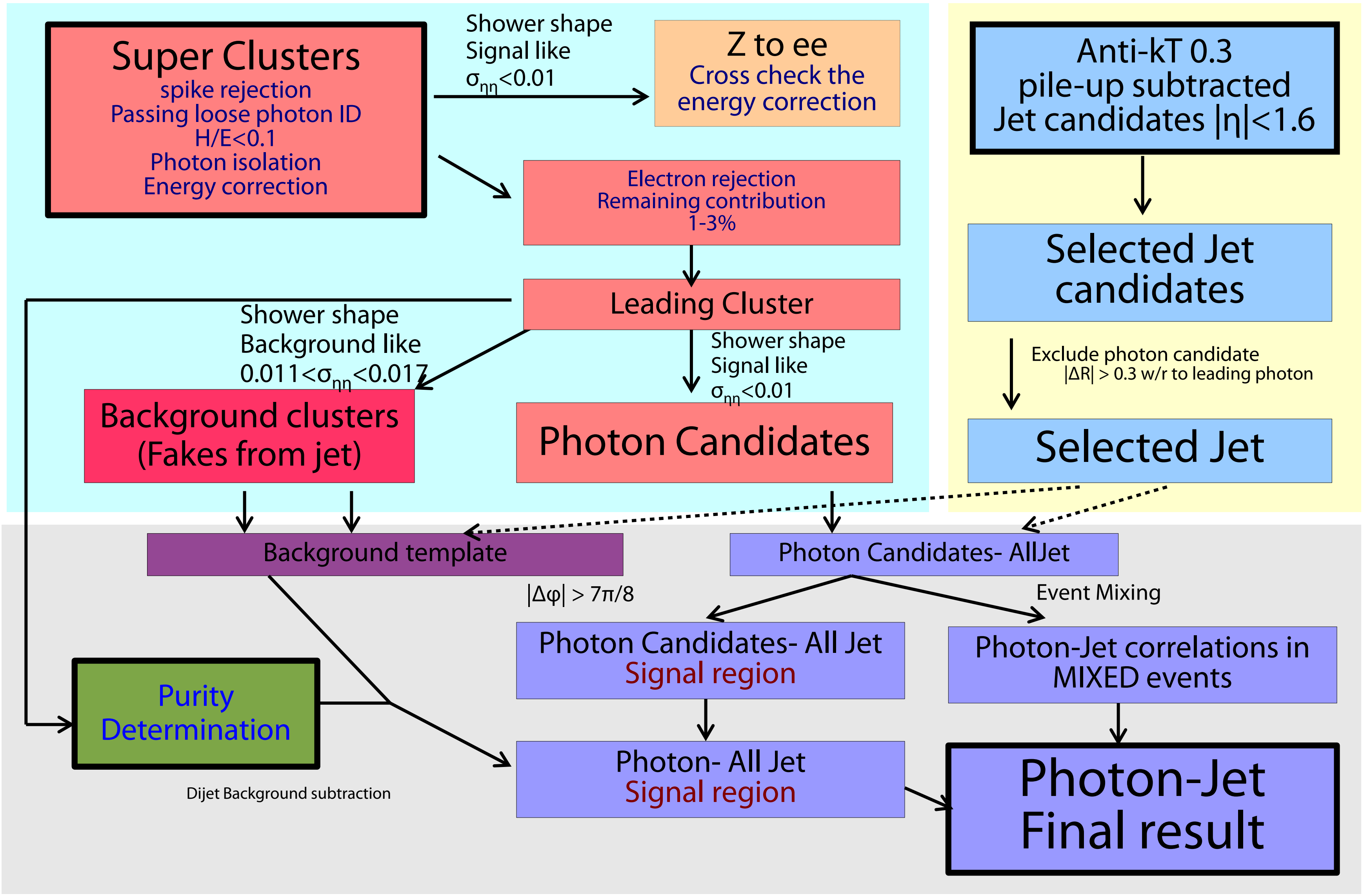
Signal Selection: Jet

- Anti-k_T particle flow jets, $R = 0.3$
- UE estimation/subtraction using φ-rings in η, excluding jet candidates (two iterations)
- Reconstruction > 90% efficient for $p_T^{Jet} > 30$ GeV/c in PbPb
- **Jet energy resolution parameterization provided in arXiv:1205.0206**



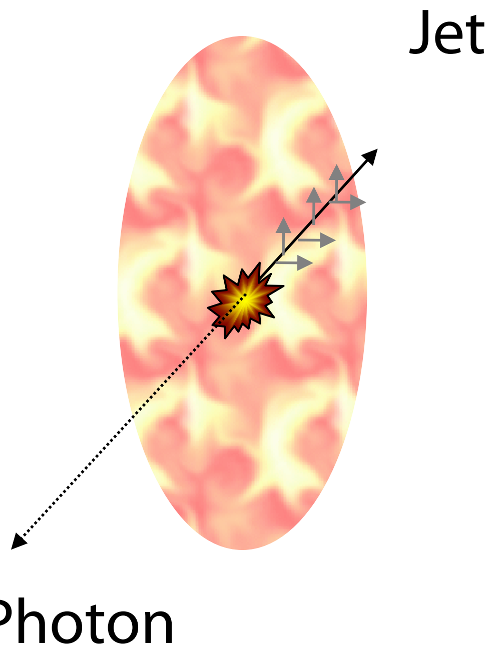


Analysis Flow Chart

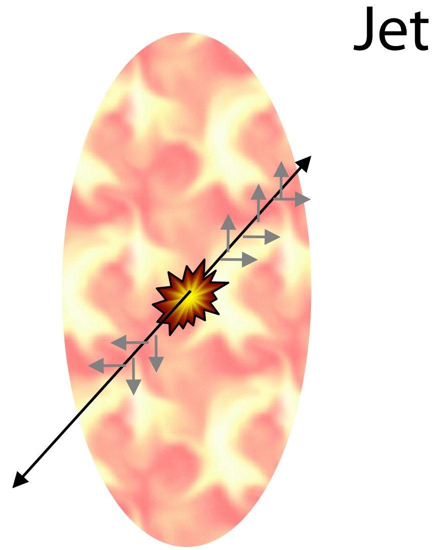


Photon–Jet Pair Sources

Signal photon-jet



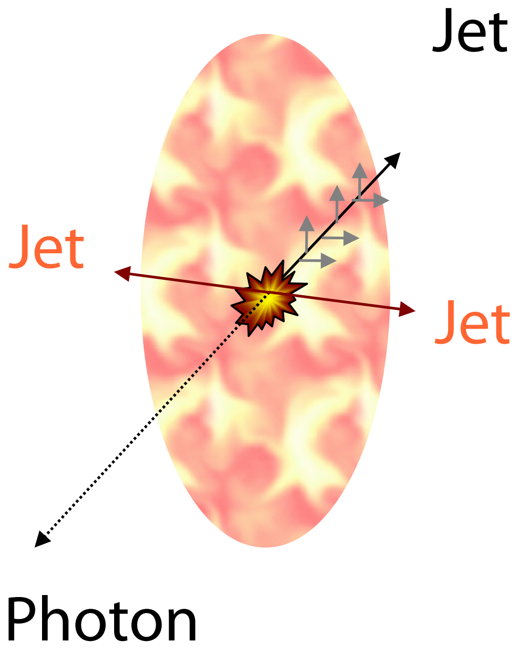
Background from dijet



Background photon from jet

Remove data-driven by shower shape

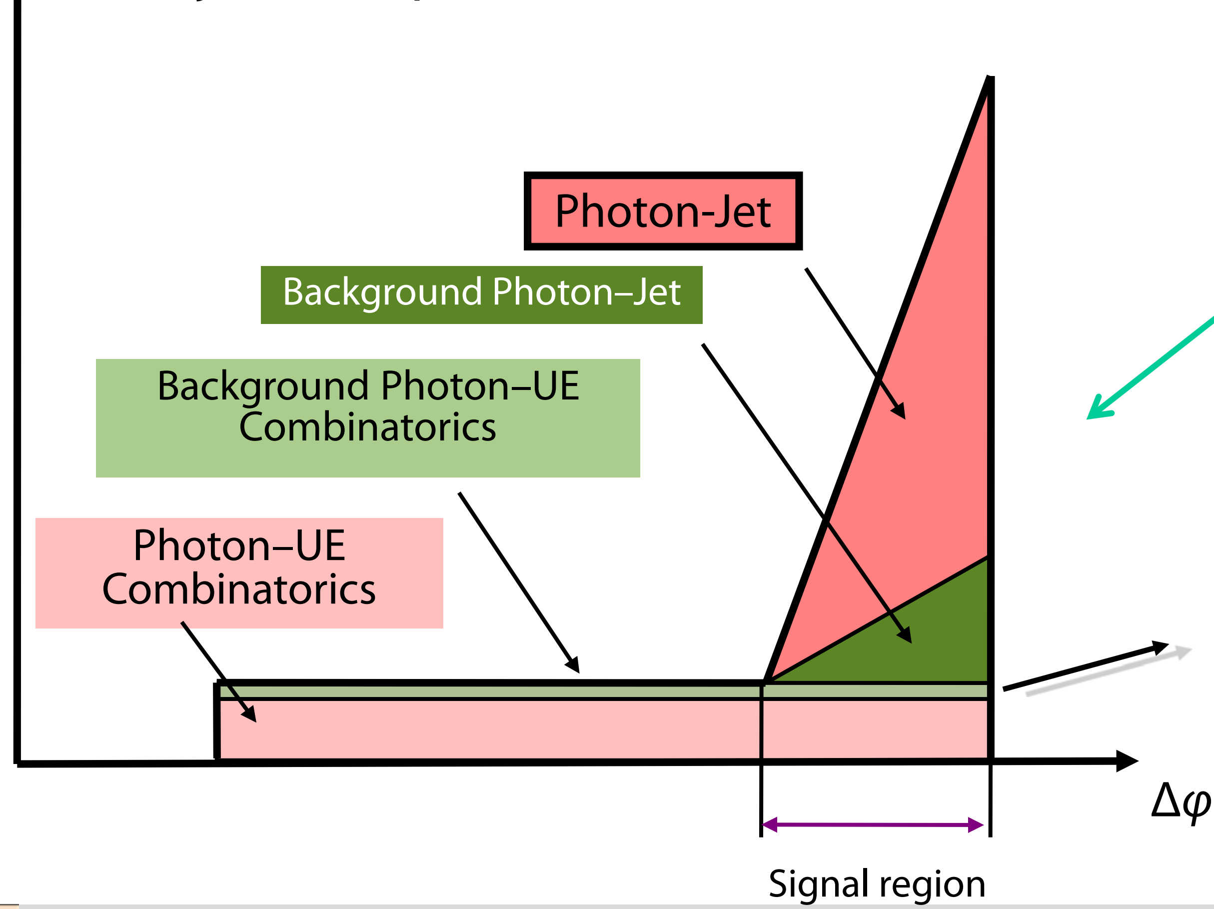
Contribution from uncorrelated multiple interaction/fake

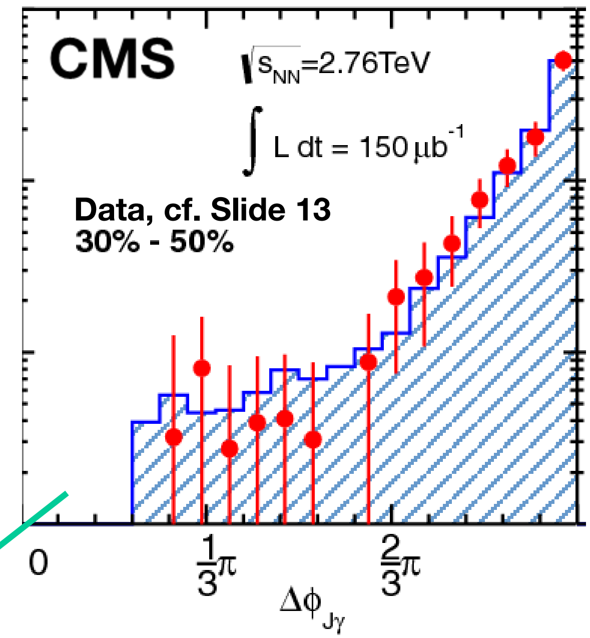


Remove by data-driven template from event mixing

Statistical Subtraction (I)

Step 1: Remove the UE combinatorics (fake jet/multiple interaction) contribution

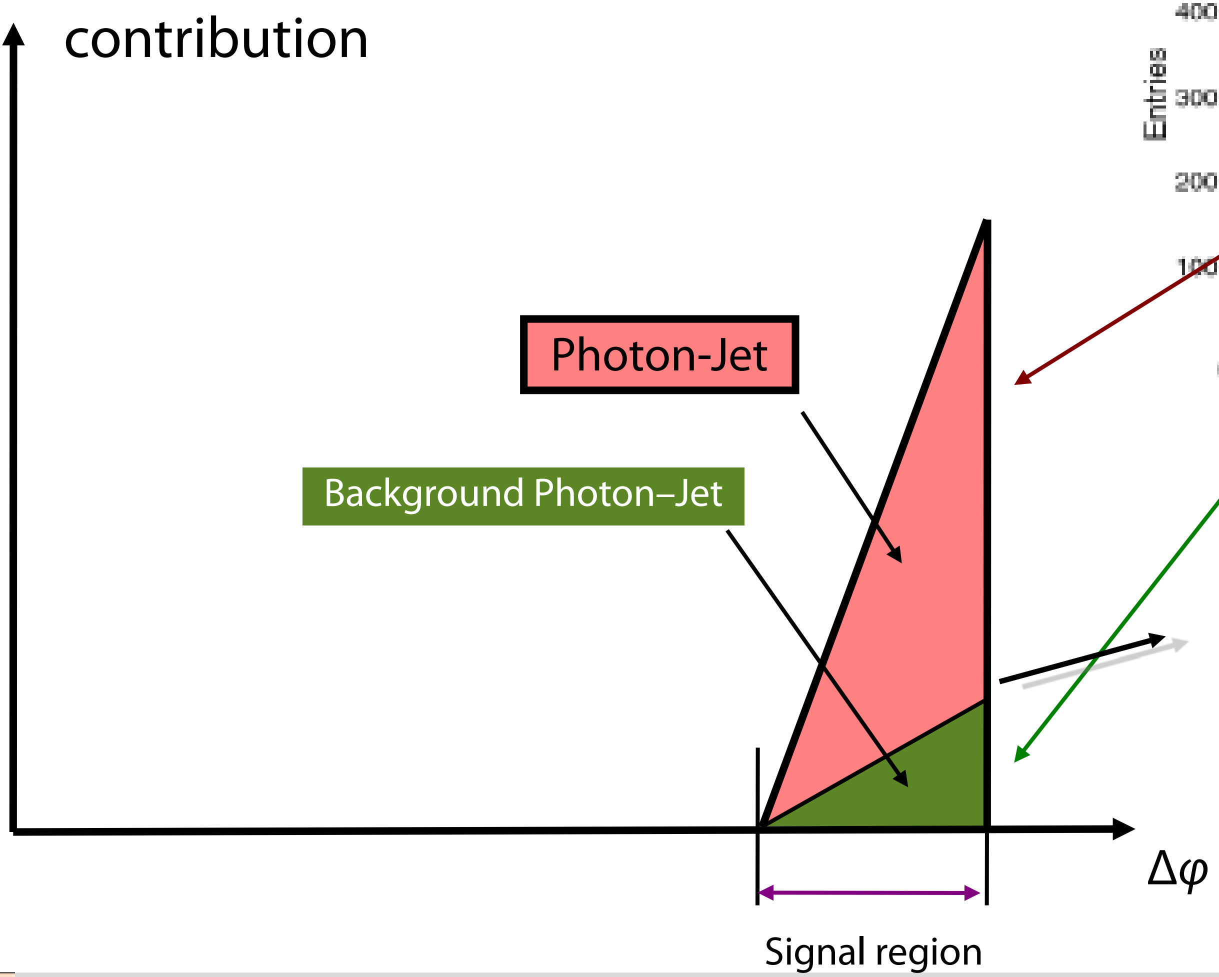


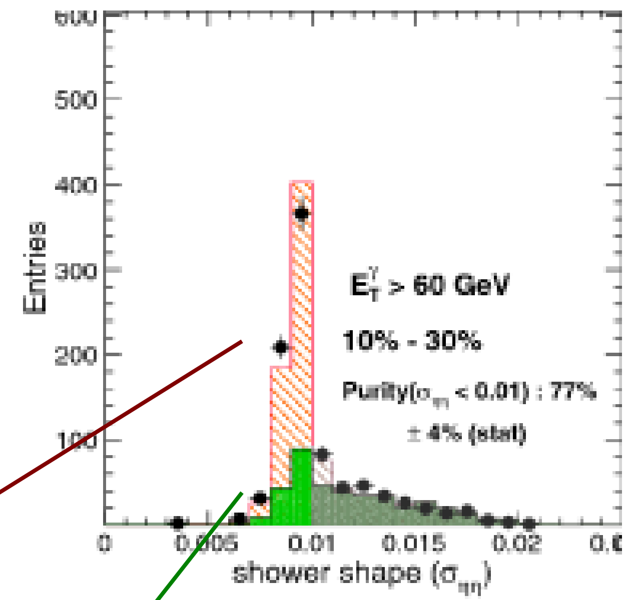


Estimated from event mixing method using minimum-bias data

Statistical Subtraction (II)

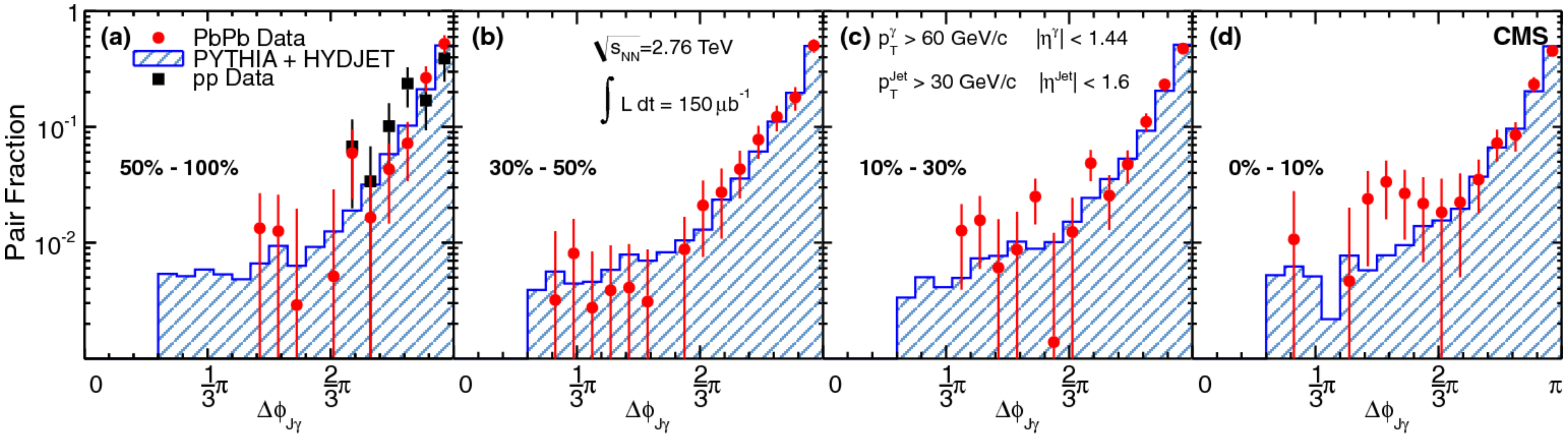
Step 2: Remove the decay photon contribution





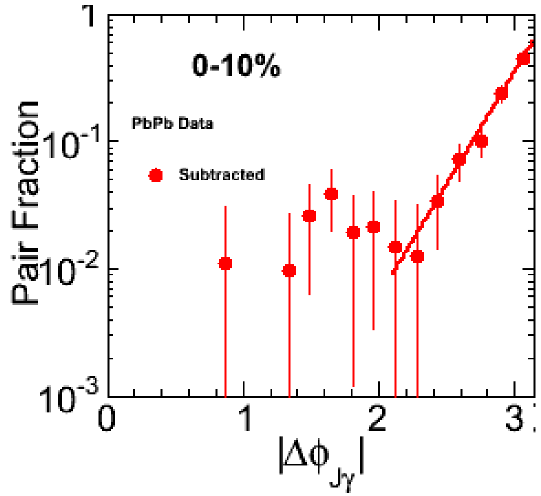
Estimated from shower shape sideband & purity

Angular Correlation: $dN/d|\Delta\varphi_{J\gamma}|$



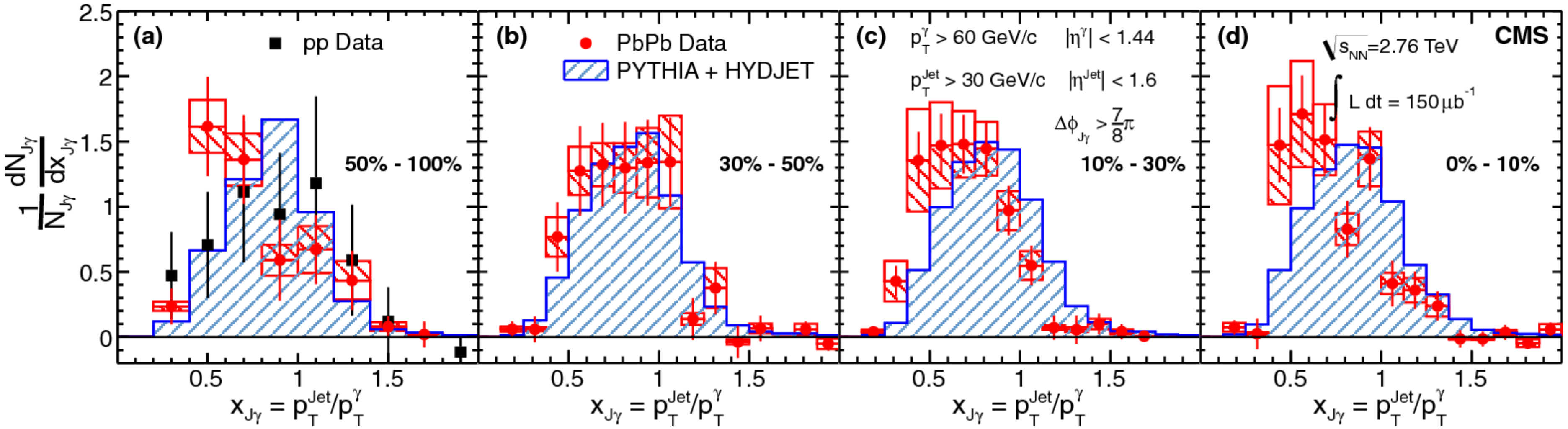
- Distribution is consistent with pp & PYTHIA tune Z2 + HYDJET
- To quantify the centrality dependence, peak region is fit with an empirical formula

$$\frac{1}{N^{\gamma-\mathrm{jet}}}\frac{dN^{\gamma-\mathrm{jet}}}{d\Delta\varphi_{J\gamma}} = \frac{e^{(\Delta\varphi-\pi)/\sigma}}{(1-e^{-\pi/\sigma})\sigma}$$



arXiv:1205.0206, submitted to PLB

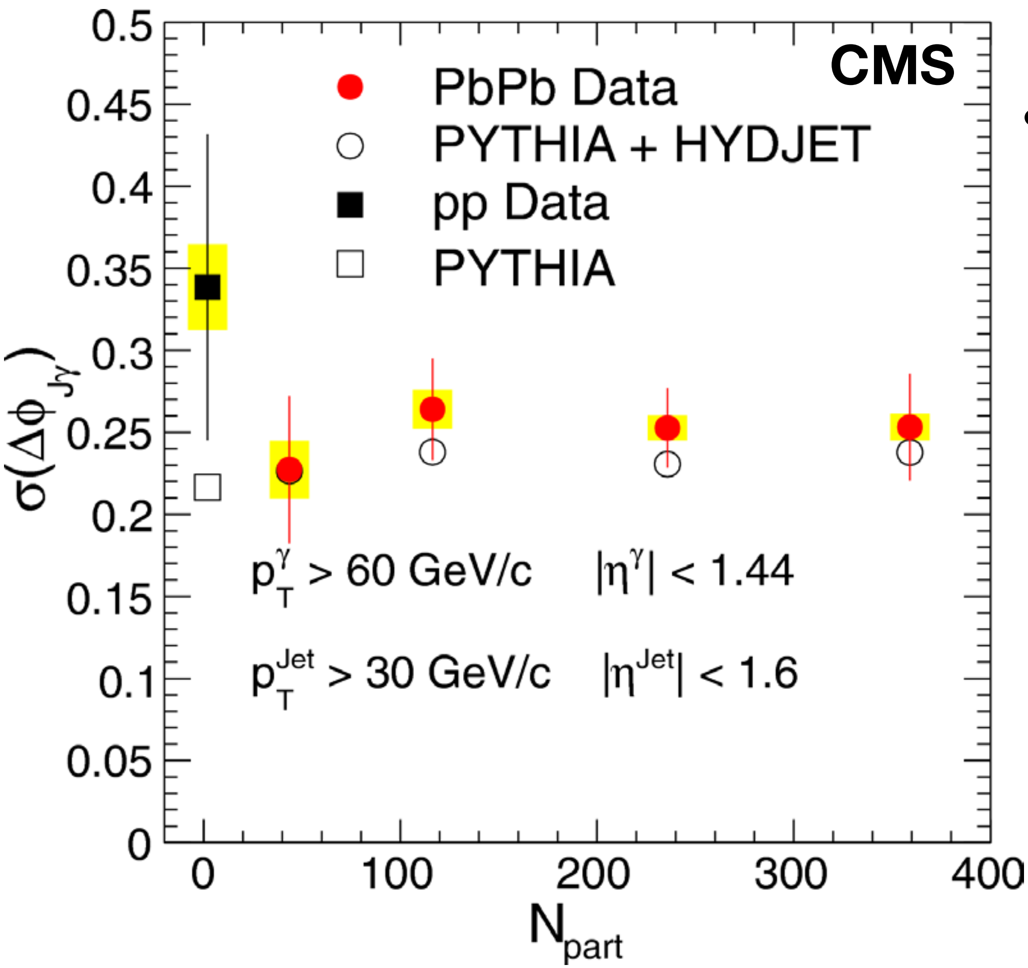
Transverse momentum Ratio: $dN/dx_{J\gamma}$



- Momentum ratio shifts/decreases with centrality
- Unitary normalized distribution, points anticorrelated
- Open/shaded boxes try to indicate possible, anticorrelated systematic variation

arXiv:1205.0206, submitted to PLB

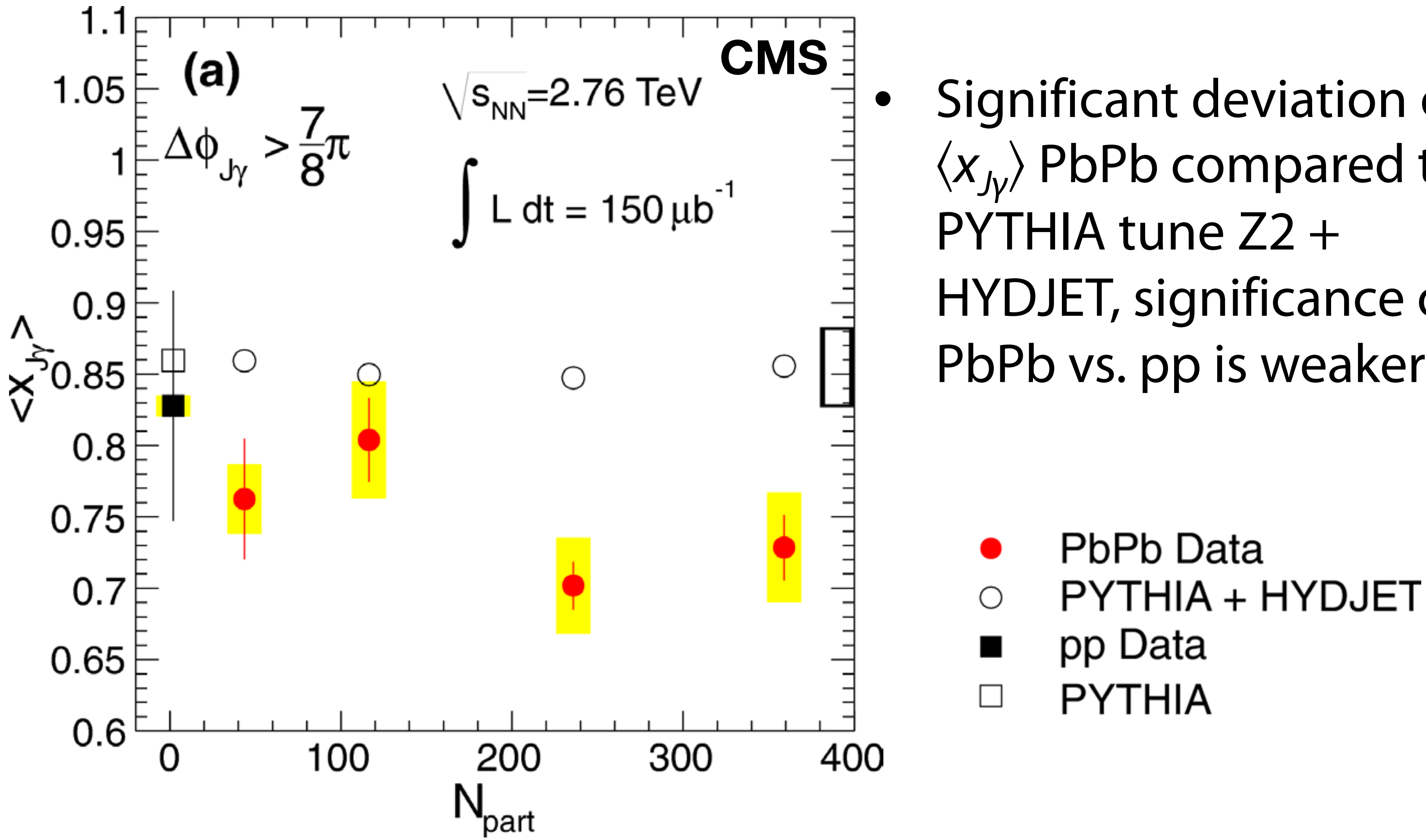
Angular Correlation Width: $\sigma(|\Delta\varphi_{J\gamma}|)$



- Angular width $\sigma(|\Delta\varphi_{J\gamma}|)$ is consistent, both PbPb to pp and PbPb to PYTHIA tune Z2 + HYDJET

arXiv:1205.0206, submitted to PLB

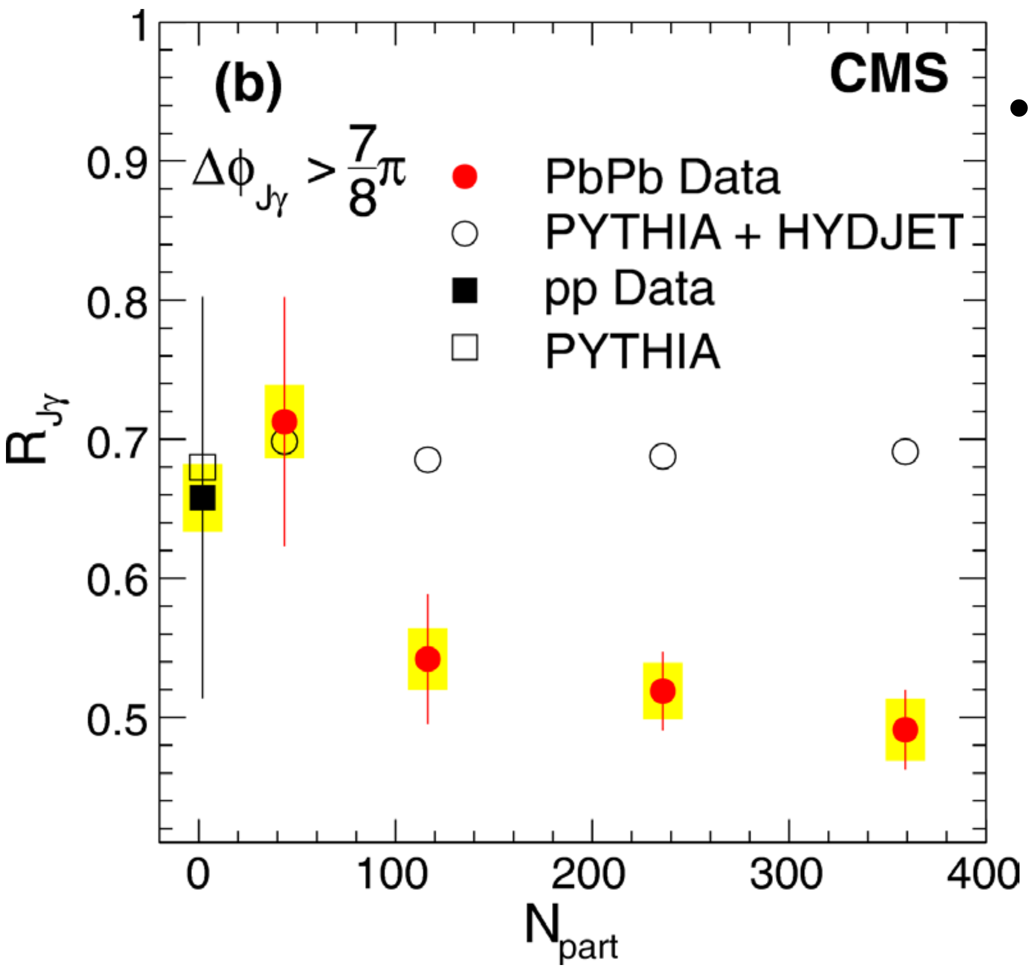
Mean Momentum Ratio: $\langle x_{J\gamma} \rangle$



- Significant deviation of $\langle x_{J\gamma} \rangle$ PbPb compared to PYTHIA tune Z2 + HYDJET, significance of PbPb vs. pp is weaker

arXiv:1205.0206, submitted to PLB

Fraction of Observing the Corr. Jet: $R_{J\gamma}$



- The centrality dependence is mostly visible in $R_{J\gamma}$ (jet p_T shifting below the 30 GeV threshold)

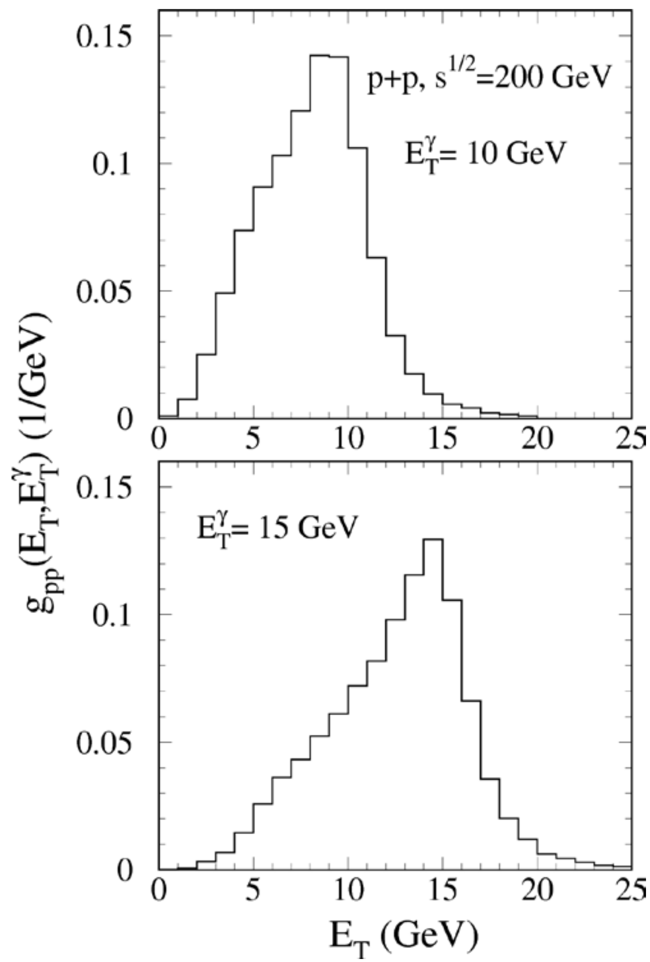
arXiv:1205.0206, submitted to PLB

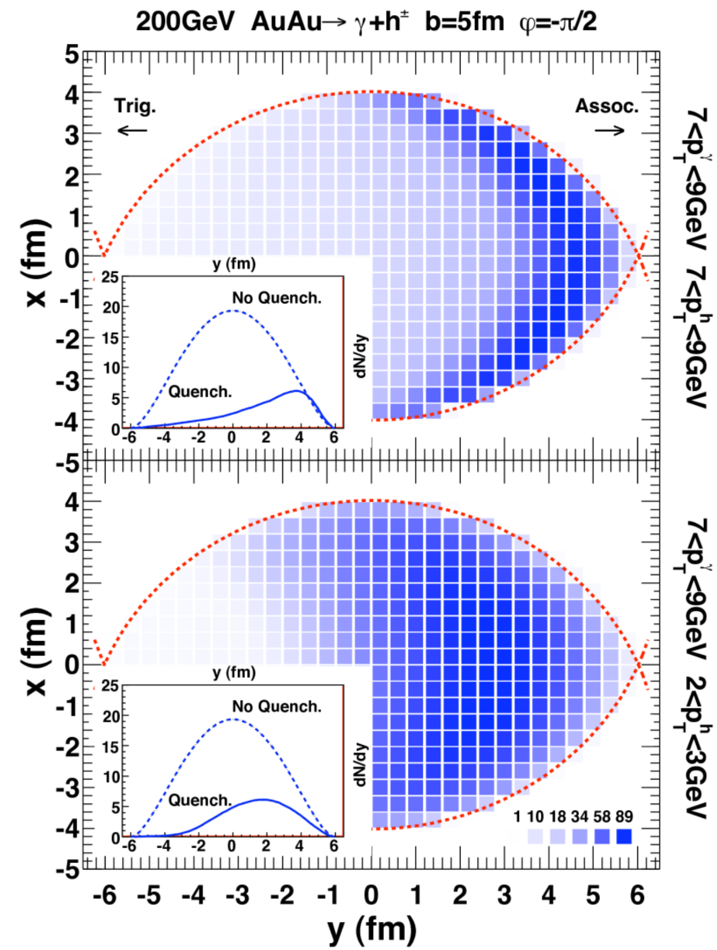
Summary

- Measurement of isolated prompt photon+jet correlation
- Direct observation of jet energy loss vs. initial parton energy
- No measurable change in $\Delta\varphi_{J\gamma}$, extends to $p_T^{Jet} = 30$ GeV/c
- Shift of associated jet towards lower p_T with centrality:
  - Observation of significant shift of jet–photon p_T ratio with respect to MC
    - Shift with respect to pp is less significant due to large pp statistical uncertainties
  - Significant fraction of associated jets are shifted to $p_T < 30$ GeV/c

Backup

15 Years of Photon–Jet Theory



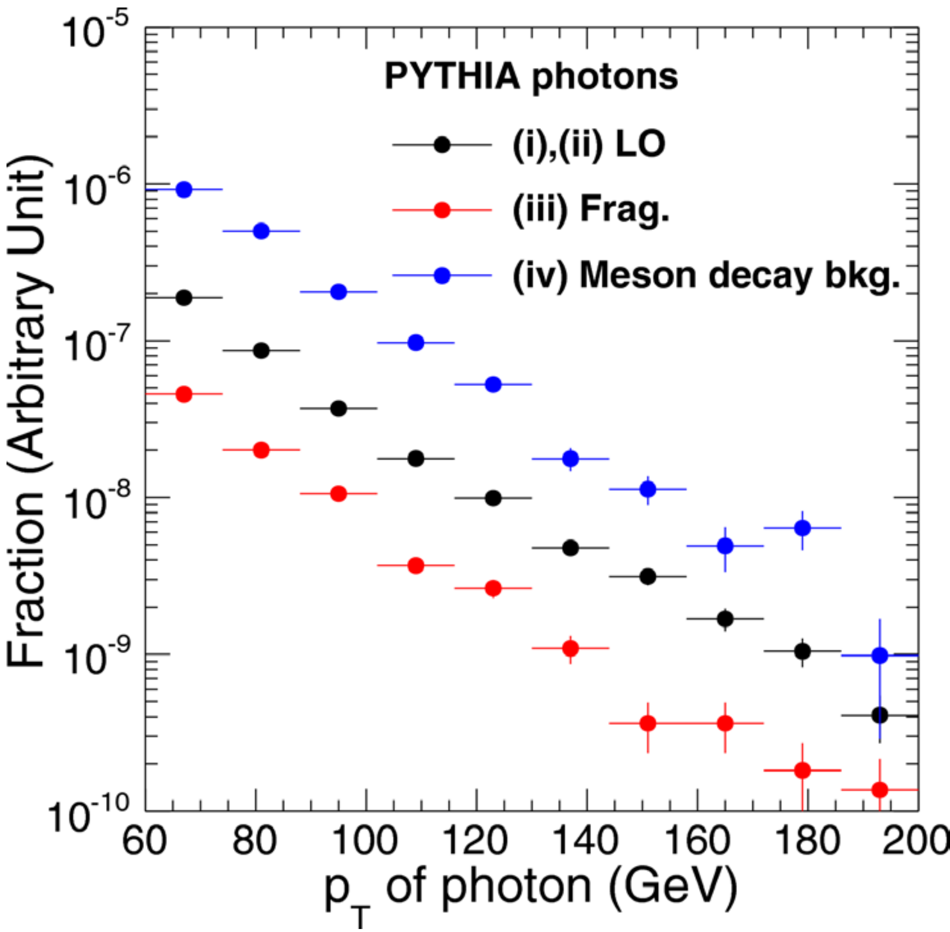


X.-n. Wang (LBNL), Z. Huang, Phys.Rev.C55:3047-3061,1997

H.-z. Zhang et al., Phys. Rev. Lett. 103, 032302 (2009)

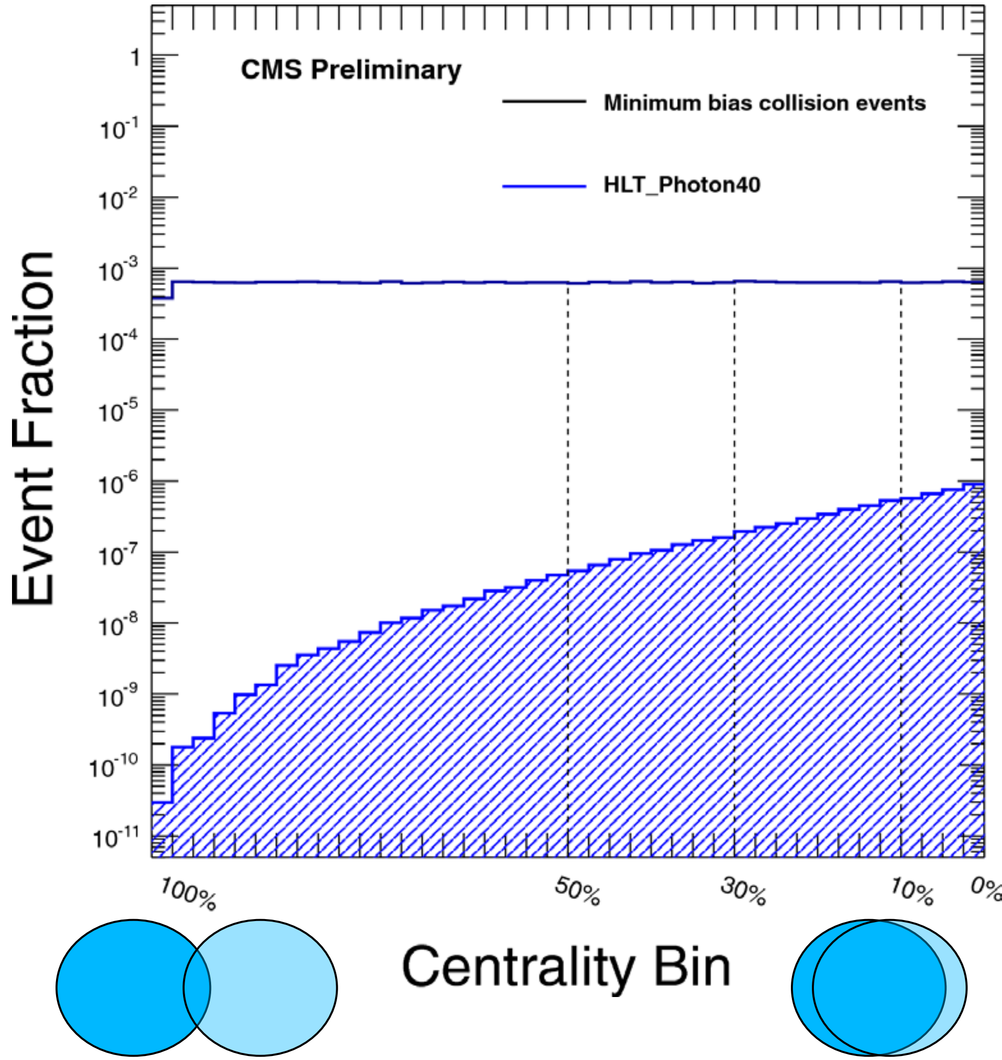
MC Reference: EM + QCD Hard Scattering

- CMSSW_4_4_2_patch3 global tag STARTHI44_V7
- PYTHIA tune Z2, D6T as cross check
- Prompt photons (LO/direct + fragmentation)
- $p_T \in \{15, 30, 50, 80\}$ GeV/c
- Underlying event (UE) using HYDJET 1.8 (DRUM) – fits CMS random cone UE data

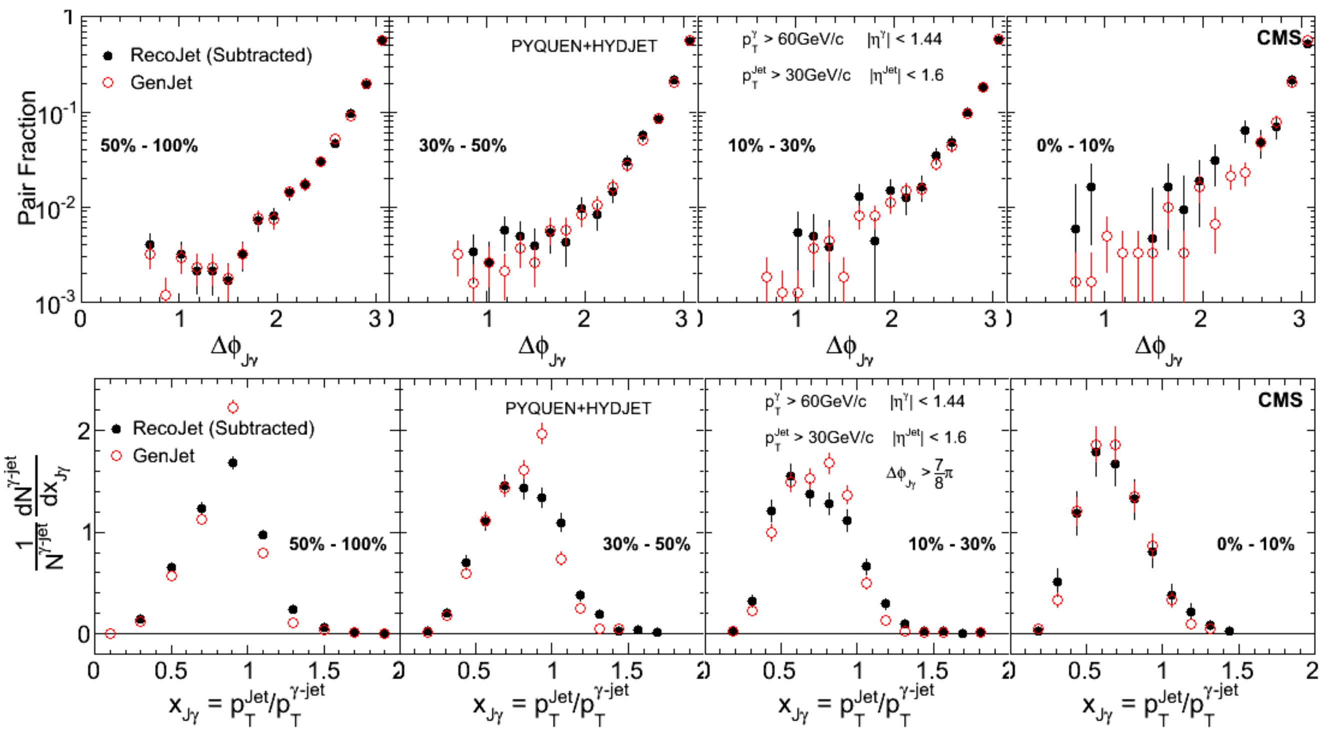


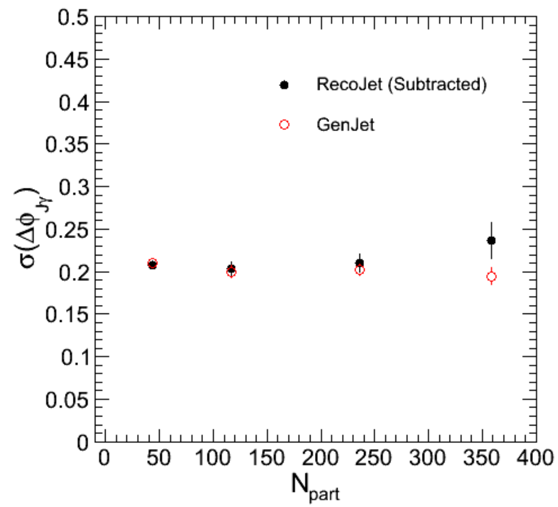
Collisional Centrality

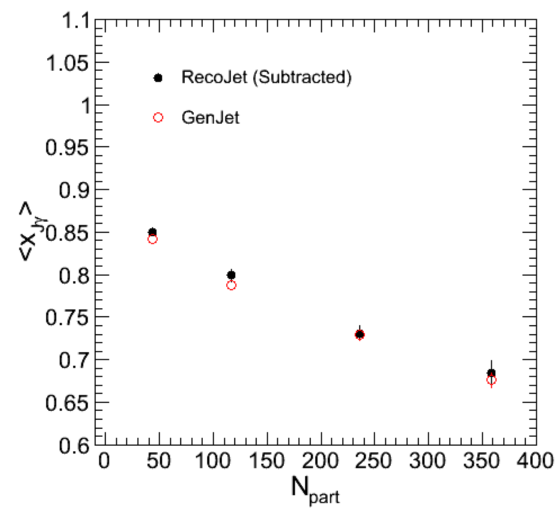
- CMS uses HF for experimental determination of centrality
- Number of participants N_{part} describes the nuclear overlap (experiment independent)
- Correlation of centrality and N_{part} determined using Glauber geometry calculation (HIJING/AMPT)



“Quenched” Closure Check: PYQUEN

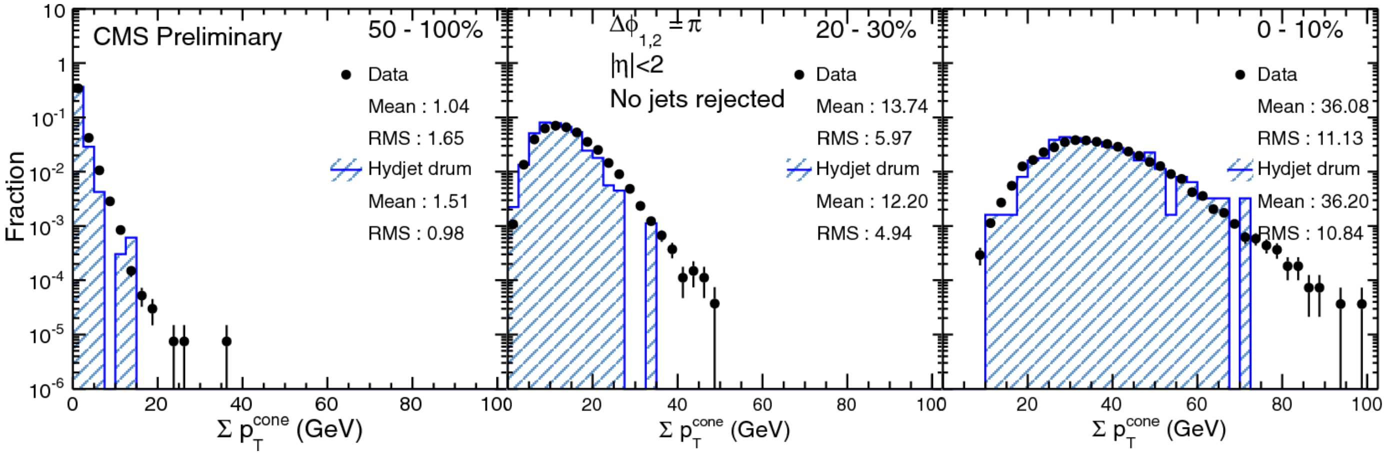


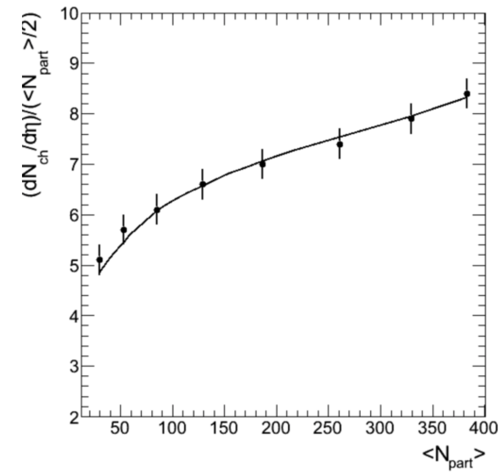




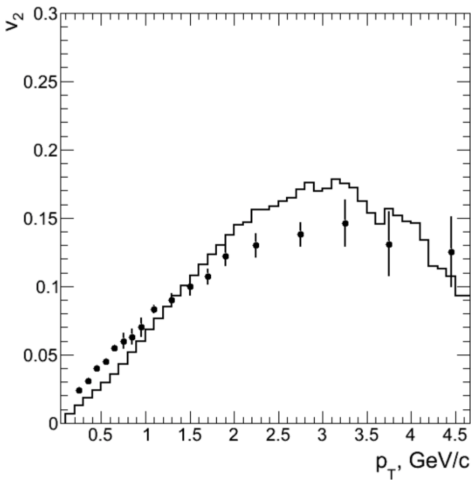
- Insert a possible model of energy loss and follow through the analysis chain
- Analysis closes on PYQUEN energy loss

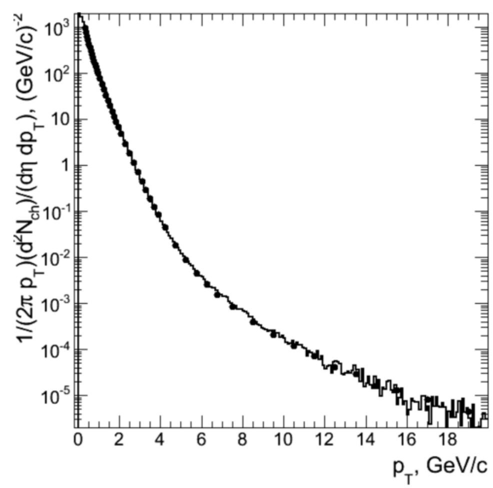
MC Reference: PbPb Underlying Event



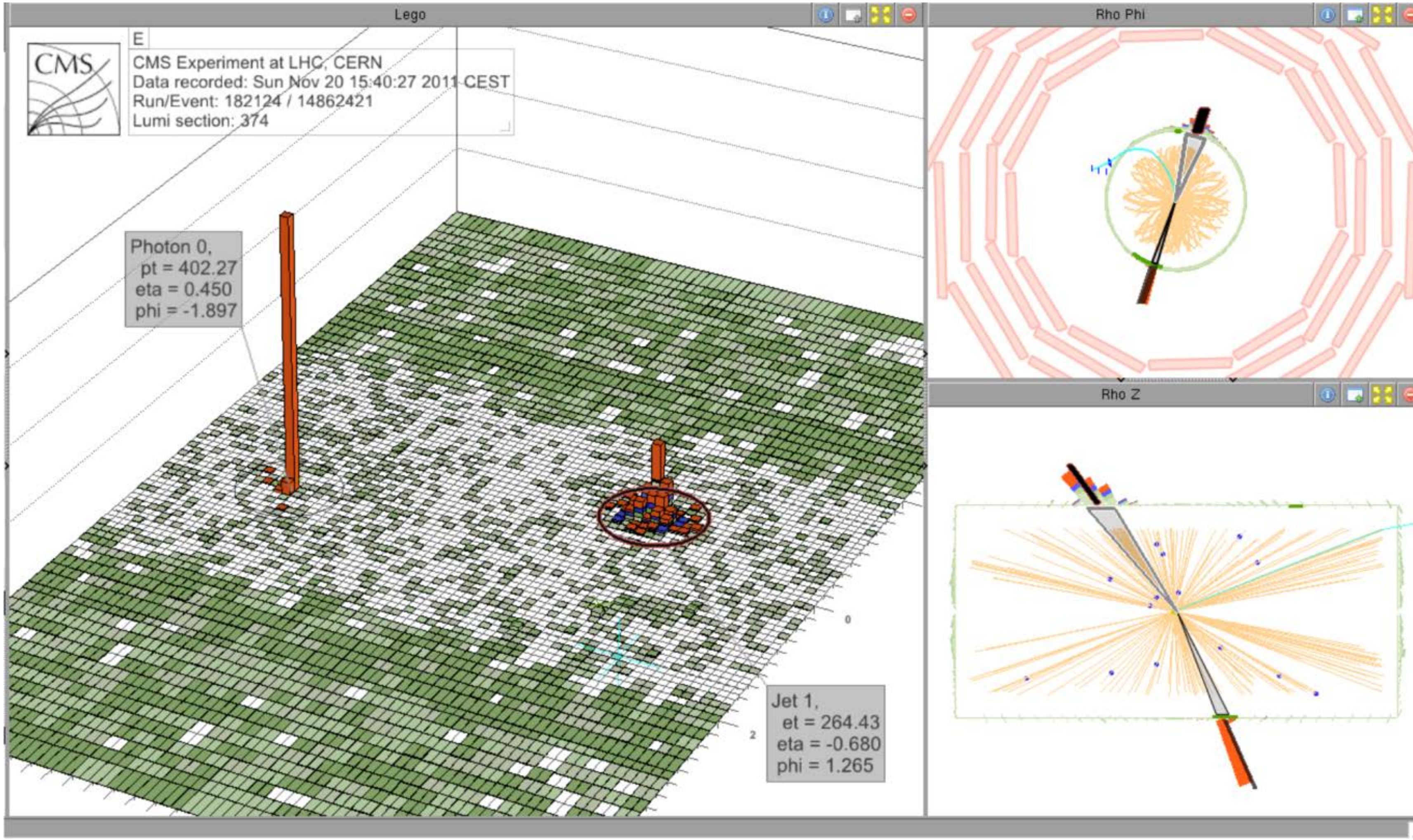


- HYDJET 1.8 (DRUM)
- Fits CMS UE (random cone)
- Fits well ALICE $dN/d\eta$, p_T spectrum, somewhat the event anisotropy (v_2) (PRL 106 (2011) 032301, PLB 696 (2011) 30, PRL 105 (2010) 252302)



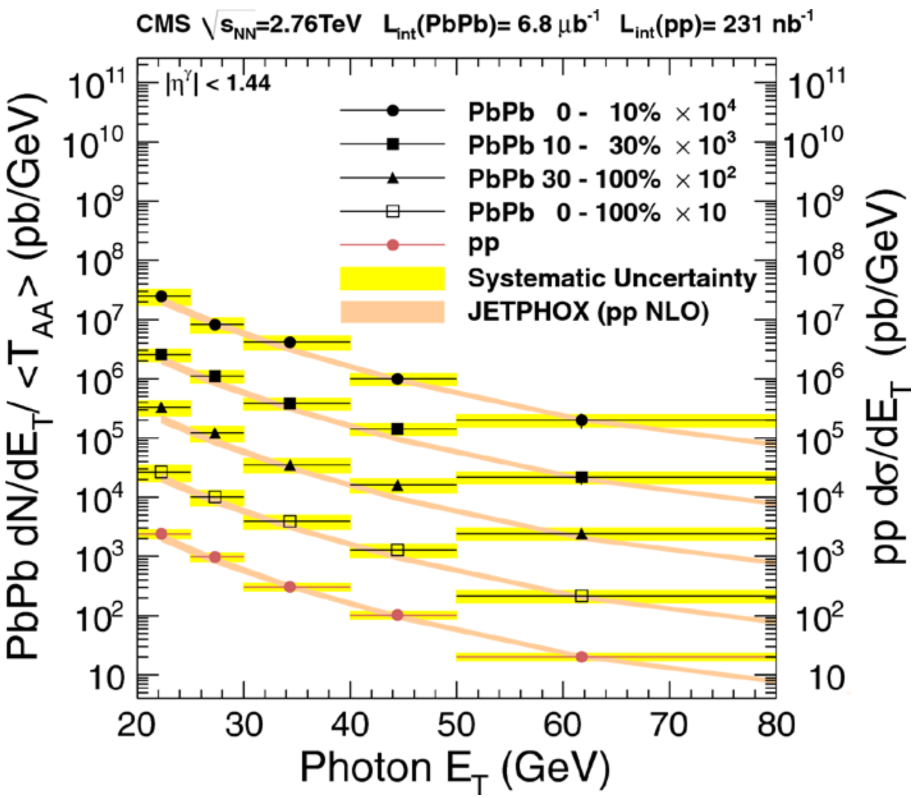


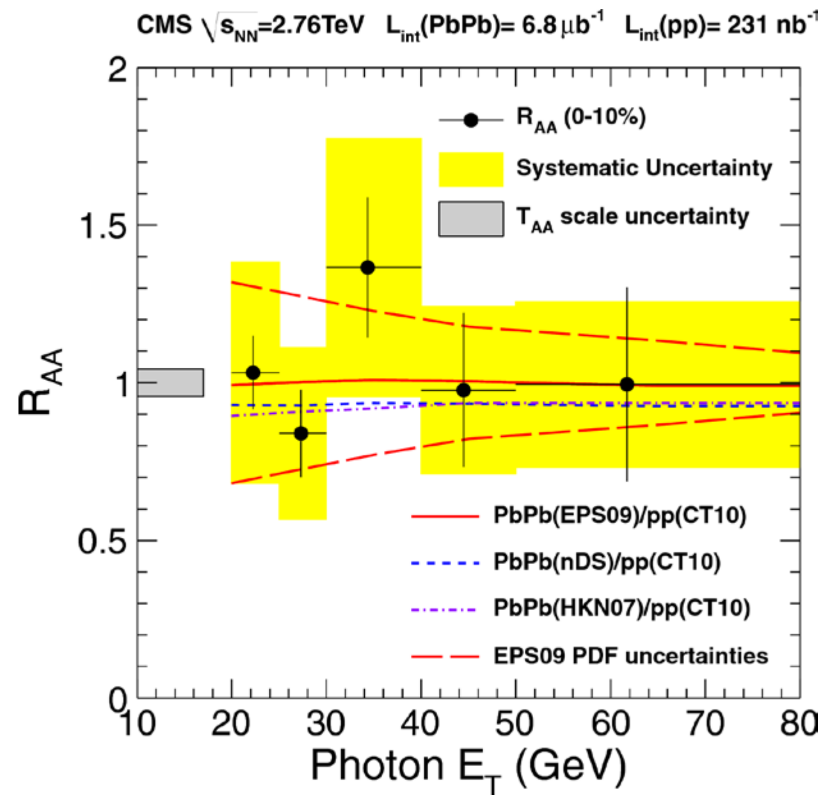
Photon–Jet in 2011 CMS PbPb



Yue Shi Lai (MIT)

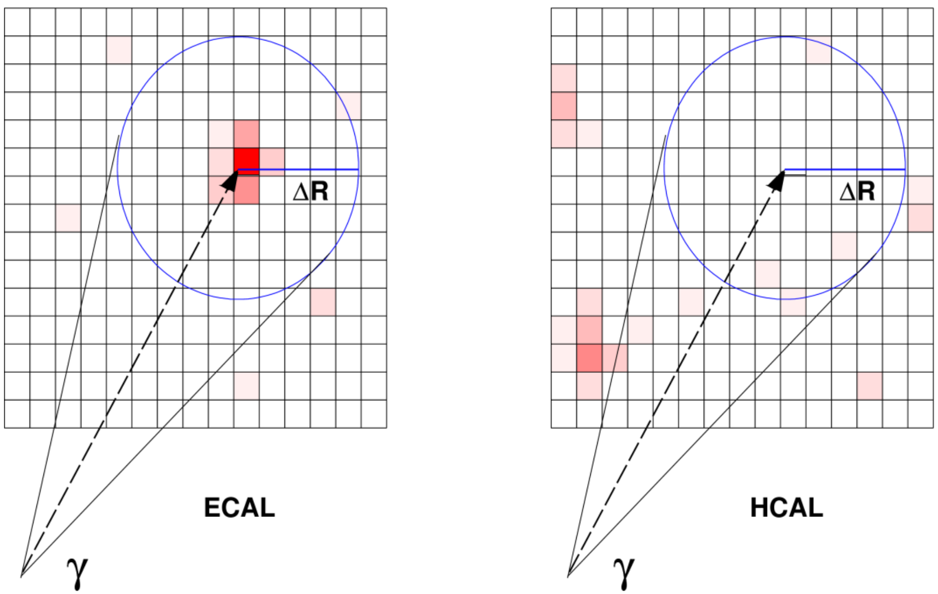
Isolated Prompt Photons in CMS





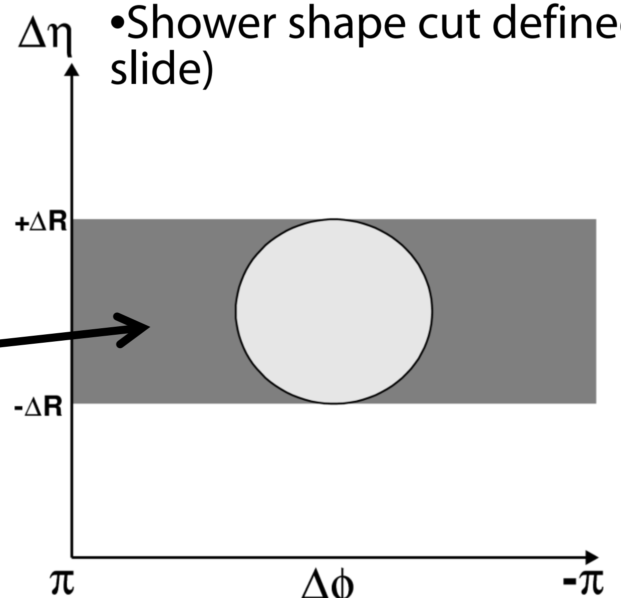
- Isolated prompt photons in 2010 PbPb Data
- Yield matches pp NLO $\times \langle T_{AA} \rangle$

Signal Selection: Photon Isolation



Photon Selection Cuts

- $|z_{vertex}| < 15$ cm
- $(1 - E_4/E_1) < 0.9$
(Index 1: highest crystal, 4: 4 adjacent crystals)
- Seed supercluster $|\Delta t| < 3$ ns
- $H/E < 0.1$
- No electron candidate
- SumIso < 1 GeV
- Shower shape cut defined next slide)



- $\mathrm{Iso}_4^{\mathrm{ECAL}} = -p_T^{\mathrm{cand}} + \Sigma_{\Delta R < 0.4}\, p_T^{j}$
- $\mathrm{Iso}_4^{\mathrm{UE\text{-}sub,ECAL}} = \mathrm{Iso}_4^{\mathrm{ECAL}} - \langle p_T^{\mathrm{Background,ECAL}} \rangle$
- Analogously for track, HCAL (without $-p_T^{\mathrm{cand}}$)

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

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: $\langle x_{J\gamma} \rangle$

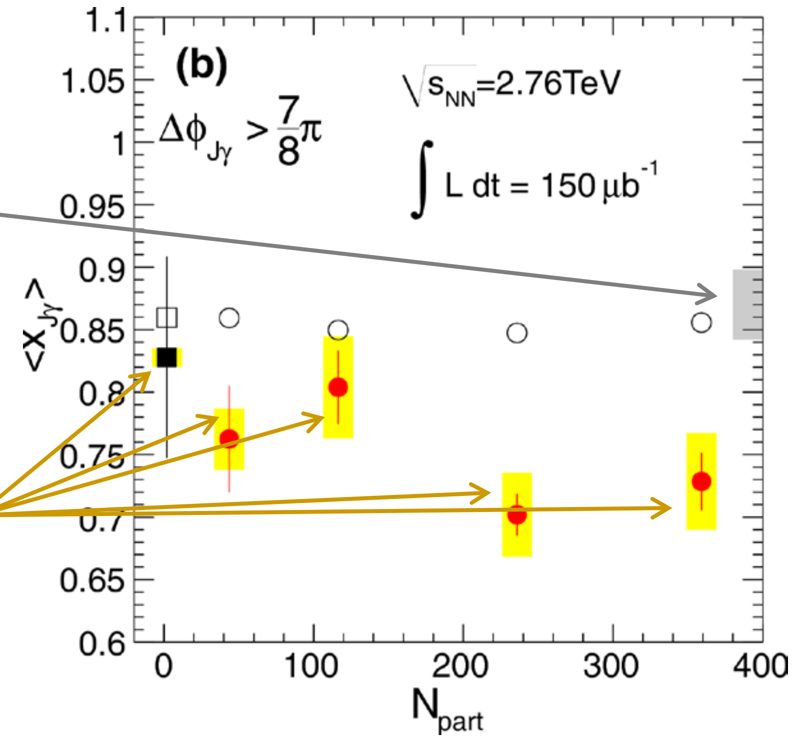
Source	pp	50–100%	30–50%	10–30%	0–10%
γ–jet rel. energy scale	2.8%	4.1%	5.4%	5.0%	4.9%
γ purity	2.2%	2.2%	1.9%	2.4%	2.7%
Jet p_T threshold	0.7%	0.7%	1.9%	1.9%	2.0%
Isolated γ definition	0.1%	0.1%	0.7%	0.4%	2.0%
γ p_T threshold	0.6%	0.6%	0.6%	0.6%	1.3%
Jet efficiency	0.5%	0.5%	0.6%	0.6%	0.5%
$e^{\pm}$ 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%**

- Correlated = min. uncertainty for γ–jet rel. energy scale $\oplus$ γ purity

Systematic Uncert.: Decorrelation for $\langle x_{J\gamma} \rangle$

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 $\oplus$ point-to-point, or Point-to-point = Total $\ominus$ correlated
- Correlated describes the overall $\langle x_{J\gamma} \rangle$ sensitivity
  - shifts all $\langle x_{J\gamma} \rangle$ points simultaneously
  - normalization-like
- Point-to-point describes pp and PbPb centrality dependence



Summary of Systematic Uncertainty: $R_{J\gamma}$

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%
$e^{\pm}$ 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%**

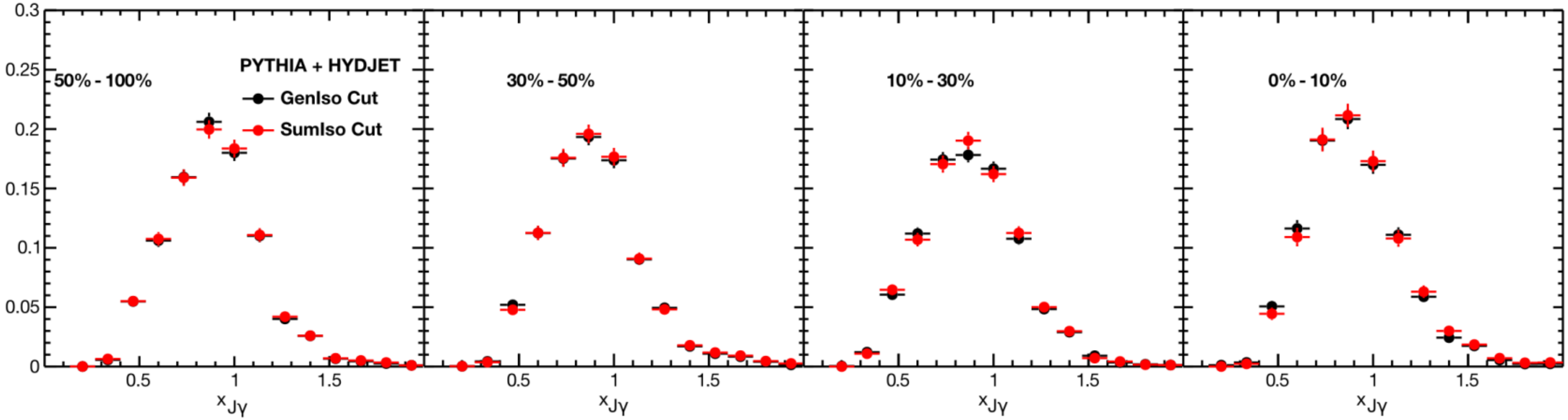
- Fully data driven, vary analysis by expected uncertainties
- Nonmonotonic centrality dependence due to statistical limitation
- $R_{J\gamma}$ is not unitary normalized, and therefore more sensitive to the jet/photon sample and jet efficiency

Jet/Photon Relative Energy Scale

Energy Scale Source	**pp**	**30–100%**	**0–30%**
pp jet–γ relative (missing E_T 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 p_T range is well calibrated (no extrapolation)
- Relative energy scale directly shifts $x_{J\gamma}$
- Absolute energy propagates into p_T thresholds

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