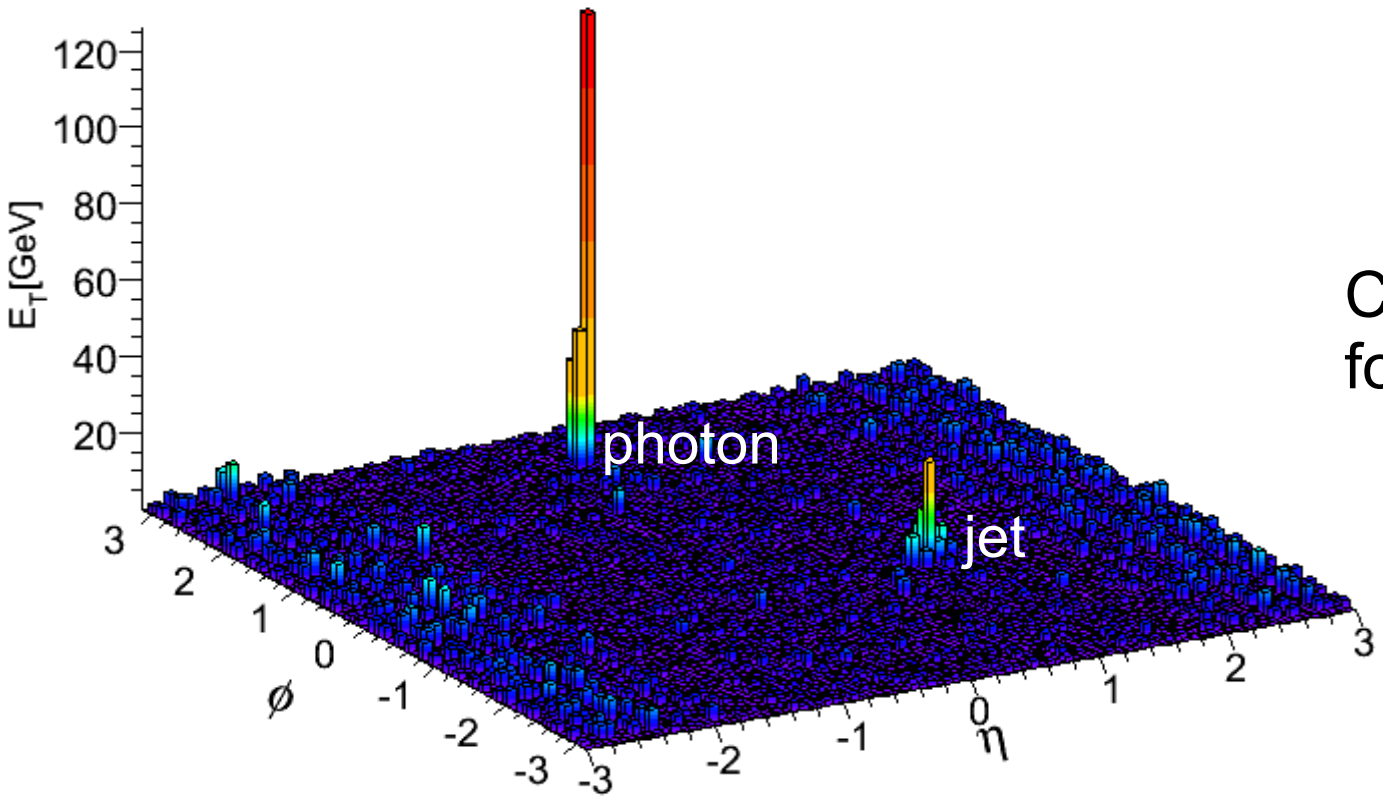
# Photon-tagged jets in Pb+Pb collisions at 5.5 TeV with the CMS detector

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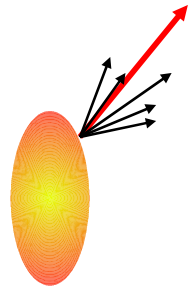
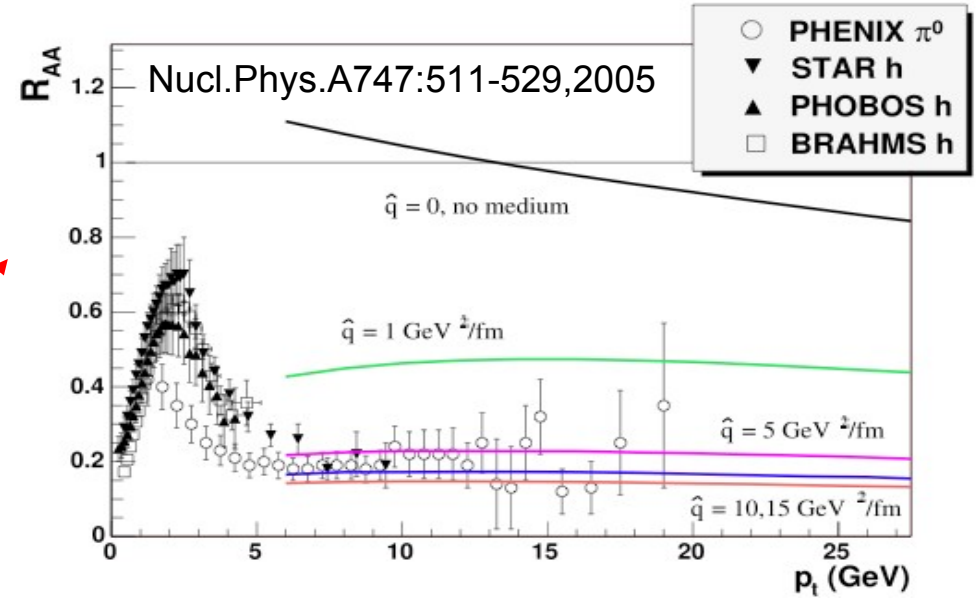
for the CMS collaboration

Quark Matter 2008, February 4-10, 2008, Jaipur, India

# Jet quenching: RHIC vs LHC

- At RHIC, suppression of **leading particles**
  - Interpreted by "parton energy loss" models
  - Surface bias dominates yield at high $p_T$

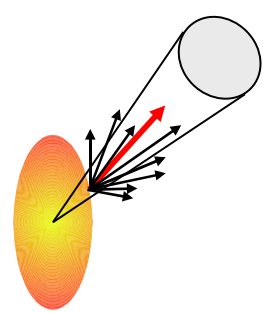




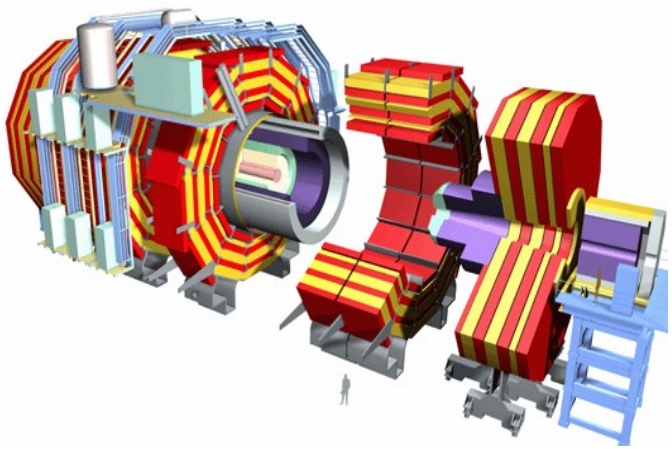

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

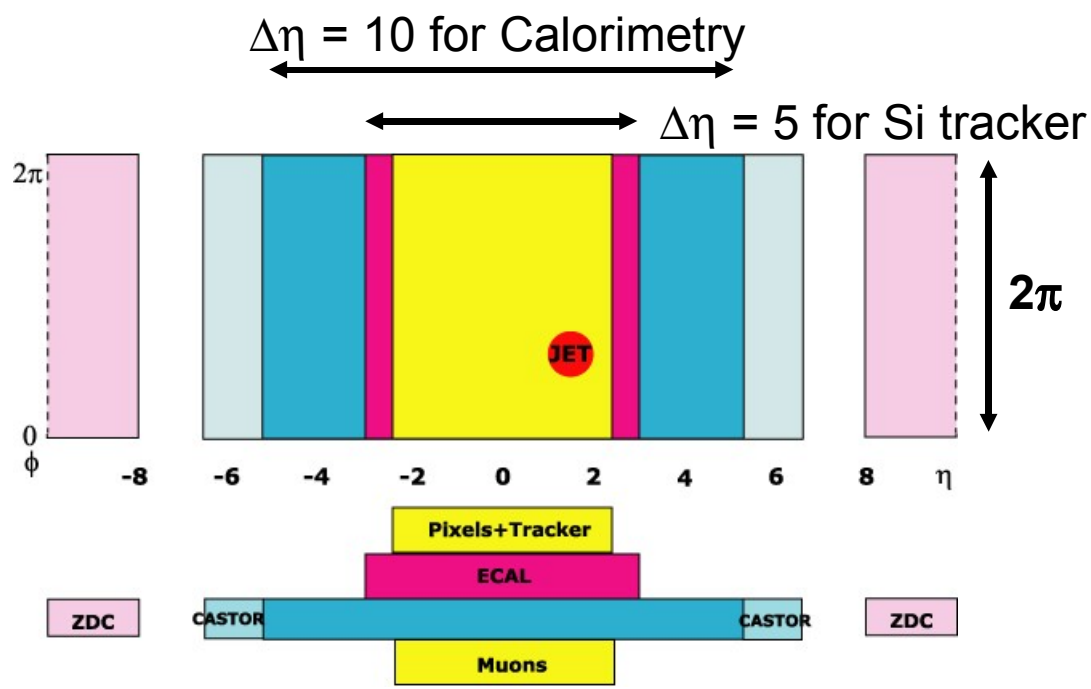
Ratio of AA/pp scaled by # of binary NN collisions

- At LHC, jet cross sections large enough to copiously produce high-$E_T$ jets that stick out of the underlying HI background
  - Use **jets** to characterize initial partons event-by-event
  - Measure how the "energy loss" is distributed inside the jet fragmentation cone



# CMS detector






**Capabilities**

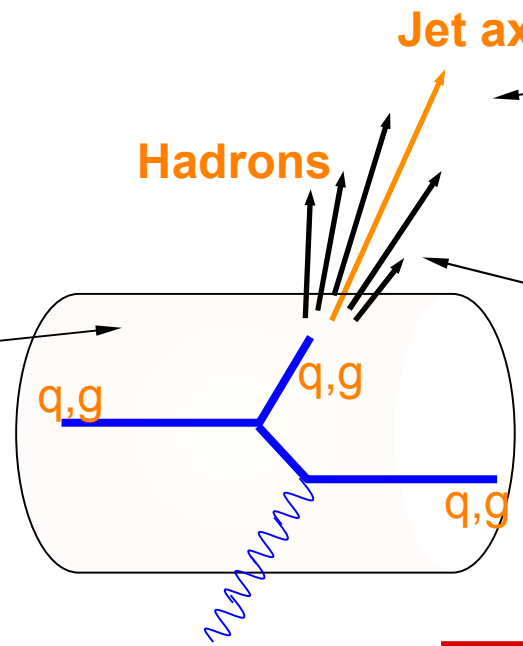
**High-precision tracking over |η| < 2.5**
**Muon identification over |η| < 2.5**
**High resolution calorimetry over |η| < 5**
**Forward coverage**
**Large bandwidth: DAQ + Trigger**

Very well suited for HI environment

J.Phys.G34:2307-2455,2007

- Large (mid-rapidity) acceptance (tracker and calorimetry)
- DAQ+HLT will inspect every single Pb+Pb event
- Large statistics for rare probes

# Photon-tagged jet fragmentation functions




**Jet axis provides parton direction**

**Multiplicity and flow measurements characterize density, path length**

**Charged hadron tracks used to calculate $z = p_T/E_T$**

**Photon energy tags parton energy $E_T$**

Measure jet fragmentation function:
$dN/d\xi$ with $\xi = -\log z$

(Illustration next slide)

**Main advantage**

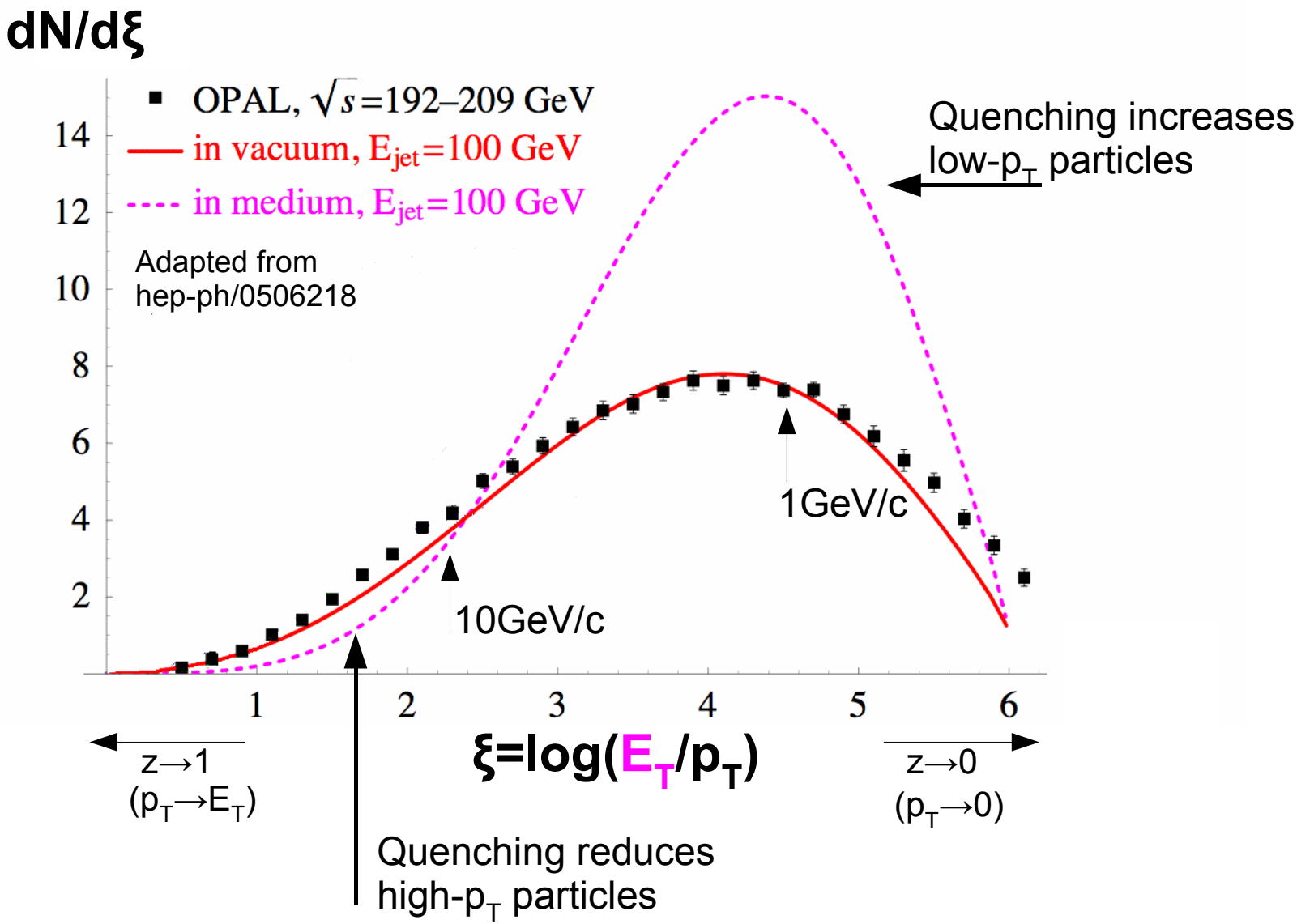
- Photon unaffected by the medium
- Avoids measurement of absolute jet energy

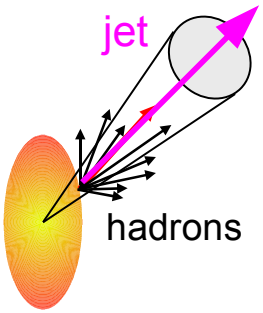
Ingredients:

- Event/Centrality selection
- Reaction plane determination
- Vertex finding
- Track reconstruction
- Jet finding
- Photon identification

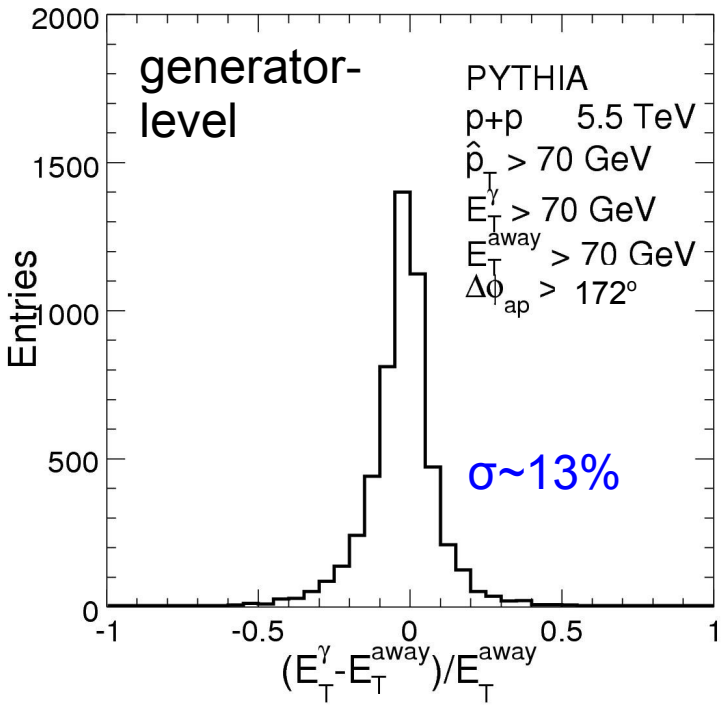
All results based on full GEANT-4 simulations using full reconstruction algorithms on expected one run-year statistics

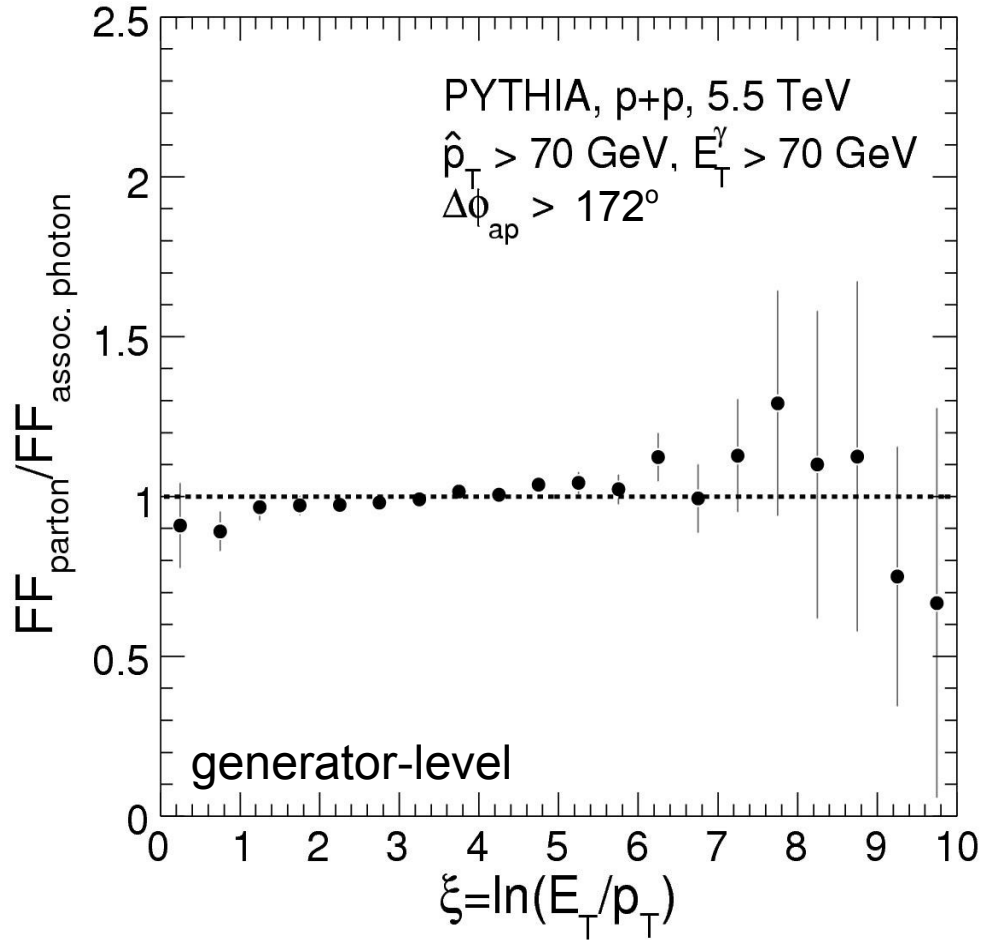
# In-medium modified fragmentation functions

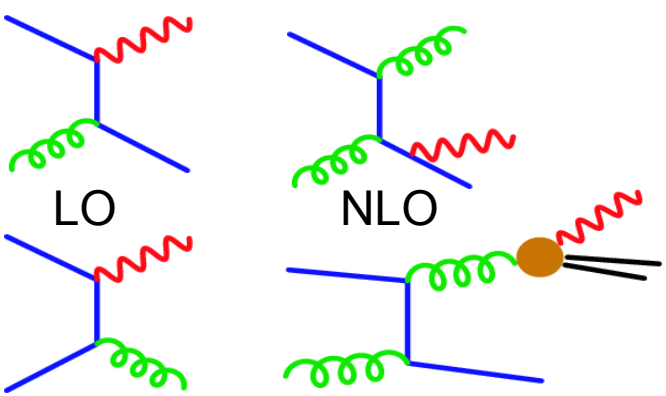


# Photon-tagged fragmentation functions



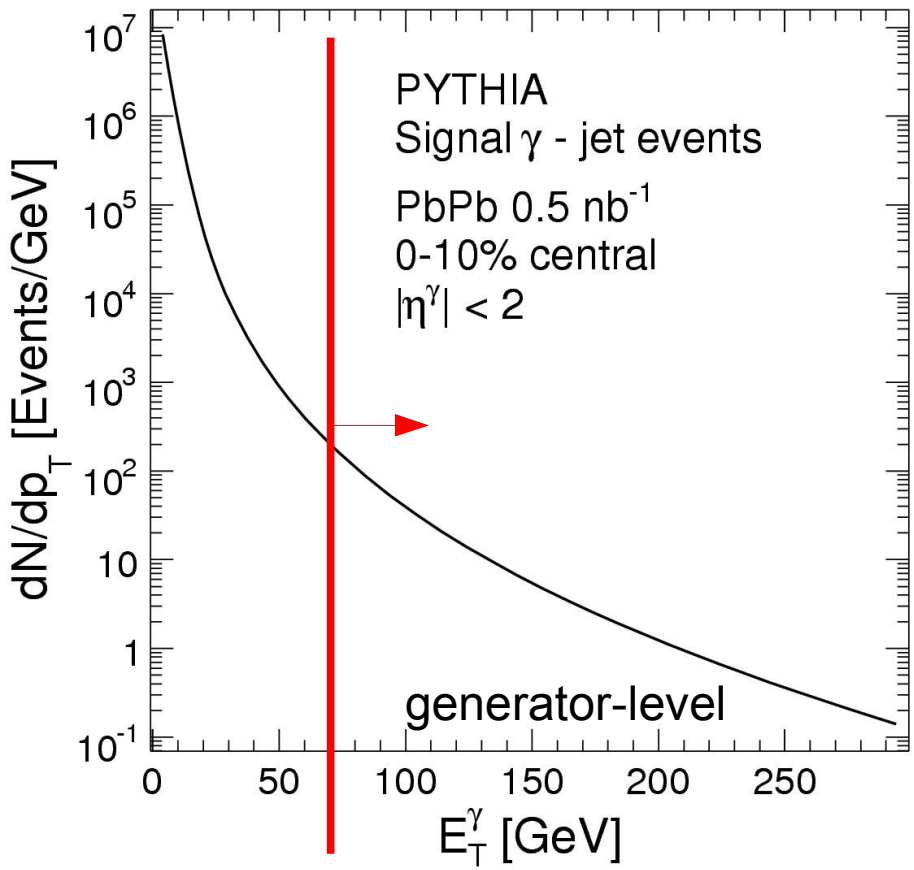

- Use isolated photons + "back-to-back" cut on azimuthal opening angle between the photon and the jet to suppress NLO and background events
  - Determines FF with <10% deviation

# Event generation

- Study two scenarios
  - No quenching: PYTHIA signal and QCD background (p+p) events mixed with central unquenched Pb+Pb HYDJET events
    - No high-$p_T$ particle suppression
    - Leads to high background rates
  - Quenching: PYQUEN signal and QCD background (p+p) events mixed with central quenched Pb+Pb HYDJET events
    - Suppression of high-$p_T$ particles
    - Energy loss radiated out of jet cone
    - Challenging for jet finder

PYQUEN v1.2: Eur. Phys. J. C 45 (2006) 211
HYDJET v1.2: hep-ph/0312204

# Signal and background statistics




- Study for one nominal LHC Pb+Pb run "year"
  - $10^6$ sec, 0.5nb$^{-1}$, 3.9 x $10^9$ events
- Use 0-10% most central Pb+Pb
  - $dN/d\eta|_{\eta=0}$~2400
- Simulate signal and background QCD (p+p) events
  - Mix into simulated Pb+Pb events (~1000 events)

| Data set | $p_T$ [GeV/$c$] | signal γ-jet | $\pi^0$ | $\pi^{\pm}$ | $\eta$ | $\eta'$ | $\omega$ |
|---|---|---|---|---|---|---|---|
| unquenched | >70 | 4288 | 23675 | 47421 | 12267 | 8194 | 30601 |
| unquenched | >100 | 1216 | 4422 | 9103 | 2357 | 1567 | 5975 |
| quenched | >70 | 4209 | 7569 | 14616 | 3825 | 2445 | 9235 |
| quenched | >100 | 1212 | 1562 | 3000 | 829 | 515 | 2051 |

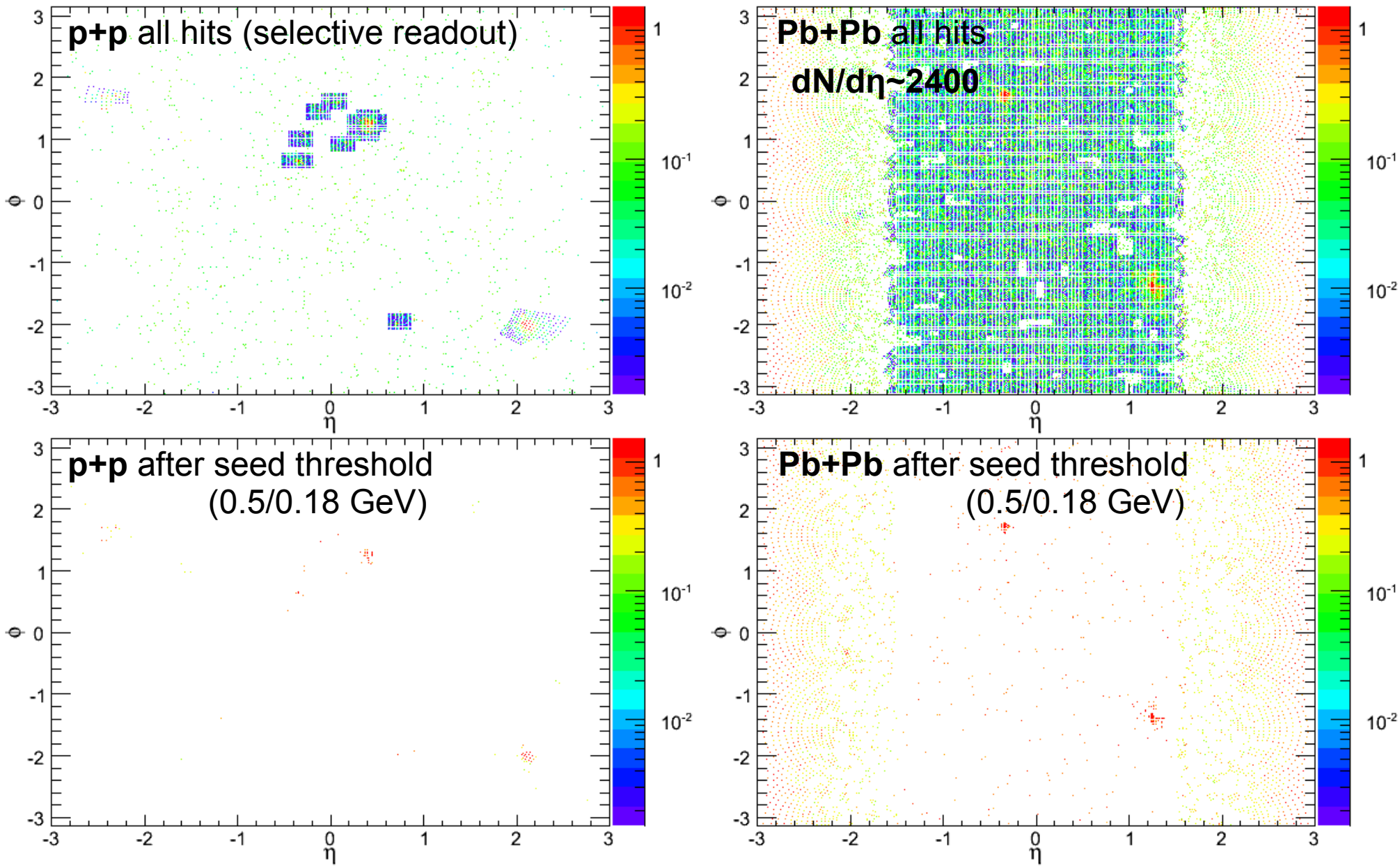
# Reconstruction

- Tracking
  - Low $p_T$ cutoff at 1GeV/c
  - Efficiency (algorithmic + geometric) ~ 50-60%
  - Fake rate ~ few %
- Jet finding
  - Iterative cone algorithm with underlying event subtraction (R=0.5)
  - Performance studies on away-side jet finding (see later)
- Photon ID
  - Reconstruction of high-$E_T$ isolated photons
  - New for this analysis (see next slides)

Tracking: NIM A566 (2006) 123

Jet finding: Eur. Phys. J. 50 (2007) 117

# ECAL response in p+p and Pb+Pb

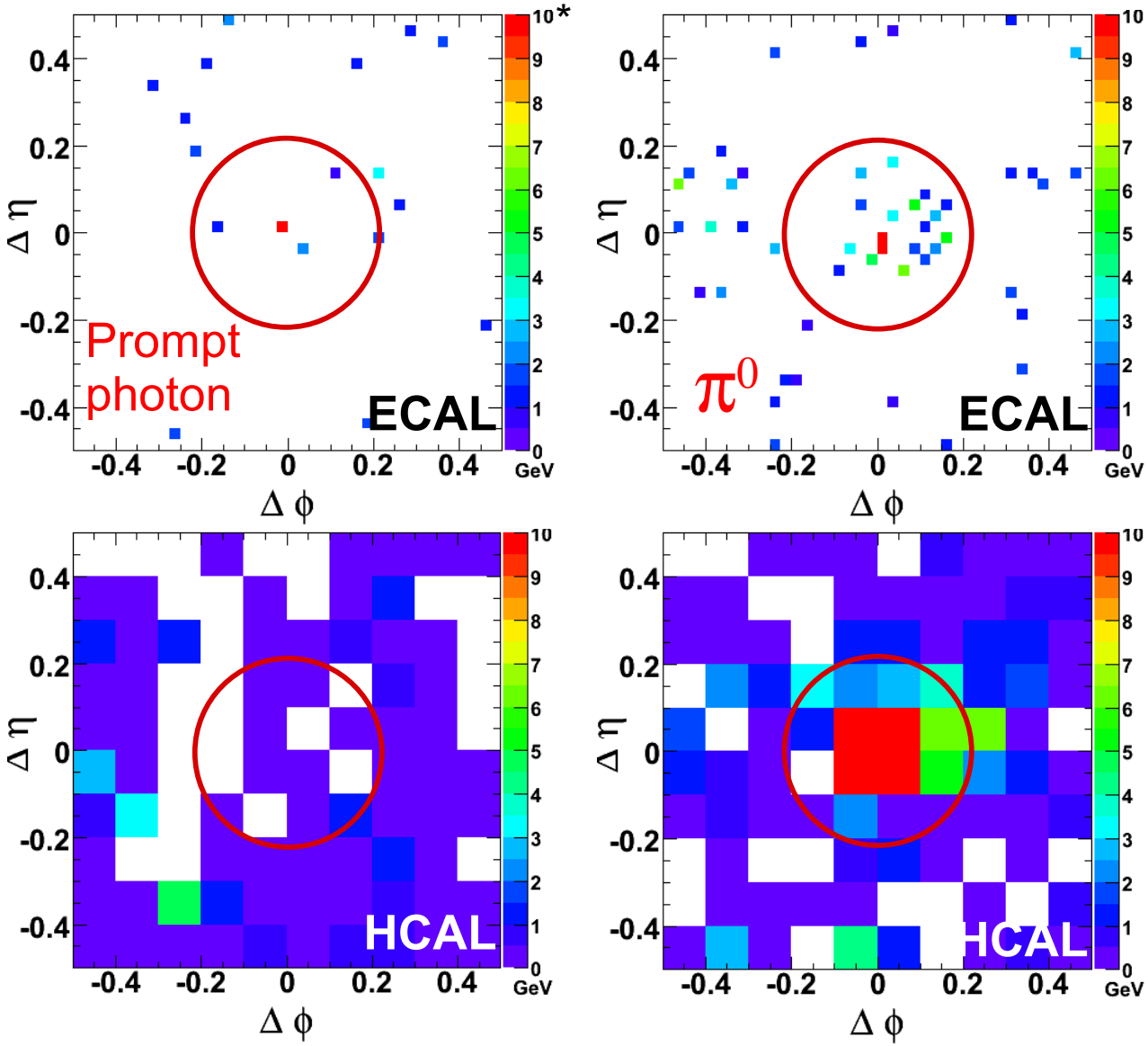



ECAL reconstruction chain used with standard p+p settings

NB: The two p+p (QCD) events are not the same.

# Photon ID: Isolation and cluster shape cuts

- Identification
  - 10 cluster shape variables
    - based on ECAL
  - 10 isolation variables
    - based on ECAL/HCAL
  - Track-based cut
- Selection
  - Total of 21 variables grouped into 3 sets
  - Linear discriminant analysis (Fisher) and cut optimization using TMVA

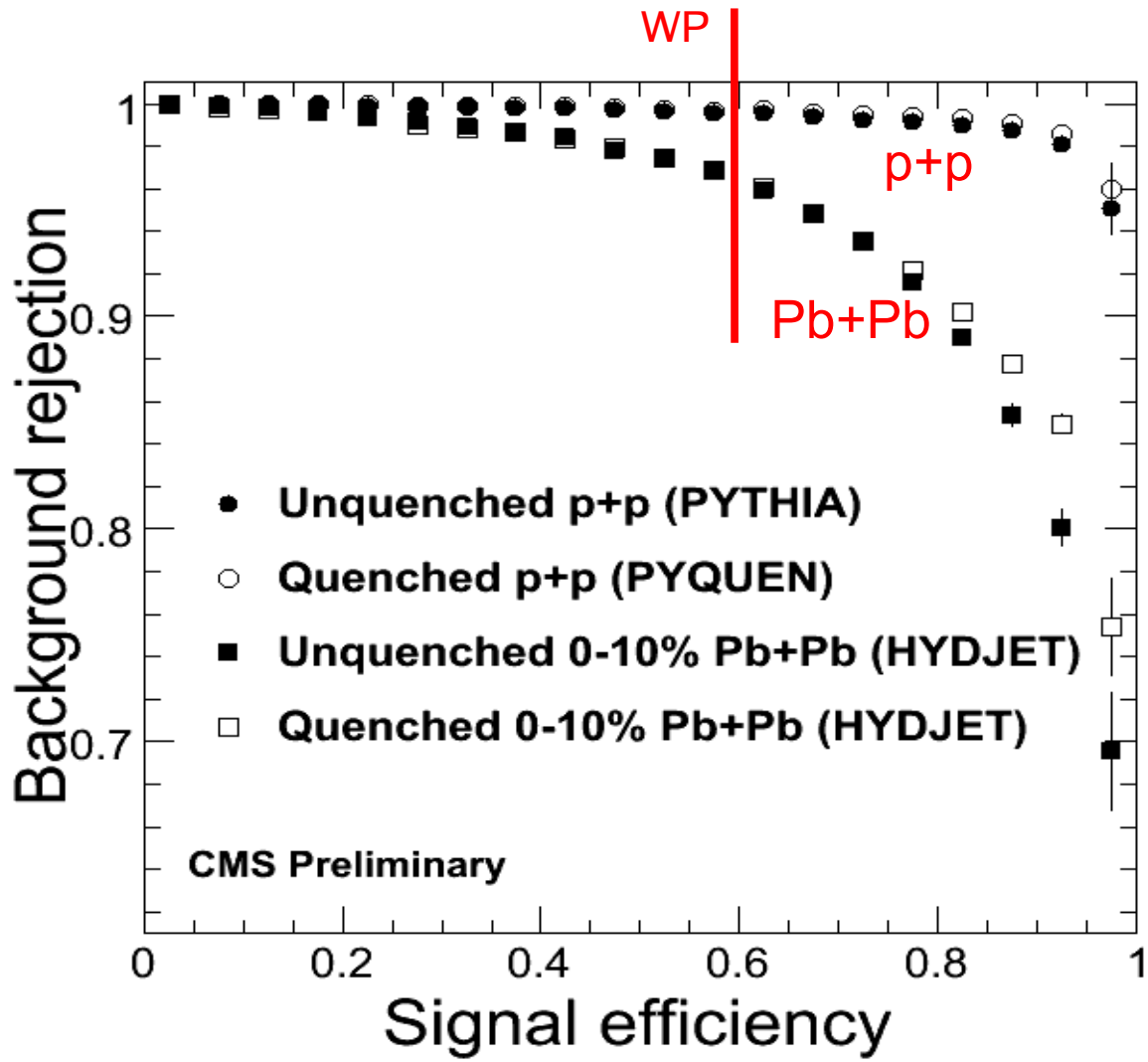



TMVA: http://tmva.sourceforge.net

*) Maximum set to 10

# Photon identification performance

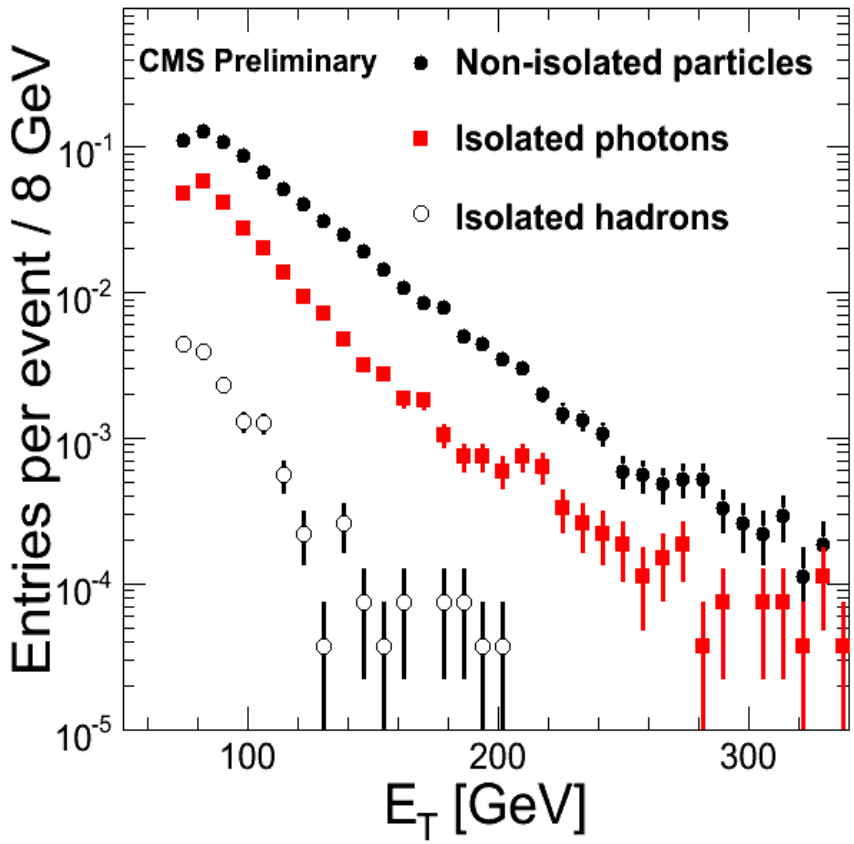
- Set working point to 60% signal efficiency
- Leads to 96.5% background rejection
- Training is done on unquenched samples only



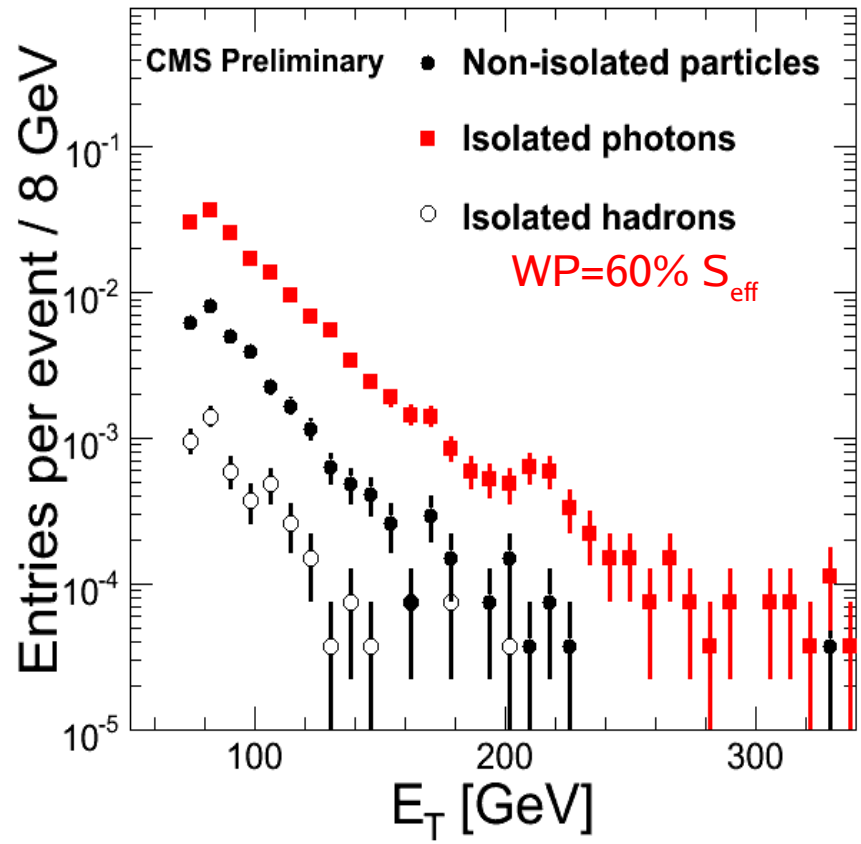
# Photon identification performance

Quenched Pb+Pb

Before cuts: S/B=0.3

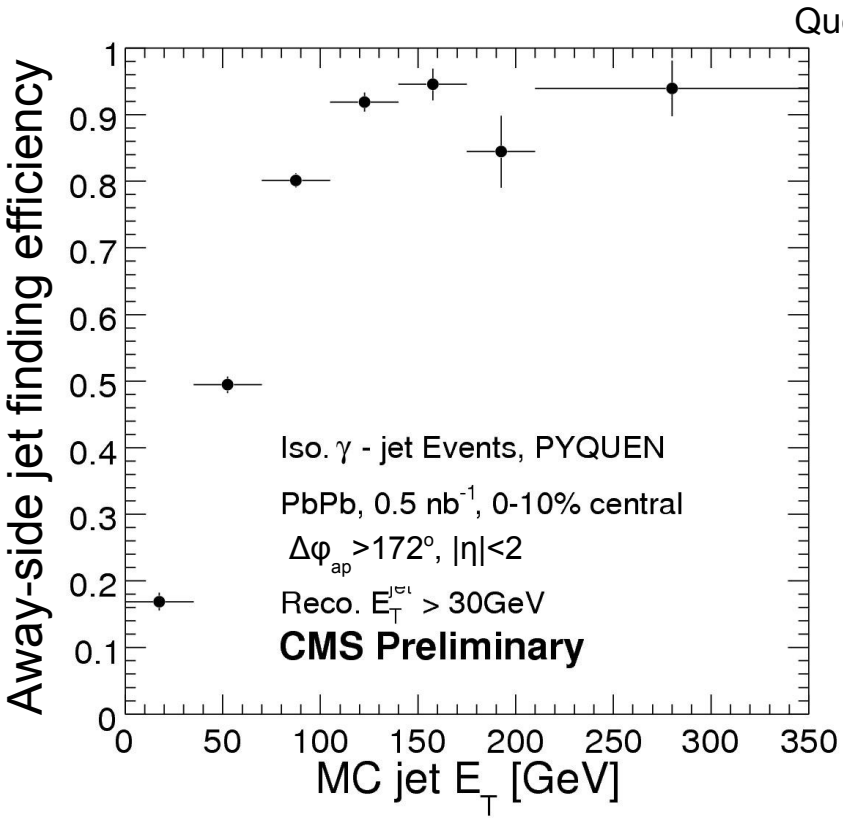


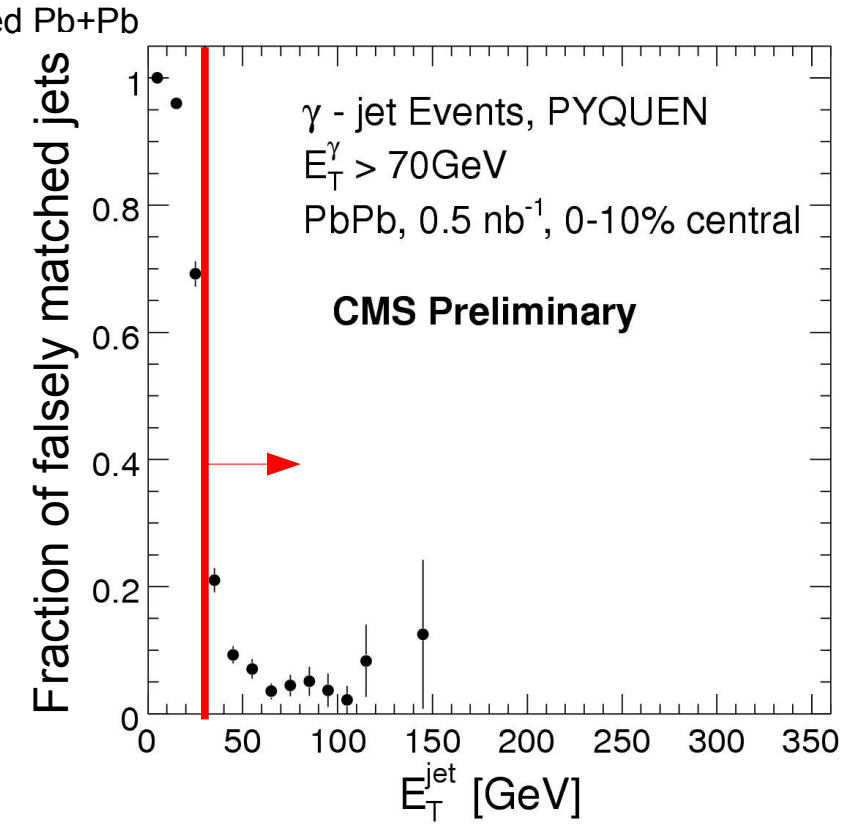

After cuts: S/B=4.5




Photon isolation and shape cuts improve S/B by factor ~15

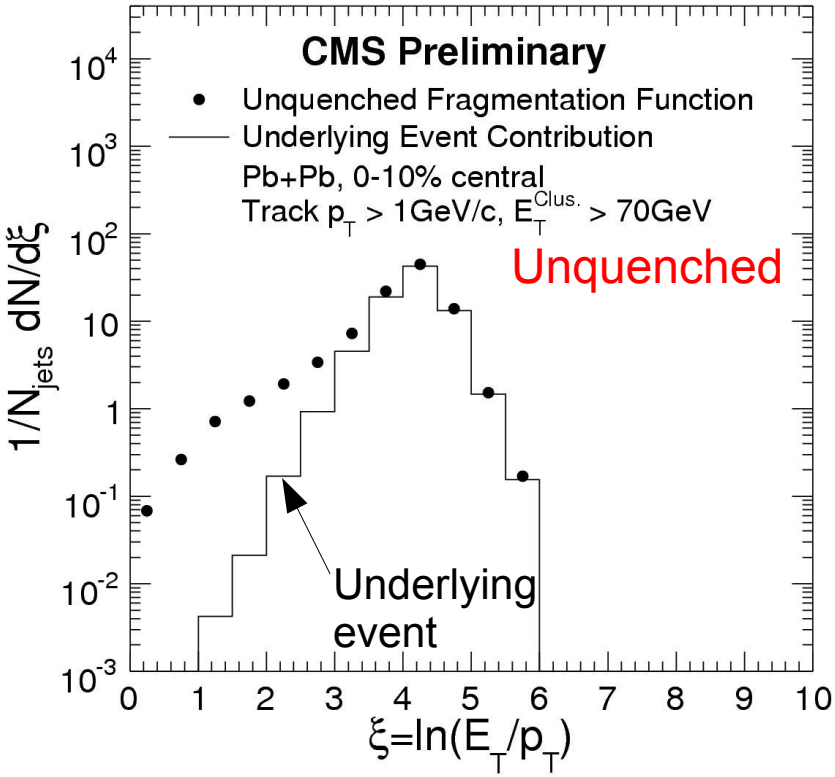
# Jet finding (away-side)

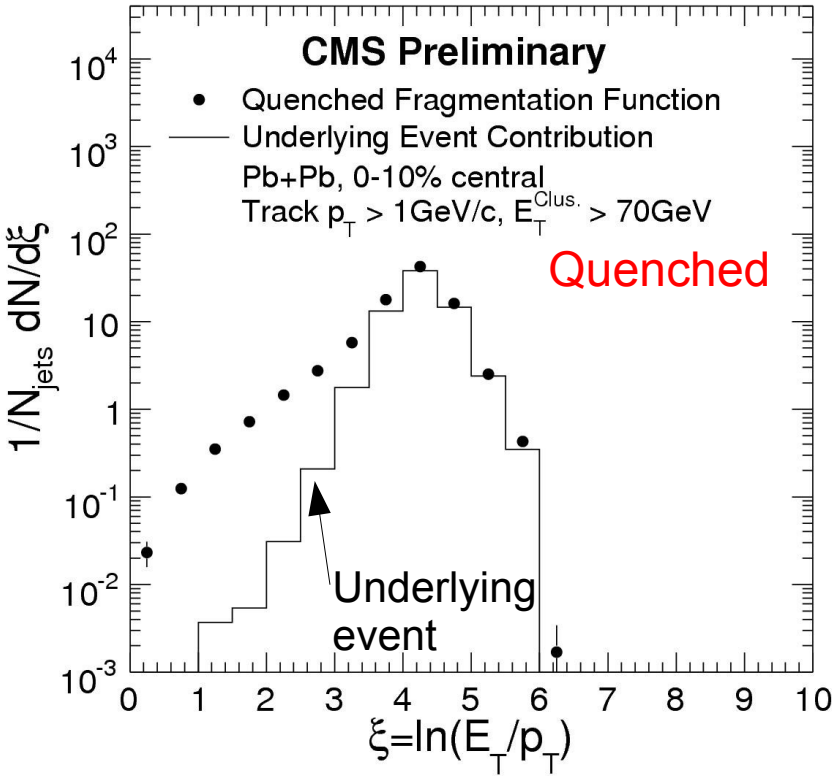



- Select away-side jet with $\Delta\phi(\gamma,\text{jet}) > 172^0$, $|\eta| < 2$ and $E_T > 30$ GeV
  - The energy cut reduces the false rate to 10% level
    - Analysis does not use jet energy otherwise
  - Jet finding efficiency rises sharply between 30-100 GeV MC jet $E_T$
    - Main source of systematic uncertainty in reconstructed FFs

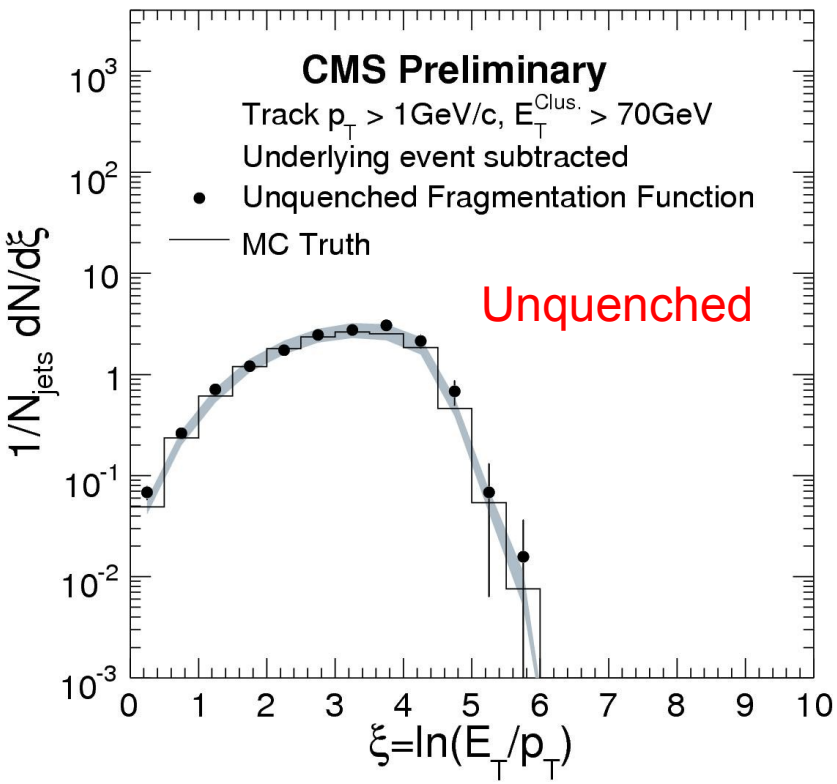
# Fragmentation Functions

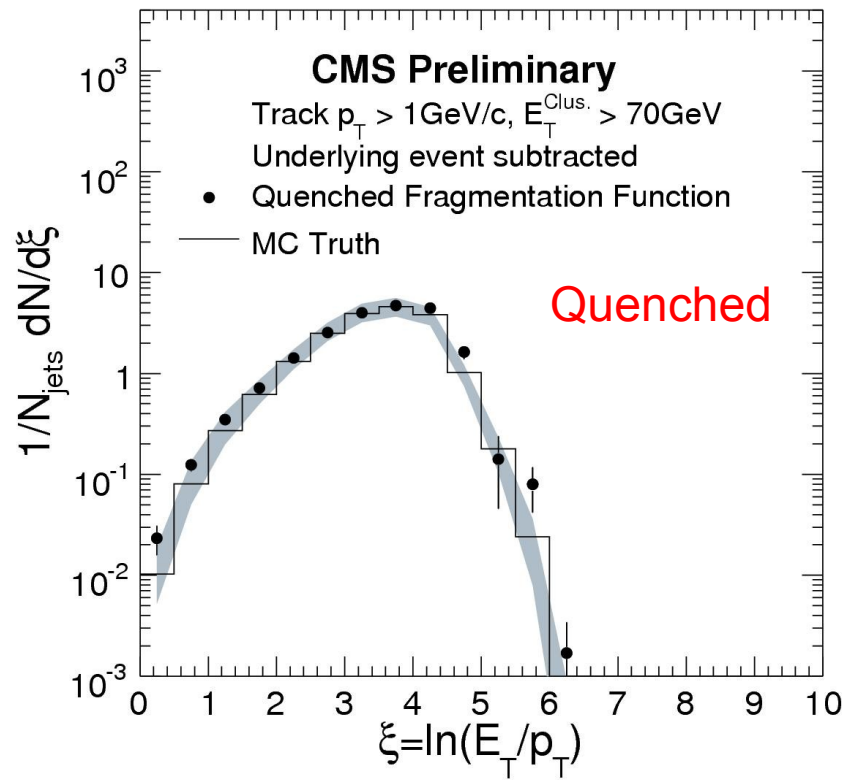



- Obtain $dN/d\xi$ using tracks in R=0.5 cone around jet axis
- For $\xi>3$ ($\sim p_T<4$GeV/c) $dN/d\xi$ dominated by underlying Pb+Pb event
  - Estimate background using R=0.5 cone rotated in $\varphi$ by 90º relative to jet
  - Sum event-by-event backgrounds and subtract

# Reconstructed fragmentation functions



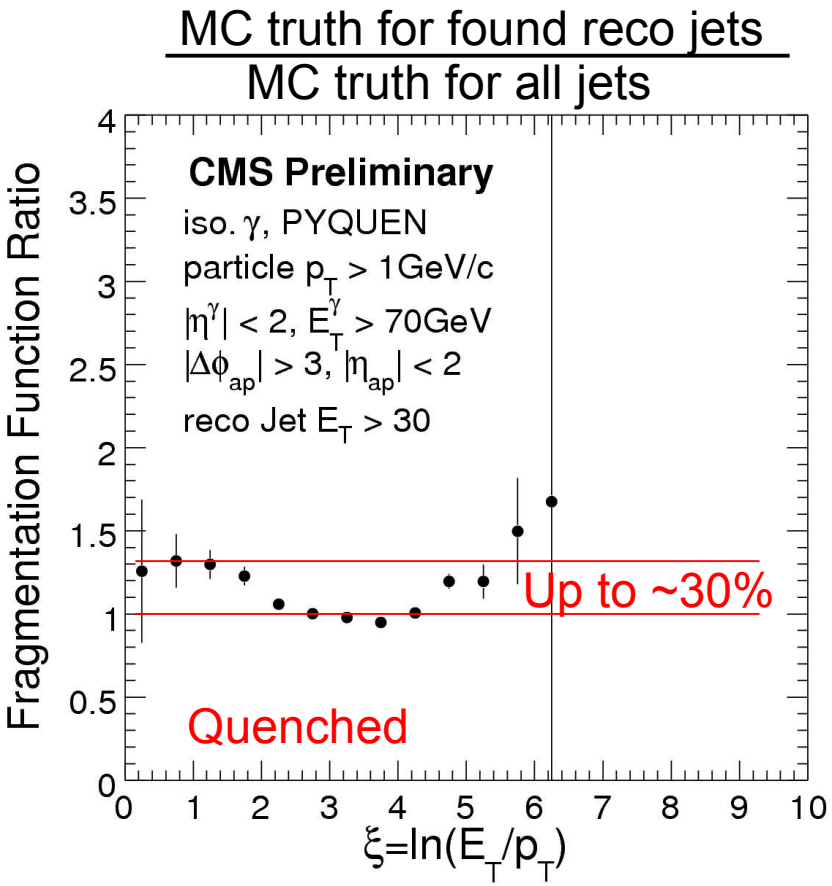

- Major contributions to systematic uncertainty (added in quadrature)
  - Photon selection and background contamination (15%)
  - Track finding efficiency correction (10%)
  - Wrong/fake jet matches (10%)

  } No or small $\xi$ dependence

  - Jet finder bias (largest contribution in quenched case, see next slide)

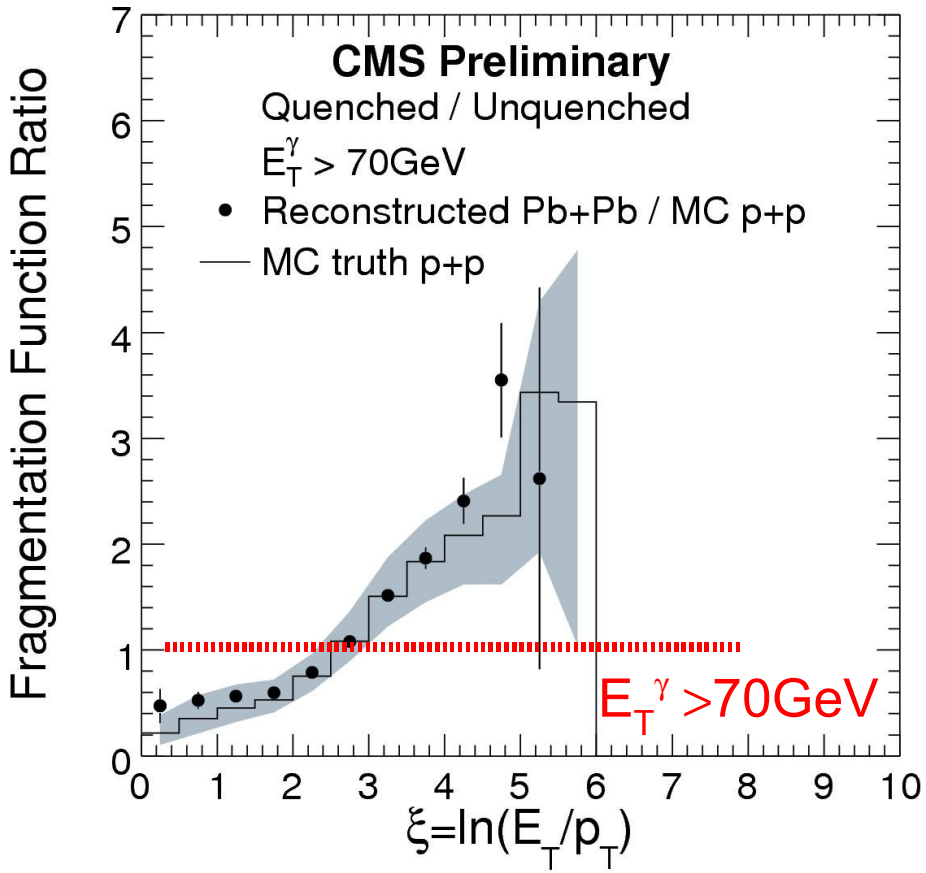
# Jet finder bias

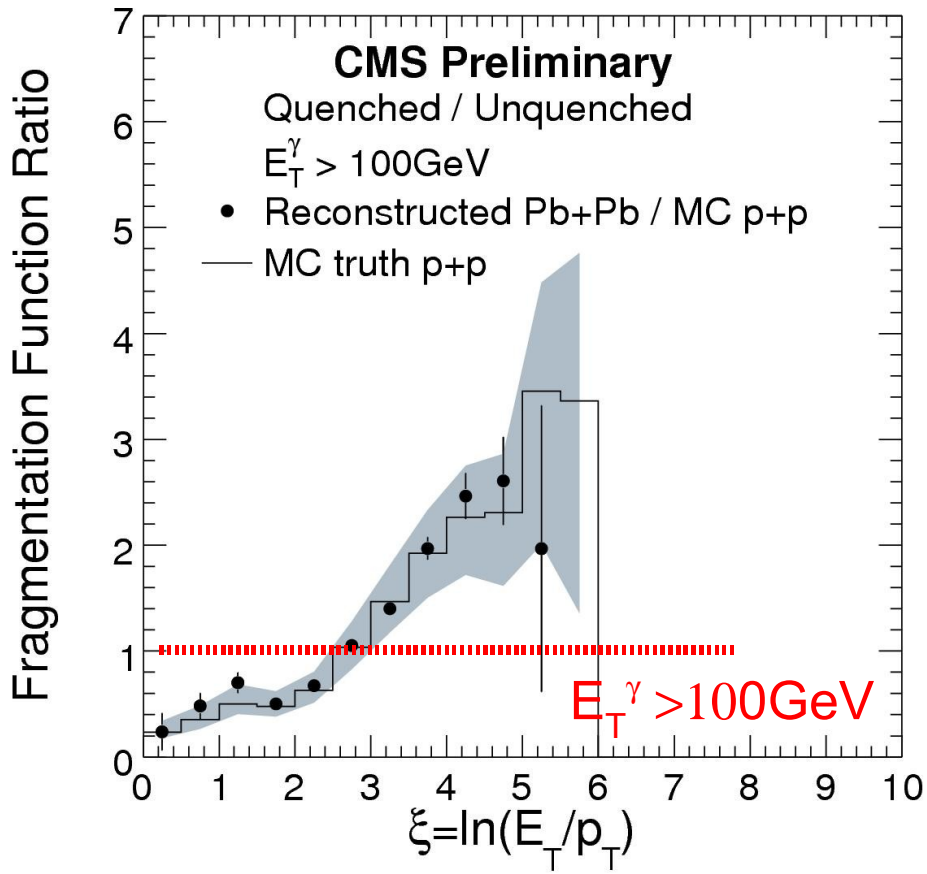
- Jet finder bias leads to about 30% in quenched case (10% for unquenched case)
- It has two contributions
  1) FFs and jet finding efficiency depend on parton $E_T$
     - Can be corrected with known turn-on curve (not done here)
  2) For a given parton $E_T$, jet finding probability depends on parton fragmentation pattern
     - The jet finder is more likely to find a jet with few high $p_T$ particles than jets with many soft particles
     - MC based correction might be possible (not done here)
- MC studies suggest that 2) dominates



# Fragmentation function ratio

Reco quenched Pb+Pb / MC unquenched p+p




- Medium modification of fragmentation functions can be measured
  - High significance for $0.2 < \xi < 5$ for both, $E_T^\gamma$ >70GeV and $E_T^\gamma$ >100GeV

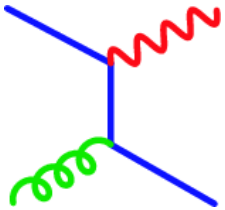
# Summary

- Complete study of in-medium fragmentation functions using photon-tagged jet events
  - Two scenarios: Unquenched and quenched cases
    - Pythia and Pyquen (+ Hydjet)
- Key features of the study
  - Full statistics expected for nominal one-year CMS Pb+Pb run at LHC
  - Full detector simulations of signal and background
  - Complete reconstruction chain
    - Track finding
    - Jet finding
    - Photon isolation
    - Underlying event subtraction
  - Analysis of systematic errors
    - Uncertainty dominated by jet finder bias
- Measurement of expected strong medium modification of fragmentation functions can be done reliably in central Pb+Pb

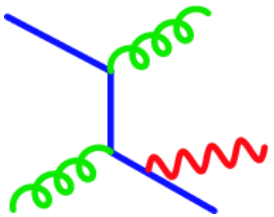
# BACKUP SLIDES

# Signal Processes

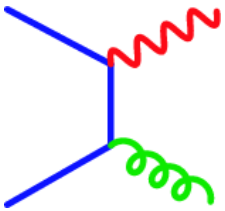
Compton



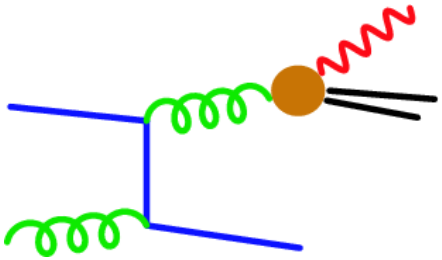
Bremsstrahlung



Annihilation



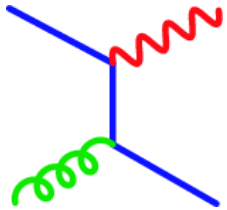
Fragmentation



- Use photon to tag parton energy
  - Goal: Best correlation of the photon and parton energy
  - Idea: Use leading order photons
  - <u>In practice:</u> Use isolated photons + cut on azimuthal opening angle between the photon and the jet to suppress higher order processes and background events
    - MC isolation definition on generator level
    - Combination of calorimeter- and track-based isolation cuts on “data”
    - Cut on opening angle of $\Delta\Phi$(photon,jet)>3.0

# MC photon isolation and signal definition

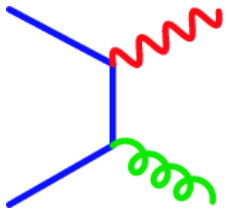
**Compton**



- For a photon, calculate total $p_T$ (*) in cone of R=0.5, $P_T^{tot}$, and find hadron with largest $P_T^{max}$
  - Require

$$(P_T^{tot} - E_T) < (5\text{GeV} + 0.05\ E_T)$$
$$P_T^{max} < (4.5\text{GeV} + 0.025\ E_T)$$

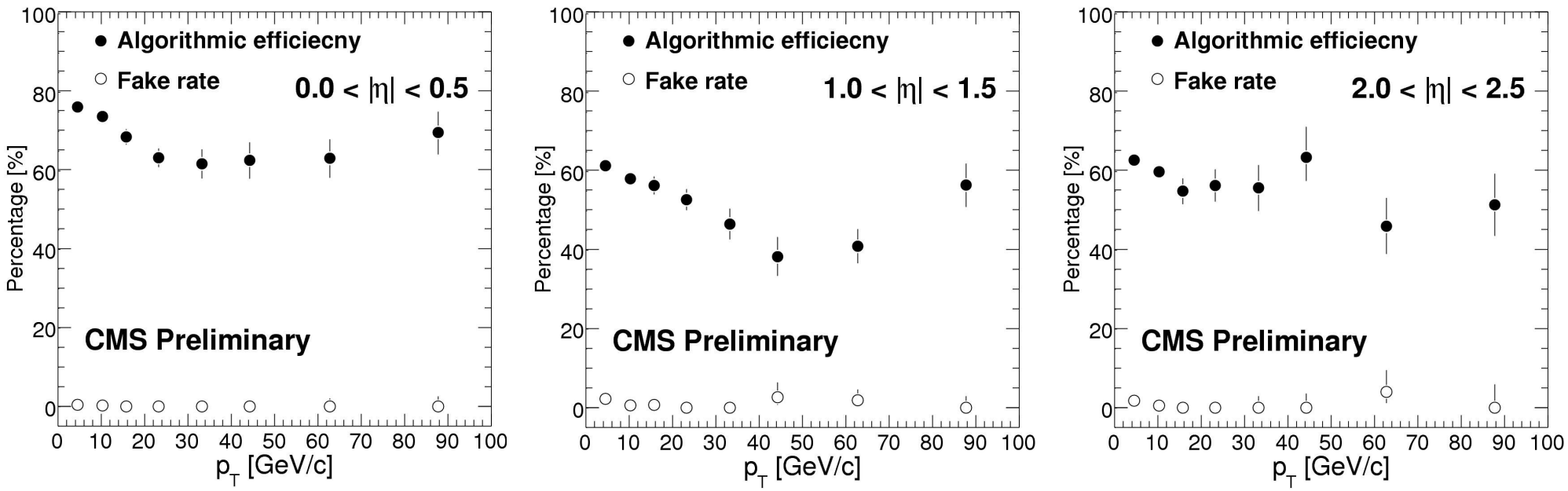
**Annihilation**



- Events where an isolated photon is emitted back-to-back with a jet are our signal events

(*) excluding neutrinos and muons

# Tracking efficiency




- Low $p_T$ cutoff at 1GeV/c
- Efficiency (algorithmic + geometric) ~ 50-60%
- Fake rate ~ few %

NIM A566 (2006) 123

# Photon isolation: Calorimeters

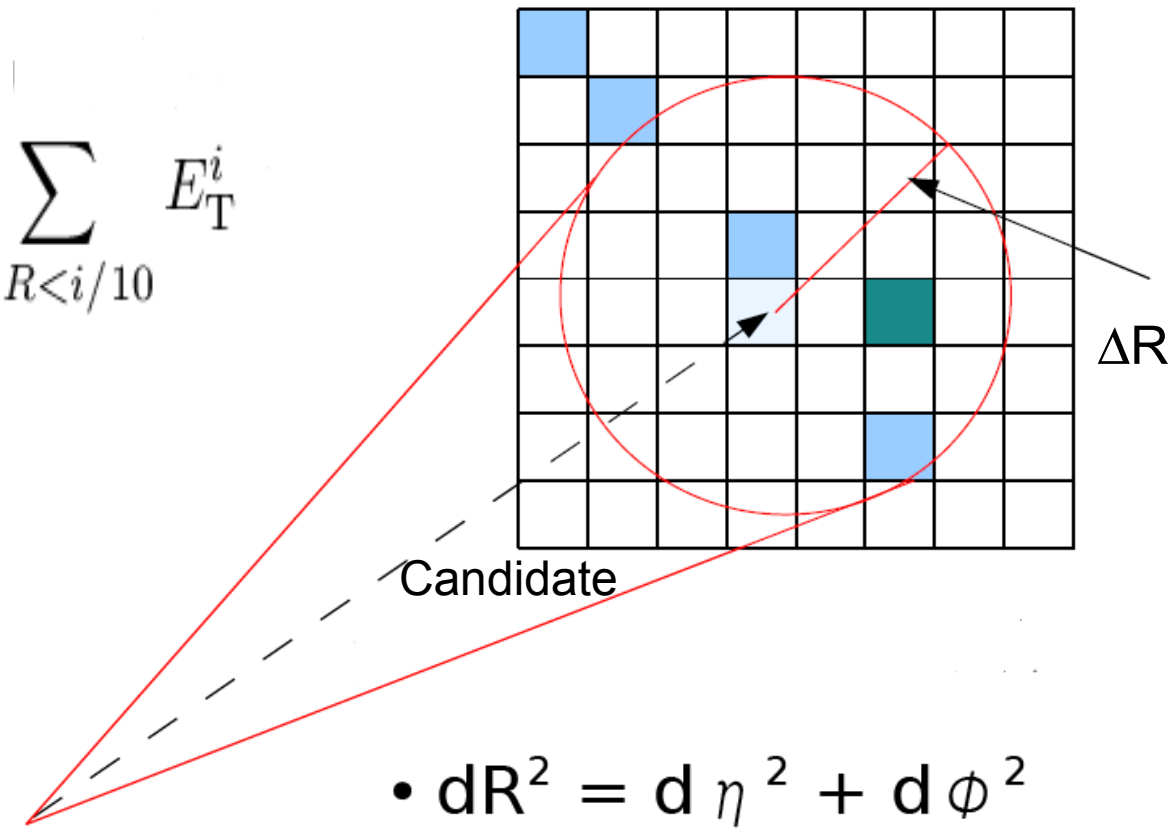
- Use the energy content in cone around candidate direction in ECAL and HCAL

- ECAL:

$$C_i = -E_{\mathrm{T}}^{\mathrm{cand}} + \sum_{\Delta R < i/10} E_{\mathrm{T}}^{i}$$

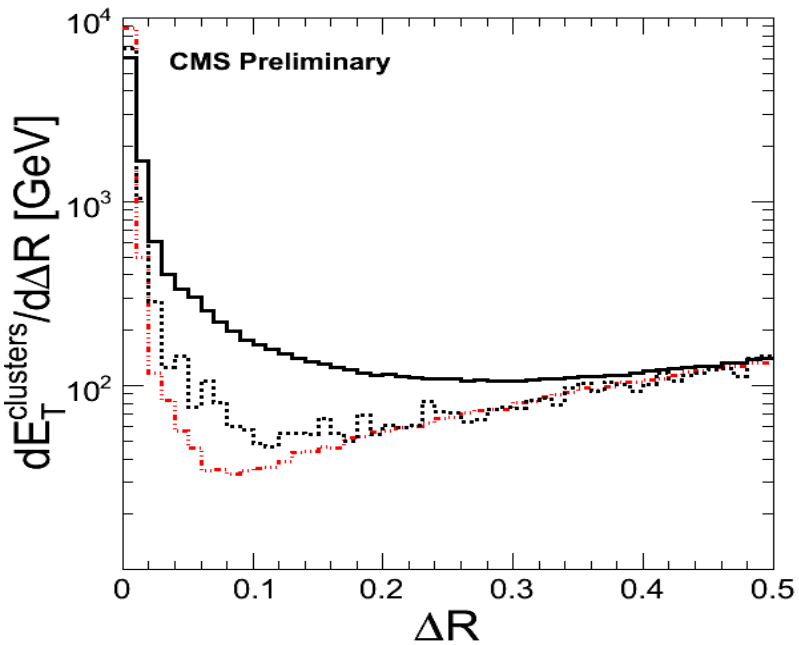
- HCAL:

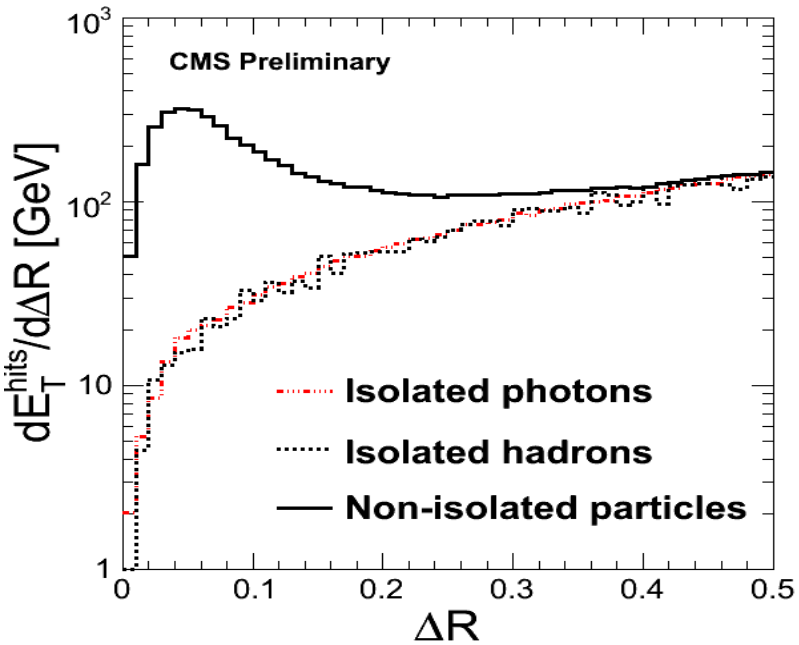
$$R_i = \sum_{\Delta R < i/10} E_{\mathrm{T}}^{i}$$



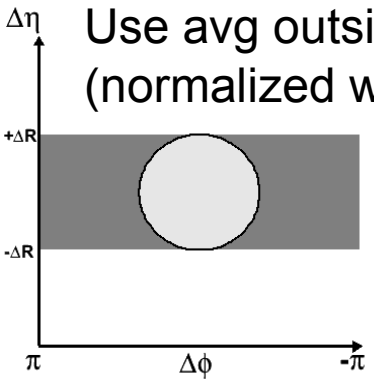

- $dR^2 = d\eta^2 + d\phi^2$

# Photon isolation: Background subtraction




- Subtract HI background
  - ECAL: $C_i' = C_i - \langle C_i \rangle$
  - HCAL: $R_i' = R_i - \langle R_i \rangle$




Use avg outside of cone (normalized with $\Delta R/4$)

# Photon isolation: Combined calorimeters

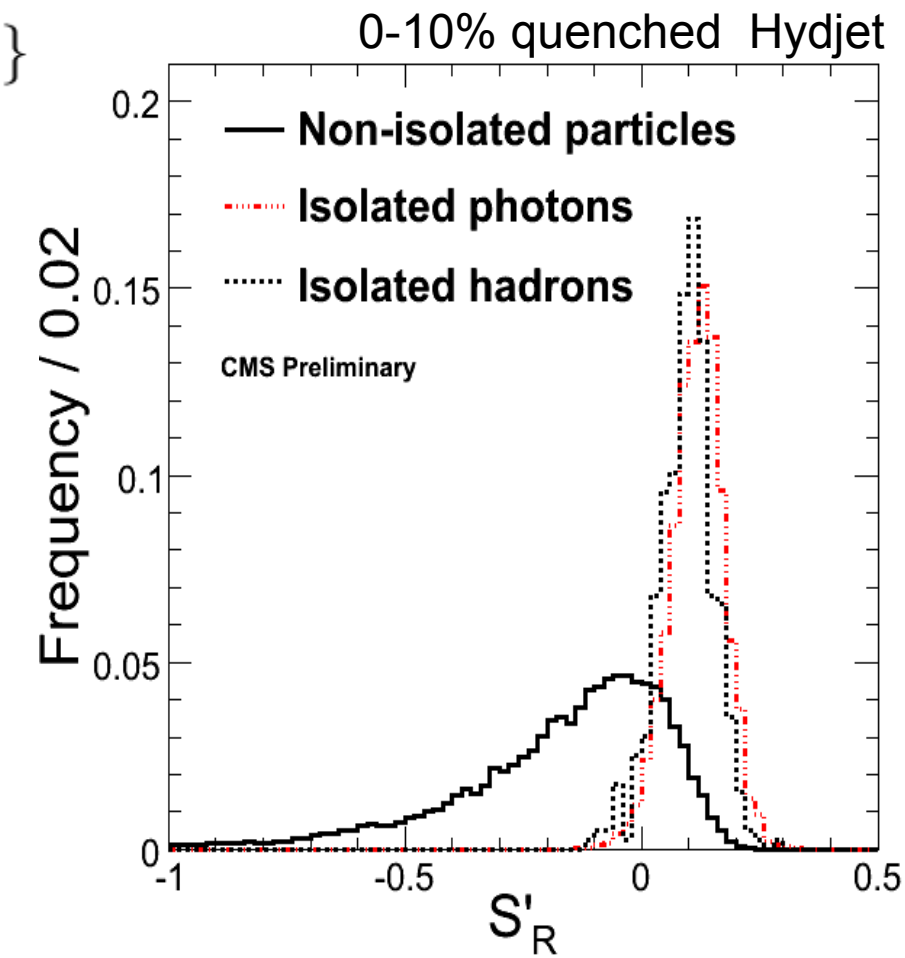
- Based on cone variables form

$$\{R'_1, R'_2, R'_3, R'_4, R'_5, C'_1, C'_2, C'_3, C'_4, C'_5\}$$

- Combine to

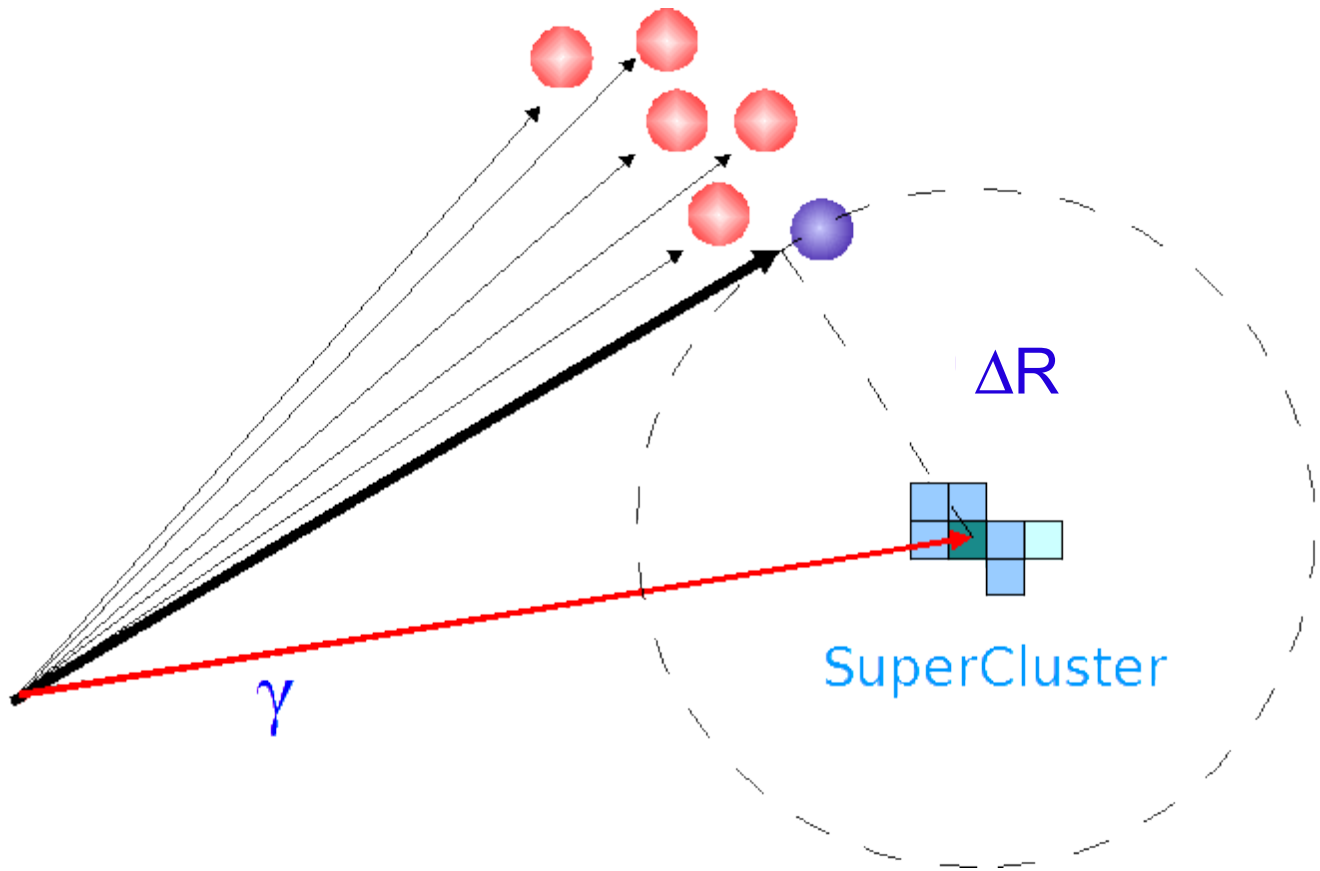
$$S'_R = \sum_i \alpha'_i R'_i + \sum_i \beta'_i C'_i$$

to be determined coefficients



# Photon isolation: Tracks

- dRxy: $\Delta R$ of (y+1$^{st}$) nearest track with $p_T$ > (0.4*x + 0.2) GeV/c
- We use
  - dR10 for p+p
  - dR41 for Pb+Pb



# Photon ID: Shape variables

- Based on ECAL shape variables form

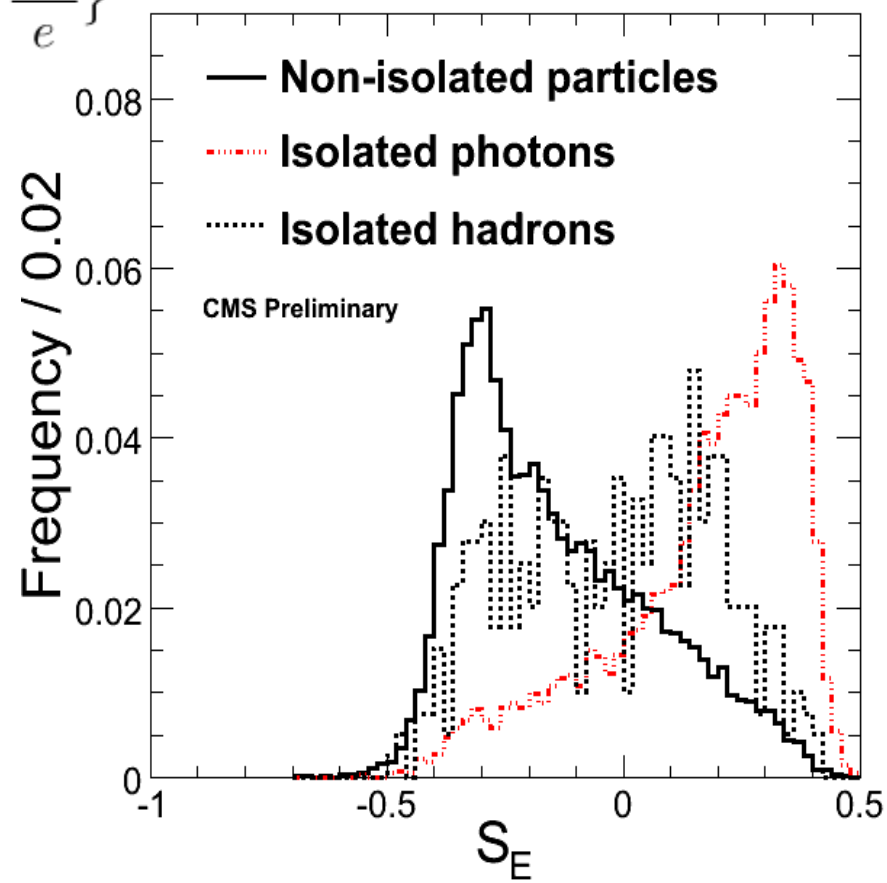
$$E_i = \{\frac{e_{\max}}{e_4}, \frac{e_{\max}}{e_9}, \frac{e_{\max}}{e_{25}}, \frac{e_{\max}}{e}, \frac{e_4}{e_9}, \frac{e_4}{e_{25}}, \frac{e_4}{e}, \frac{e_9}{e_{25}}, \frac{e_9}{e}, \frac{e_{25}}{e}\}$$

- Combine to

$$S_E = \sum_i \gamma_i E_i$$

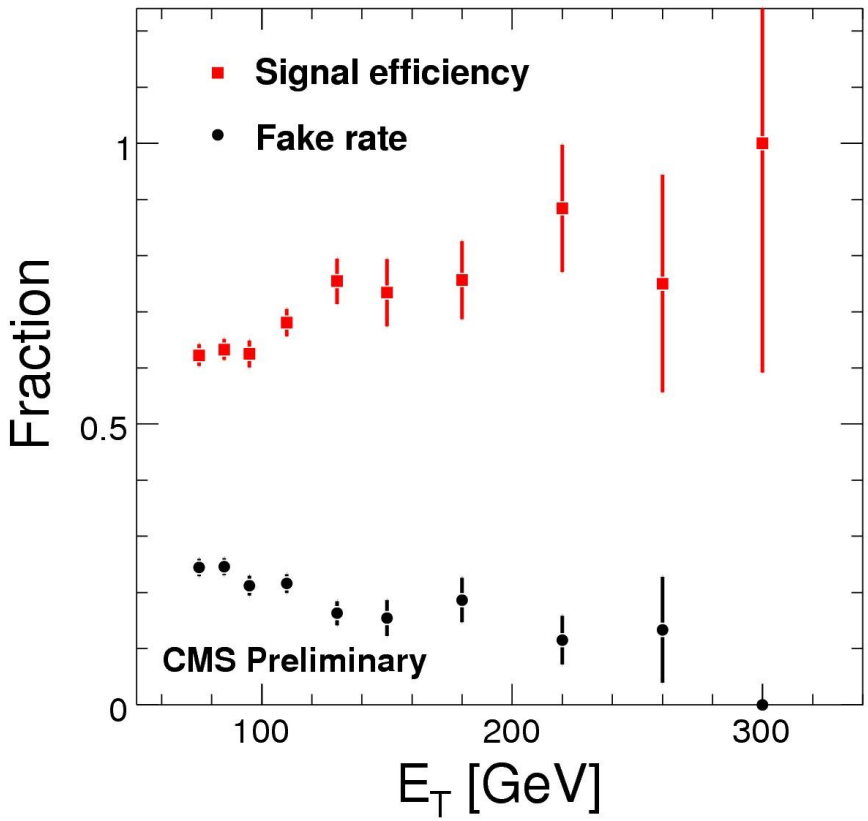
to be determined coefficients

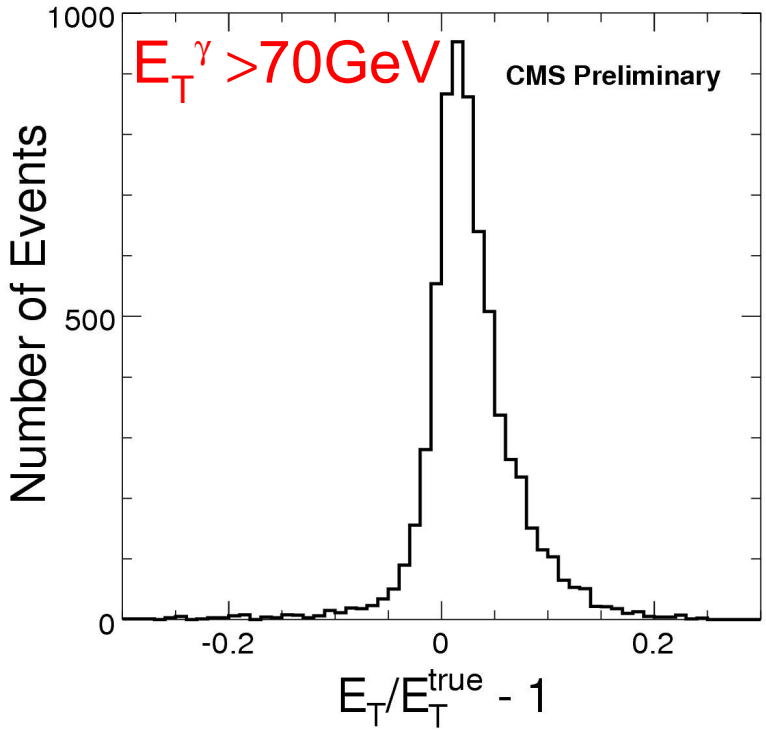
0-10% quenched Hydjet



# Isolated photon reconstruction

Quenched Pb+Pb



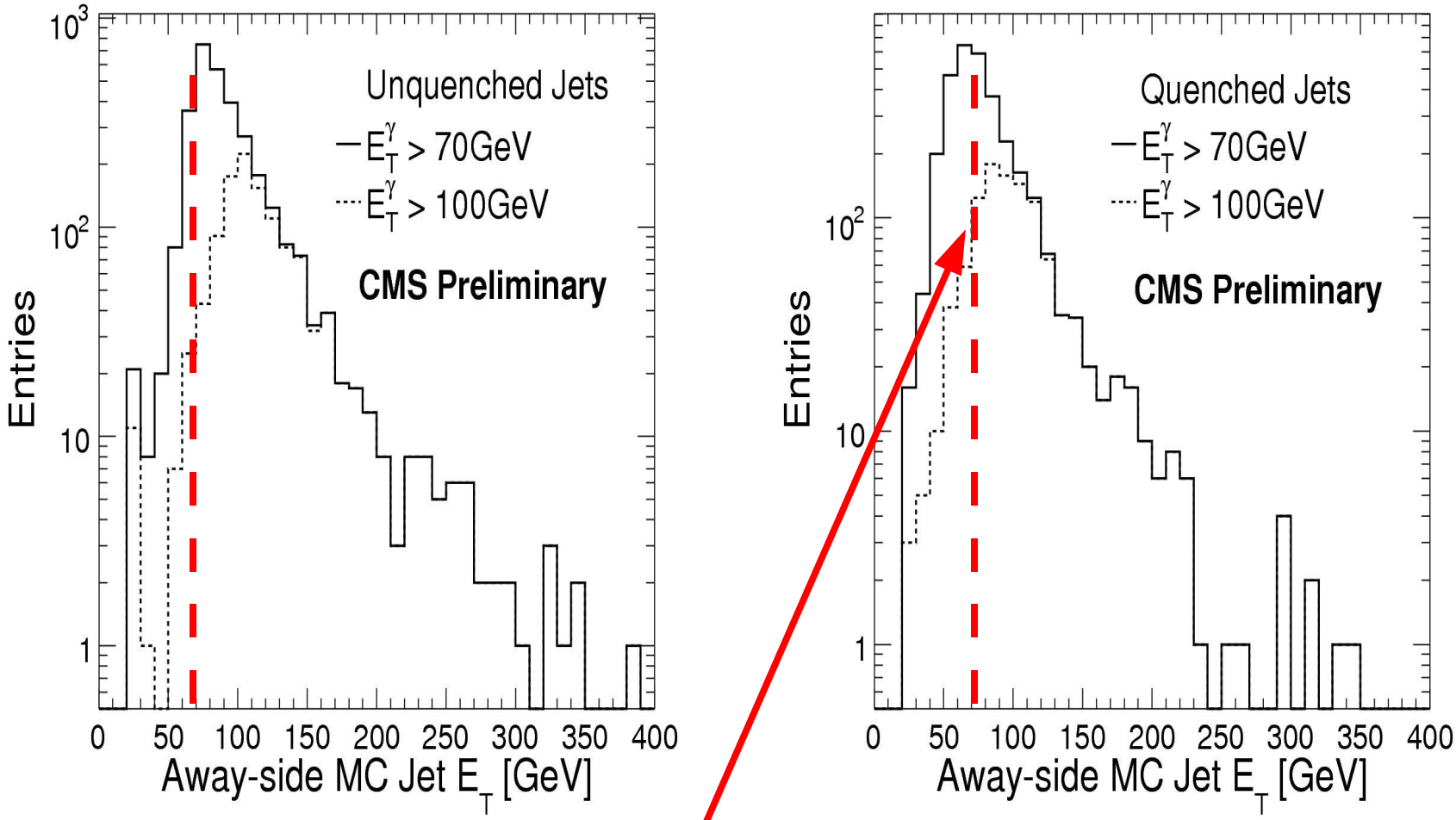




- Performance for $E_T^\gamma$ >70GeV
  - Efficiency > 60%
  - Fake rate < 20%
  - Transverse energy resolution: 2-5%

Before cuts: S/B=0.3

After cuts: S/B=4.5

# Jet Finding in PYQUEN

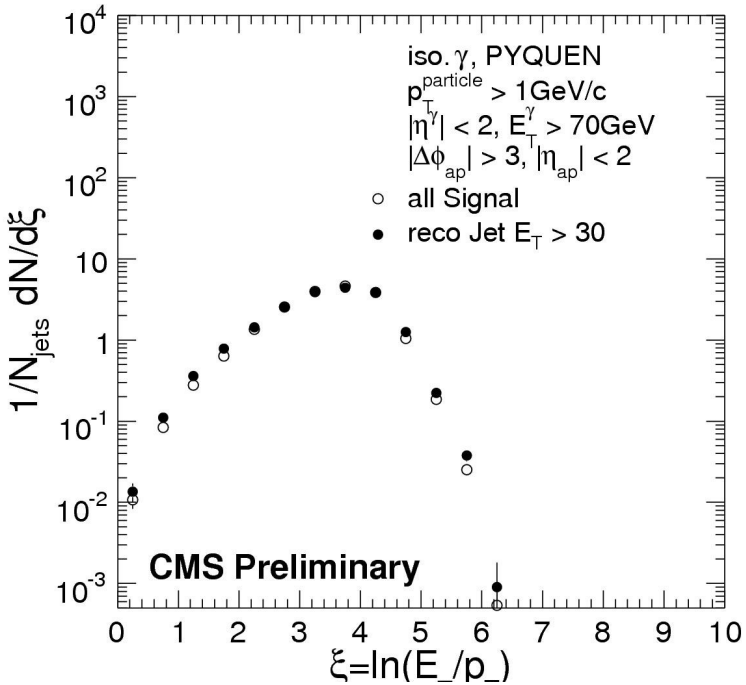


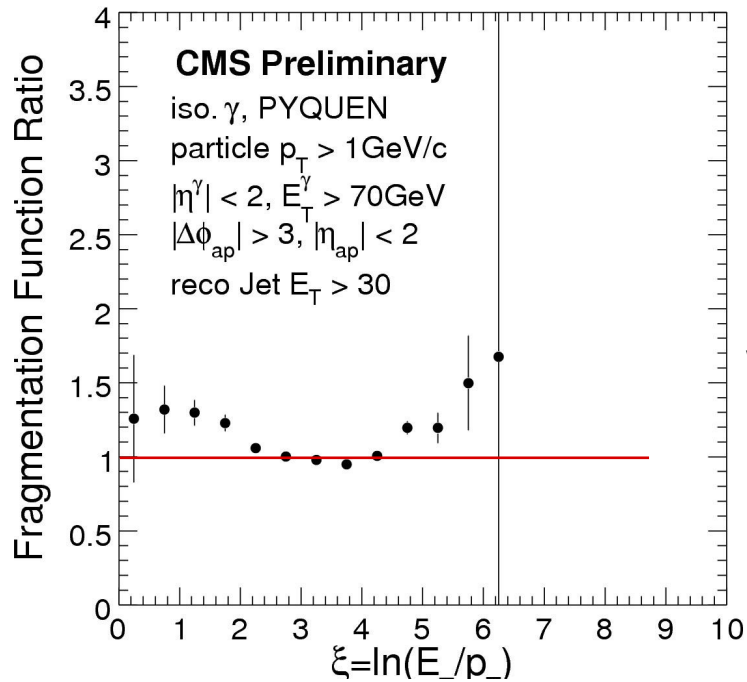

- Quenching mechanism in PYQUEN moves energy out of R=0.5 cone
- This lowers jet finding efficiency for a given initial parton $E_T$

# Event selection summary

- Pb+Pb background events
  - 0-10% HYDJET v1.2, 1000 events, $dN/d\eta \sim 2400$
- PYTHIA (v6.411)/PYQUEN (v1.2) events
  - $E_T > 70$ GeV potential trigger particle
  - $E_T > 60$ GeV reconstructed supercluster
- Tracks
  - $p_T > 1$ GeV/c, > 8 hits, prob > 0.01
- Reconstructed events
  - Isolated photon with $E_T > 70$ (100) GeV, $|\eta| < 2$
  - Jet with $E_T > 30$ GeV, $|\eta| < 2$, $\Delta\phi(\gamma,\text{jet}) > 3$
- Fragmentation function
  - Cone-size around jet axis: 0.5

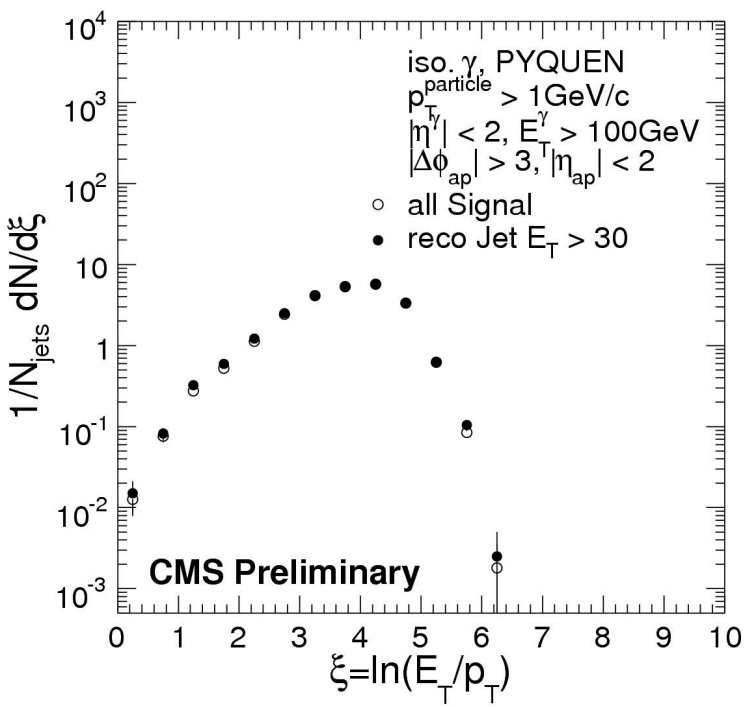
# Jet Finder Bias (Quenched Jets)

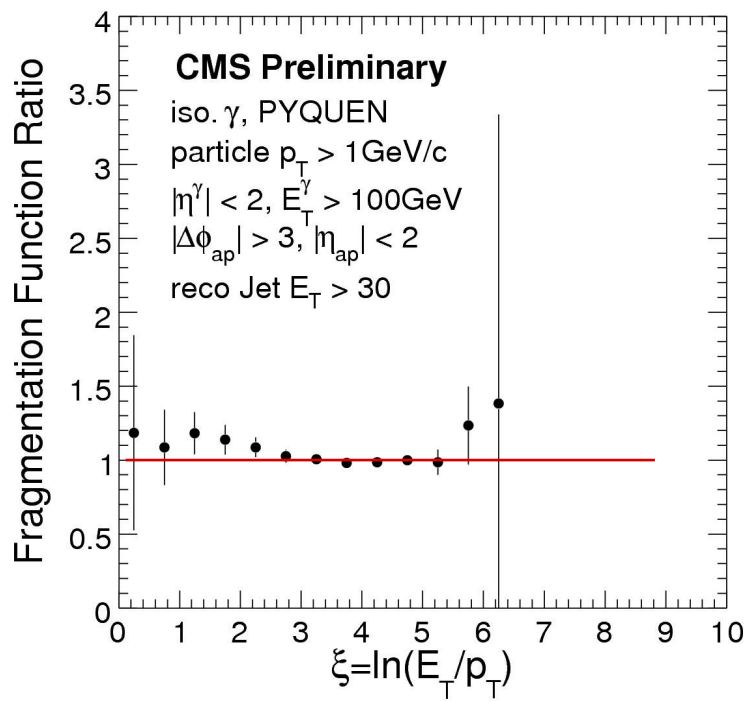



Significant bias (up to 30%) in quenched sample with **$E_{T,\gamma}$ > 70GeV**

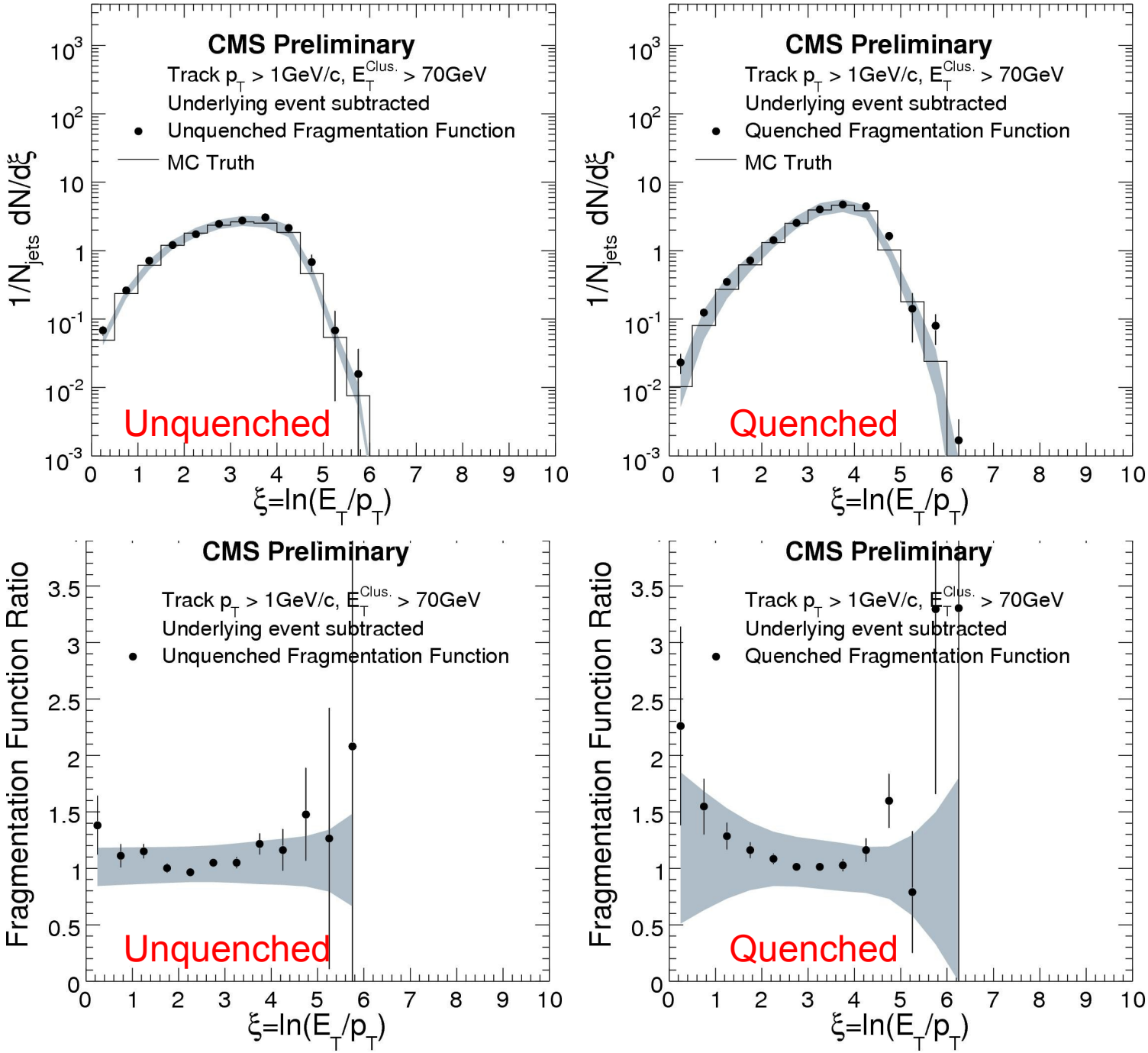
N.b.: Bias is present in p+p, i.e. can be studied independent of our measurement in Pb+Pb




Bias about 50% smaller for **$E_{T,\gamma}$ > 100GeV**

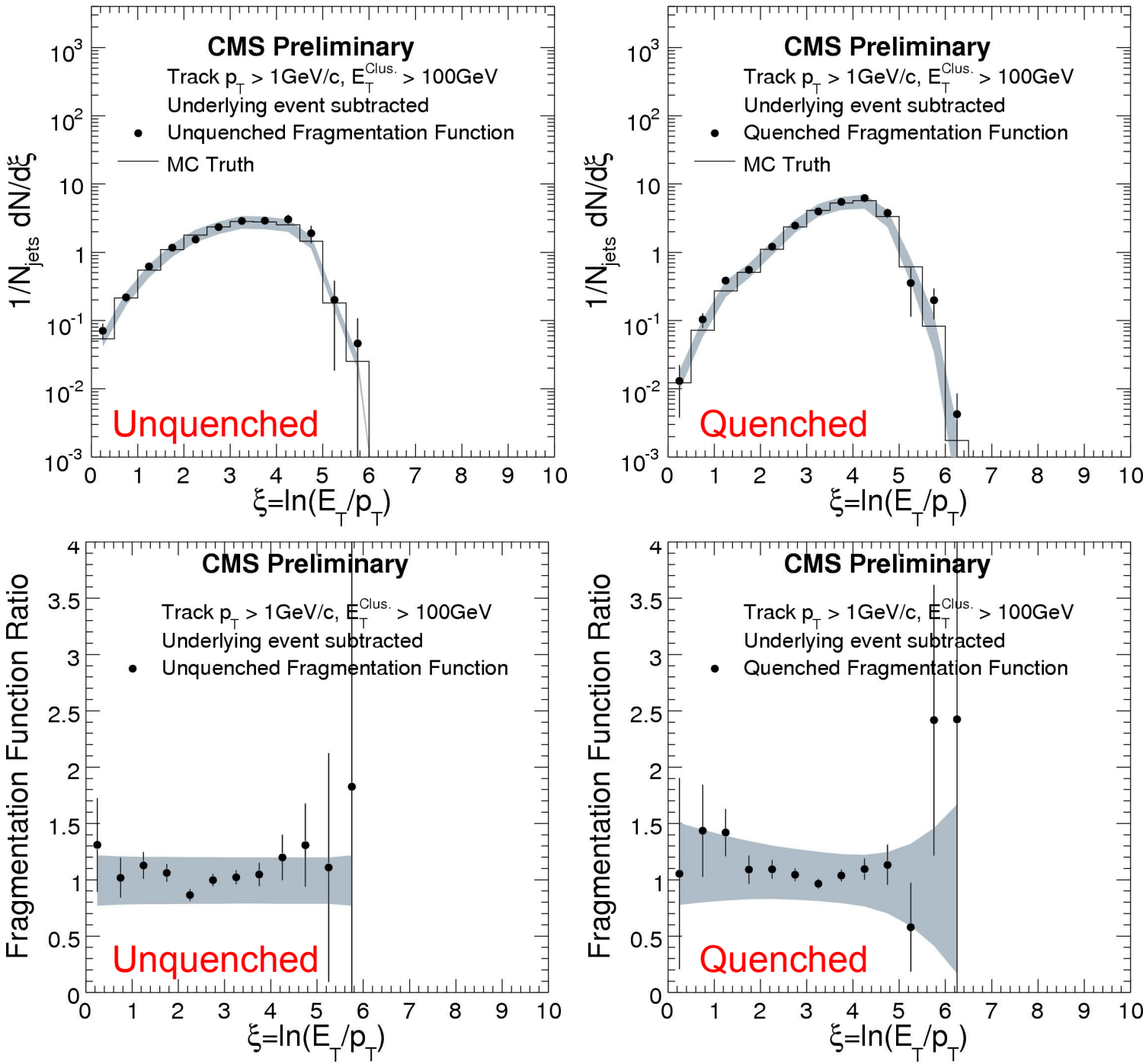
# Fragmentation function results ($E_{T,\gamma}$ > 70 GeV)




Reconstructed FF agrees with MC FF within expected uncertainty

Largest deviation at small $\xi$ (large z)

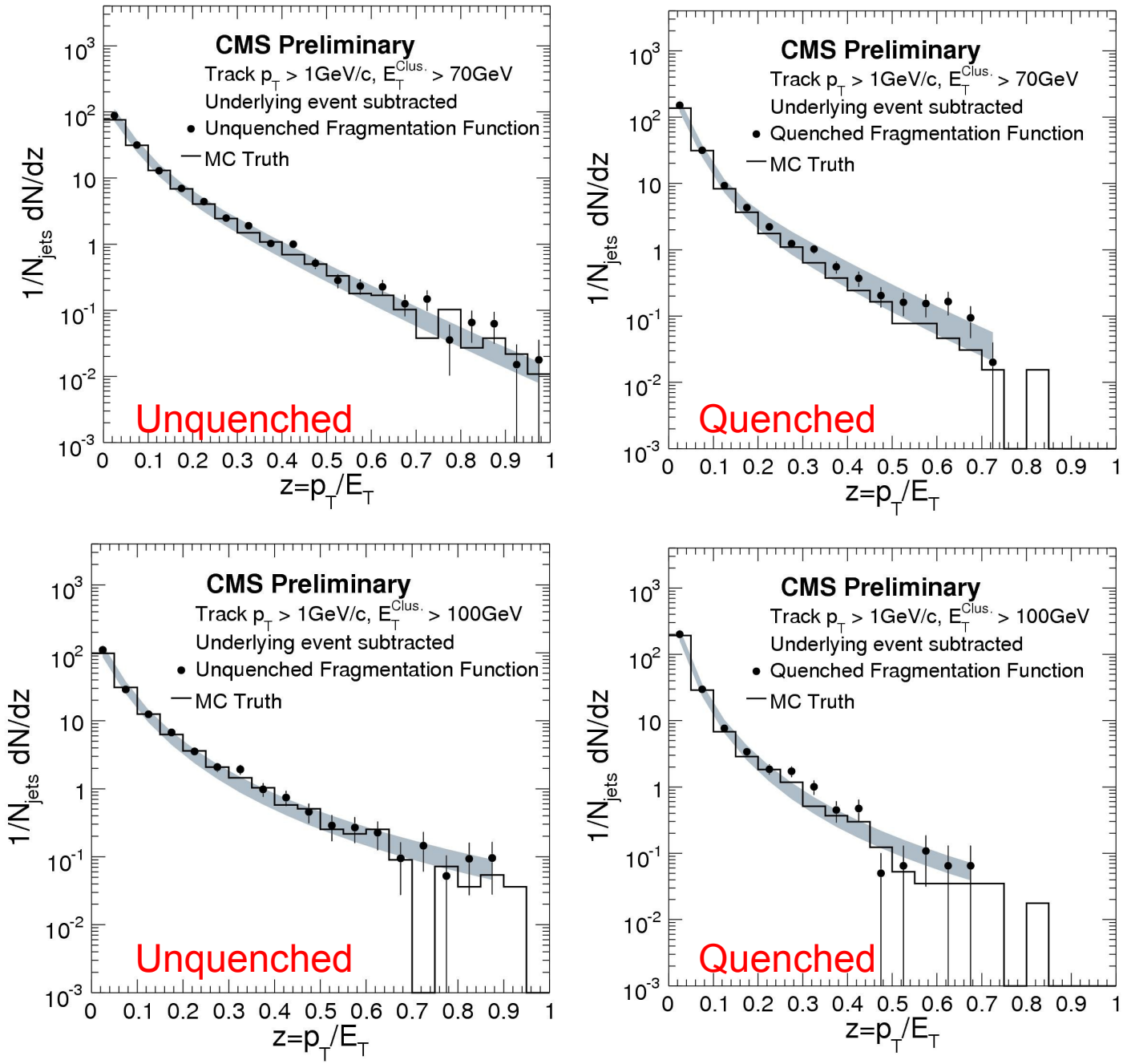
# Fragmentation functions ($E_{T,\gamma}$ > 100 GeV)




Reconstructed FF agrees with MC FF within expected uncertainty

**70 vs 100 GeV:** Trade-off between statistical and systematic uncertainties

# Fragmentation functions (vs z)




$E_{T,\gamma}$ > 70GeV

$E_{T,\gamma}$ > 100GeV