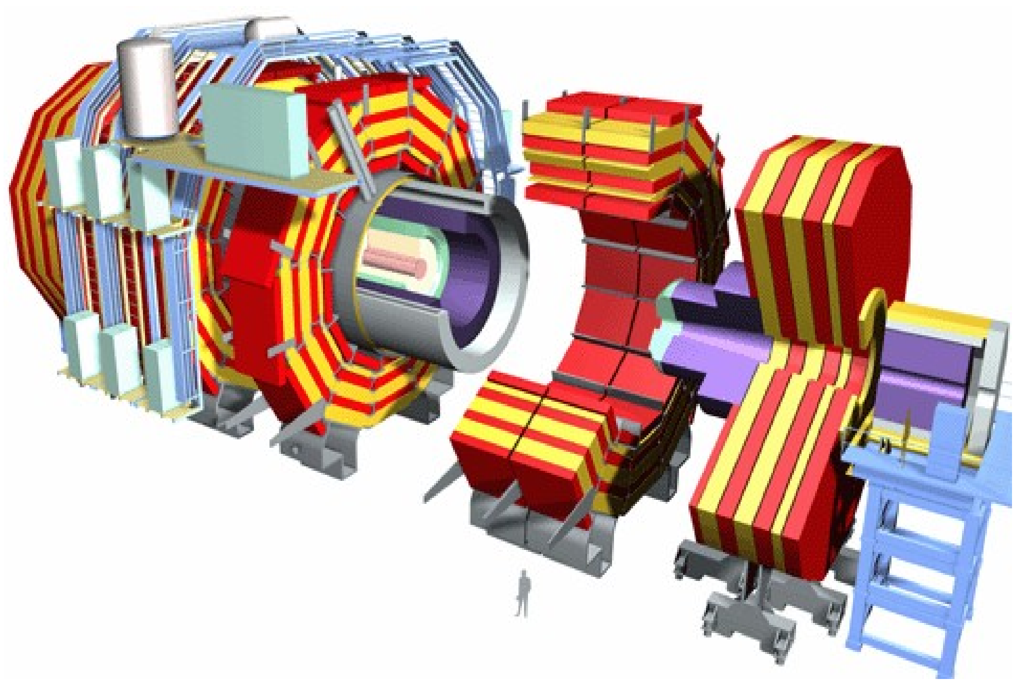
Jet physics in HI with CMS



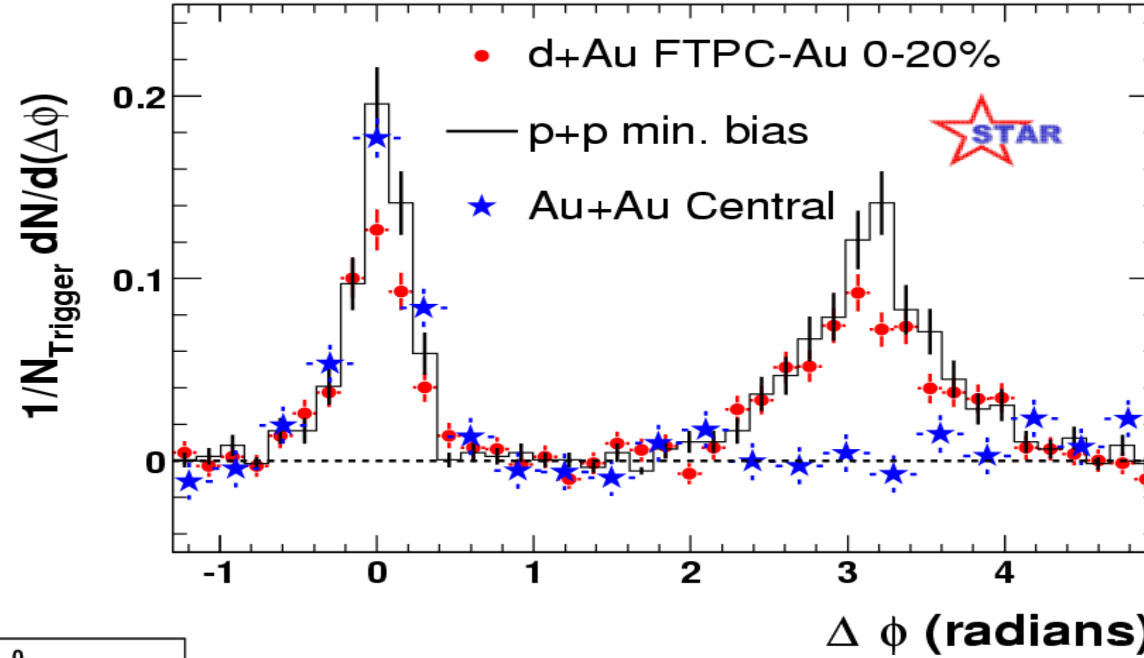
Constantin Loizides
(MIT)

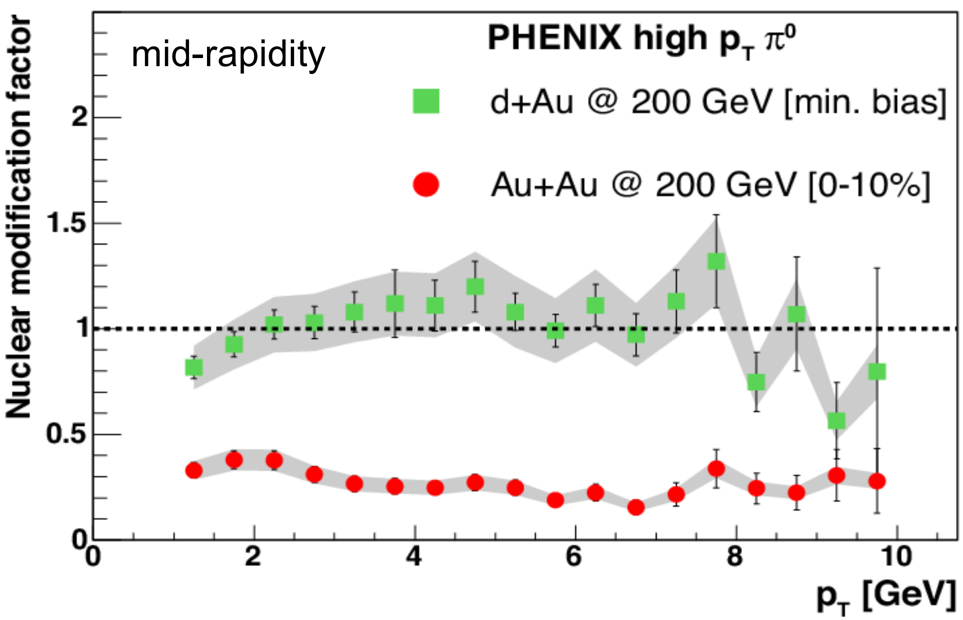
CMS HI groups: Athens, Auckland, Budapest, CERN, Chongbuk, Colorado, Cukurova, Ioannina, Iowa, Kansas, Korea Univ., Lisbon, Los Alamos, Lyon, Maryland, Minnesota, MIT, Moscow, Mumbai, Seoul, Vanderbilt, UC Davis, UI Chicago, Vilnius, Zagreb

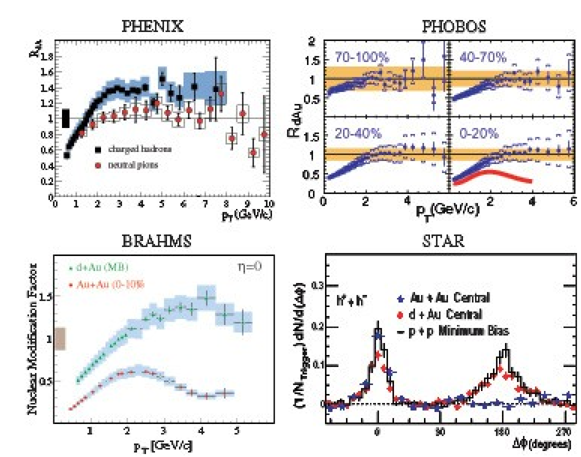
Heavy-Ion Forum, Dec 2008, CERN

Key physics results from RHIC

- High-transverse momentum particle suppression
- Energy loss of partons in medium

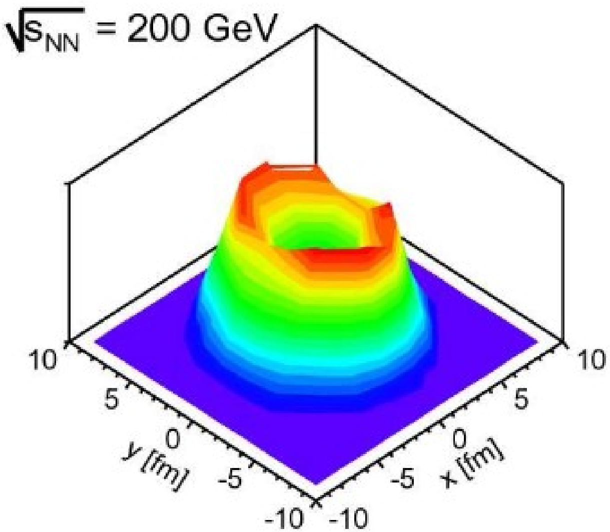






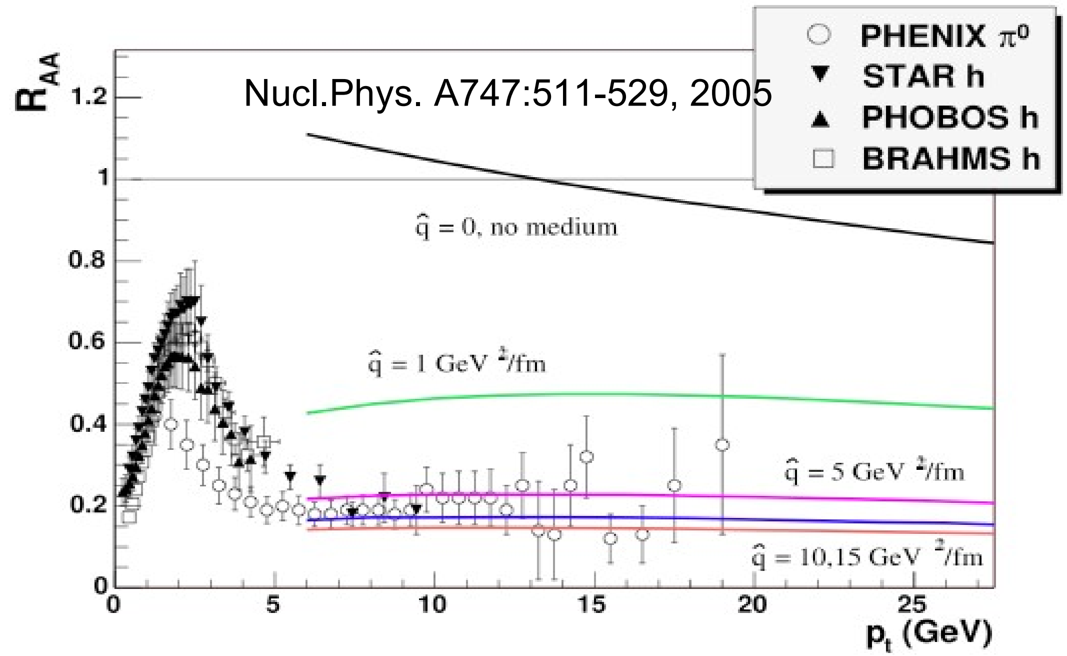
PRL, Volume 91, Issue 7
(15 Aug 2003)

Surface effect



Origin of partons that yield >5GeV hadron in central Au+Au

Eur.Phys.J. C38: 461, 2005



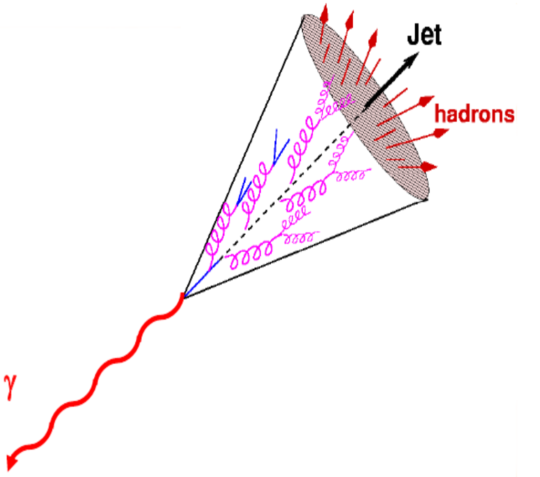
- Strong suppression and steeply falling parton production spectrum
- Observed spectra dominated by emission from surface
- Complicates understanding of suppression mechanism

How can we learn more?

Almost everything you want to know about jets can be found using 2-particle correlations

M.Tannenbaum, PoSCFRNC2006:001, 2006

- Only "almost" since the shape of the away-side particle distribution relative to the trigger particle (x_E distribution) does not depend on the fragmentation function (FF)
  - Reason is trigger (leading particle) bias
- Trigger bias can be overcome by
  - γ-h correlations
    - Also overcomes surface effect
  - Full jet reconstruction
    - Challenging, but much higher rate

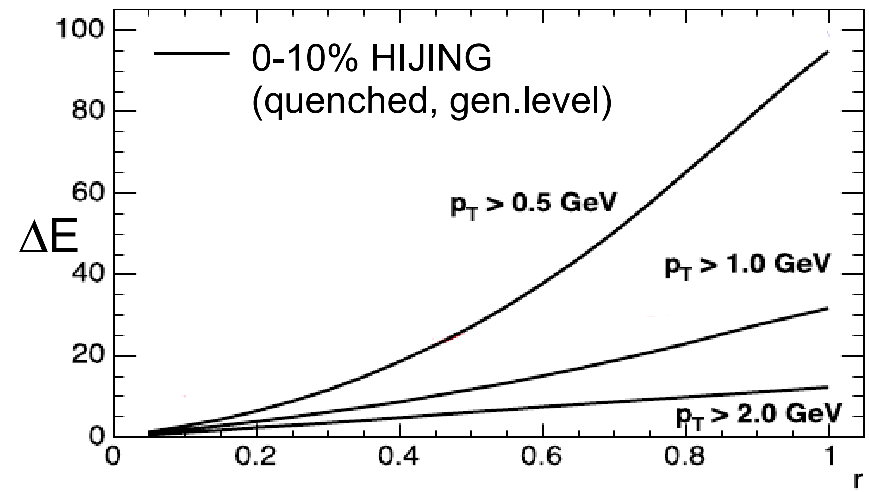


Jet reconstruction in HI collisions

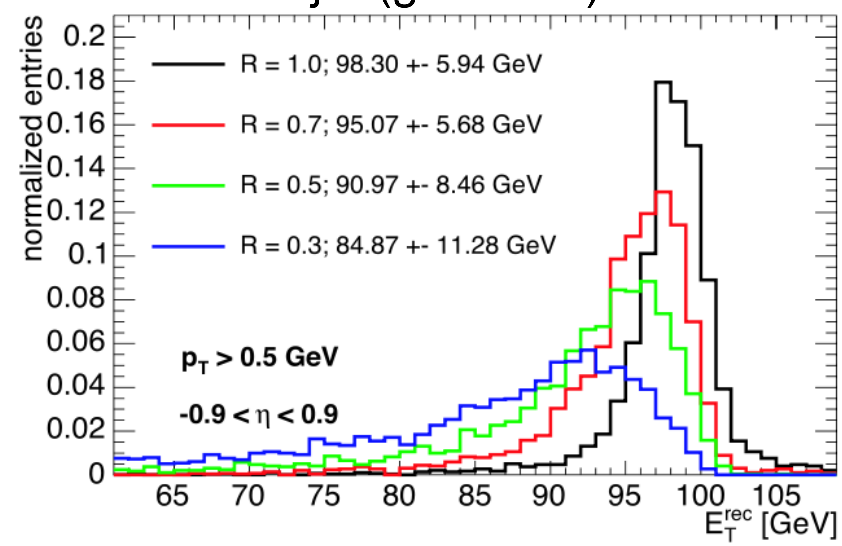
- Consequences of HI background
  - Mean energy in cone R

    $$E_{bgk} = 0.5 R \, dE_T / d\eta$$
  - For R=0.5,
    - 75 GeV in central Au+Au, RHIC
    - ~150 GeV in central Pb+Pb, LHC
- Furthermore, jet energy resolution degraded by
  - Background fluctuations
  - Out-of-cone fluctuations
  - Possible out-of-cone radiation
- Typically R=0.3 to 0.5 in HI

Background fluctuations



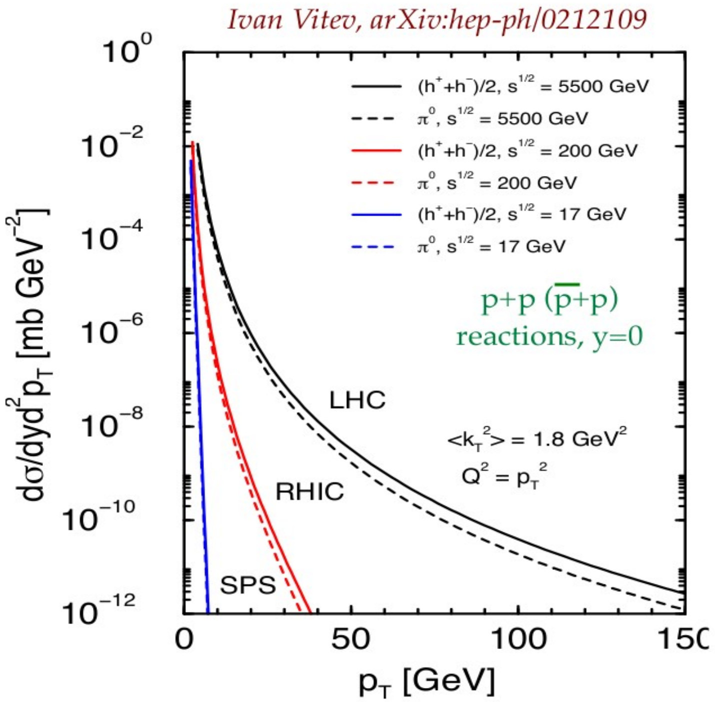
Out-of-cone fluctuations for 100 GeV jet (gen.level) PYTHIA

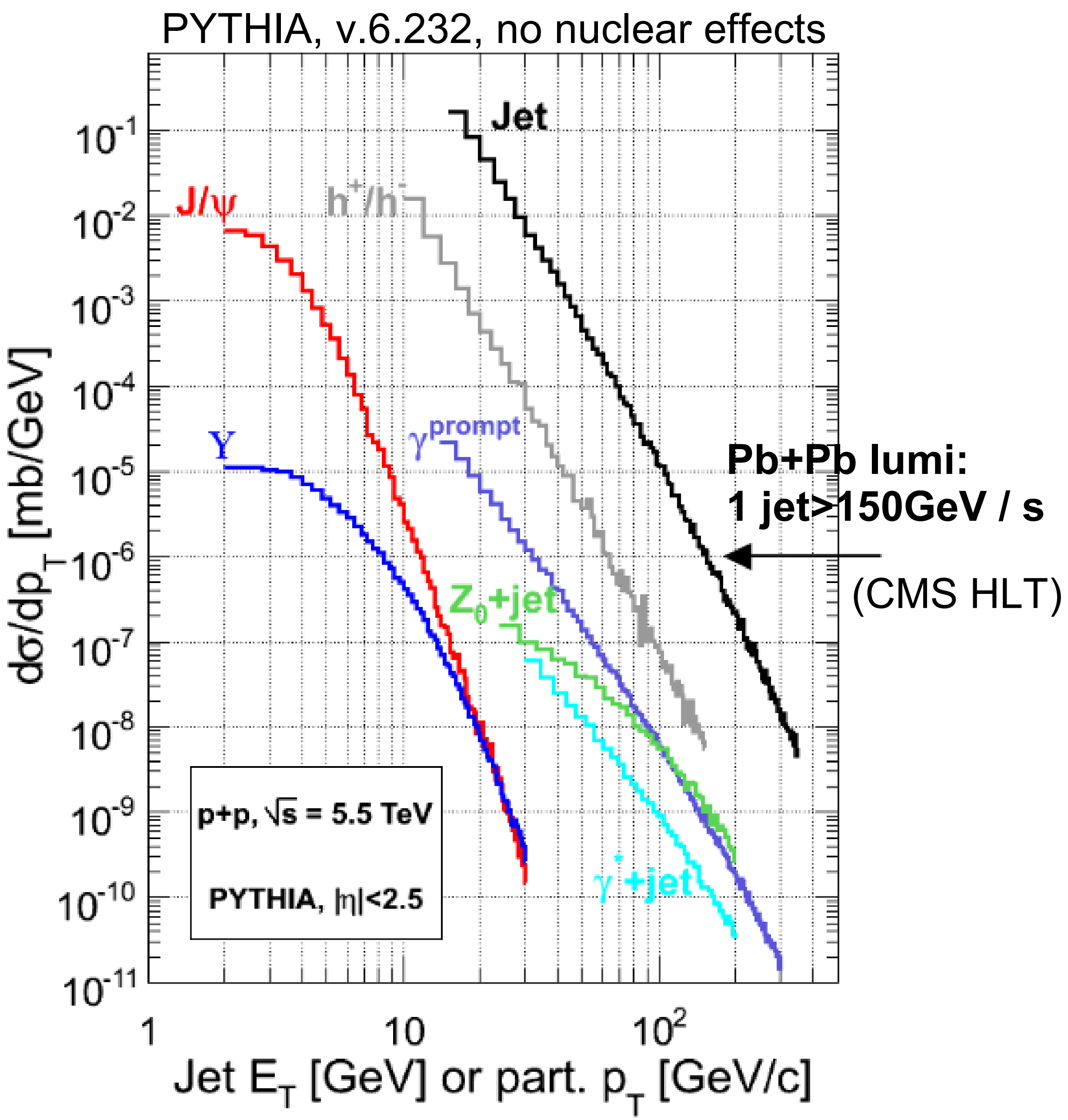


CL, thesis, nucl-ex/0501017

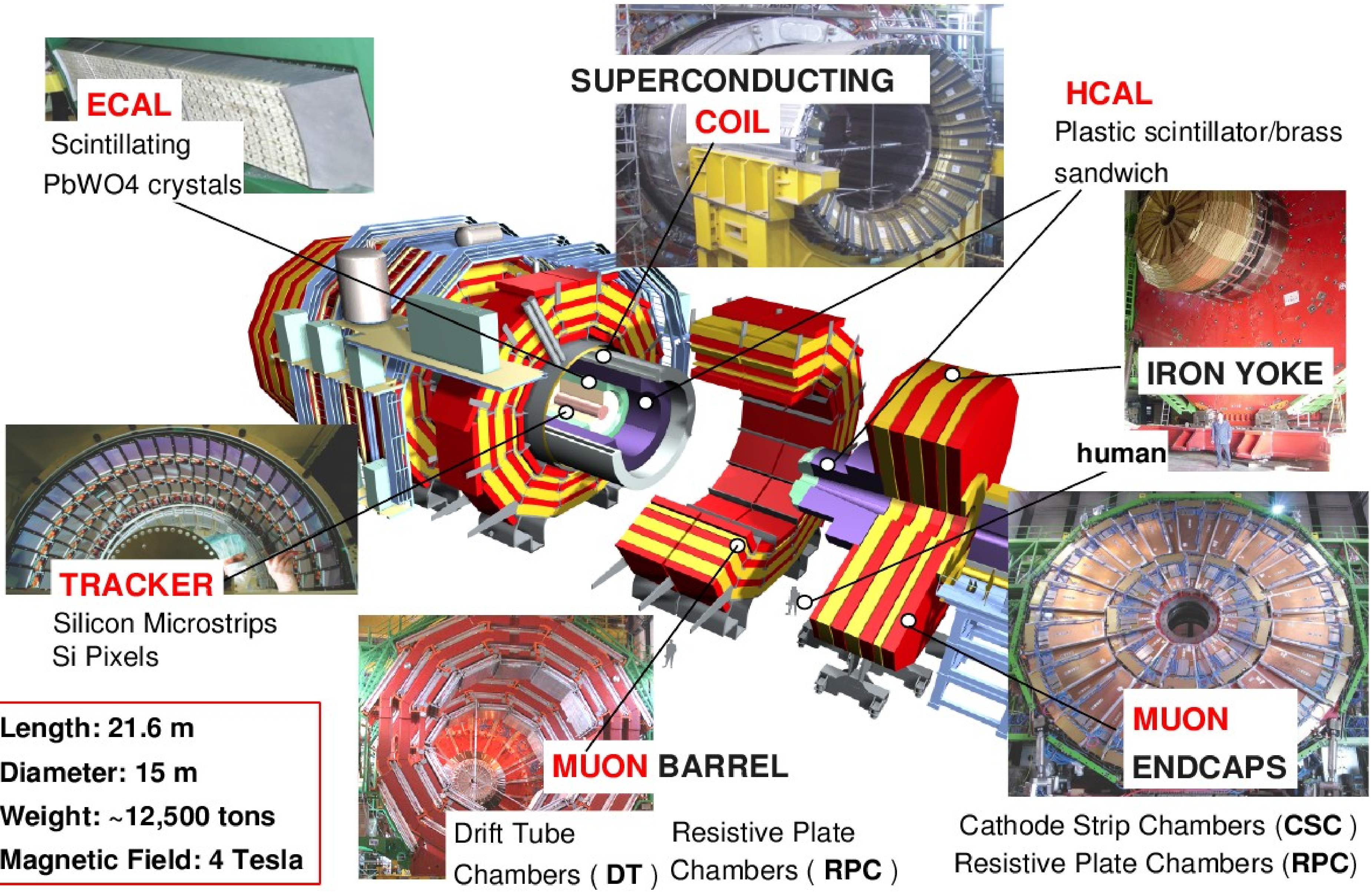
From RHIC to LHC

- High p_T probes abundant
- Qualitative new probes
  - Jets, γ/Z_0-jets
- Detailed study of hard scattering





Compact Muon Solenoid



Length: 21.6 m

Diameter: 15 m

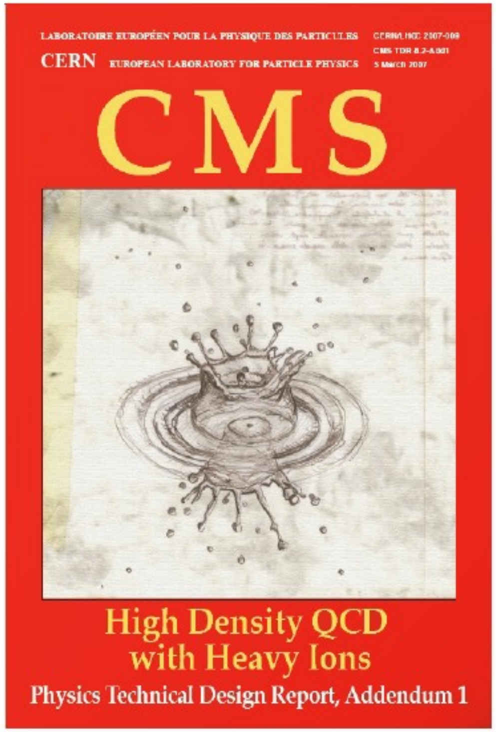
Weight: ~12,500 tons

Magnetic Field: 4 Tesla

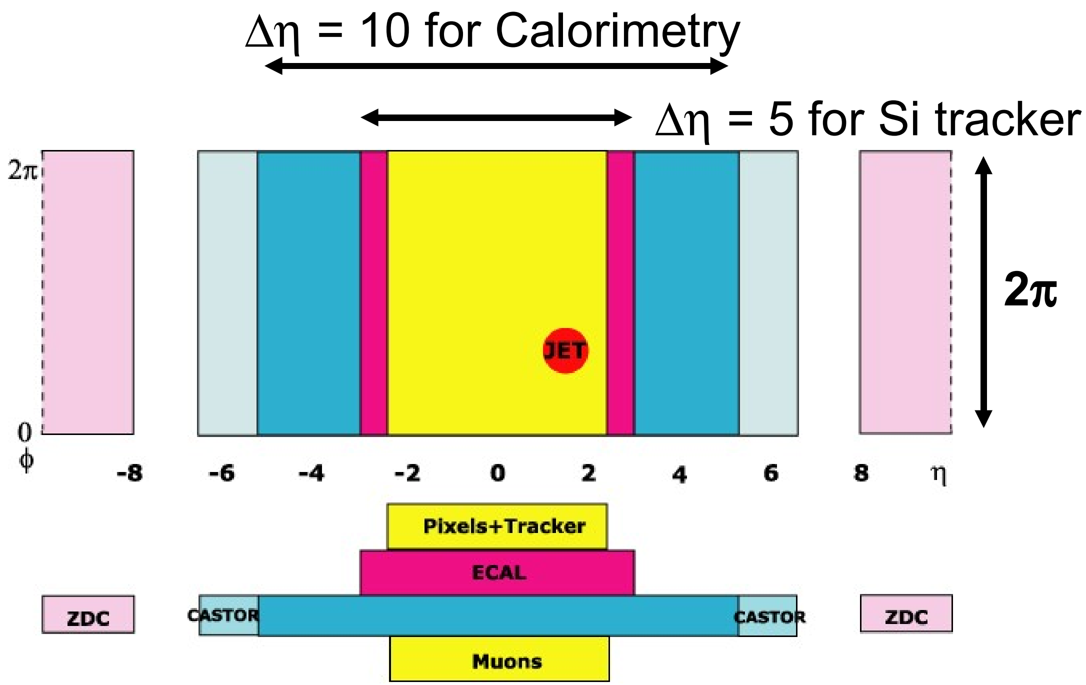
CMS is "on shell"

- CMS is ready for collisions
  - Over 300 000 000 cosmic events recorded with full detector just in the past month

CMS as a HI experiment



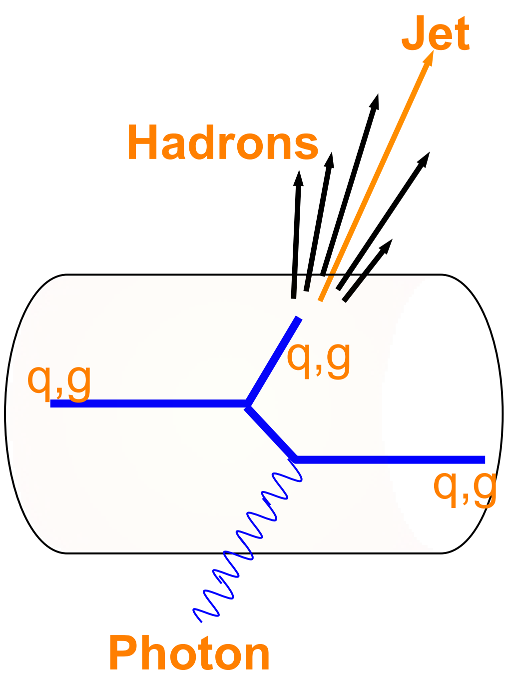
J.Phys.G34:2307-2455,2007

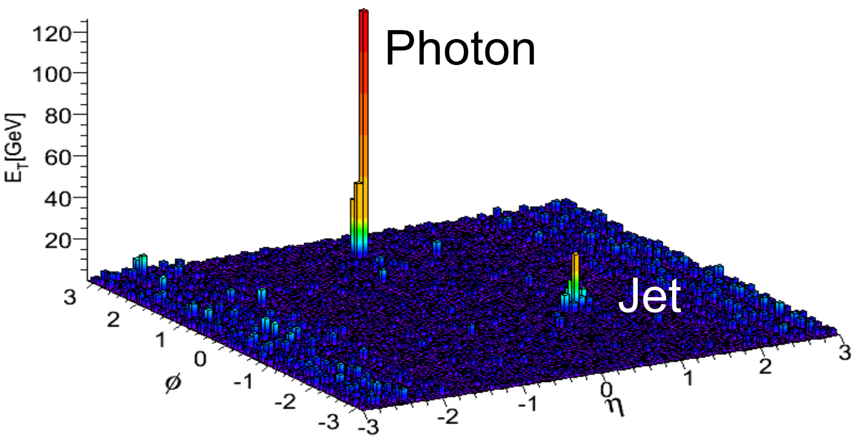


- Large (mid-rapidity) acceptance (tracker and calorimetry)
  - Also large forward coverage
- DAQ+HLT capable to inspect every single Pb+Pb event
- Large statistics for rare probes

Jet physics in HI with CMS

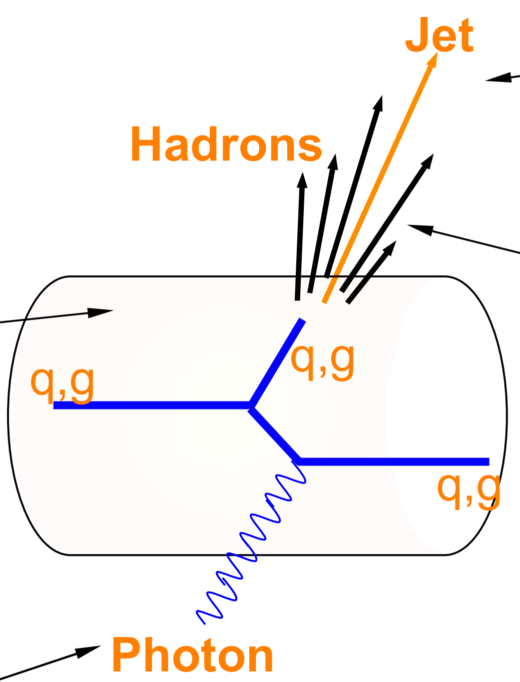
For the rest of talk: Use specific example of γ-jet correlation measurement to discuss the high-pt capabilities of CMS





Goal: Measurement of the jet fragmentation function for "known" parton energy

Photon-tagged jet fragmentation functions



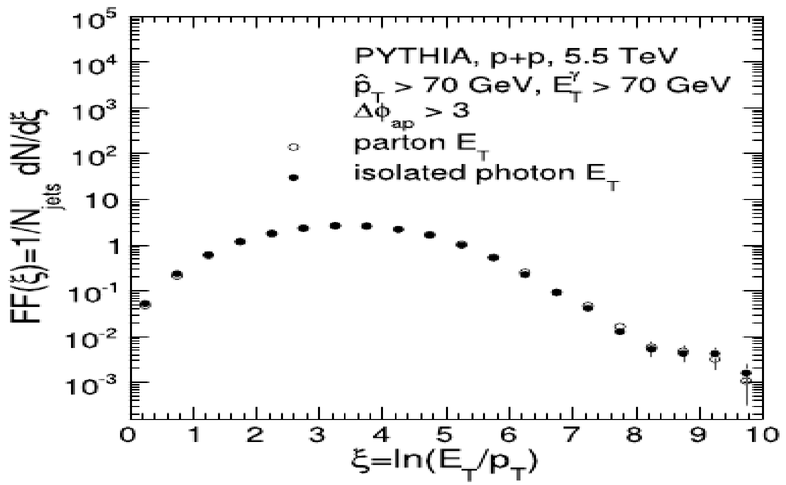
Jet axis **provides parton direction**

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

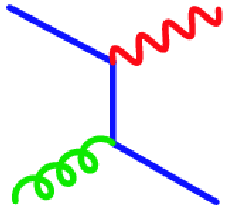
Measure jet fragmentation function:
$dN/d\xi$ with $\xi = -\log z = \log p_T/E_T$



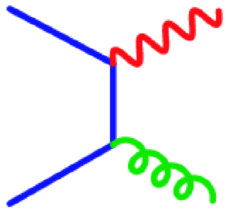
All results based on full GEANT-4 simulations using full reconstruction algorithms on full one run-year statistics

Signal and background processes

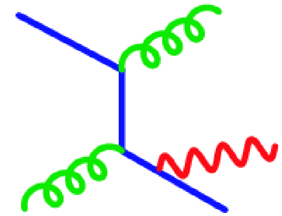
Compton



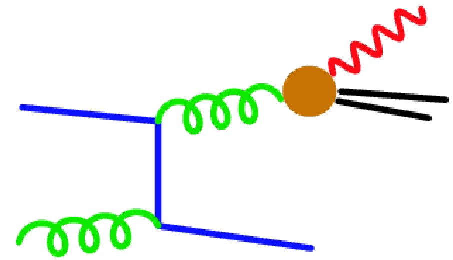
Annihilation



Bremsstrahlung



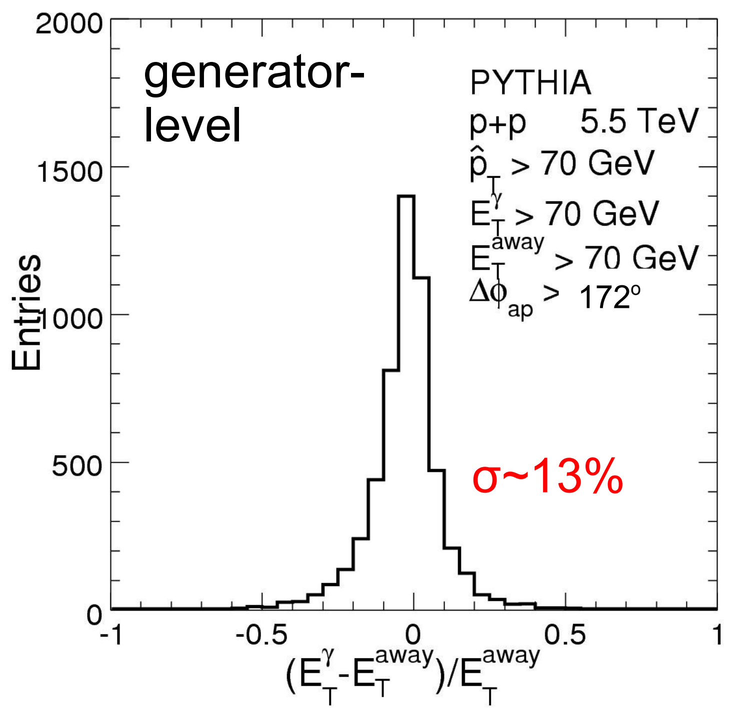
Fragmentation

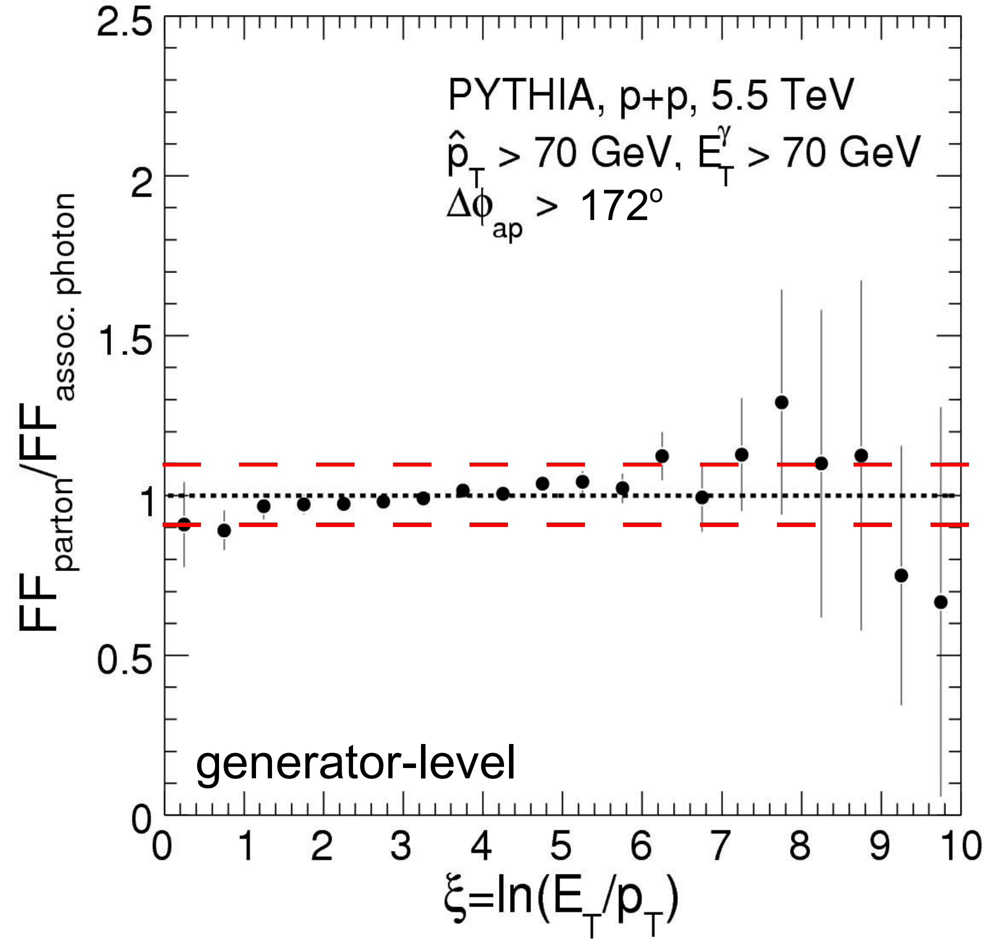


Background photons usually associated with jets

- Use photon to tag parton energy
  - Goal: Best correlation of the photon and parton energy
  - Ideally: “Use” leading order photons
  - In practice: Determine isolated photons + use cut on azimuthal opening angle between the photon and the jet to select events
    - Isolation cuts in data analysis and in calculation

Photon-tagged jet fragmentation functions





- Generator-level studies
  - Using MC isolation definition + opening angle cut
  - FF can be determined well with <10% deviation

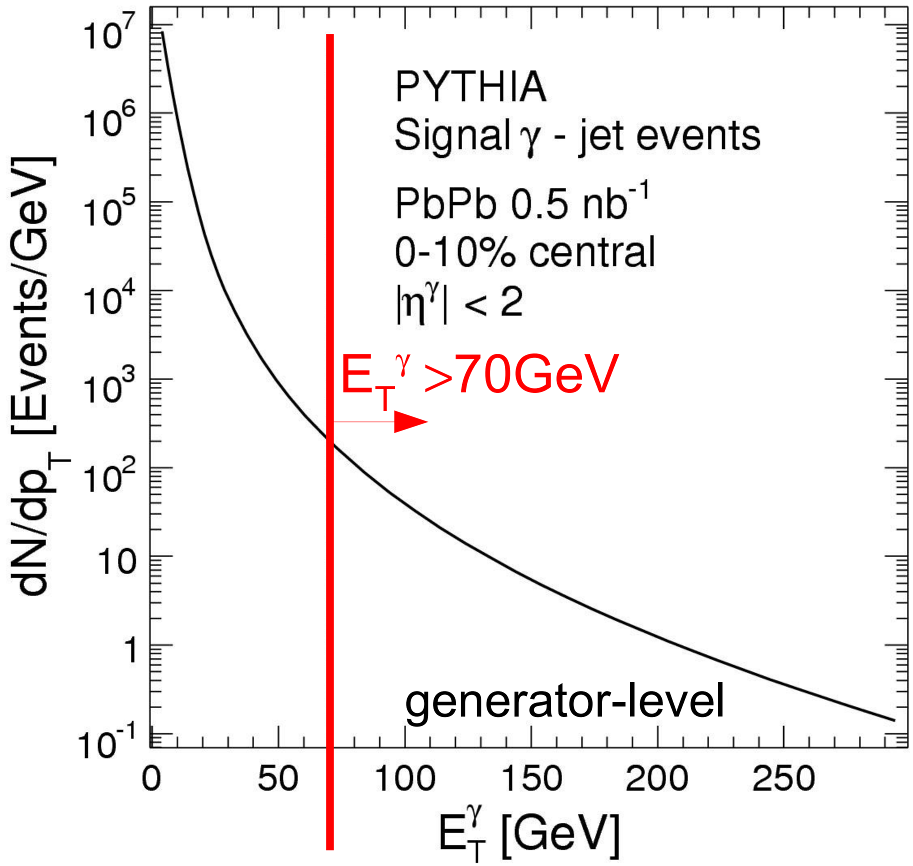
Event generation

- Study two scenarios
  - Unquenched: PYTHIA signal and QCD background (p+p) events mixed with central unquenched Pb+Pb HYDJET events
    - No high-p_T particle suppression
    - Worst case of high background rates
  - Quenched: PYQUEN signal and QCD background (p+p) events mixed with central quenched Pb+Pb HYDJET events
    - Suppression of high-p_T particles
    - Energy loss of partons radiated out of jet cone
    - Worst case for jet finding

PYQUEN/HYDJET v1.2
used with standard settings

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

Signal and background statistics



- Study for expected statistics in one nominal LHC Pb+Pb run "year"
  - 10^6 sec, $0.5 nb^{-1}$, 3.9×10^9 events
- Use 0-10% most central Pb+Pb
  - 10% smallest impact parameter
  - $dN/d\eta|_{\eta=0} \sim 2400$
- Require photon and jet to be "back-to-back" in azimuth
  - $\Delta\phi(\gamma,\text{jet}) > 172^0$

Data set	p_T cut [GeV/c]	isolated γ	signal γ	π^0	$\pi_\pm$	η	η′	ω
unquenched	>70	6531	4288	23675	47421	12267	8194	30601
unquenched	>100	1841	1216	4422	9103	2357	1567	5975
quenched	>70	6512	4209	7569	14616	3825	2445	9235
quenched	>100	1860	1212	1562	3000	829	515	2051

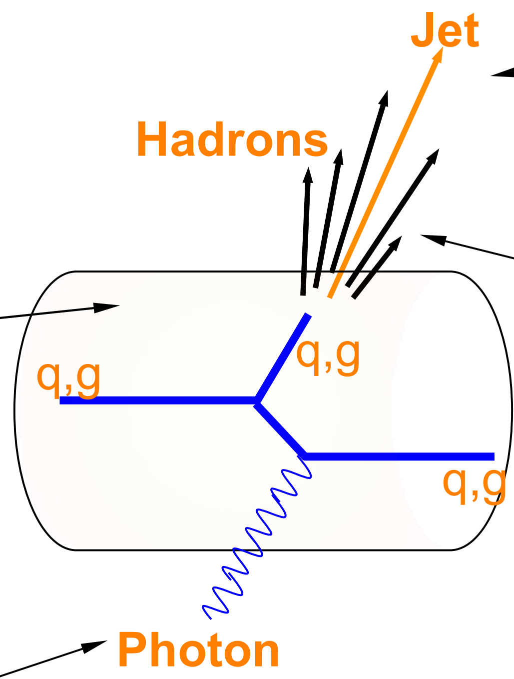
Signal

Potential background

Measuring photon-tagged jet FFs

3) Jet axis provides parton direction

1) Multiplicity and flow measurements characterize density, path length

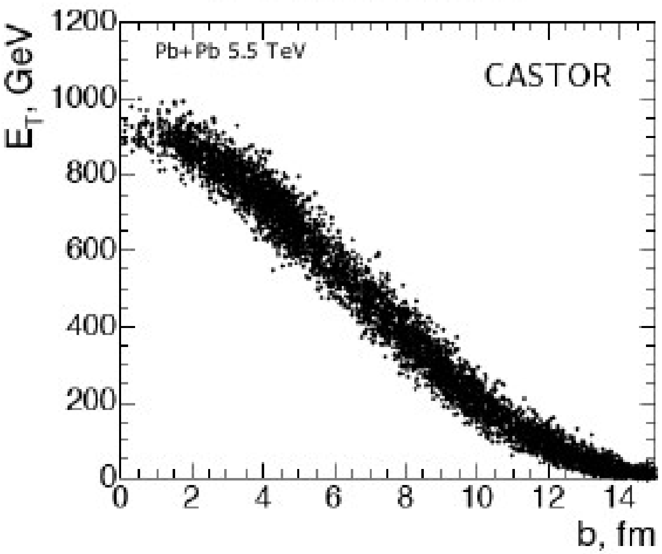


4) Charged hadron tracks used to calculate $z = p_T/E_T$

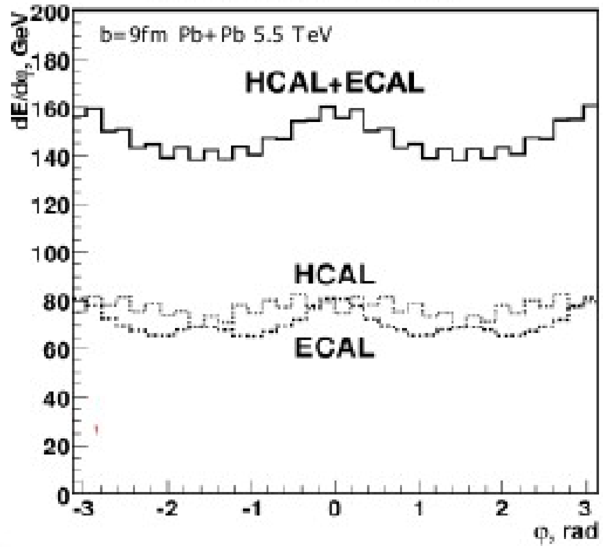
2) Photon energy tags parton energy E_T

Event characterization

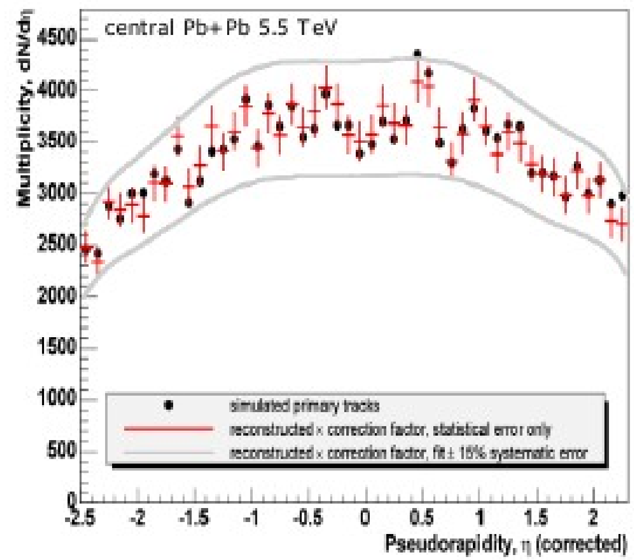
Centrality
(event-by-event)



Event Plane
(event-by-event)

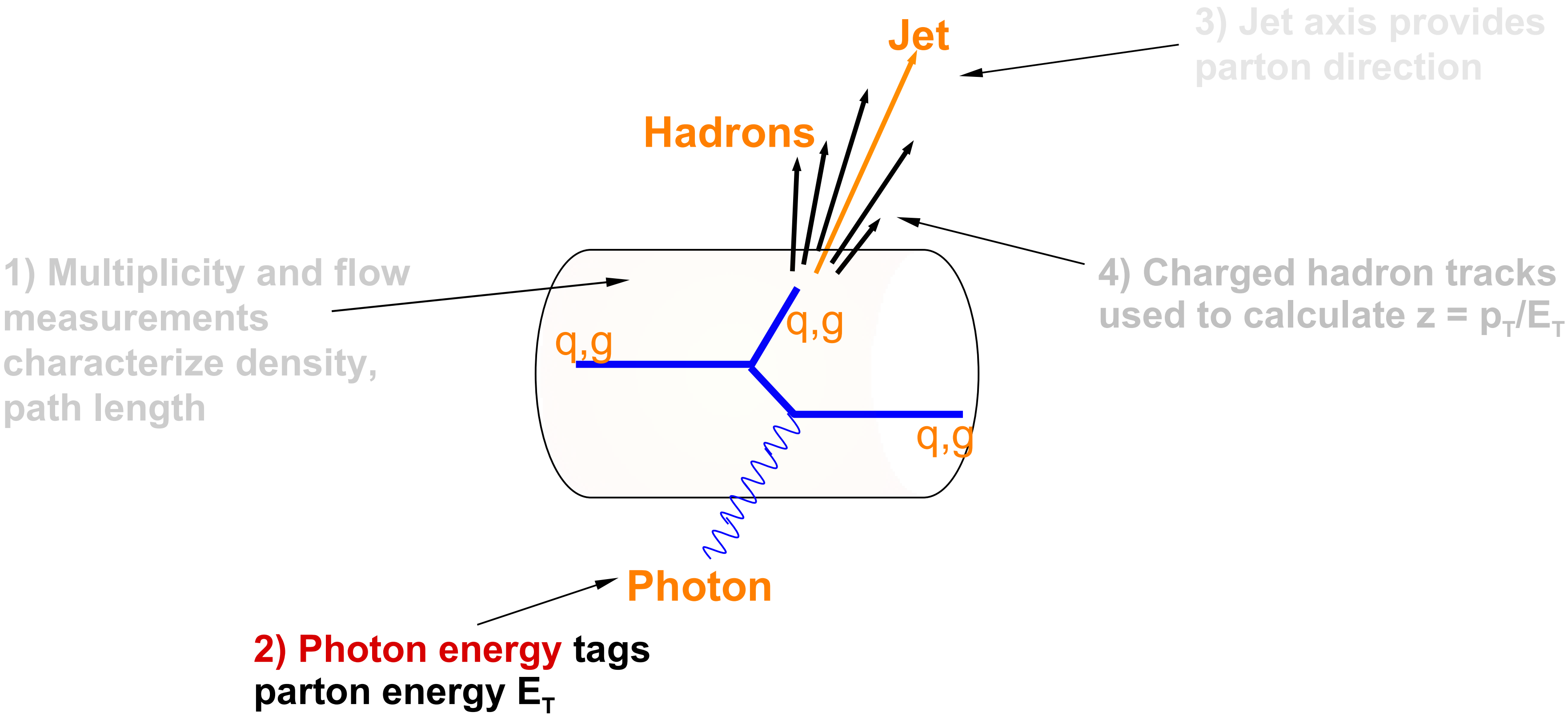


Multiplicity
(event-by-event)

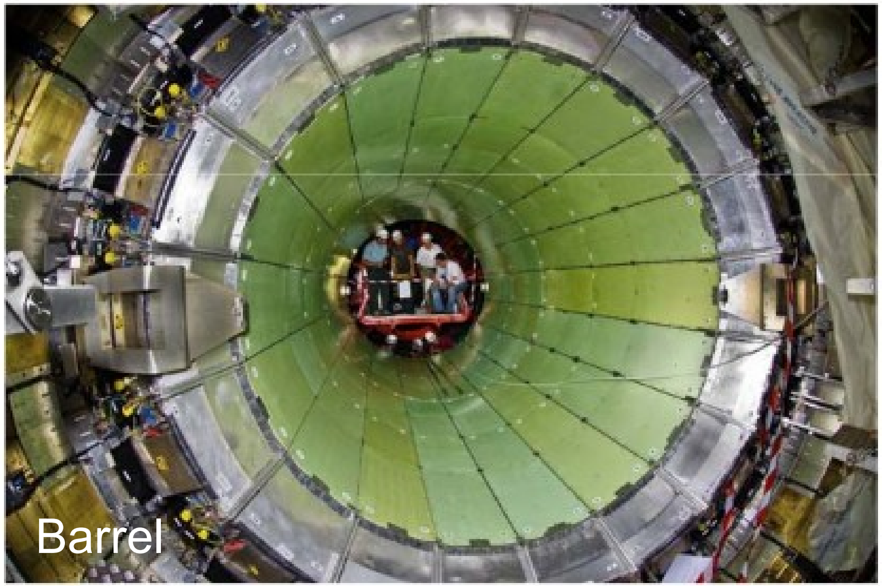


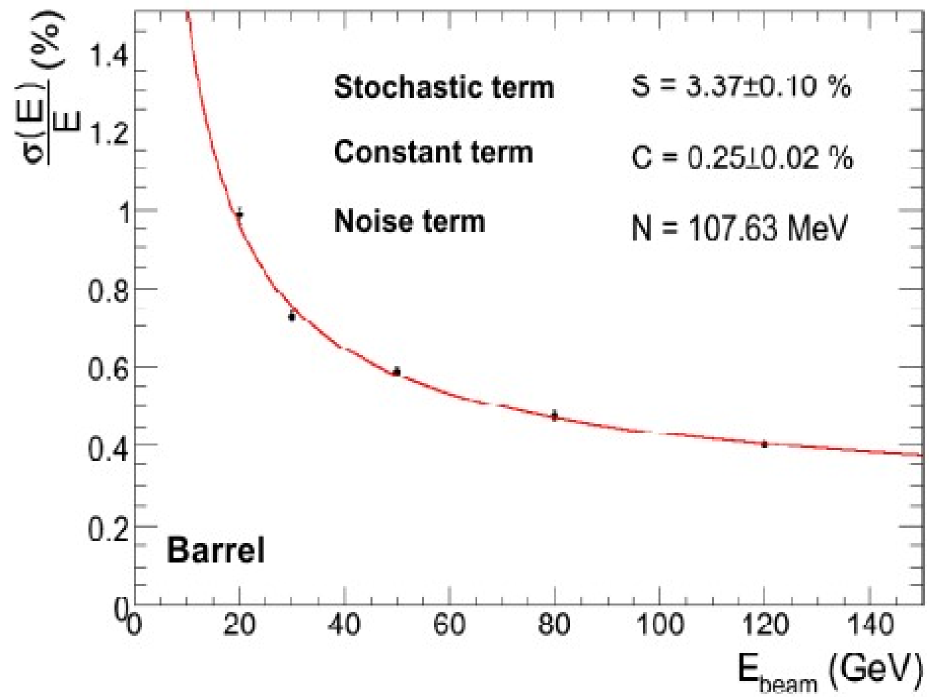
- Use of (forward) calorimeters and large acceptance tracker allows to characterize single events
  - Centrality
  - Event plane
  - Multiplicity
  - Mean p_T (not shown here)

Measuring photon-tagged jet FFs

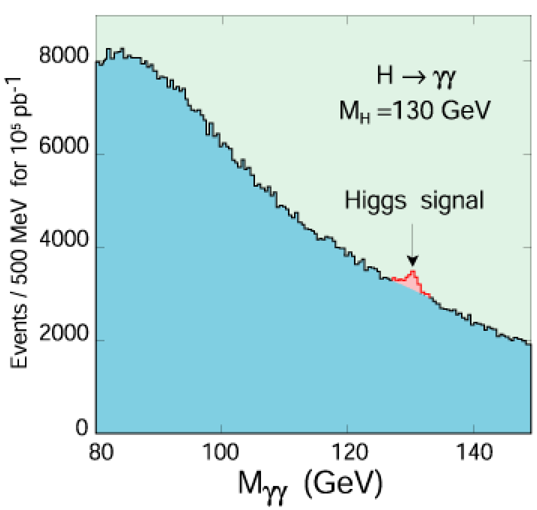


Electromagnetic calorimeter



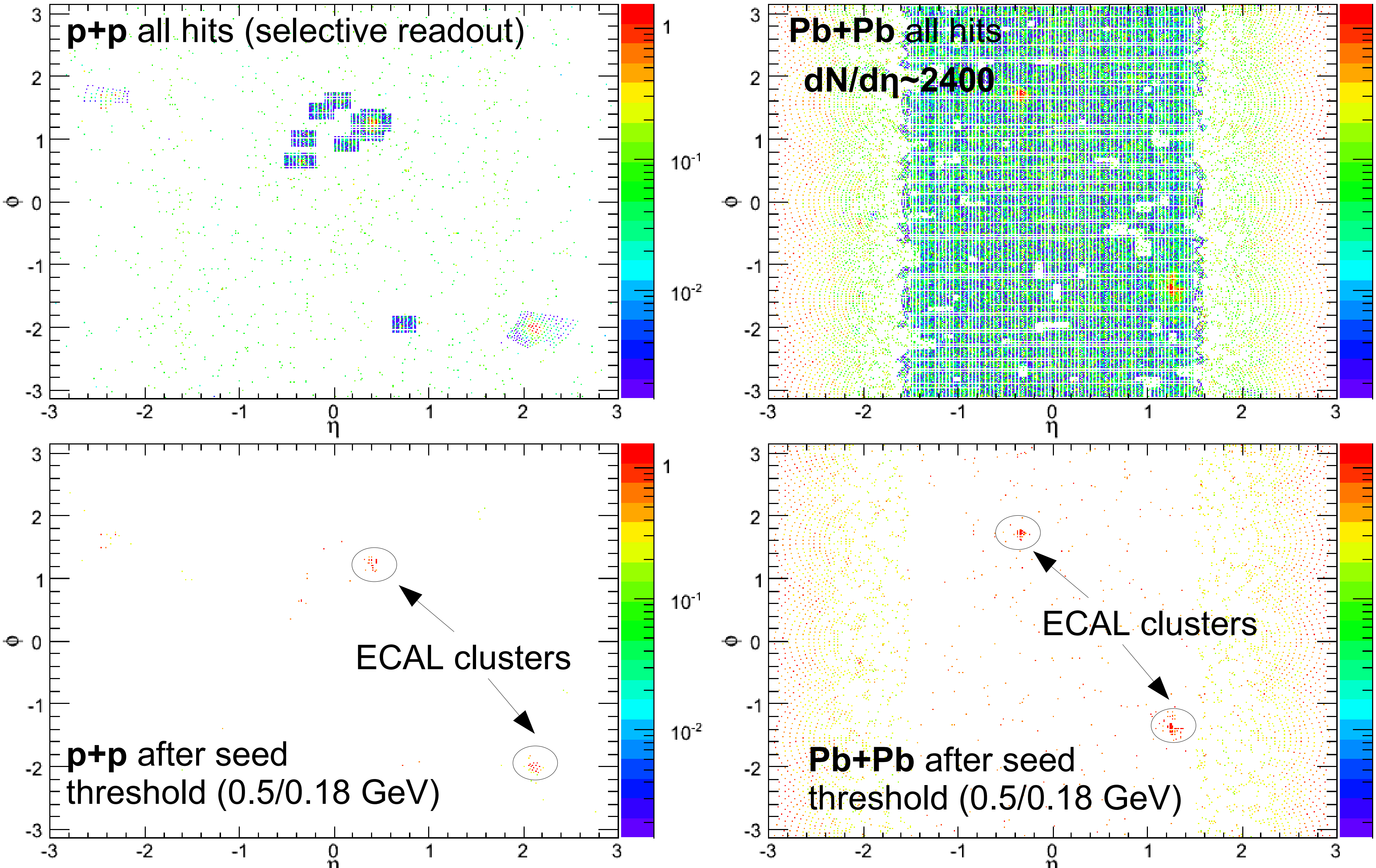


Benchmark:



- 75.000 lead tungstate crystals (+APD)
  - Granularity 0.017x0.017 to 0.05x0.05
  - Coverage up to |η|<3
- ΔE/E < 0.5% for E>100 GeV
  - No pre-shower detector yet, only use lateral shower shape

ECAL response in p+p and Pb+Pb

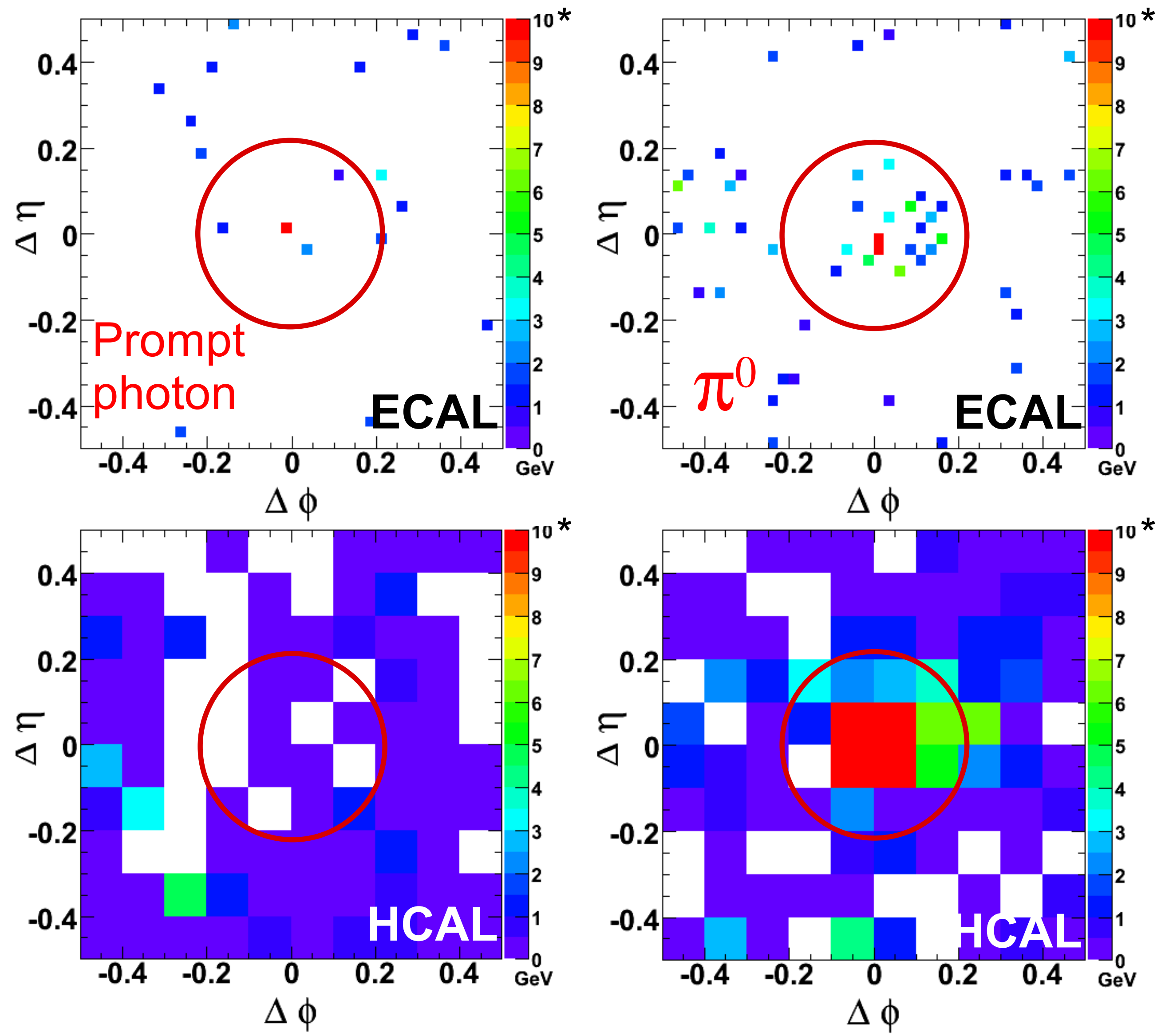


ECAL reconstruction chain used with standard p+p settings

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

Photon ID: Isolation and cluster shape cuts

- Selection variables
  - Cluster shape in ECAL
  - ECAL/HCAL energies in cones with R≤0.5
    - Background subtraction
  - Track isolation
- Total of 21 variables
  - Linear discriminant analysis (Fisher) and cut optimization using TMVA

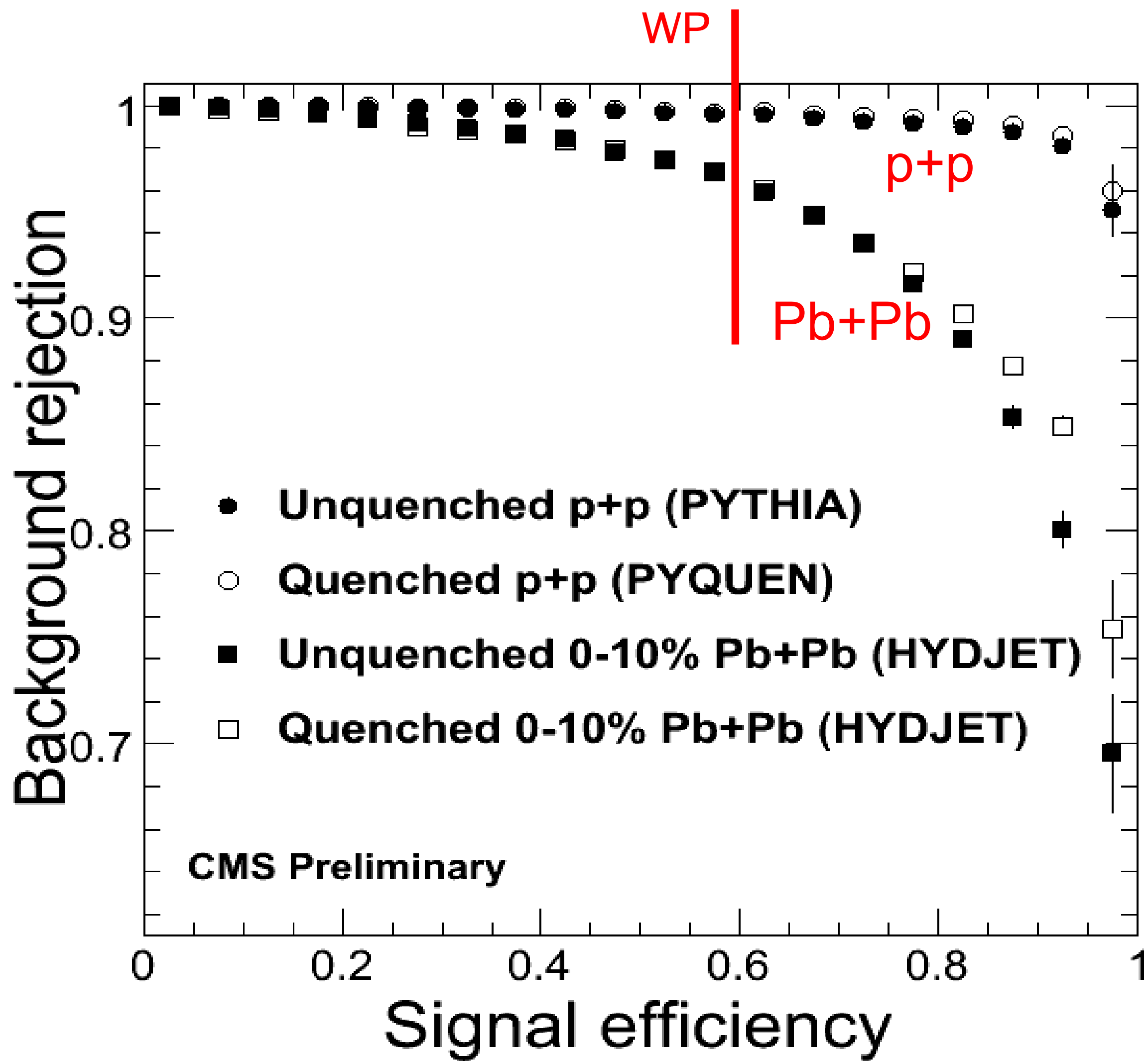


TMVA: http://tmva.sourceforge.net

*) Maximum set to 10 GeV

Photon identification performance

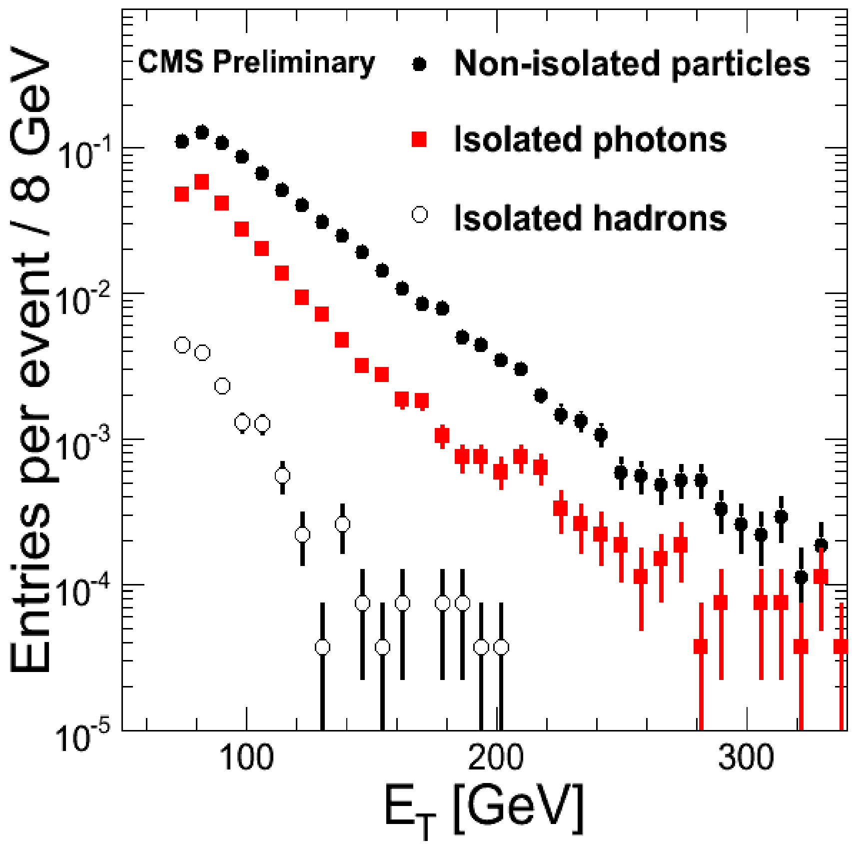
- Set working point to 60% signal efficiency
- Leads to 3.5% false acceptance (96.5% rejection)
- Training was done on unquenched samples only



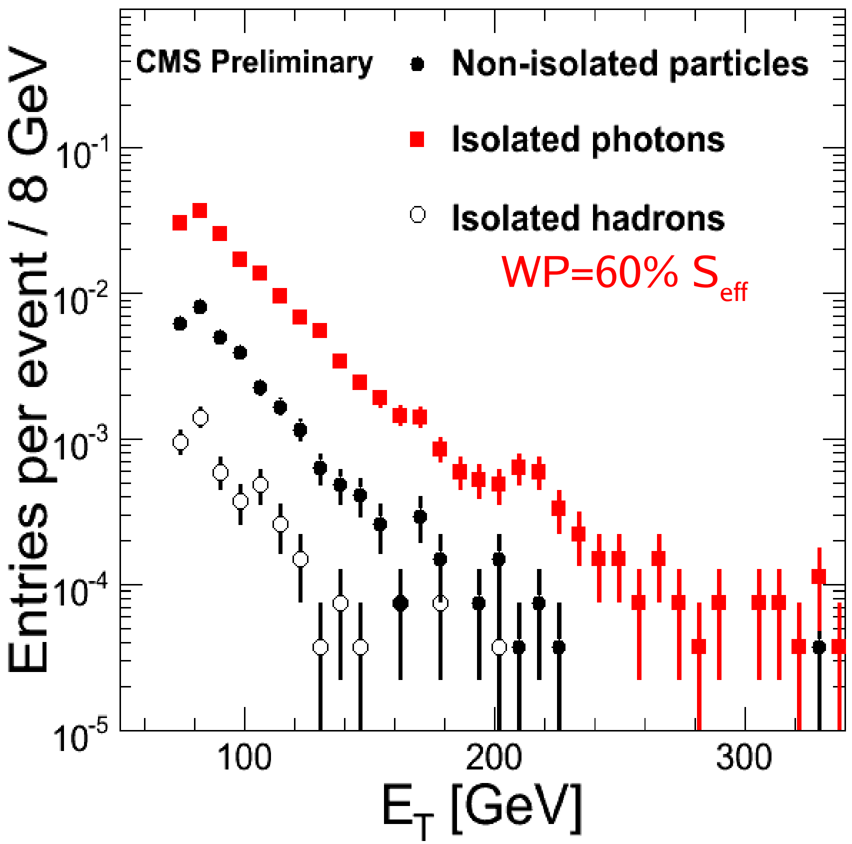
Photon identification performance

Quenched Pb+Pb

Before cuts: S/B=0.3



After cuts: S/B=4.5



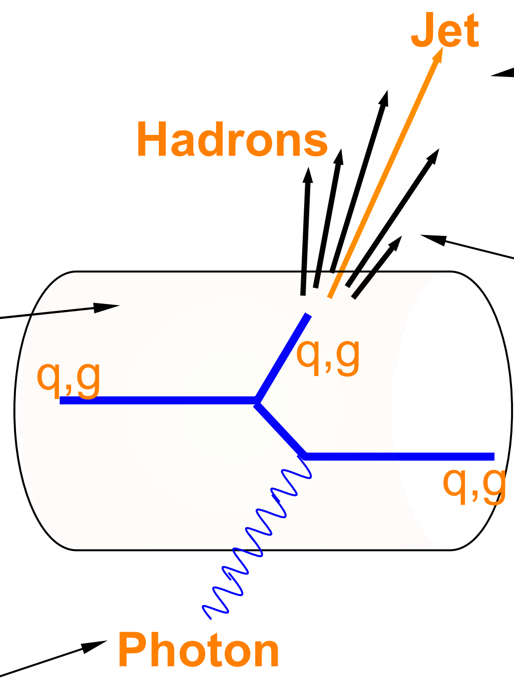
Photon isolation and shape cuts improve S/B by factor ~15

Measuring photon-tagged jet FFs

3) Jet axis provides parton direction

1) Multiplicity and flow measurements characterize density, path length

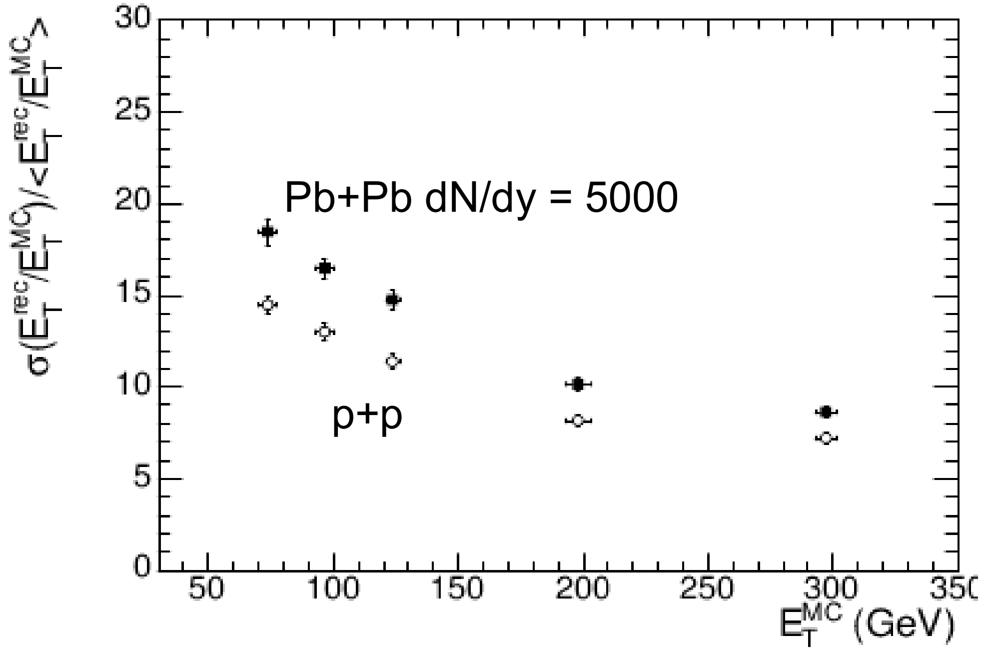
4) Charged hadron tracks used to calculate $z = p_T/E_T$

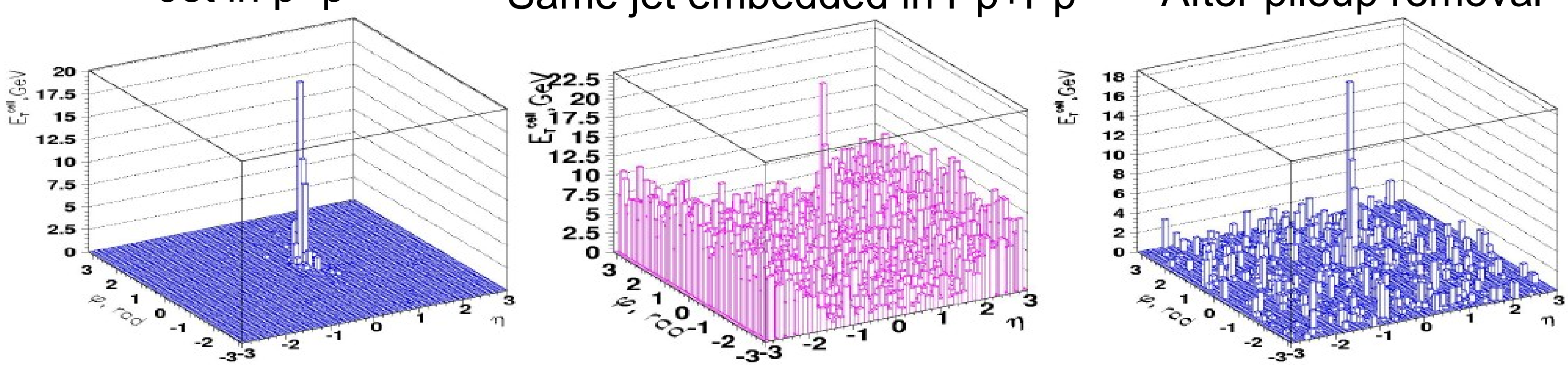


2) Photon energy tags parton energy E_T

Calorimetric jet reconstruction

- Iterative cone jet finder with background (pileup) removal
  - R=0.5
- Spatial resolution in $\eta,\phi < 0.05$
- Jet energy correction non-trivial
  - γ-jet analysis does not use jet energy, except for a minimal cut on uncorrected jet E_T>30 GeV

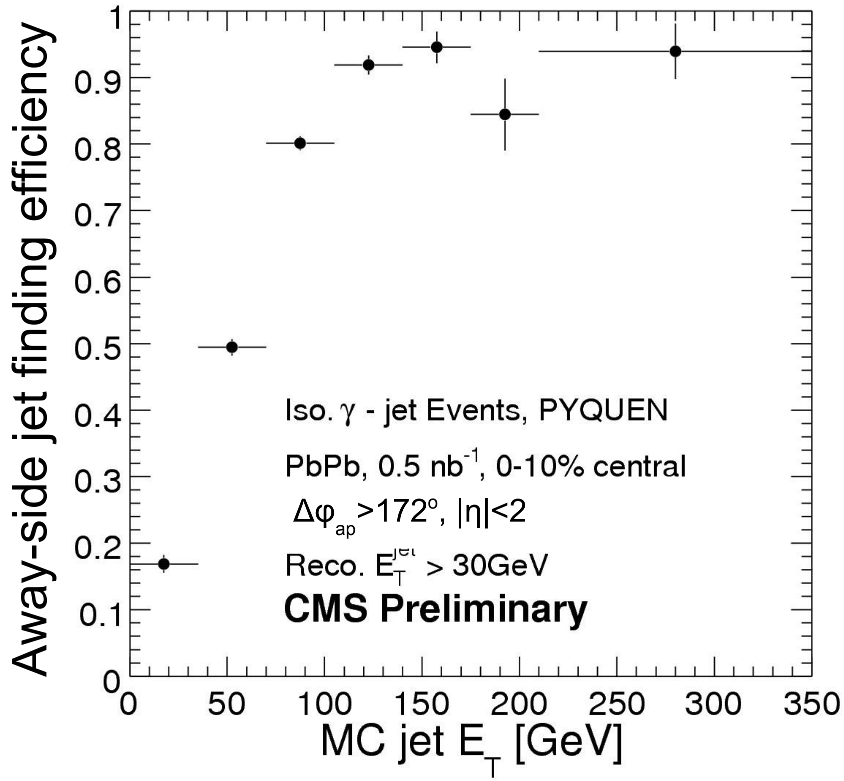


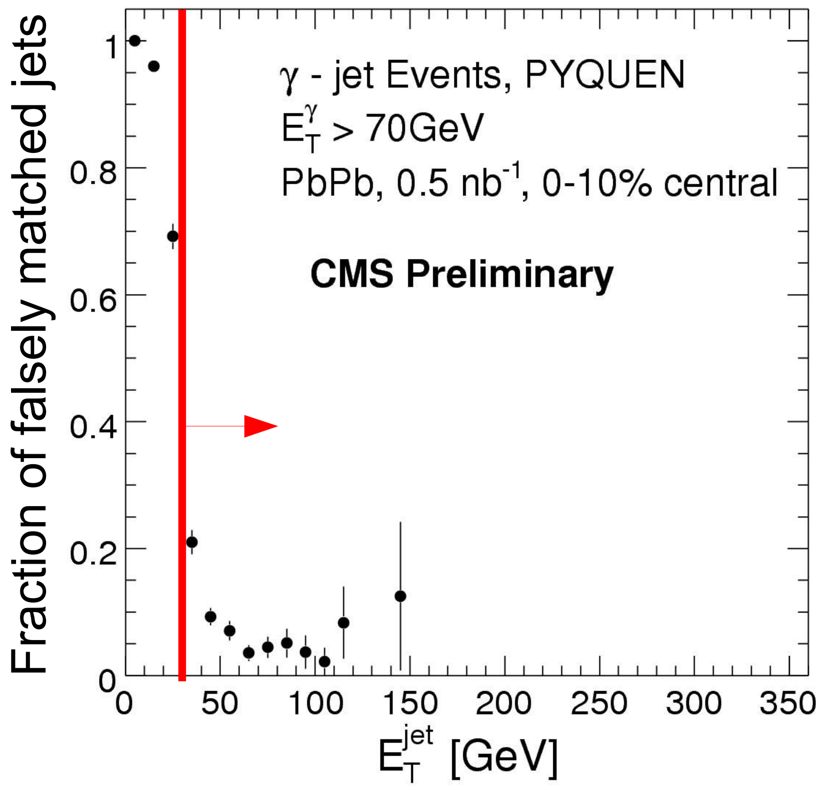


Eur. Phys. J. 50 (2007) 117

Away-side jet finding (for tagged jets)

Quenched Pb+Pb

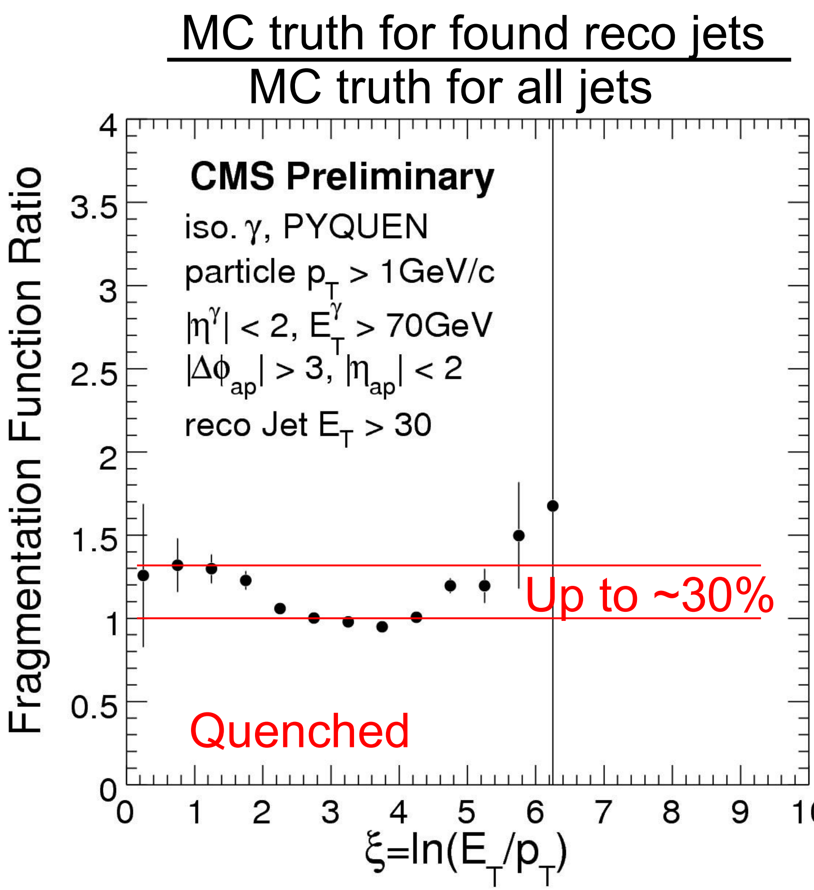




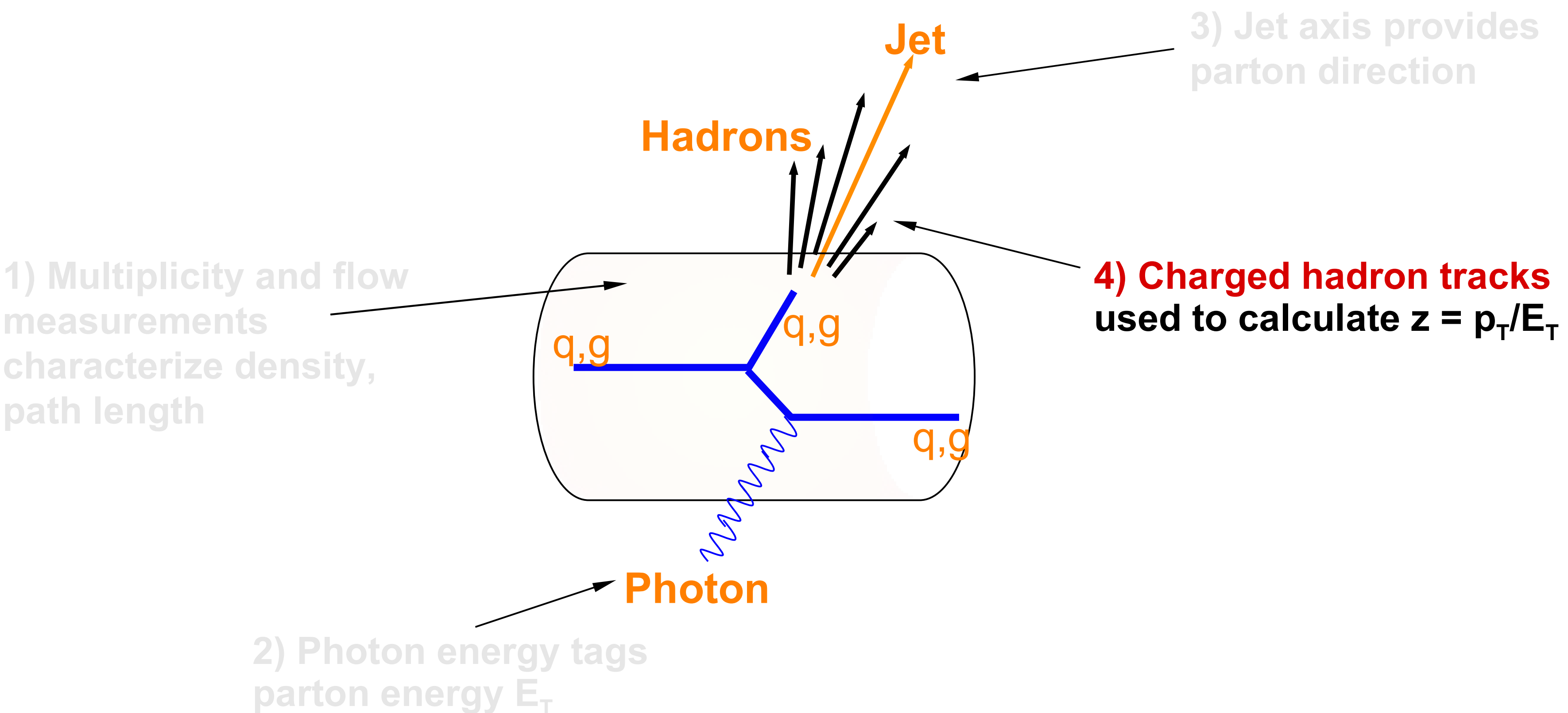
- Select away-side jet with $\Delta\phi(\gamma,jet) > 172^0$, $|\eta| < 2$ and $E_T > 30$ GeV
  - The energy cut reduces the false rate to 10% level
    - Analysis does not use jet energy otherwise
  - Jet finding efficiency rises sharply
    - Main source of systematic uncertainty in reconstructed FFs

Jet finder bias

- Jet finder bias leads to about 30% deviation in quenched case (10% in 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 truth studies in narrow bins of parton E_T suggest that 2) dominates

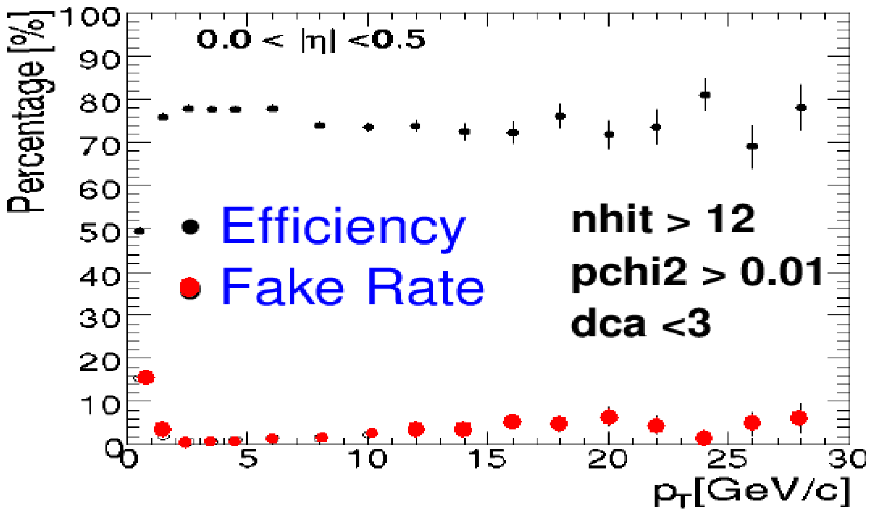


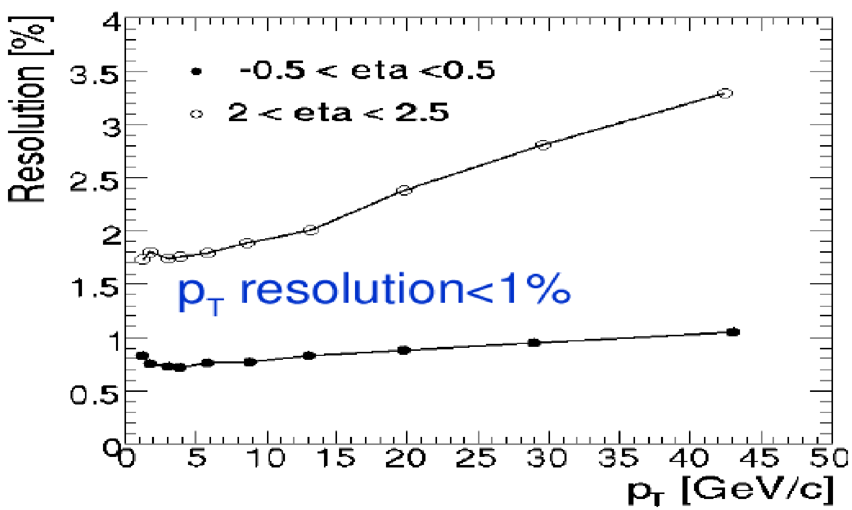
Measuring photon-tagged jet FFs



Tracking in HI collisions

- Charged particle reconstruction using the silicon tracker
  - Algorithm is based on seeds from the silicon pixel detector
  - Extension of p+p with cuts optimized for Pb+Pb
  - Performance
    - Good efficiency
    - Low fake rate
    - Excellent momentum resolution





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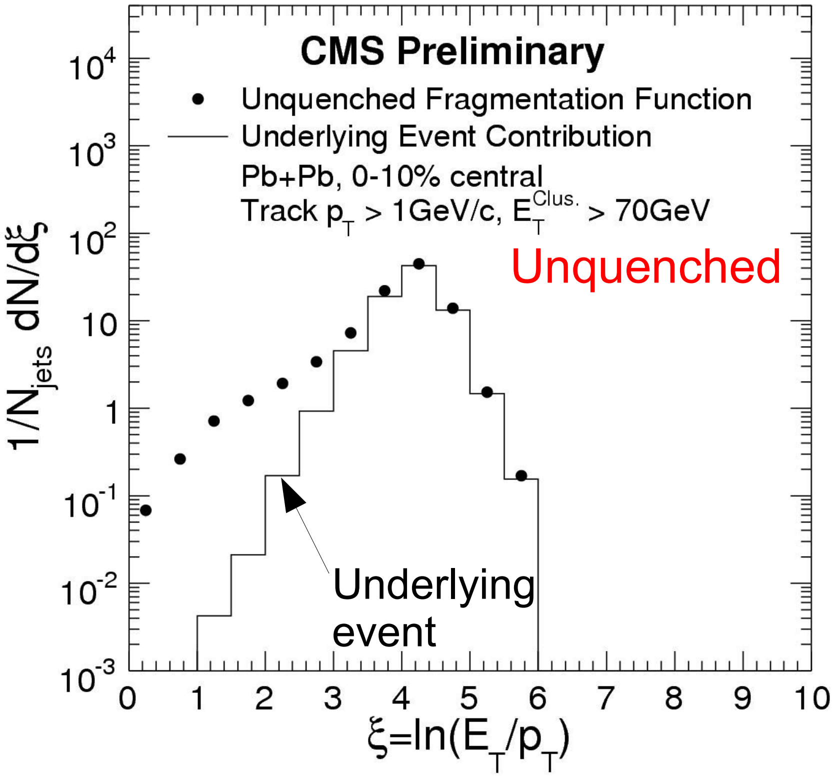
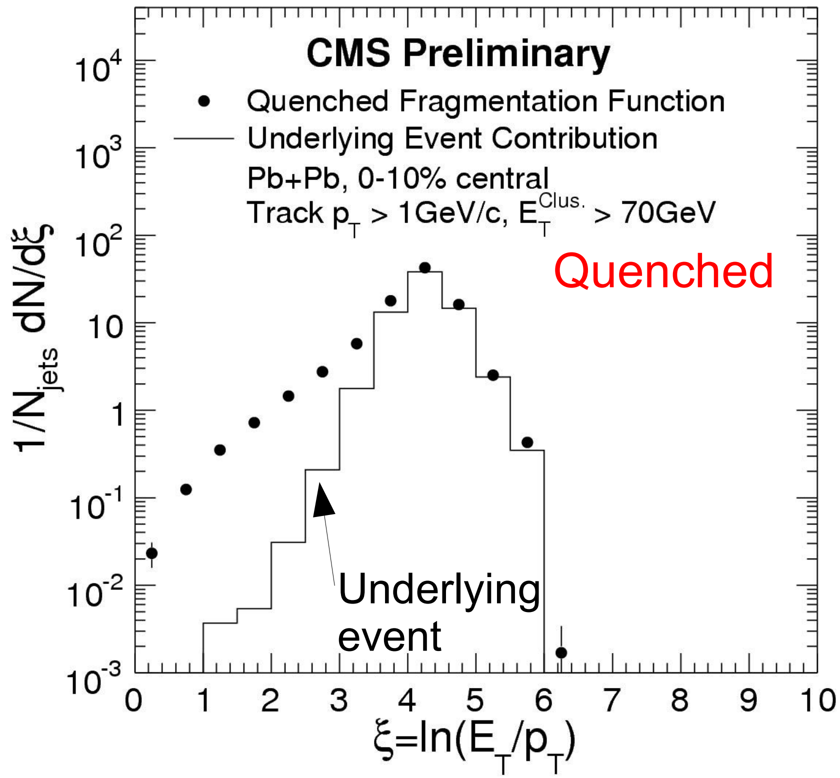
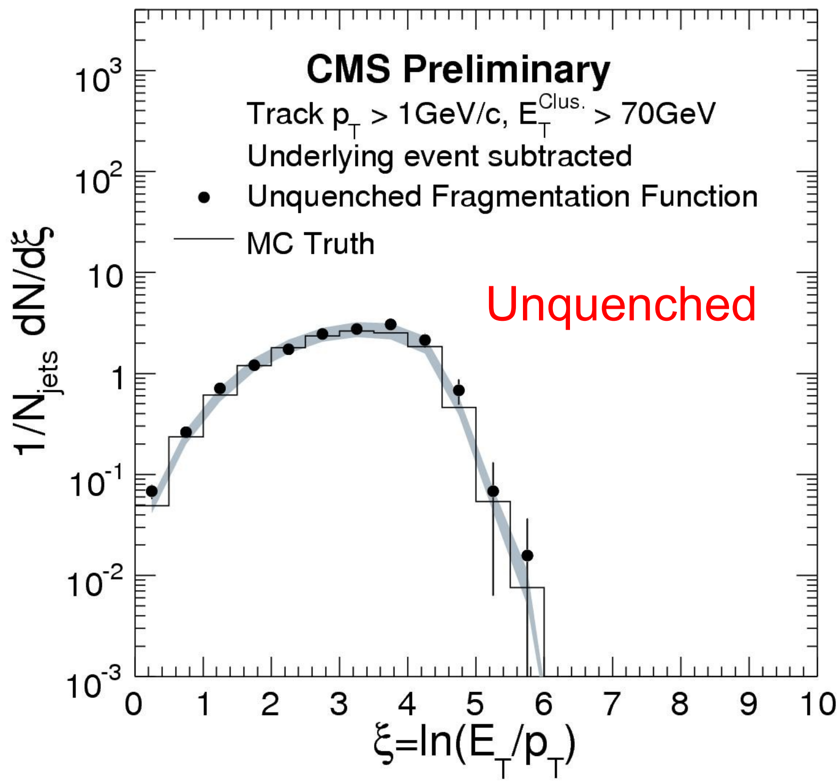
Reconstructed FFs

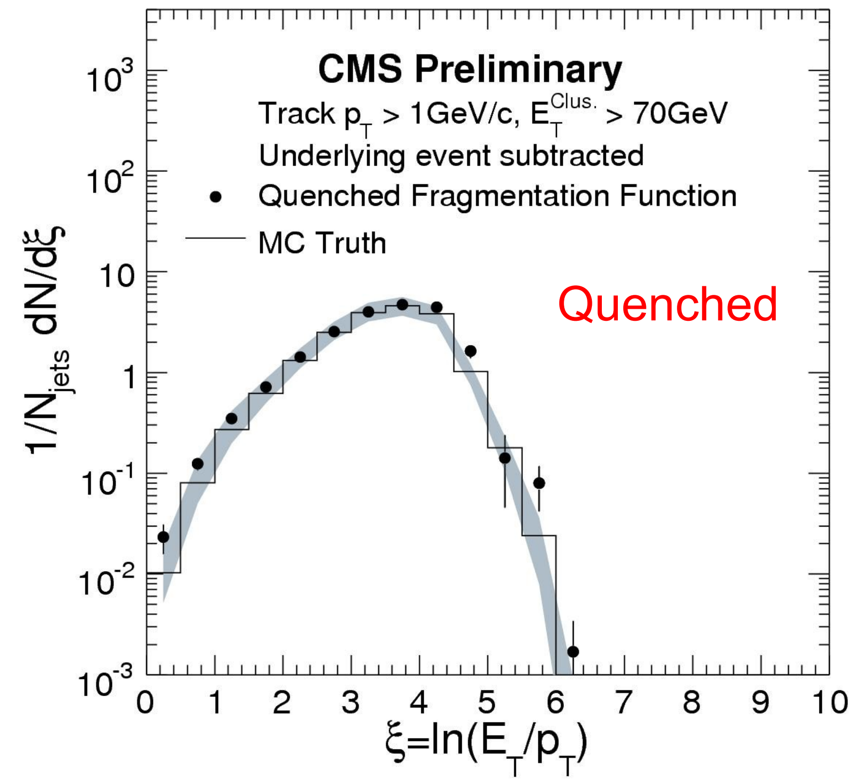




- Obtain dN/dξ using tracks in R=0.5 cone around jet axis
- For ξ>3 (~p_T<4GeV/c) dN/dξ dominated by underlying Pb+Pb event
  - Estimate background with R=0.5 cone rotated in φ by 90º rel. to jet
  - Sum event-by-event backgrounds and subtract
  - Correct for track finding efficiency

Reconstructed FFs



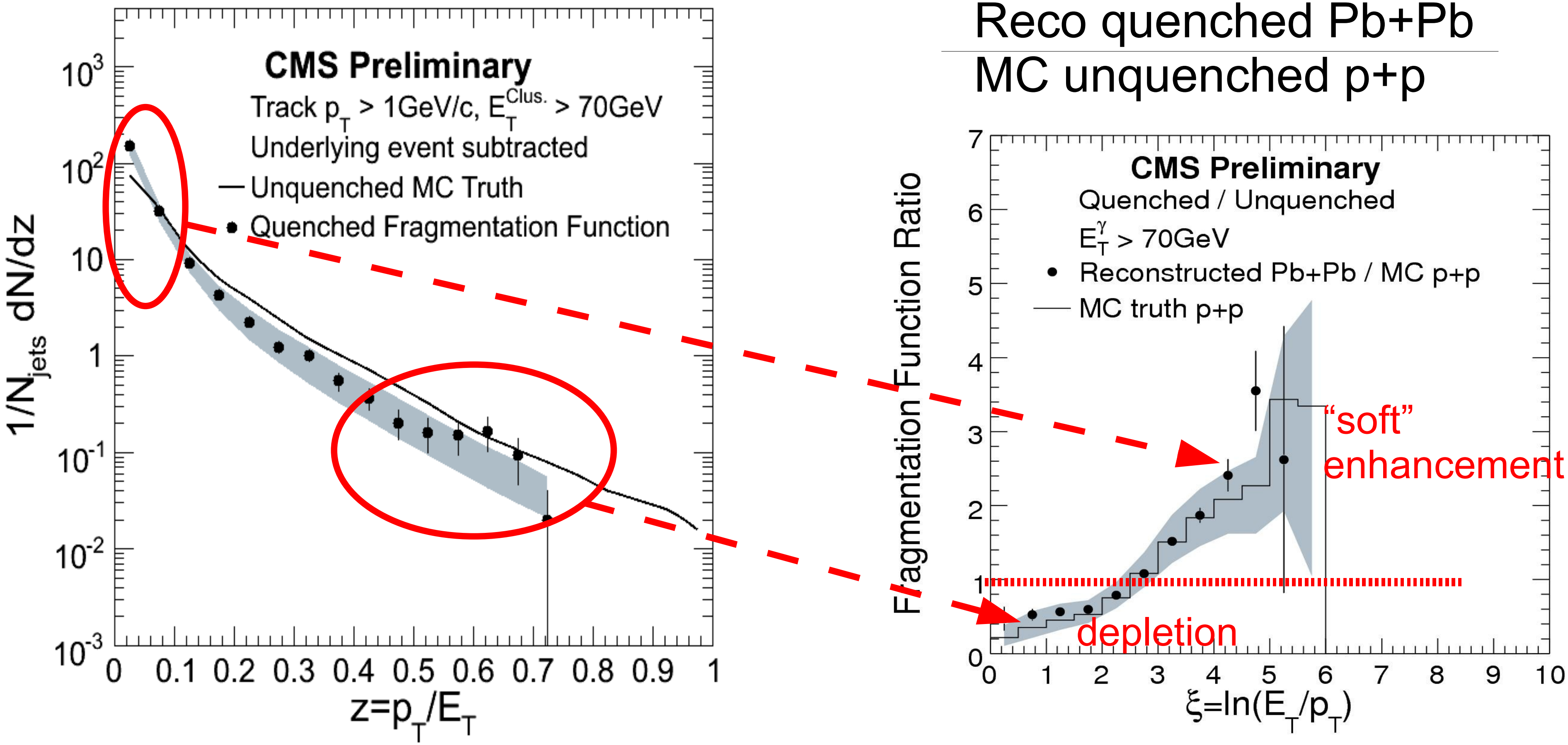


- Major contributions to systematic uncertainty (added in quadrature)
  - Photon selection and background contamination (15%)
  - Track finding efficiency correction (10%)
  - Wrong/fake jet matches (10%)
  - Jet finder bias (as discussed before)

} No or small ξ dependence

Final result: FF ratio

Reco quenched Pb+Pb / MC unquenched p+p



- Medium modification of fragmentation functions can be measured
  - High significance for $0.35 < \xi < 5$ (or $z < 0.7$)

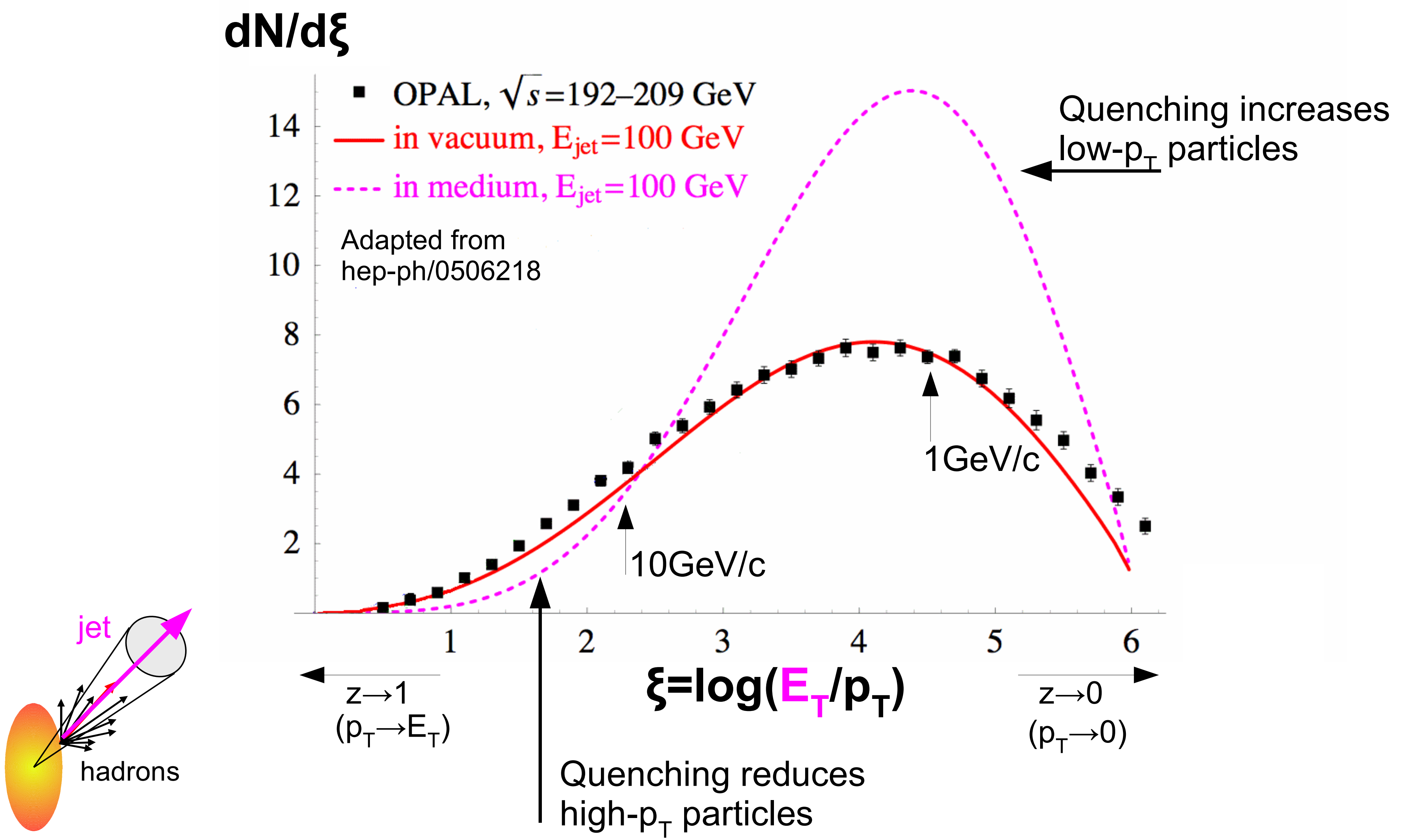
E_T^{γ} >70GeV

Summary

- CMS will be able to reliably measure modified jet FFs in central Pb+Pb using photon-tagged jet events
  - Estimated systematic errors are small wrt expected modification
- This analysis is one example of how the superb capabilities of CMS can be combined in HI collisions
  - High resolution calorimeters
    - Jets, photons
  - High resolution large tracker
    - Charged hadrons from ~100's MeV to 100's GeV
  - Fast flexible DAQ (L1 + HLT)
    - Jet, photon, muon and electron triggers
  - Event-by-event characterization
    - Flow, centrality, multiplicity, mean pt
    - (also due to large acceptance forward calorimetry)

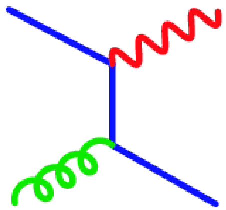
BACKUP SLIDES

In-medium modified fragmentation functions



MC photon isolation and signal definition

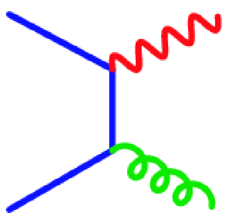
Compton



- 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

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

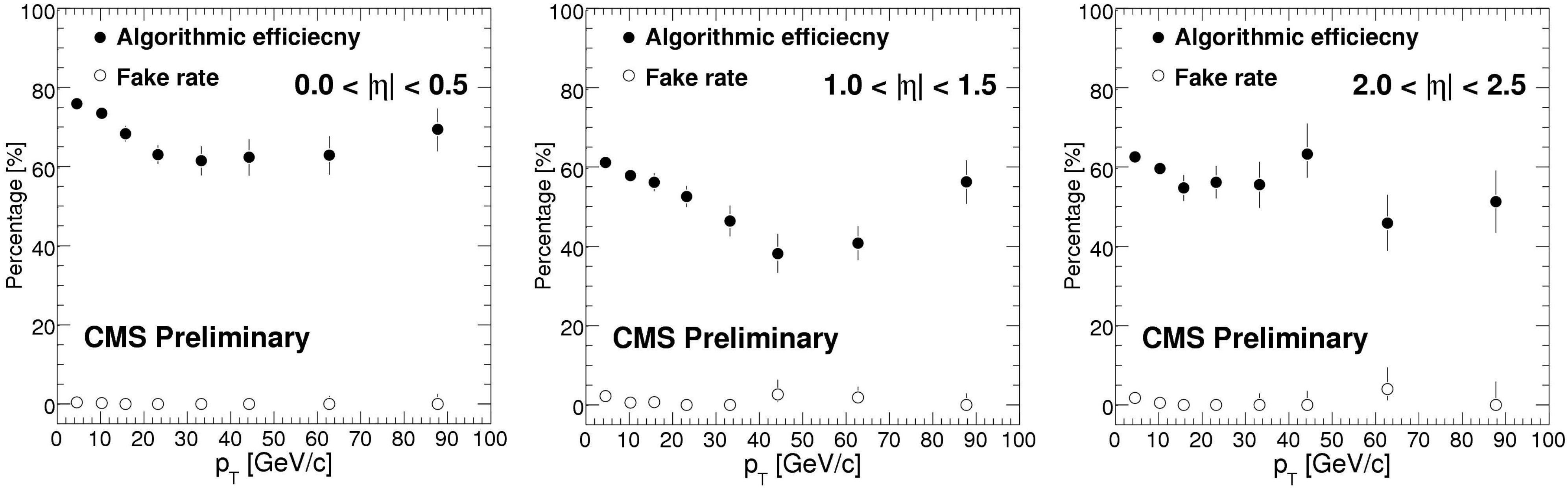
Annihilation



- 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 %

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Photon isolation: Calorimeters

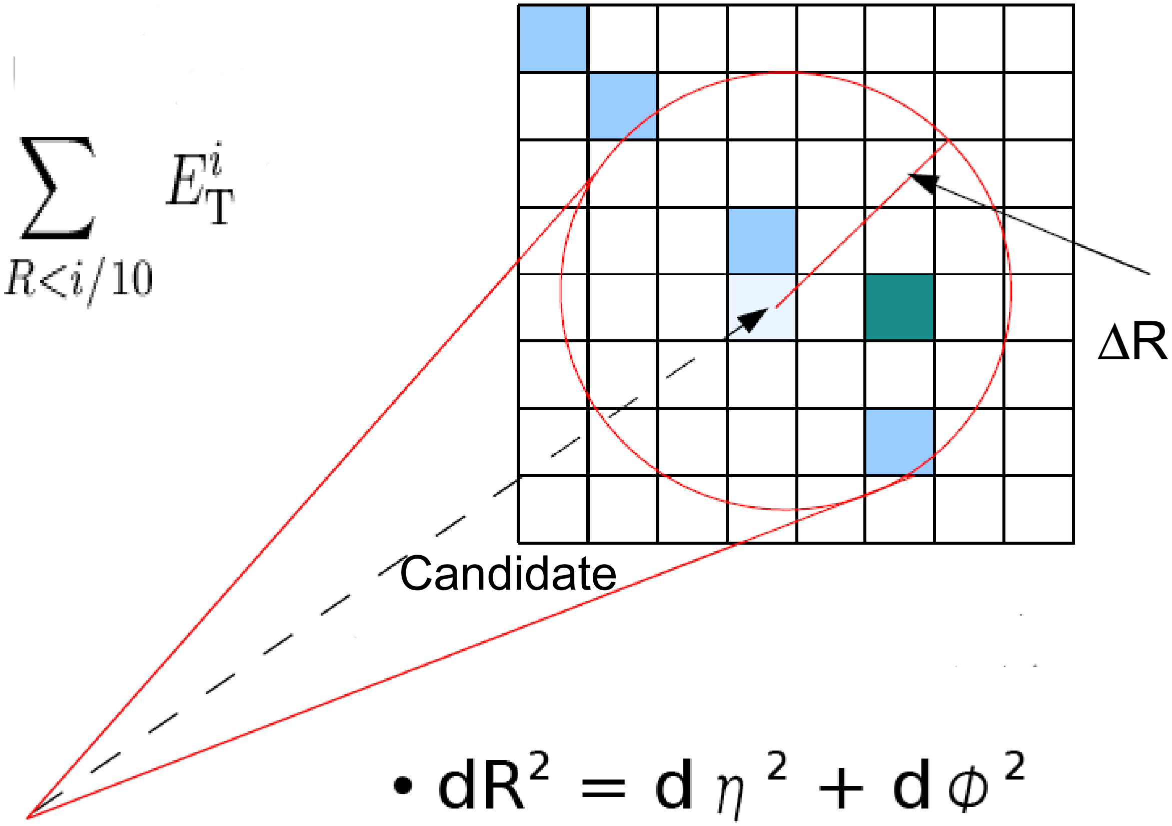
- Use the energy content in cone around candidate direction in ECAL and HCAL

- ECAL:

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

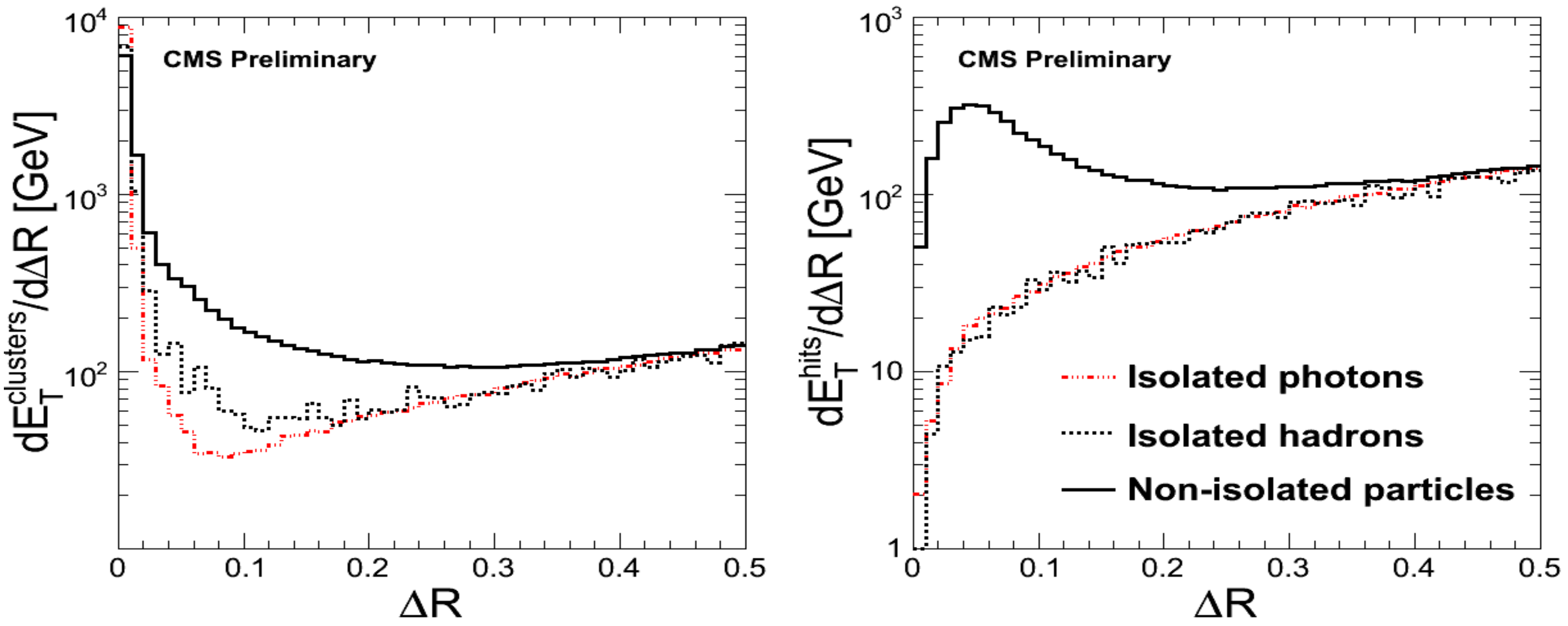
- HCAL:

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



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

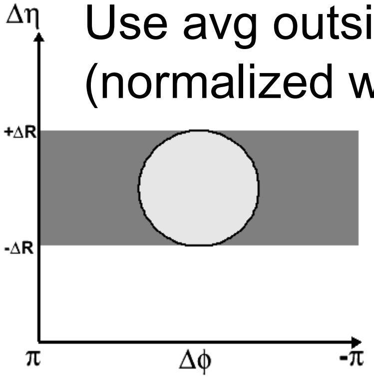
Photon isolation: Background subtraction



- Subtract HI background
  - ECAL:
  - HCAL:

$$C_i' = C_i - \langle C_i \rangle$$

$$R_i' = R_i - \langle R_i \rangle$$



Use avg outside of cone (normalized with ΔR/4)

Photon isolation: Combined calorimeters

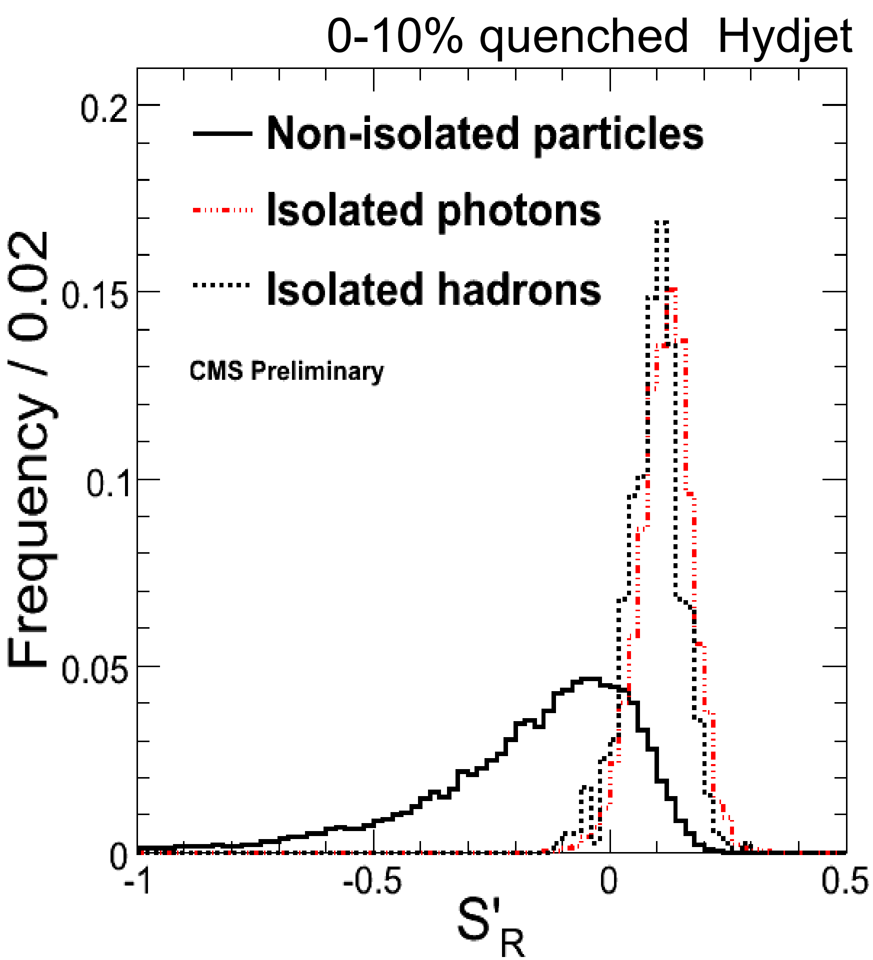
- Based on cone variables form

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

- Combine to

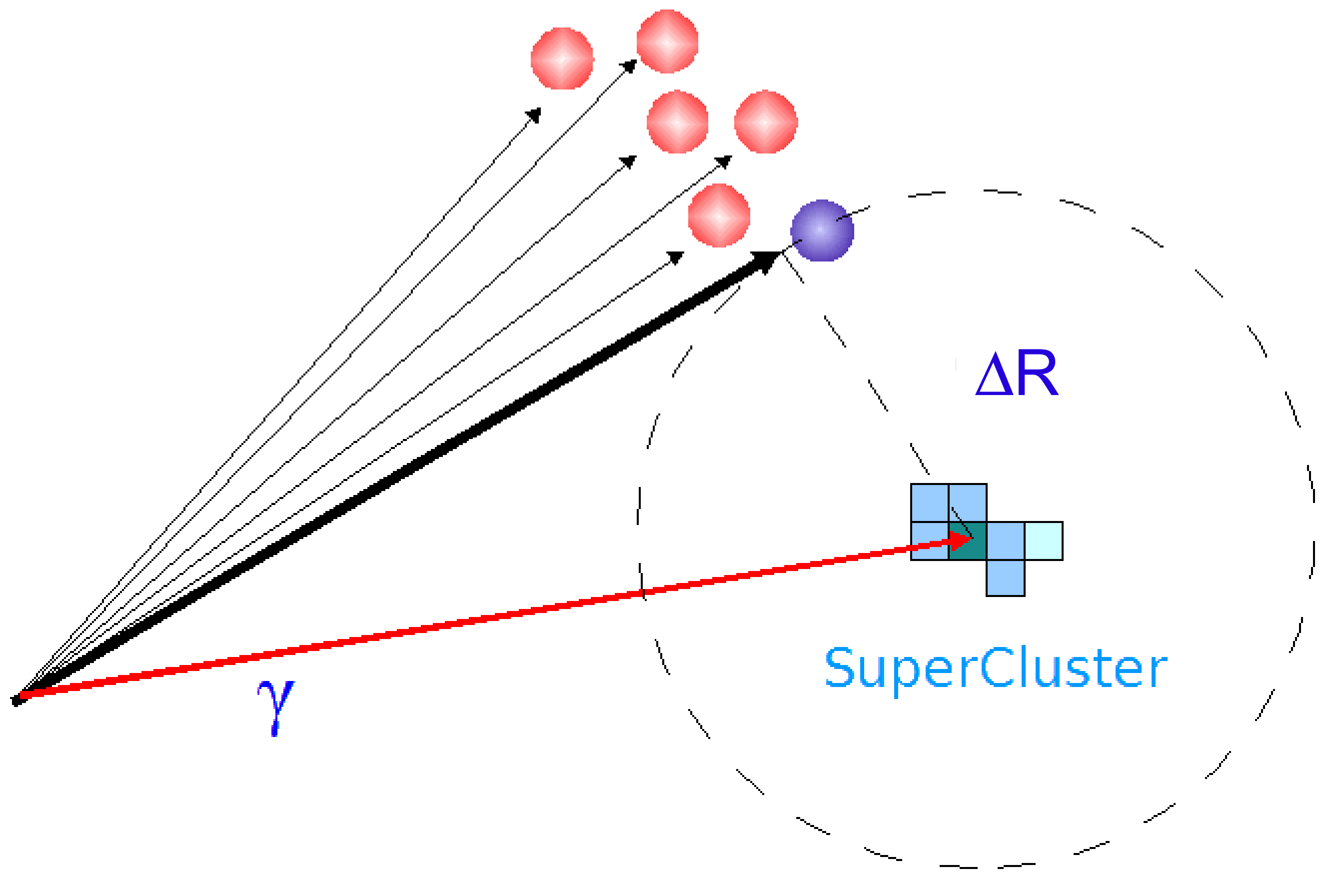
$$S'_R = \sum_i \alpha'_i R'_i + \sum_i \beta'_i C'_i$$

to be determined coefficients



Photon isolation: Tracks

- dRxy: ΔR of (y+1st) 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

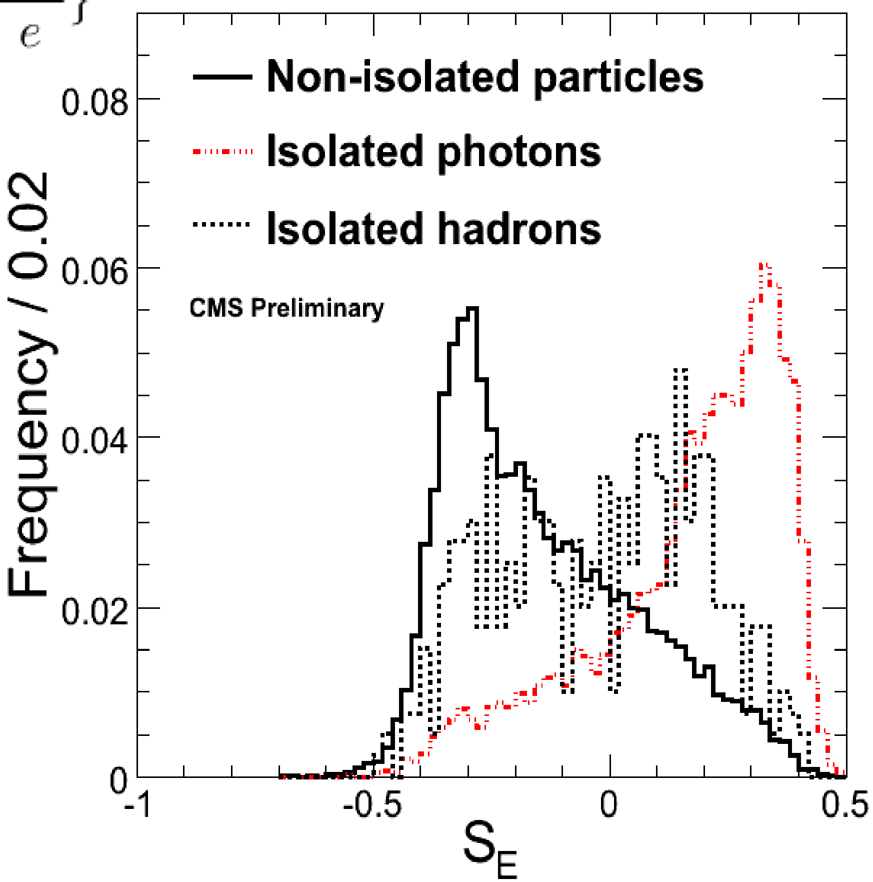
$$E_i = \{\frac{e_{\max}}{e_4}, \frac{e_{\max}}{e_9}, \frac{e_{\max}}{e_{25}}, \frac{e_{\max}}{e}, \frac{e_4}{e_9}, \frac{e_4}{e_{25}}, \frac{e_4}{e}, \frac{e_9}{e_{25}}, \frac{e_9}{e}, \frac{e_{25}}{e}\}$$

- Combine to

$$S_E = \sum_i \gamma_i E_i$$

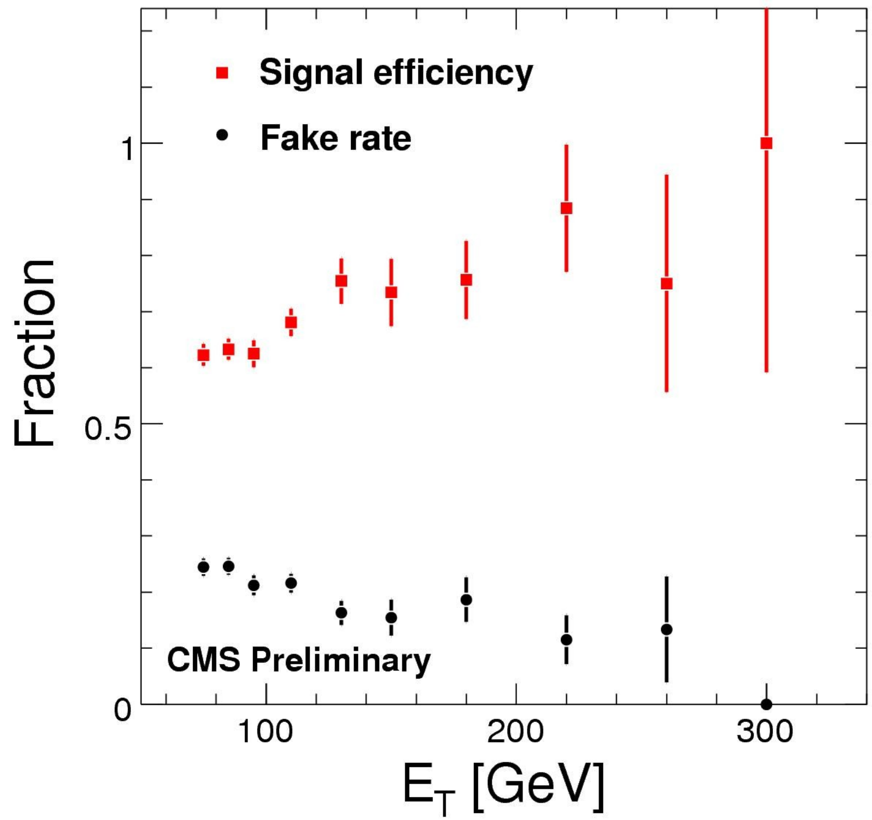
to be determined coefficients

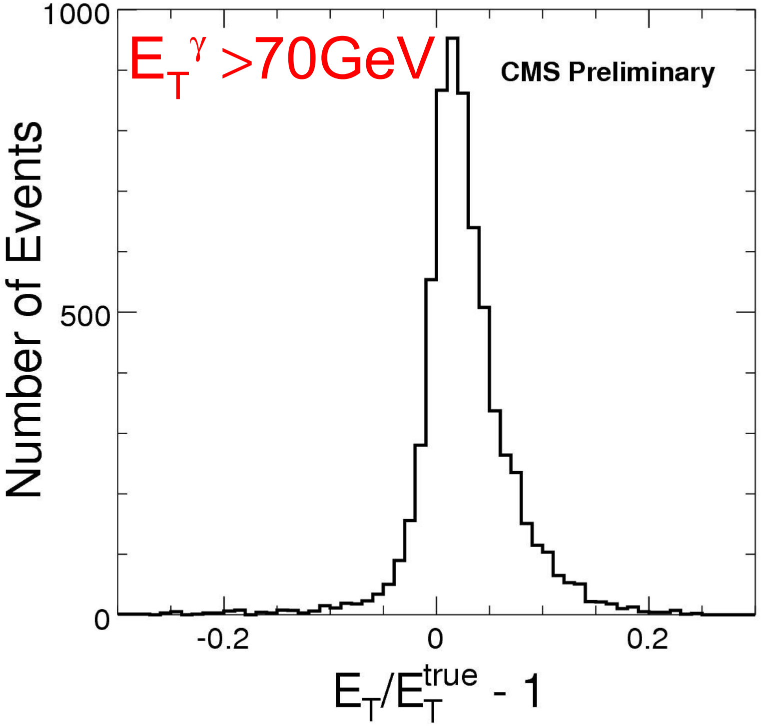
0-10% quenched Hydjet



Isolated photon reconstruction

Quenched Pb+Pb



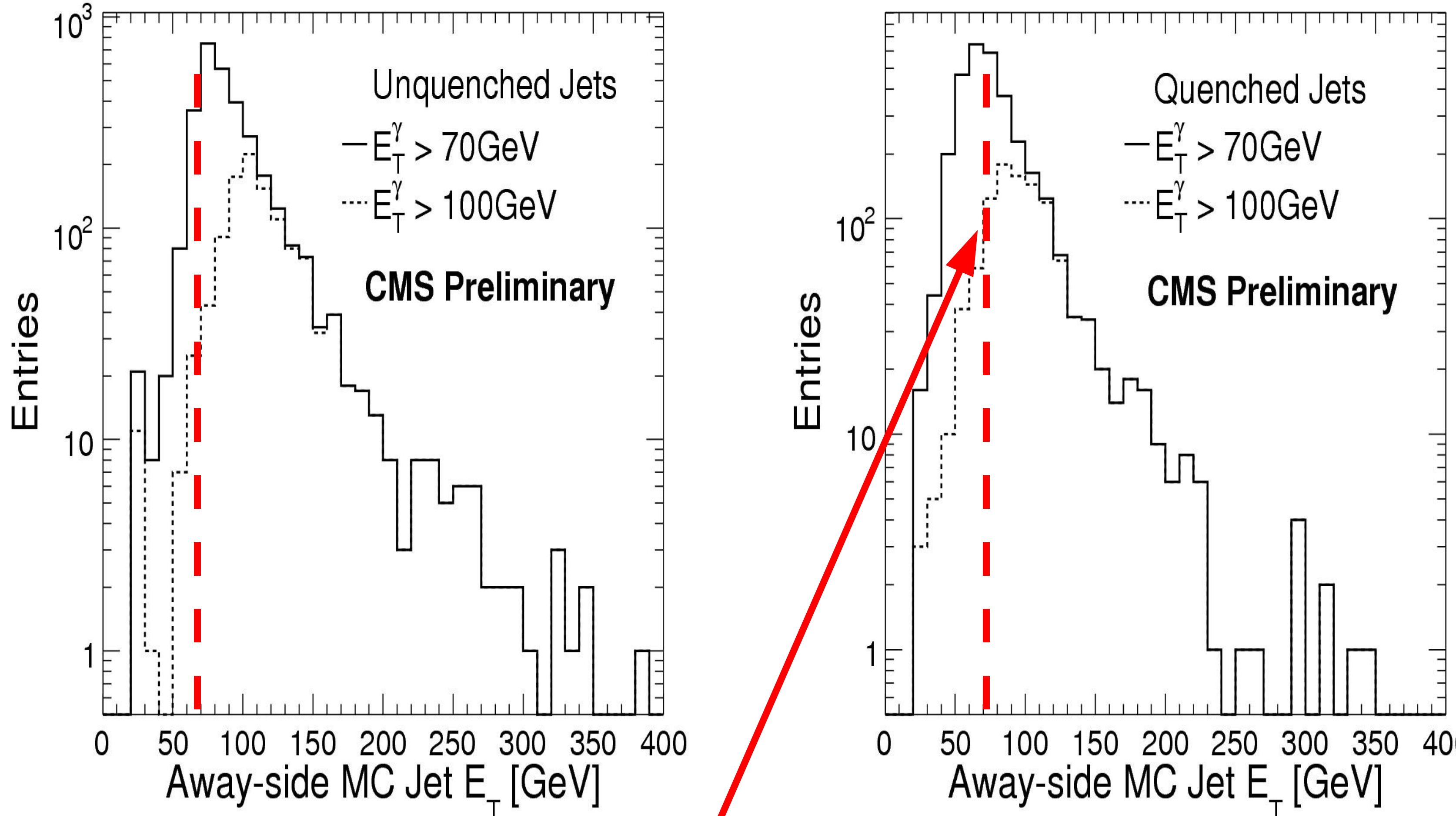


- Performance for $E_T^\gamma > 70$GeV
  - Efficiency > 60%
  - Fake rate < 20%
  - Transverse energy resolution: 2-5%

Before cuts: S/B=0.3

After cuts: S/B=4.5

Jet Finding in PYQUEN

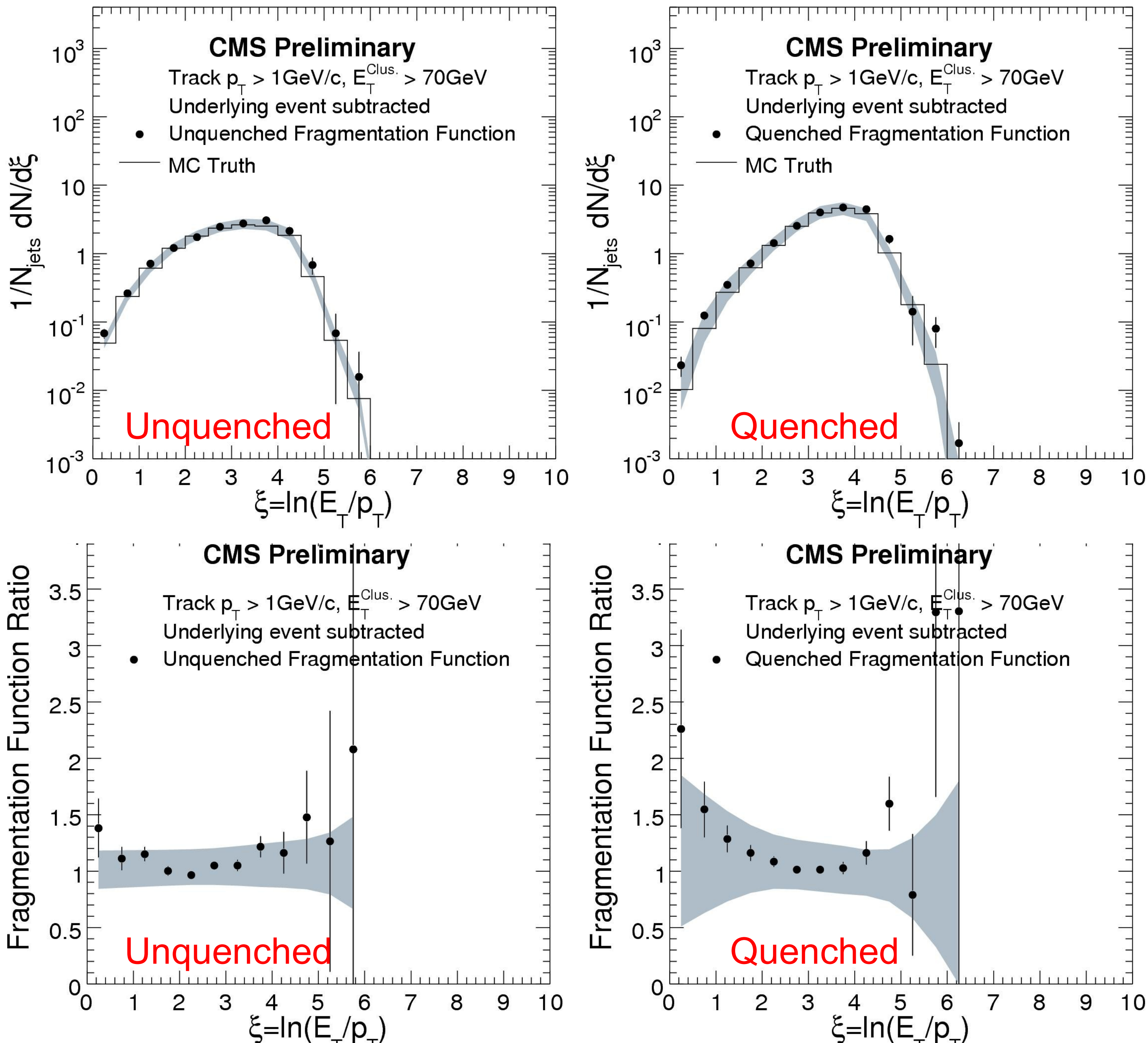


- Quenching mechanism in PYQUEN moves energy out of R=0.5 cone
- This lowers jet finding efficiency for a given initial parton E_T

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

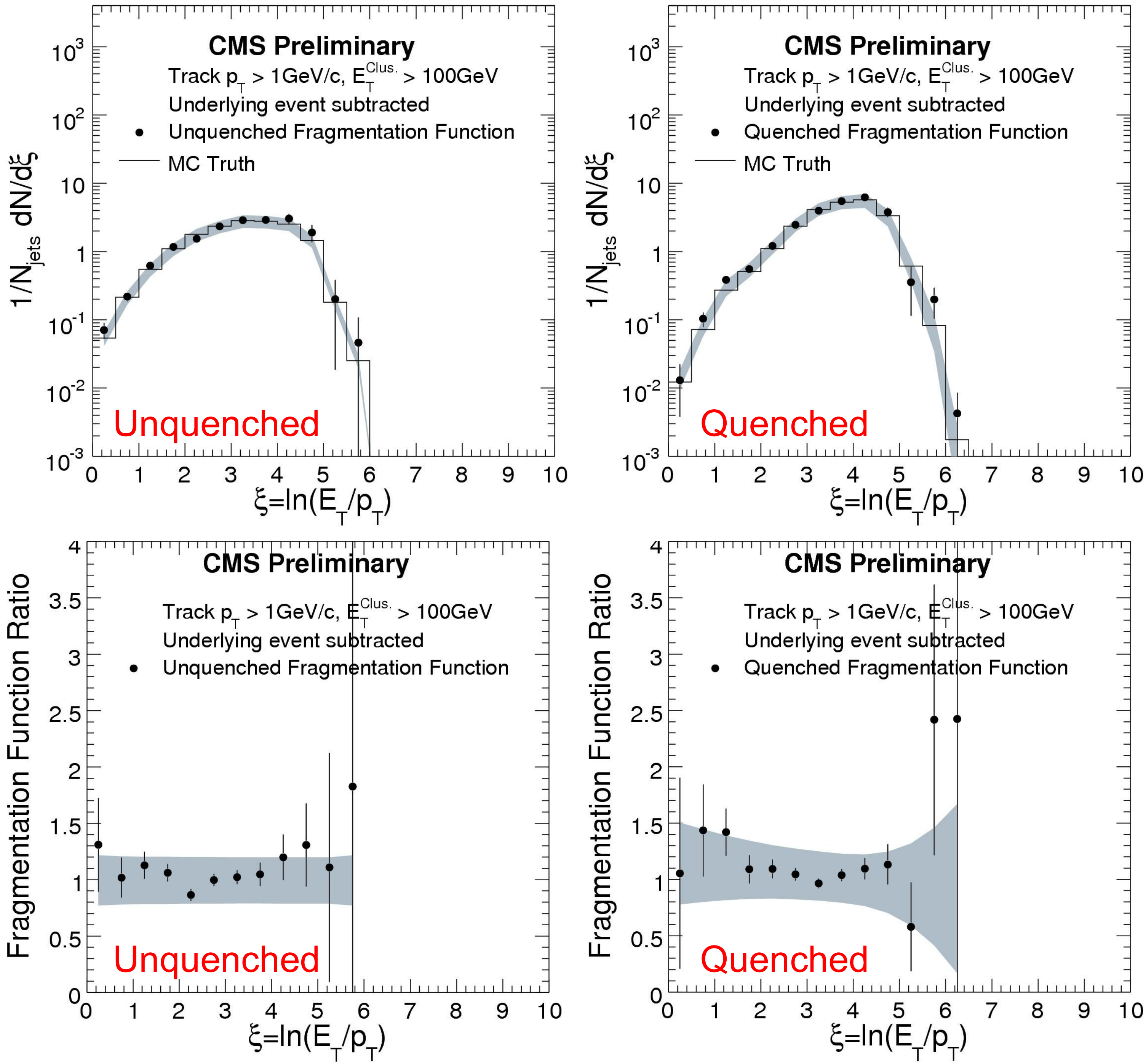
Fragmentation function results ($E_{T,\gamma} > 70$ GeV)



Reconstructed FF agrees with MC FF within expected uncertainty

Largest deviation at small ξ (large z)

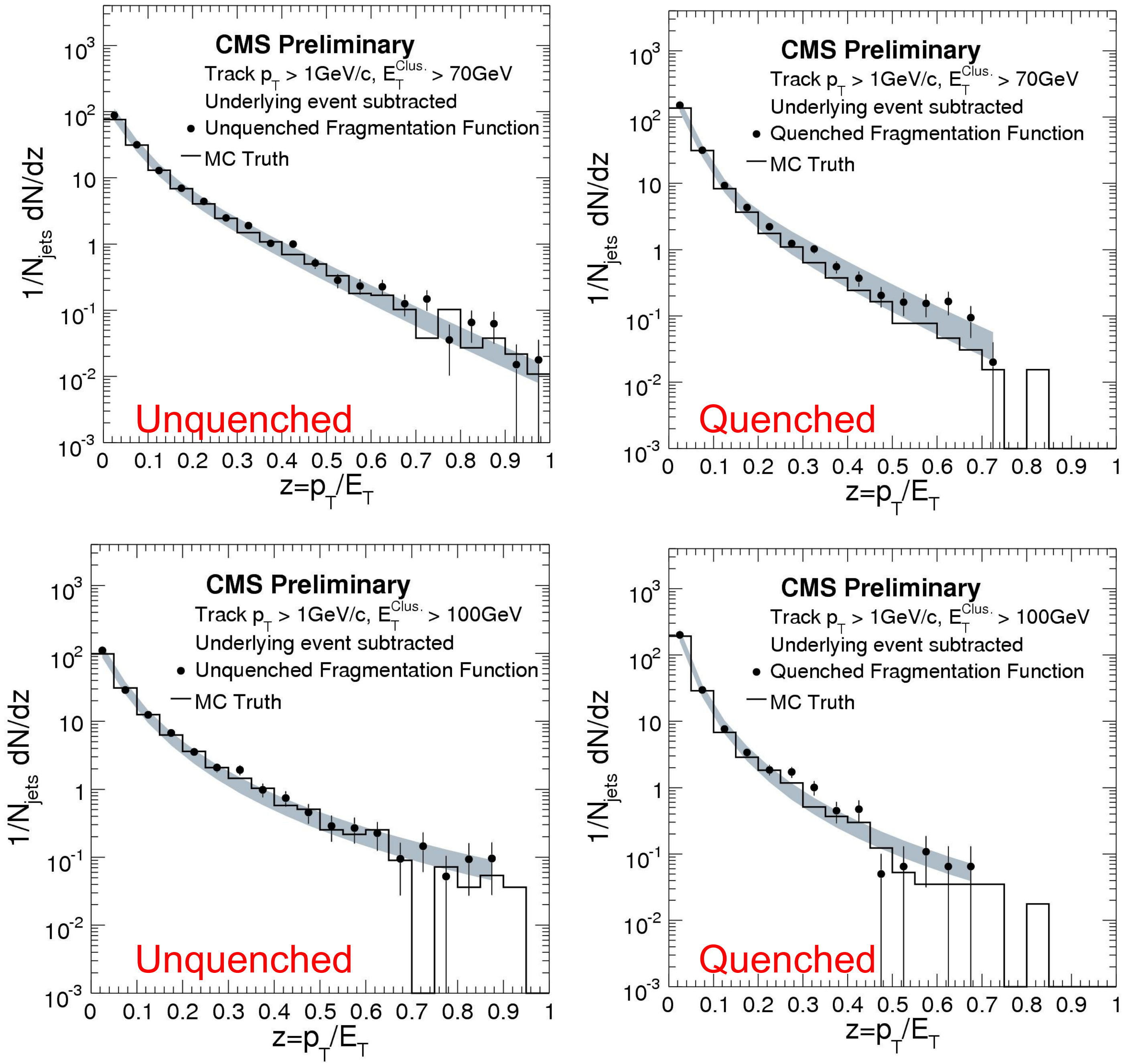
Fragmentation functions ($E_{T,\gamma}$ > 100 GeV)



Reconstructed FF agrees with MC FF within expected uncertainty

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

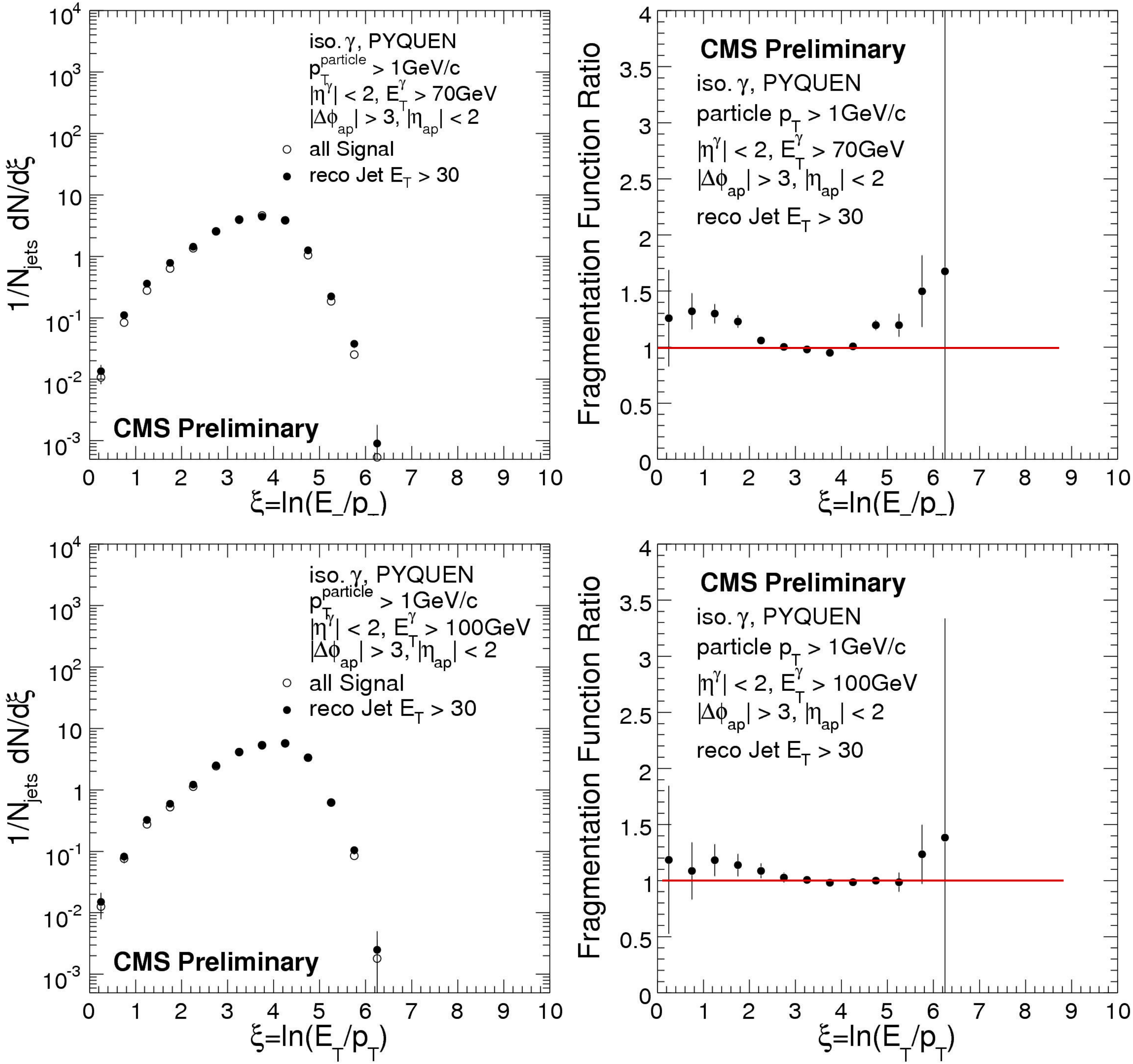
Fragmentation functions (vs z)



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

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

Jet Finder Bias (Quenched Jets)



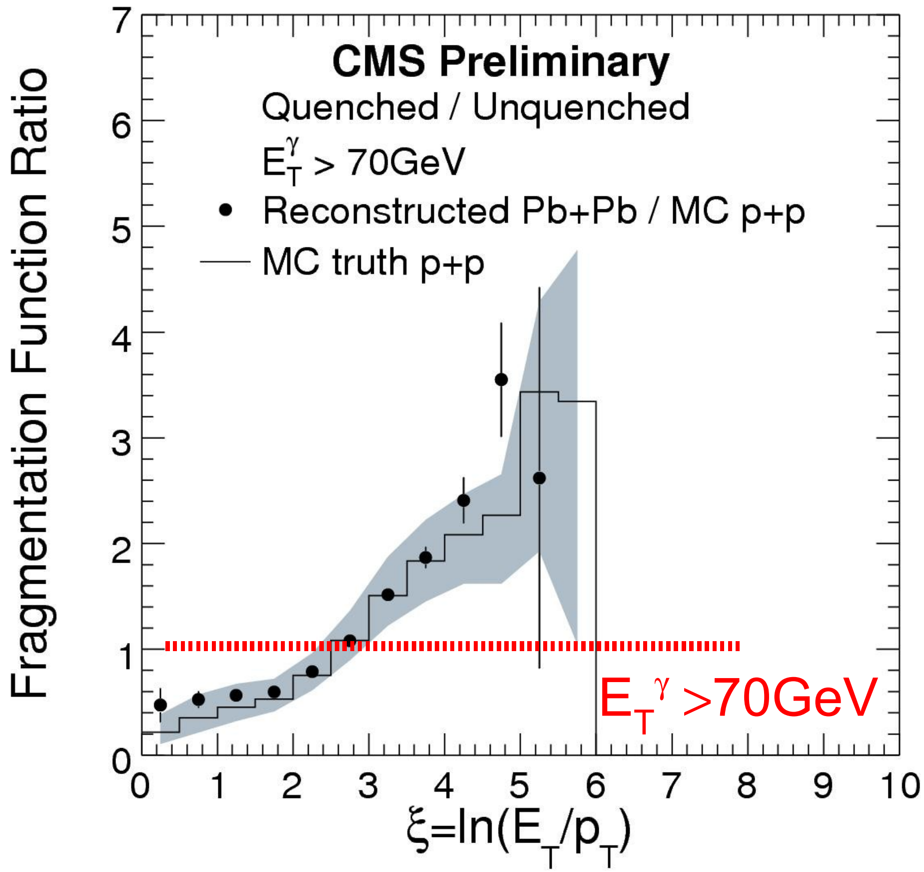
Significant bias (up to 30%) in quenched sample with **$E_{T,\gamma}$ > 70GeV**

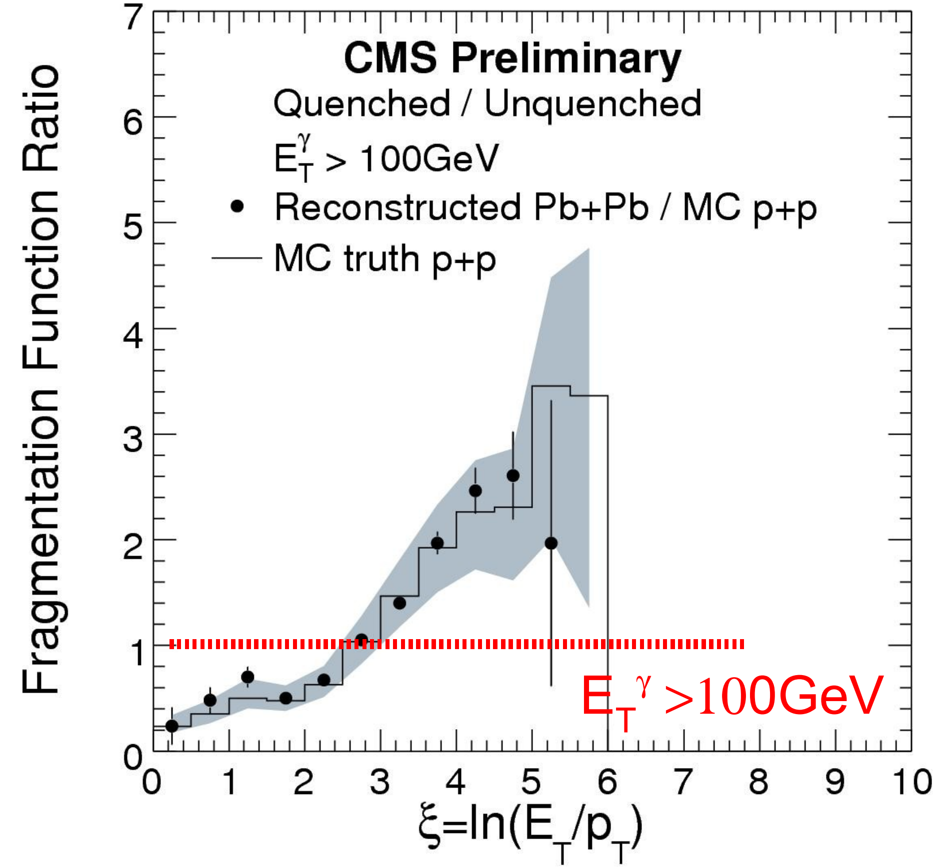
N.b.: Bias is present in p+p, i.e. can be studied independent of our measurement in Pb+Pb

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

Final result: Fragmentation function ratio

Reco quenched Pb+Pb / MC unquenched p+p

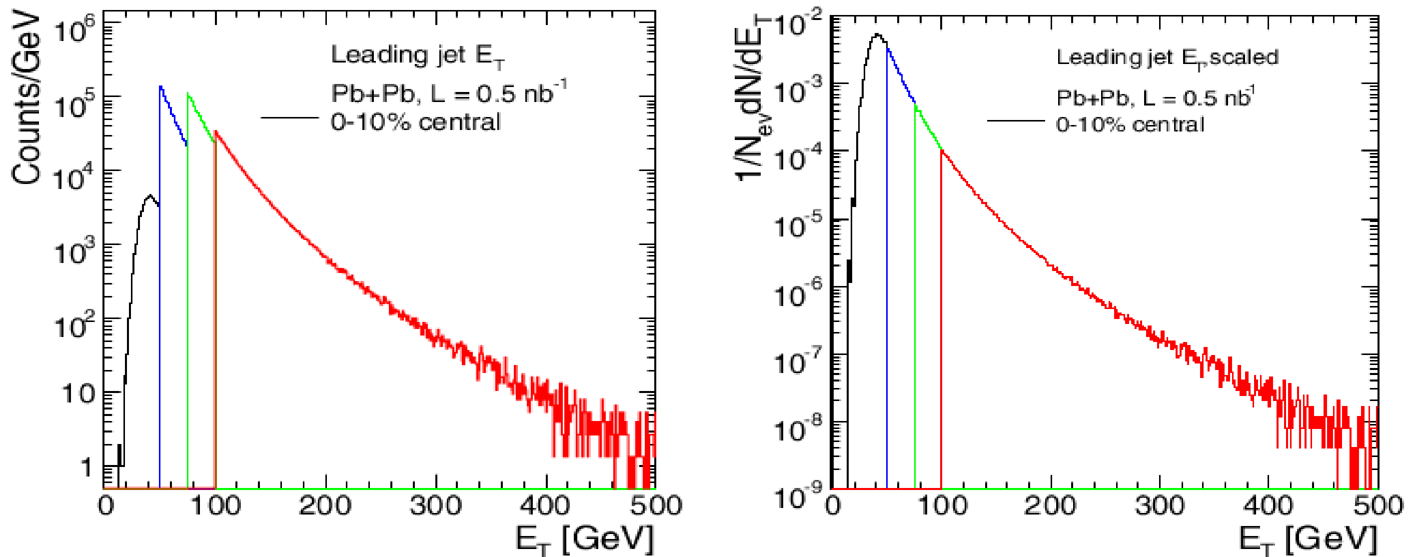




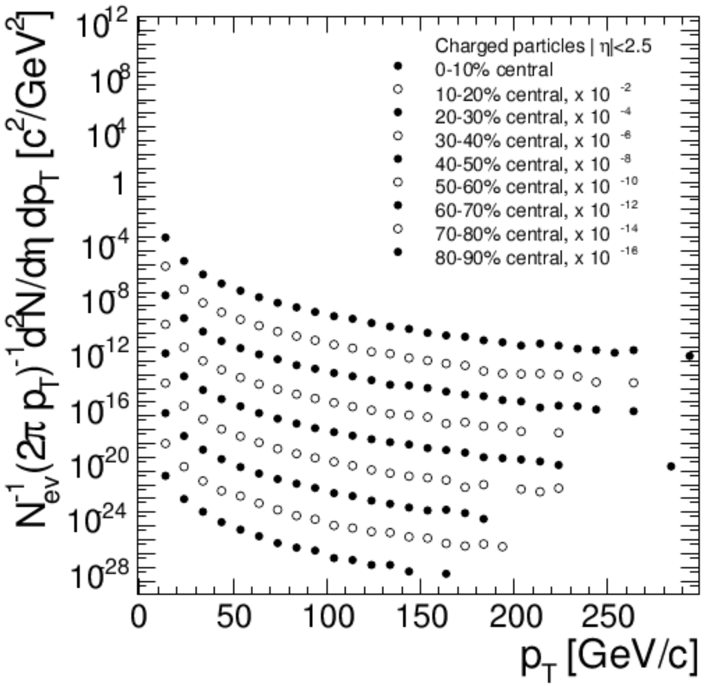
- Medium modification of fragmentation functions can be measured
  - High significance for $0.35 < \xi < 5$ for both, $E_T^\gamma > 70$GeV and $E_T^\gamma > 100$GeV

Physics reach with jet trigger in HLT

HYDJET simulations



CMS



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