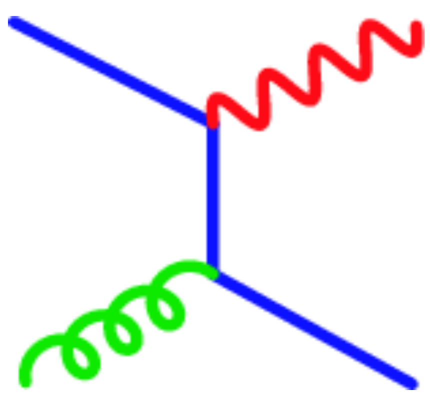
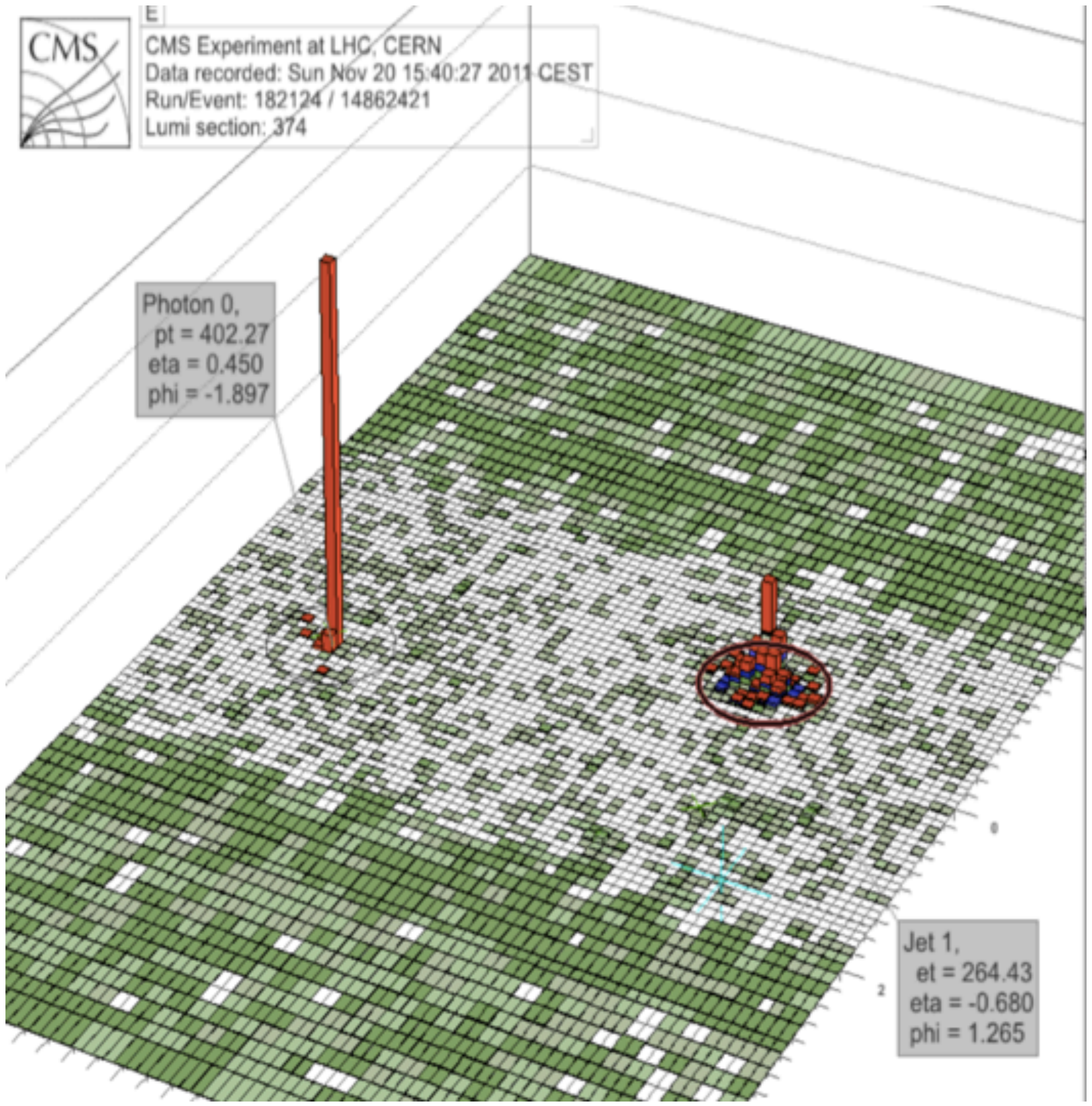
Direct gamma/Z^0 measurements at the LHC (and RHIC)





Gunther Roland
Massachusetts Institute of Technology

2nd Jet Workshop on Jet Modifications
Wayne State University August 2013

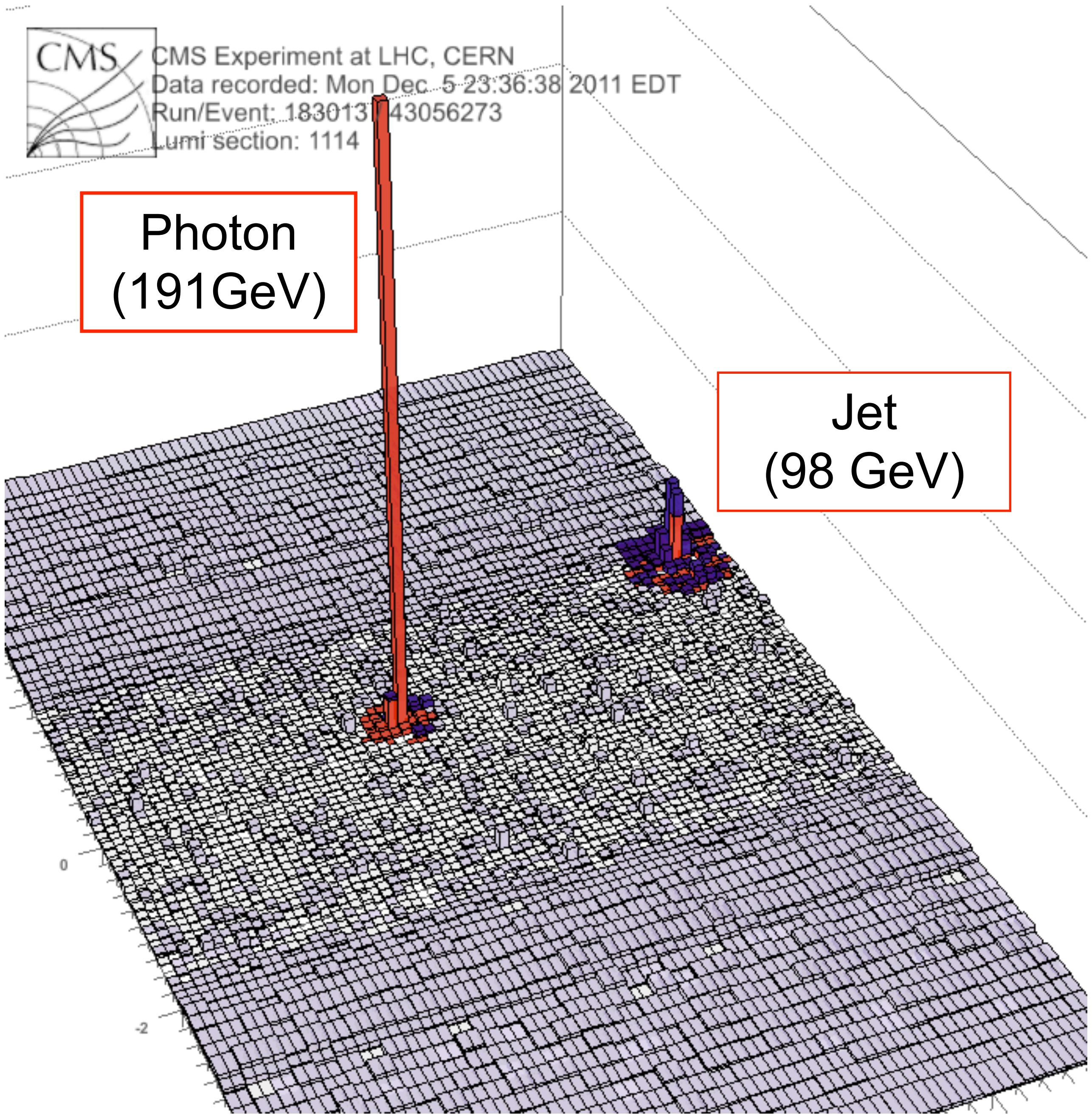
Overview

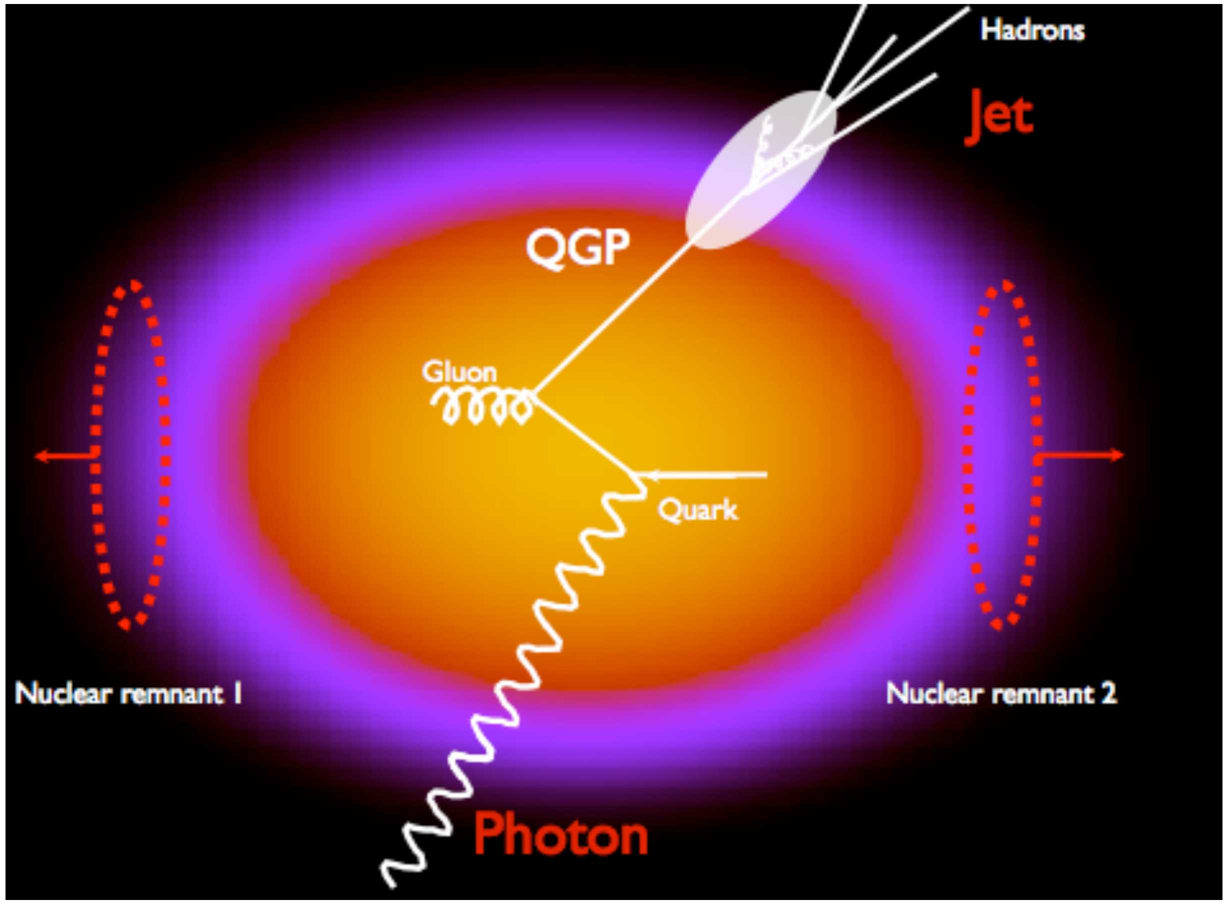
- Focus on **high p_T** results
  - no conversions, thermal photons, photon v_2
- Experimental results on
  - Isolated (direct) photon and Z^0 production at LHC (RHIC)
  - Isolated photon/Z^0-jet (hadron) correlations at LHC (RHIC)
- A few model comparisons, but no exhaustive survey
- Comments on
  - Considerations for comparison to theory
  - Consistency of experimental results
  - Near- and medium future experimental outlook

Experimental bibliography (LHC)

- Isolated photons at LHC
  - **CMS PLB 710 (2012) 256**
  - ATLAS-CONF-2012-051
- Z^0s at LHC
  - **ATLAS PLB 697 (2011) 294-312**
  - **CMS PRL 106 (2011) 212301**
  - **ATLAS PRL 110, 022301 (2013)**
  - CMS PAS HIN-13-004
- Z^0-jet correlations
  - ATLAS-CONF-2012-051
- Isolated photon-jet correlations
  - CMS CR-2011/88, CMS PAS HIN-12-004 (jet performance)
  - CMS PAS HIN-11-011, **CMS PLB 718 (2013) 773**
  - ATLAS-CONF-2012-121

γ/Z^0+jet: u,d quark energy loss





Photon tag:

- Identifies jet as u,d quark jet
- Provides initial quark direction
- Provides initial quark p_T

Promises, promises...

- Absolute measurement of quark energy loss
  - Initial parton energy is known event-by-event (to ~15%)
- Fragmentation functions wrt initial jet energy
  - Initial parton energy is known event-by-event (to ~15%)
- Better handle on path length dependence
  - No surface bias for production vertex
- Cleaner handle on medium response
  - No medium (geometry, flow) bias on photons

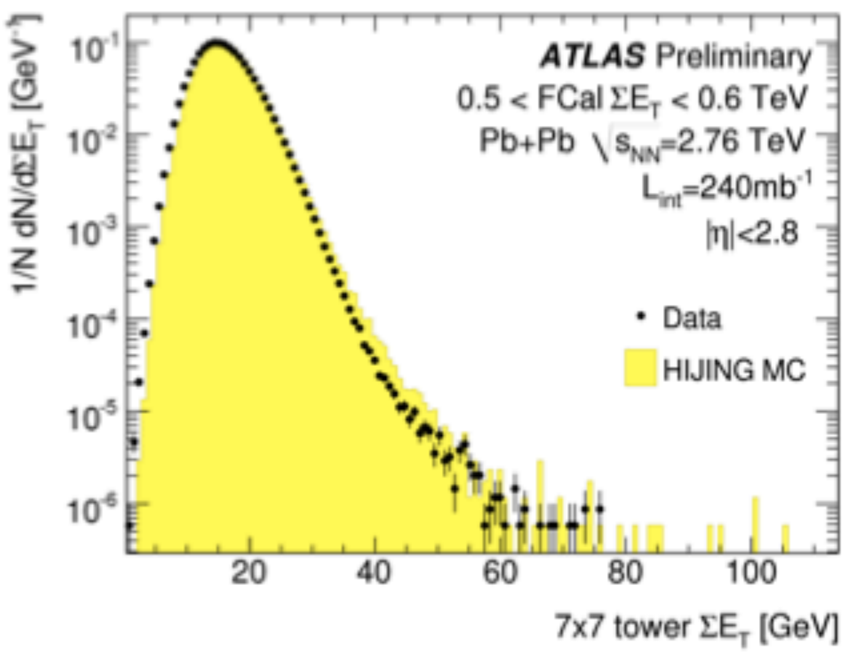
- Downside: Huge statistics penalty (after cuts)
  - O(10^5) dijets, 100’s of photon-jet, 10’s of Z^0-jet (for 150/nb)

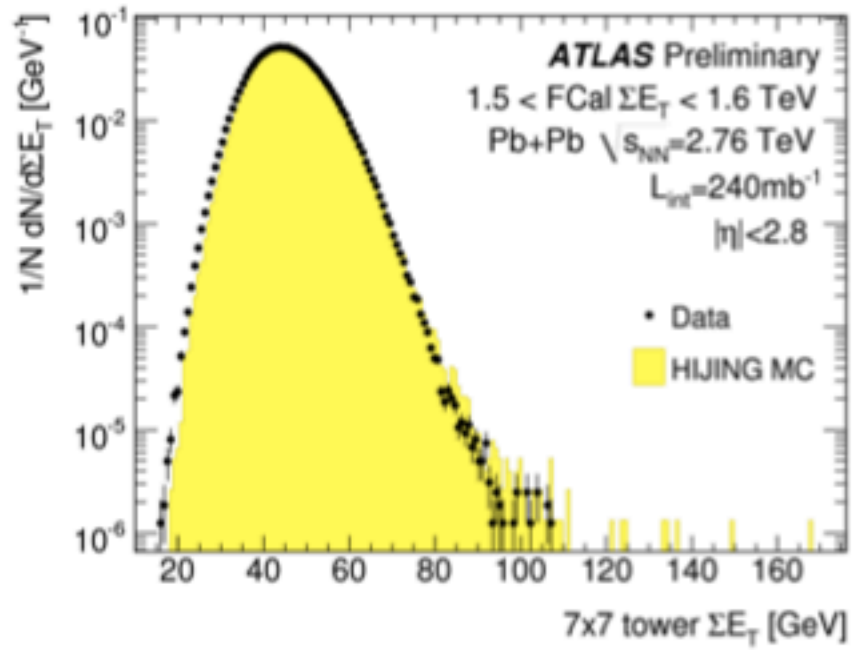
A few words on jets

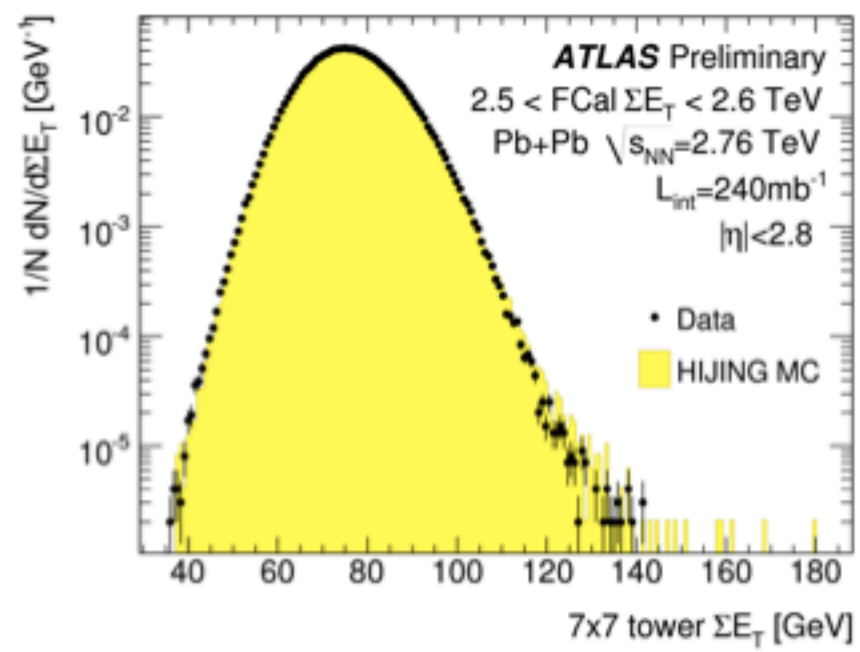
Jet reconstruction parameters

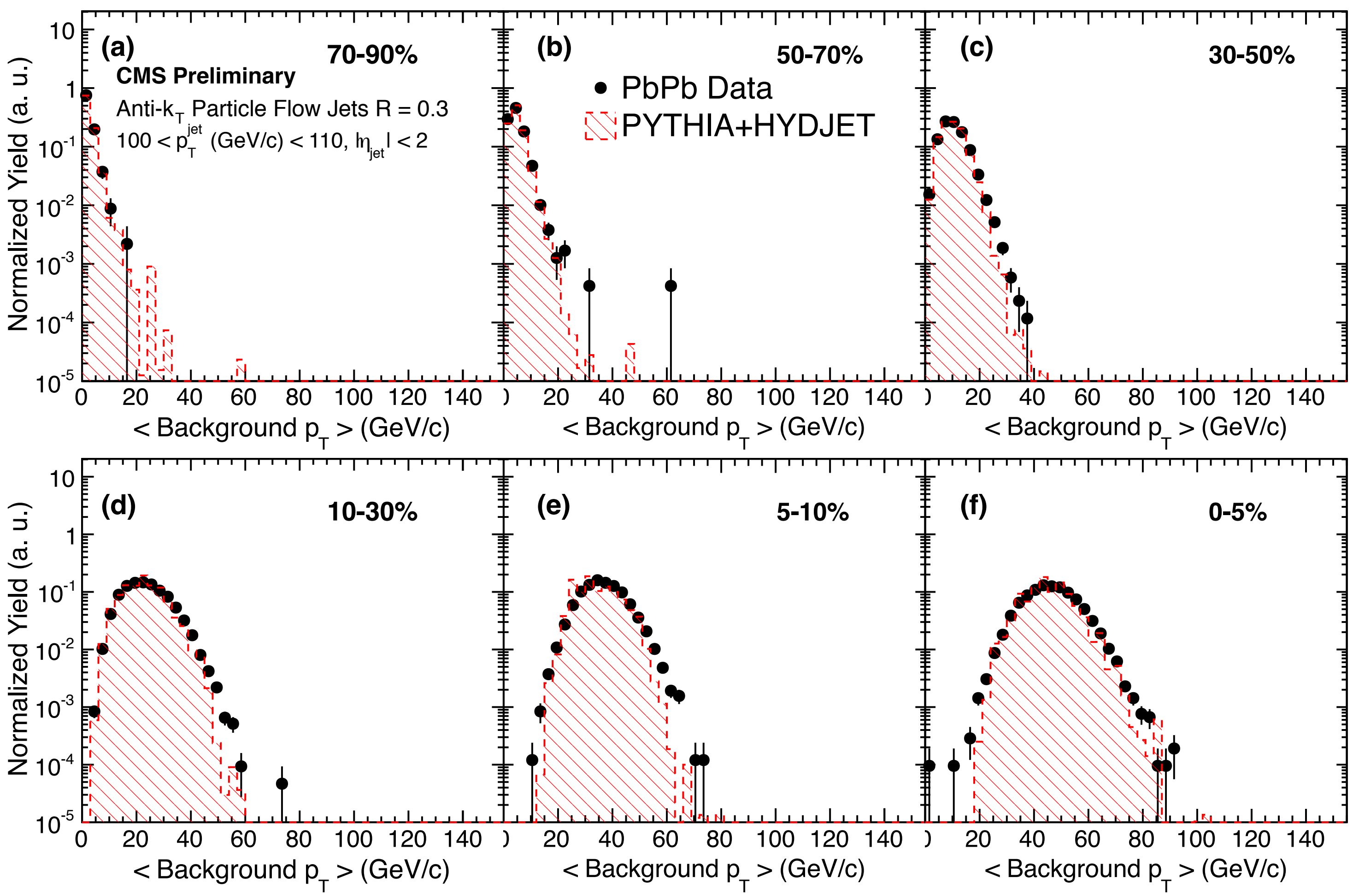
- Jet finding algo: Anti-k_T , using R from 0.2 to 0.5
- Background subtraction
  - ALICE, STAR: ρ x Area
  - ATLAS, CMS: iterative background subtraction in eta-rings
- Jet constituents
  - ALICE: tracks; tracks + ECAL matching
    - tracks from p_T > 0.15 GeV/c
  - ATLAS: calorimeter (ECAL+HCAL) towers; tracks
    - calo jets from p_T > 0.5-1GeV (?)
  - CMS: Particle flow (combined tracks, ECAL, HCAL); calorimeter towers
    - PF objects from p_T > ~1 GeV

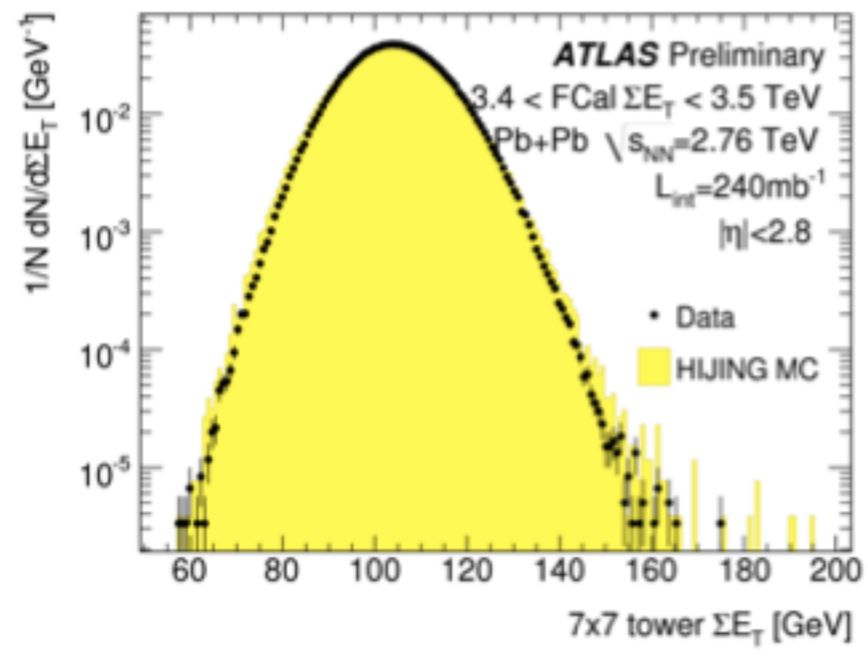
Background in data and MC





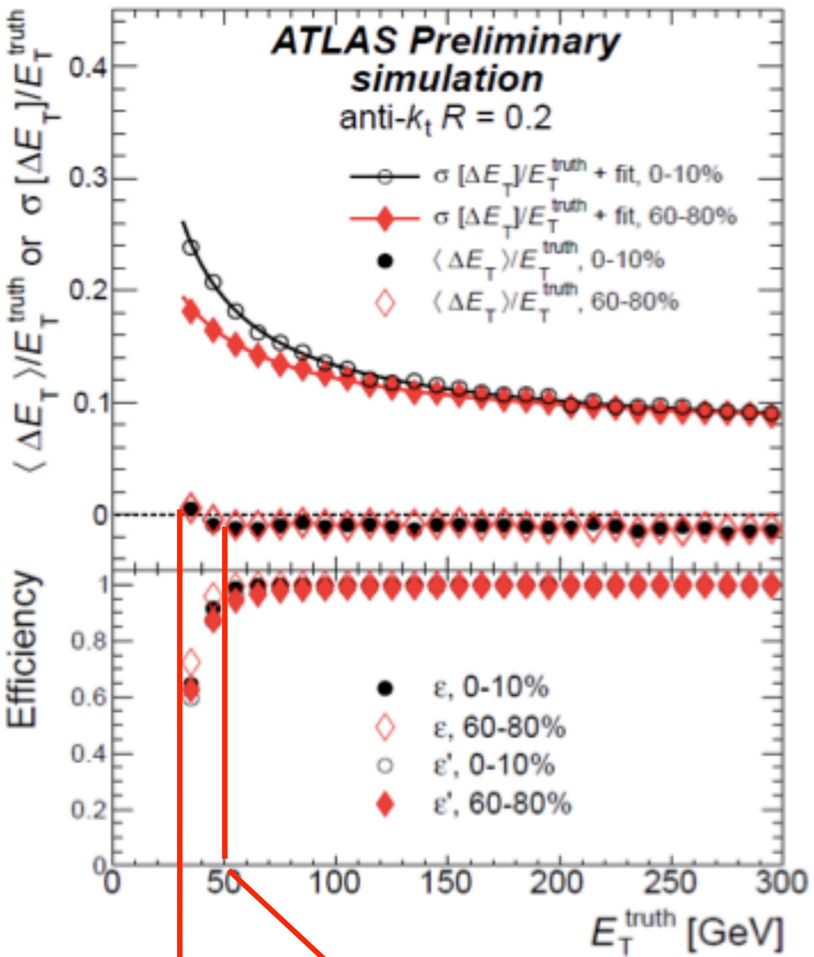


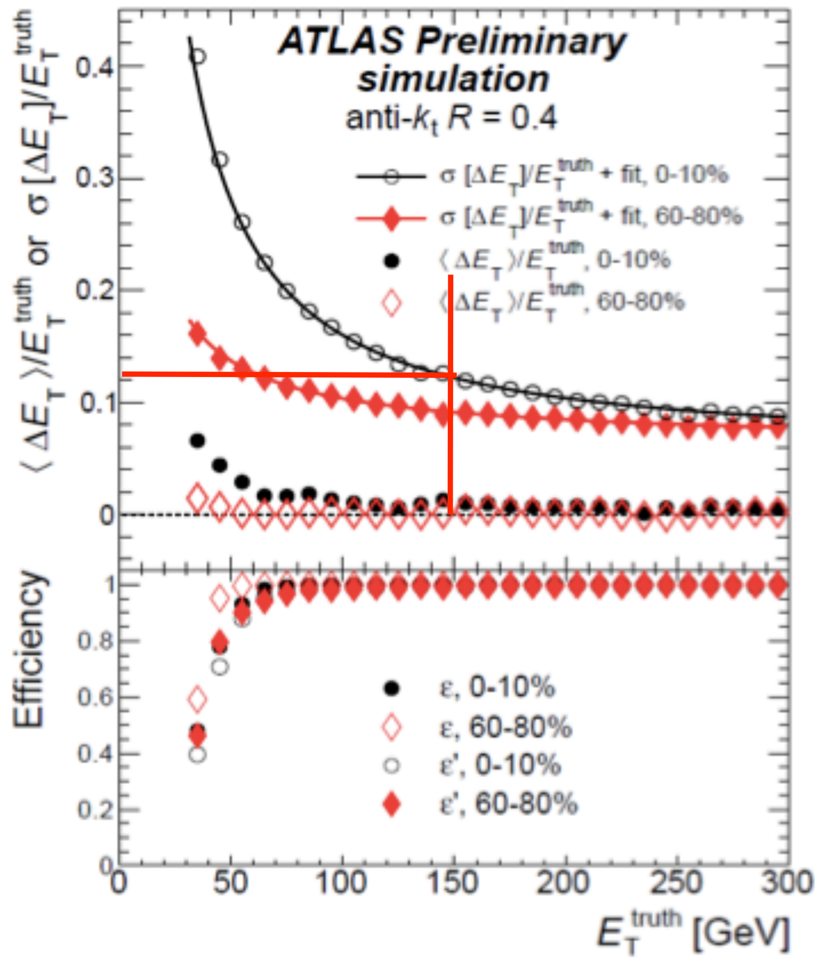


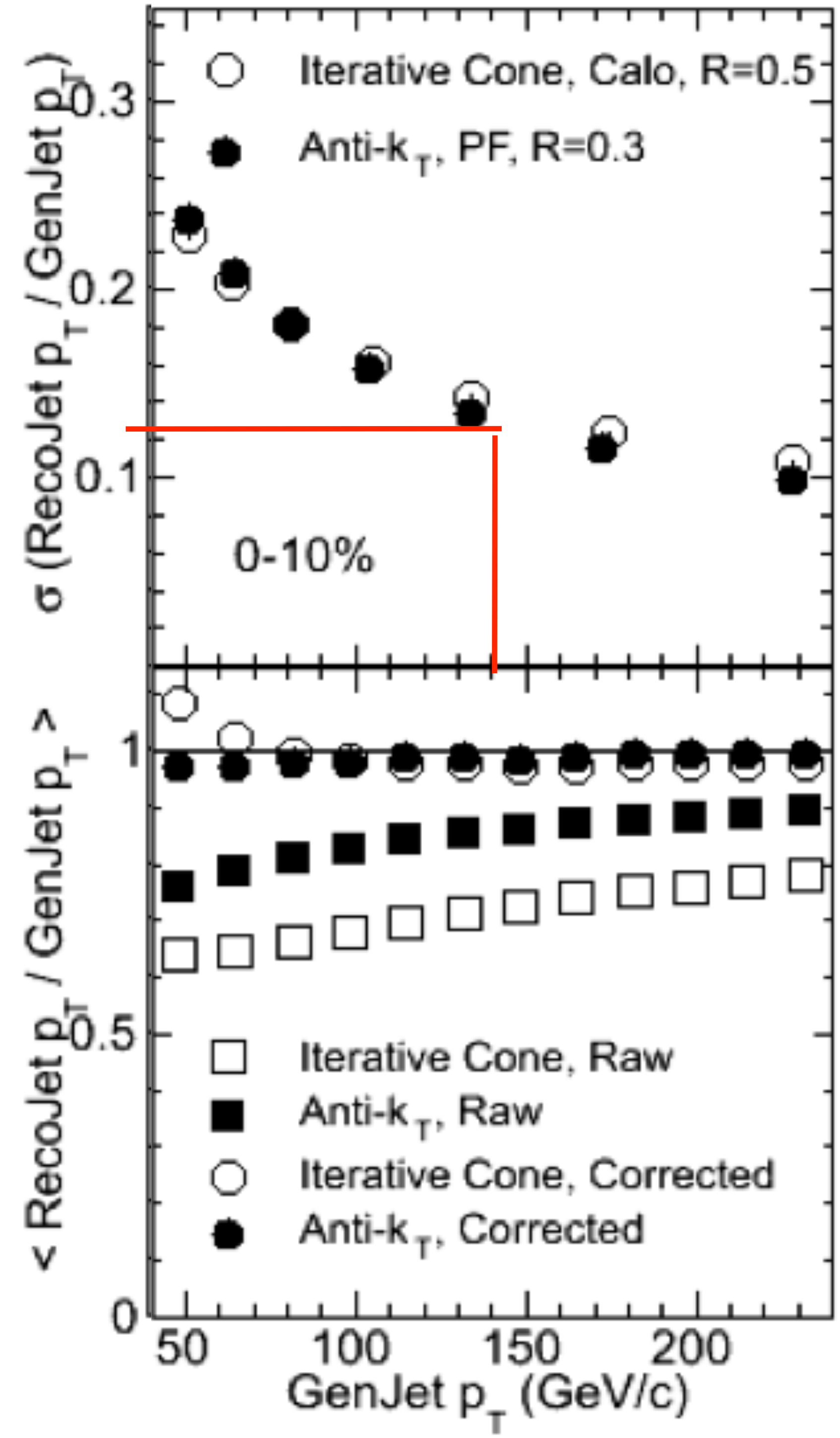


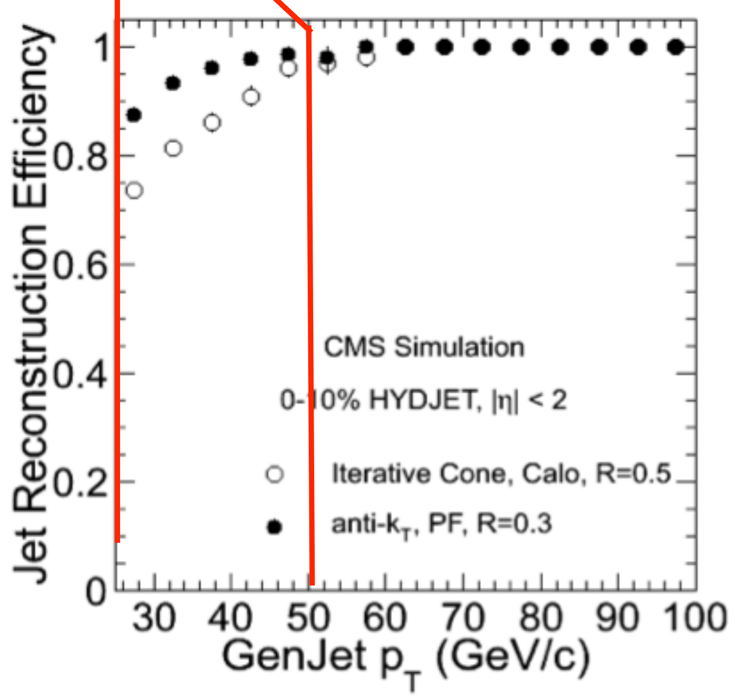
UE fluctuations now well understood

Jet finding performance: ATLAS vs CMS









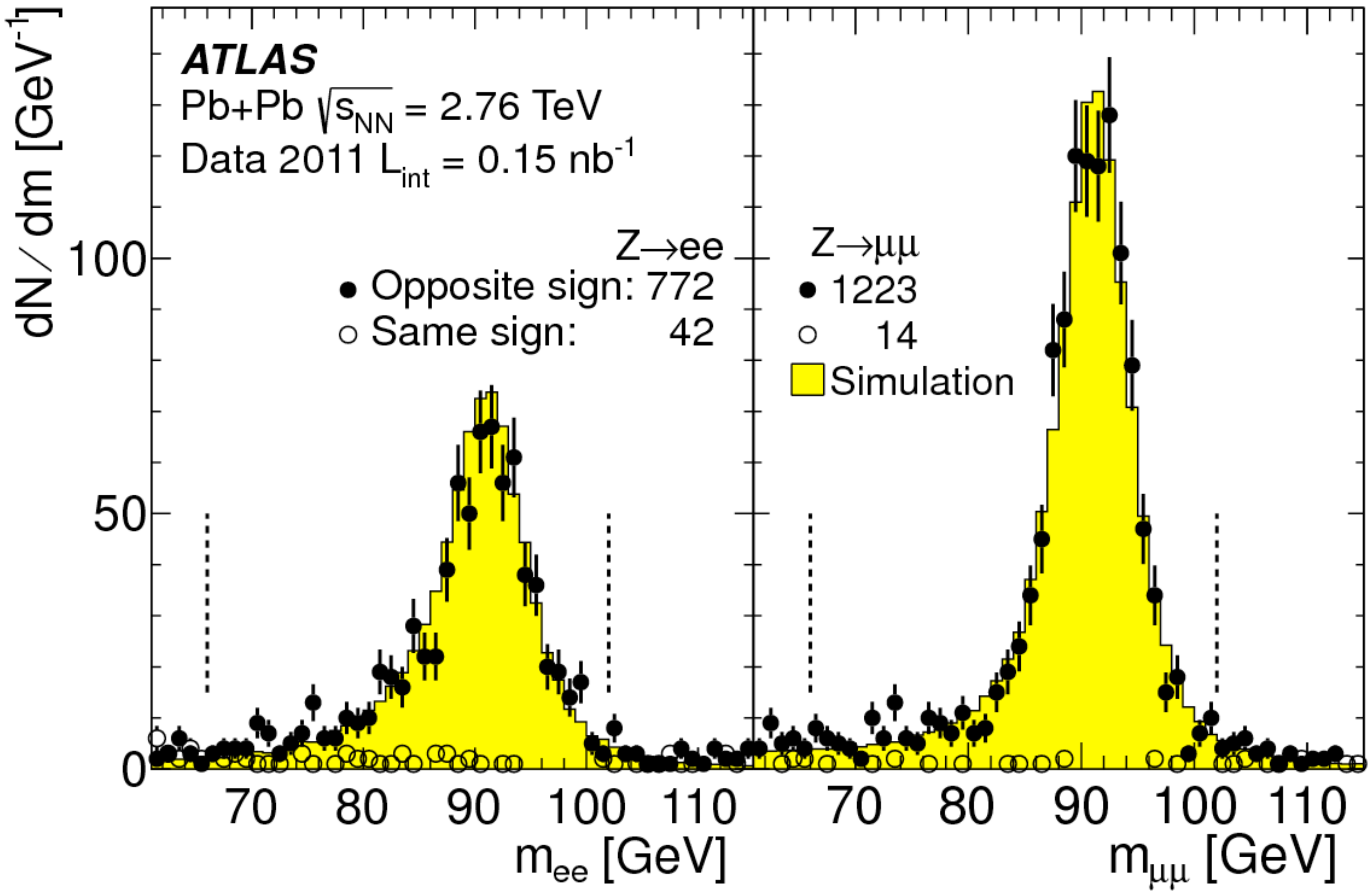
Jet finding performance deteriorates below 50 GeV (for R=0.3)

Lower limit 25-30GeV scale set by fluctuations

Z^0s

ATLAS Z^0 from 2011 data

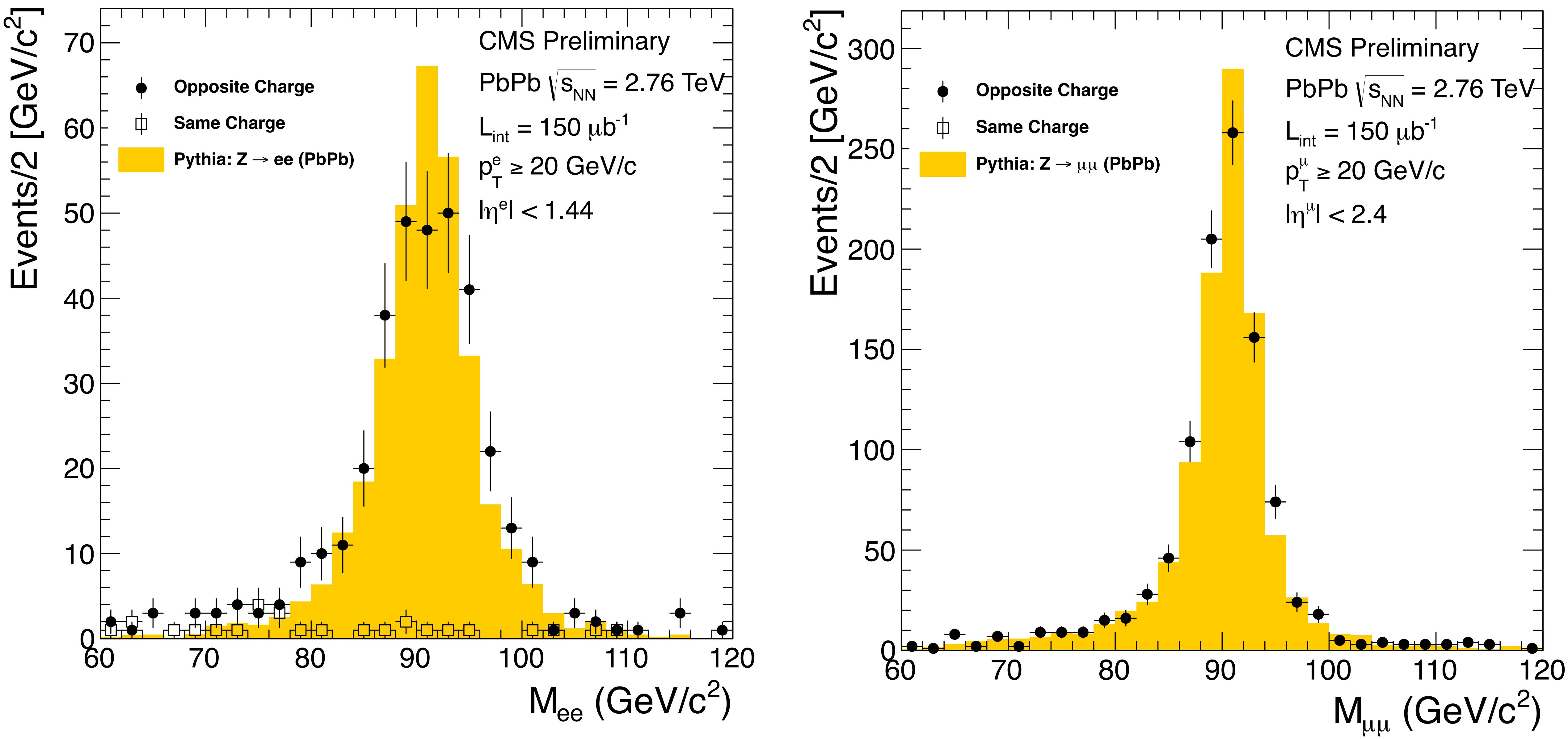
Peter Steinberg, QM'12



Electrons require match of track with EM cluster, along with shower shape cuts

Muons reconstructed using combination of MS and/or ID: optimized for Z efficiency, high quality muons p_T>10 GeV lower quality p_T>20 GeV

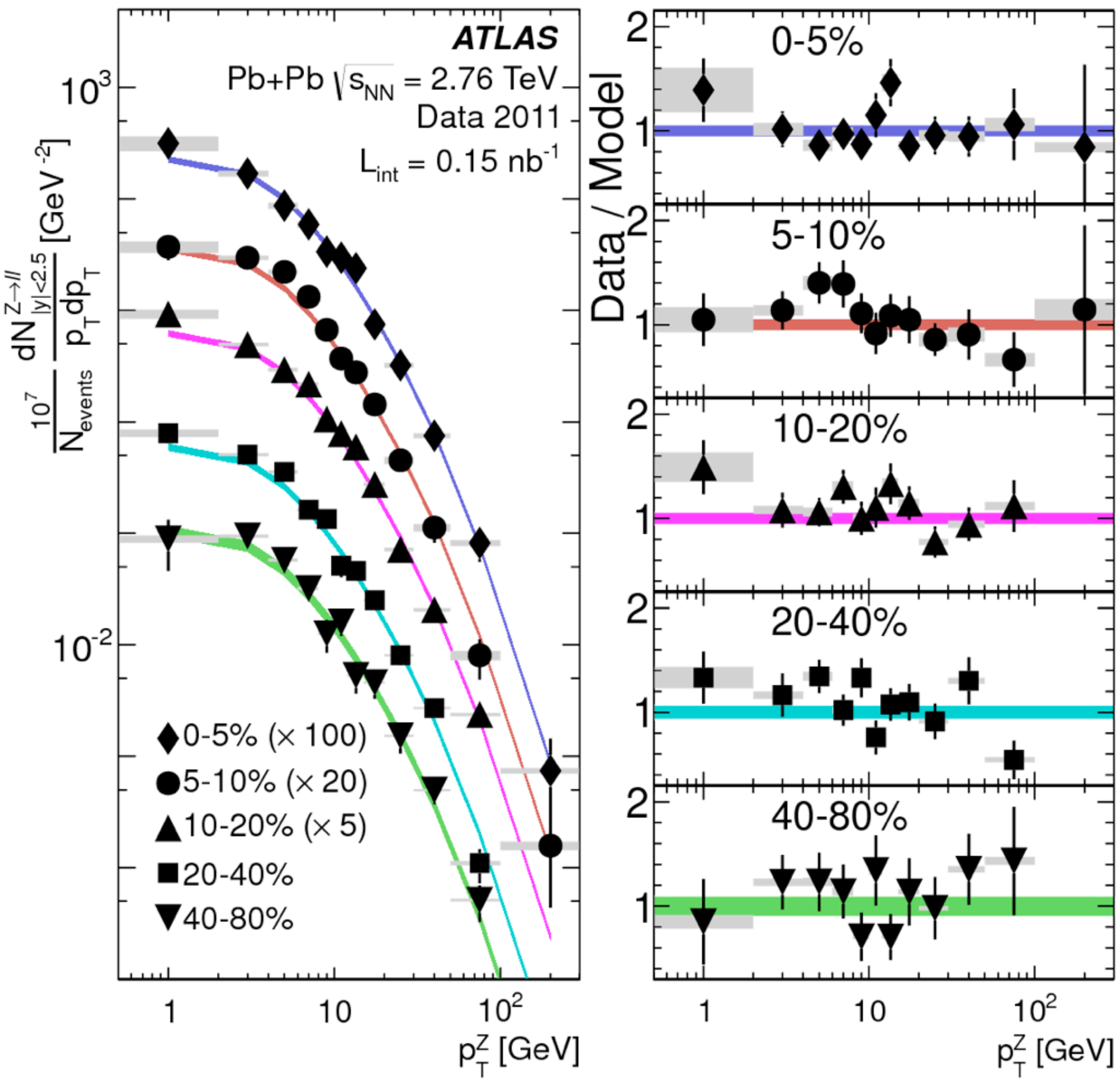
CMS Z^0 from 2011 data



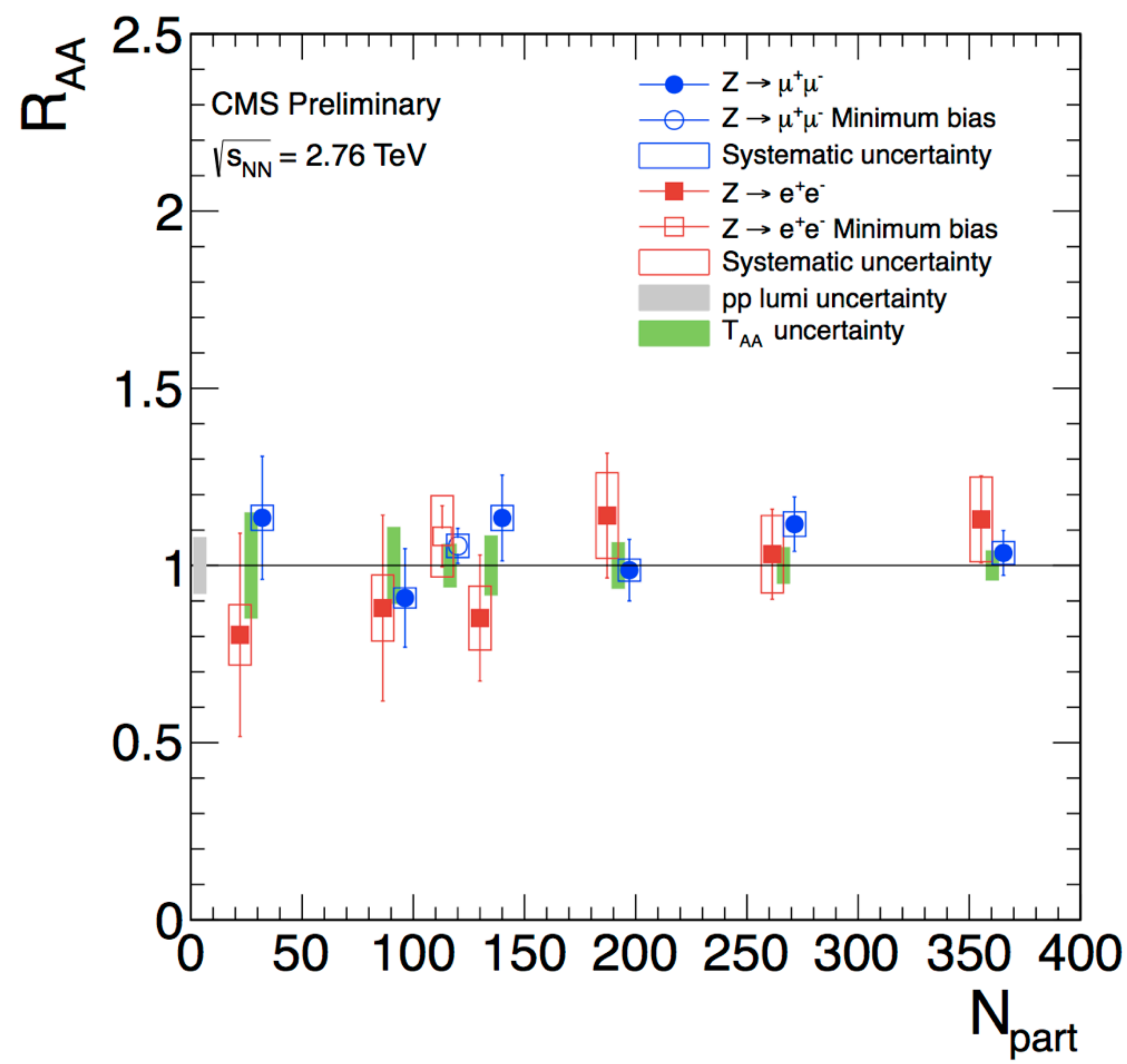
Electrons reconstructed using track + ECAL supercluster match in ECAL barrel region

"Global" tracker + muon chamber muons
Now using regional iterative tracking to increase efficiency (vs QM'12 result)

Z^0 "R_{AA}"



PbPb compared to PYTHIA normalized to NNLO pp x-section x N_{coll}



PbPb compared to pp x N_{coll}

Expected N_{coll} scaling is seen

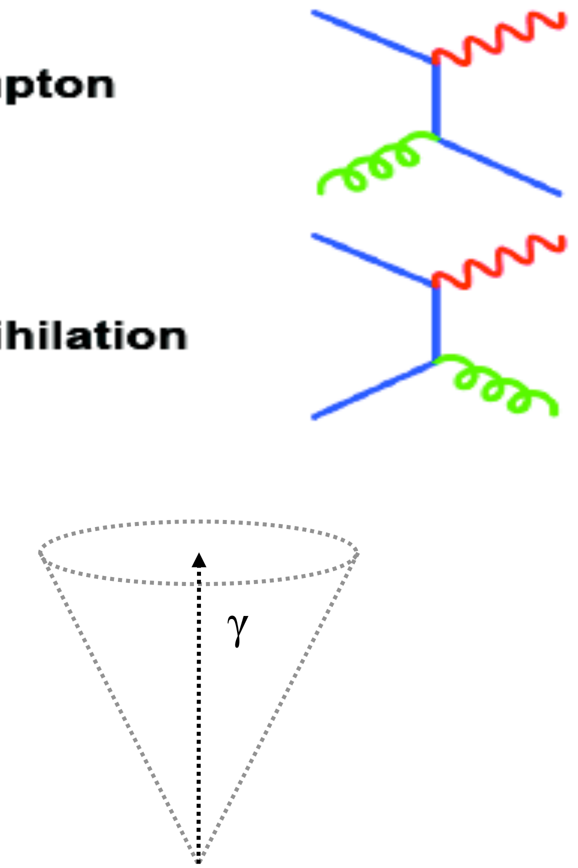
Isolated photons

Isolated photons

Leading order

Compton

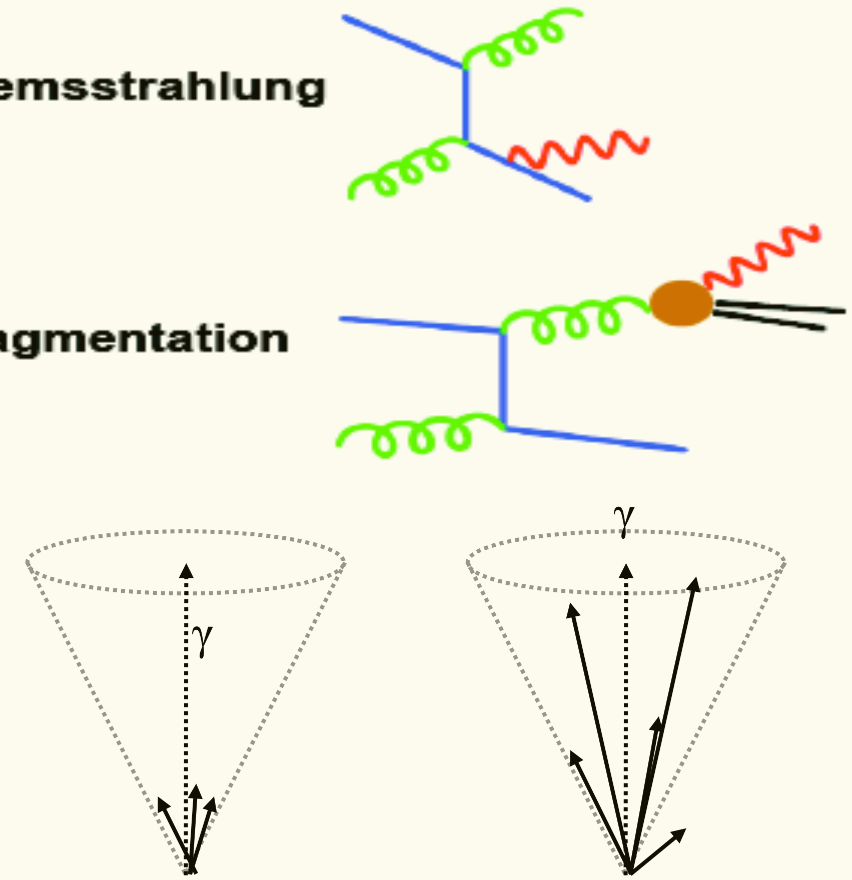
Annihilation



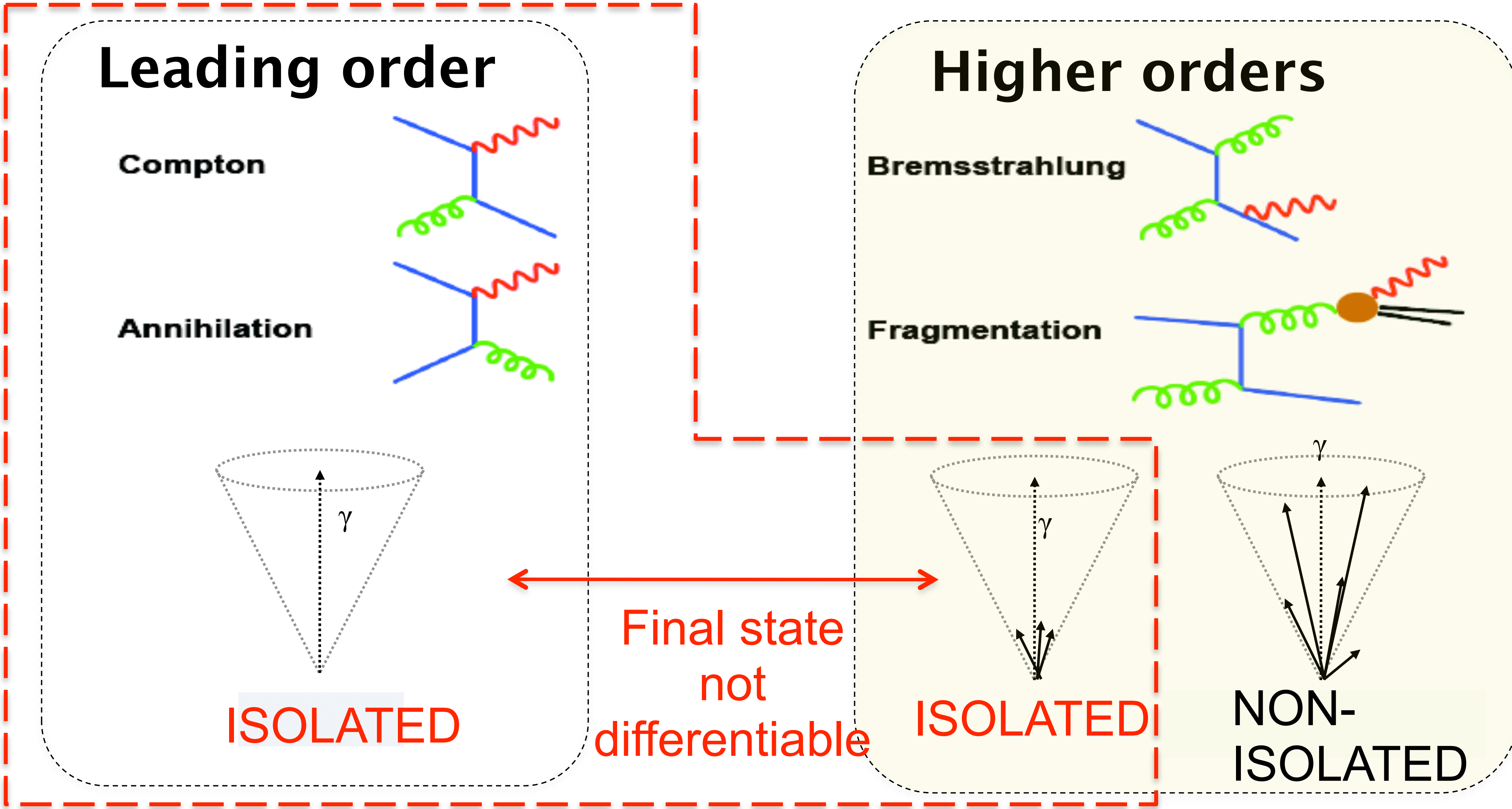
Higher orders

Bremsstrahlung

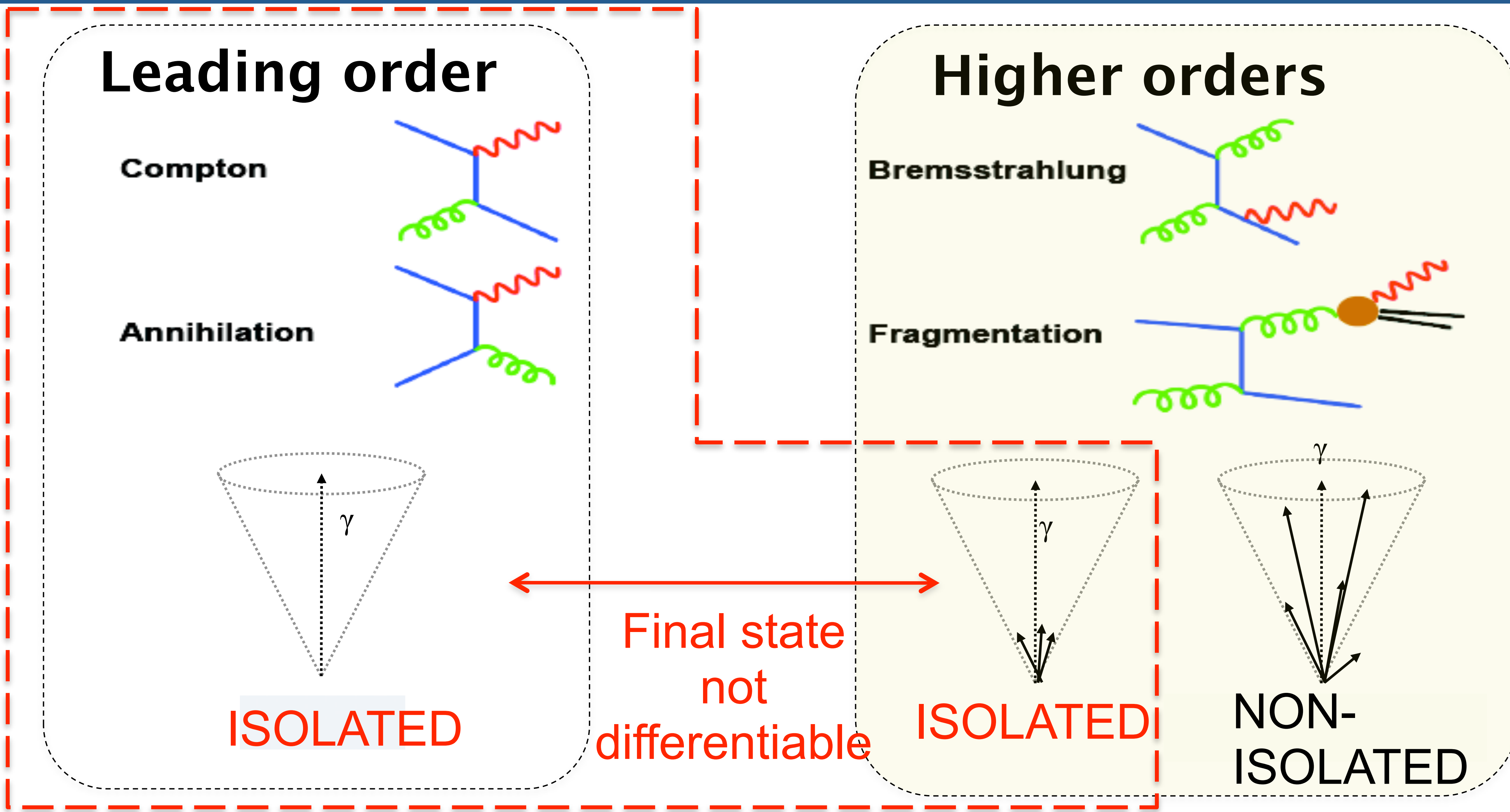
Fragmentation



Isolated photons

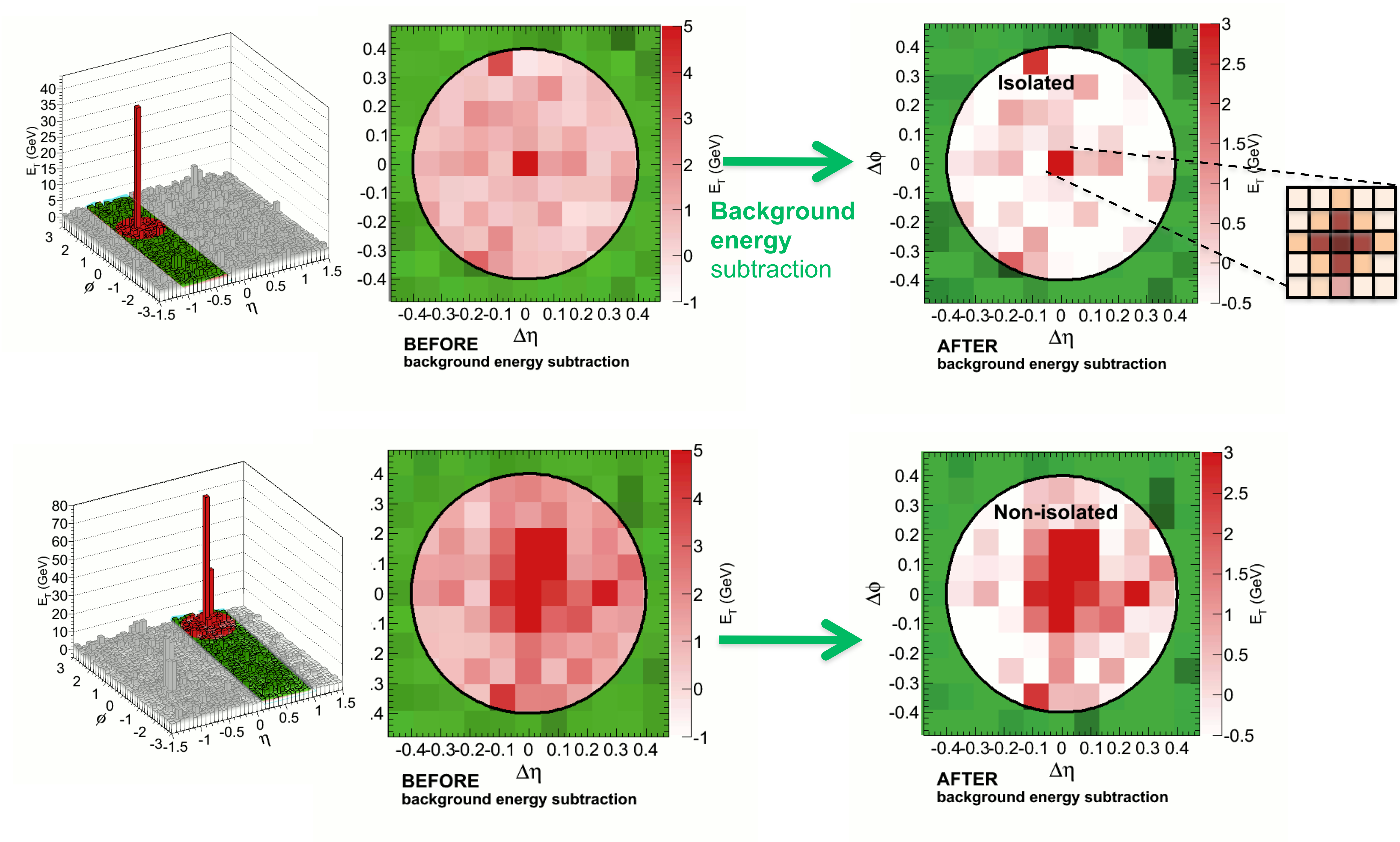


Isolated photons

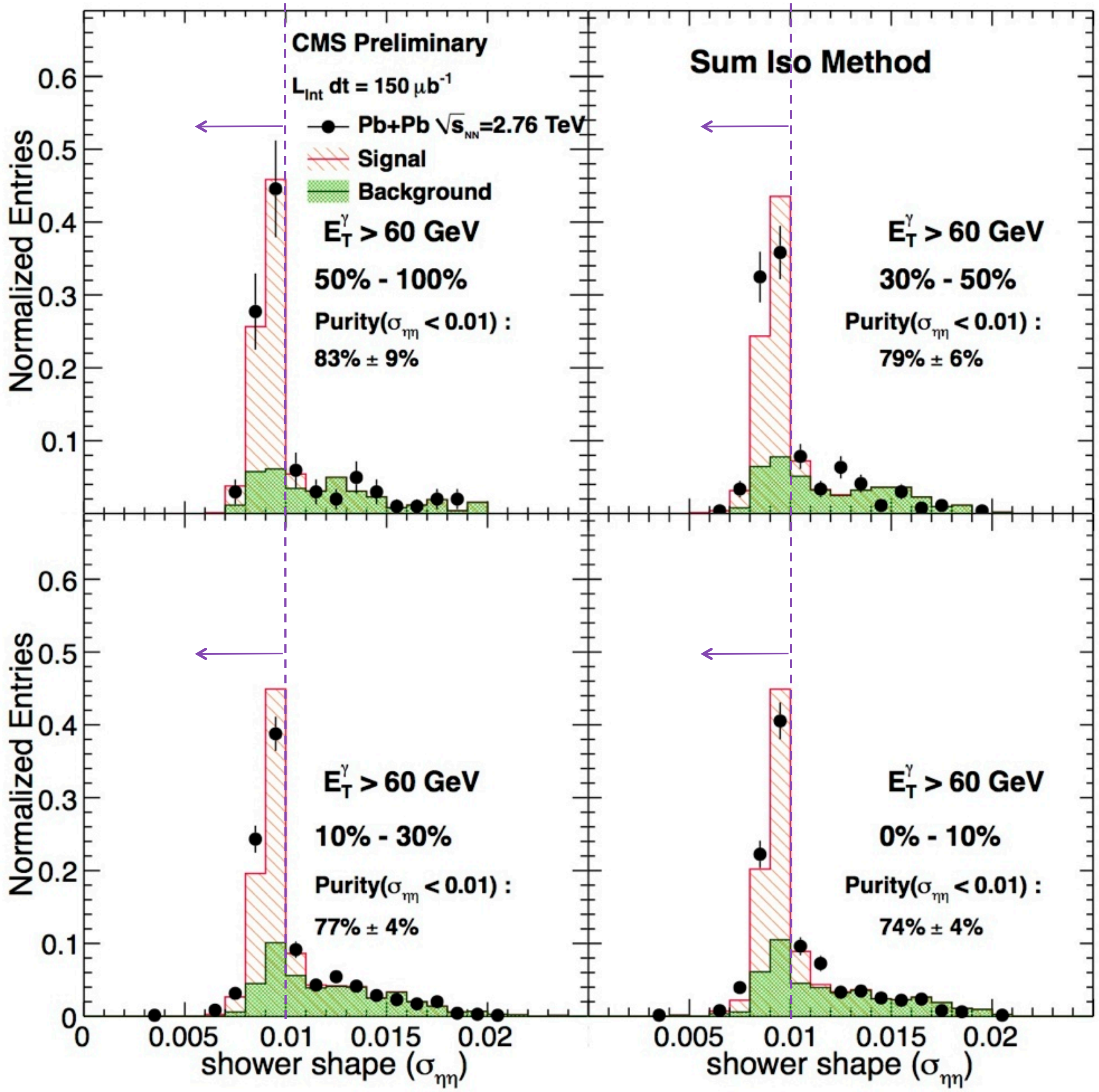


- SumIso = uncorrected Track + ECAL + HCAL E_T in R < 0.4
- GenIso = generator level particle energy in R < 0.4
- Isolated prompt (non-decay) photons with SumIso < 1 GeV
- Comparison to MC definition GenIso < 5 GeV
- SumIso ≠ GenIso due to PbPb underlying event fluctuation

CMS photon isolation in PbPb



Rejection of decay photons

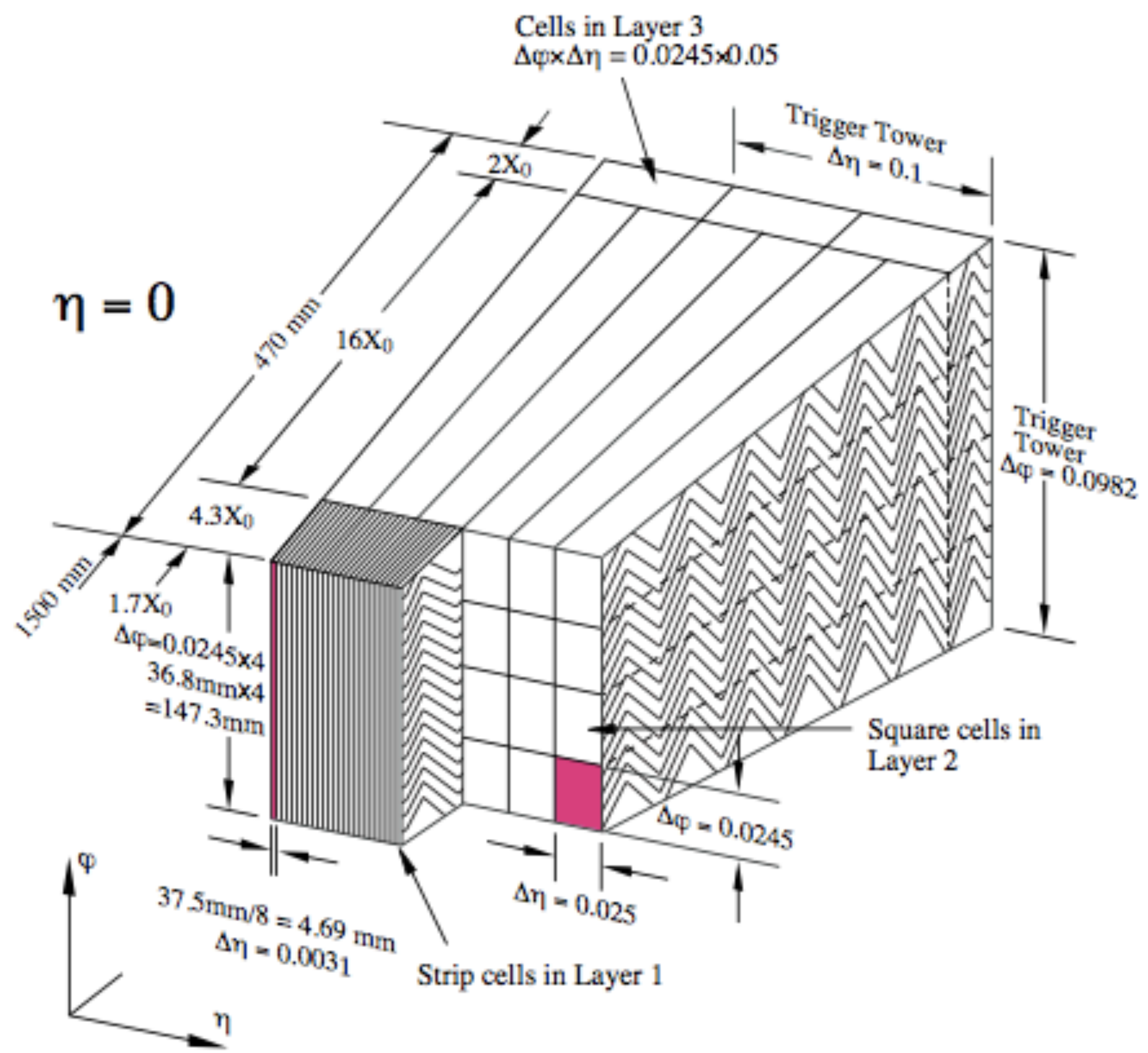


- Shower shape
  $\sigma_{\eta\eta} = \sum_i^{5\times5} w_i (\eta_i - \eta_{5\times5})^2 / \sum_i^{5\times5} w_i$
  $w_i = \max(0, c + \ln E_i / E_{5\times5})$
- Signal photons selected by cutting on $\sigma_{\eta\eta} < 0.01$
- Decay photons contribution determined by fit of (signal + background templates in $\sigma_{\eta\eta}$
- Background $\sigma_{\eta\eta}$ template found **using data** from photons failing the SumIso cuts

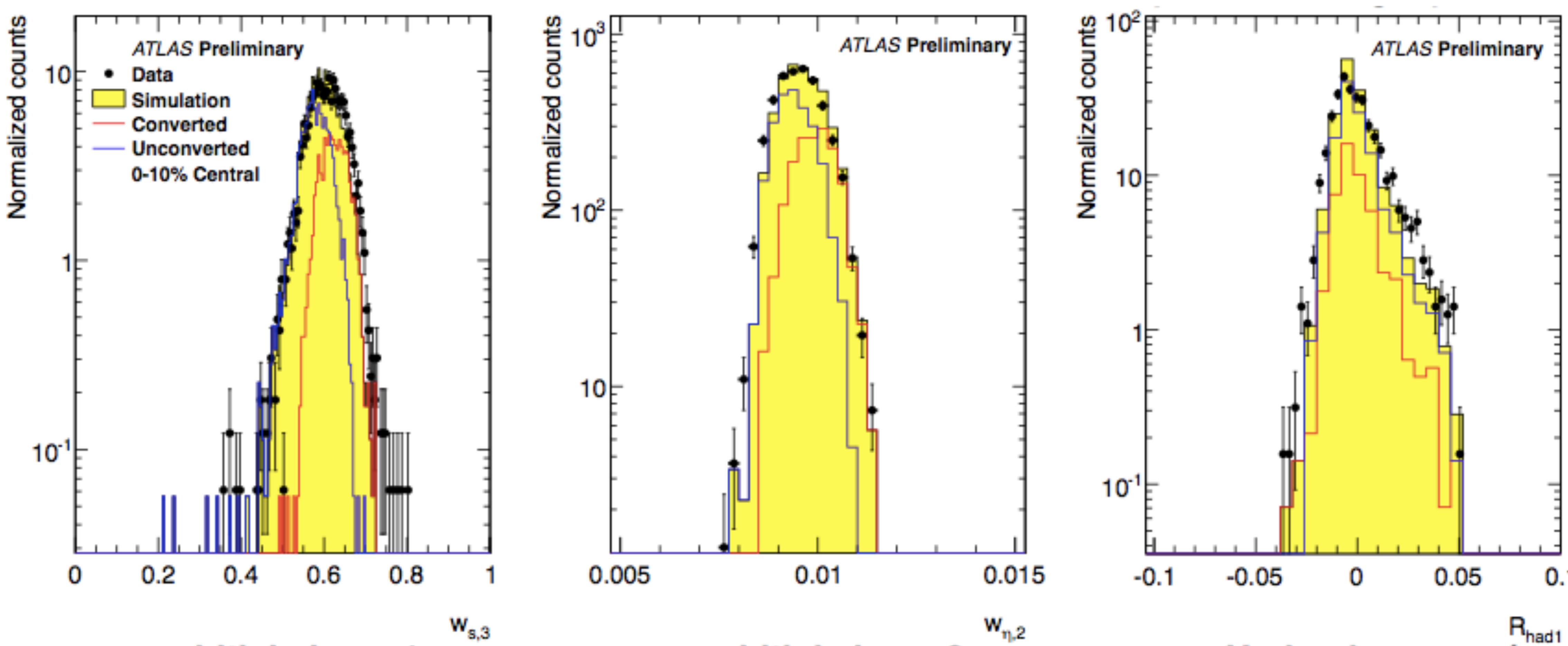
ATLAS photon reconstruction - I

Peter Steinberg, QM'12

- **Photon reconstruction is seeded by calorimeter clusters of at least 2.5 GeV**
  - Sliding window algorithm applied in 2nd sampling layer, which gets >50% of photon energy.
- **No conversion recovery is applied: all photons treated as unconverted.**
  - High energy converted photons deposit most energy in only a slightly wider ϕ region than photons
- **Energy measurement is made using all three layers**
  - Area is 3x5 layer-2 cells (each cell is $\Delta\eta x \Delta\phi \sim 0.025 \times 0.025$)
  - Background subtraction gives corrections of O(1 GeV) even in central events



ATLAS shower shape: Data vs MC



η width in layer 1 (strip units)

η width in layer 2 (η units)

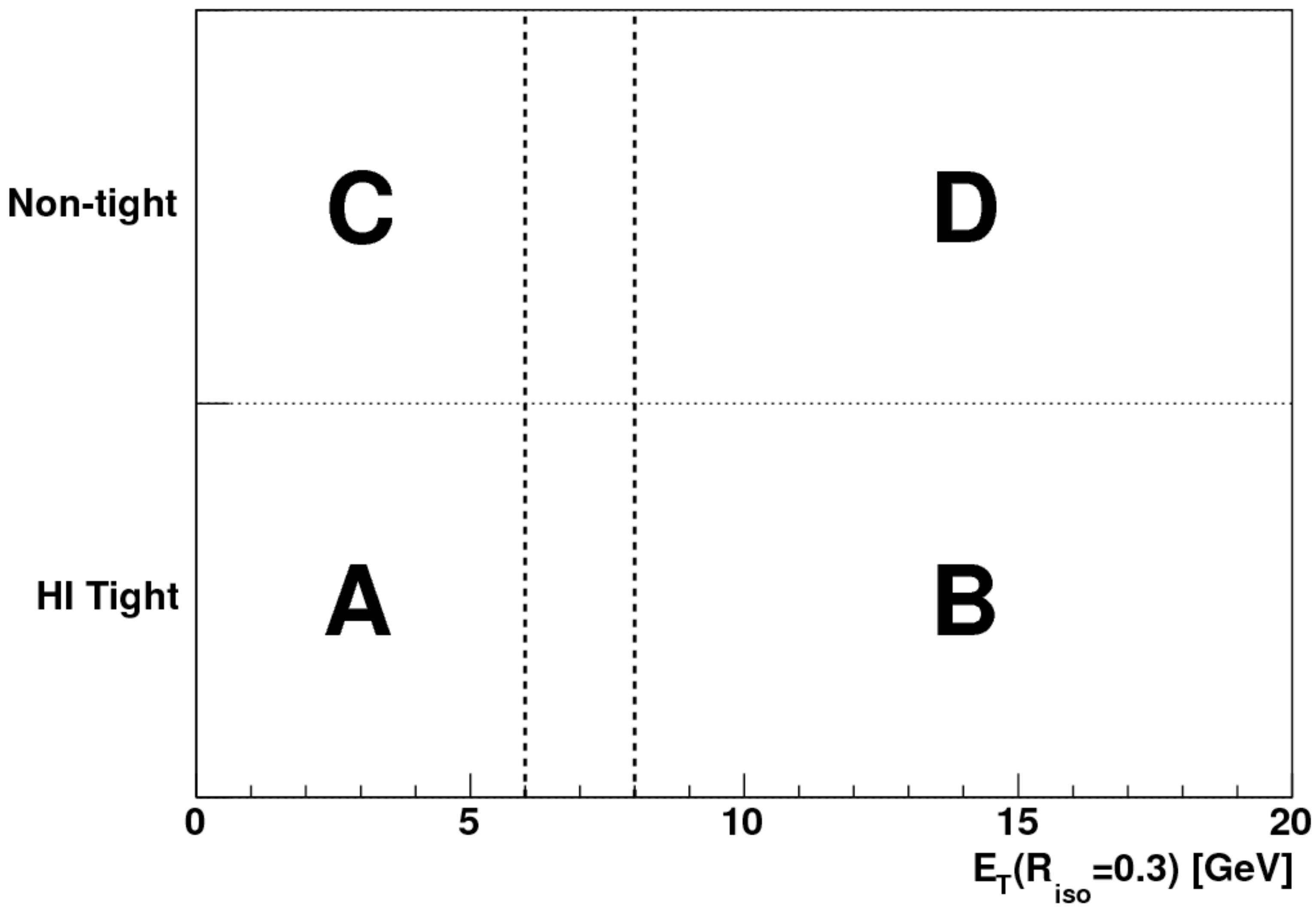
Hadronic energy/ cluster energy

Excellent shower shape match of data vs MC

(after “tight” photon selection on set of 9 variables)

ATLAS Purity Measurement

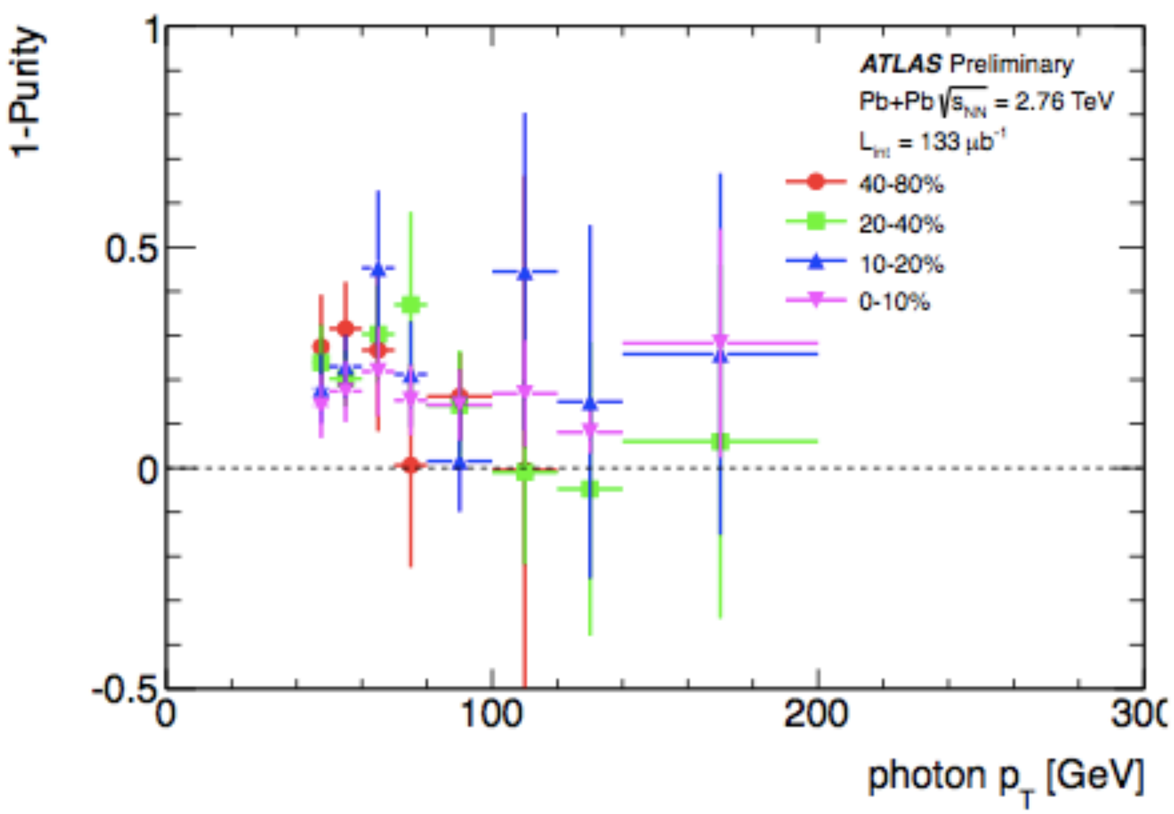
- Double Sideband Technique
- Photon candidates binned on two axes
  - Isolation energy
  - Tight or loose cut

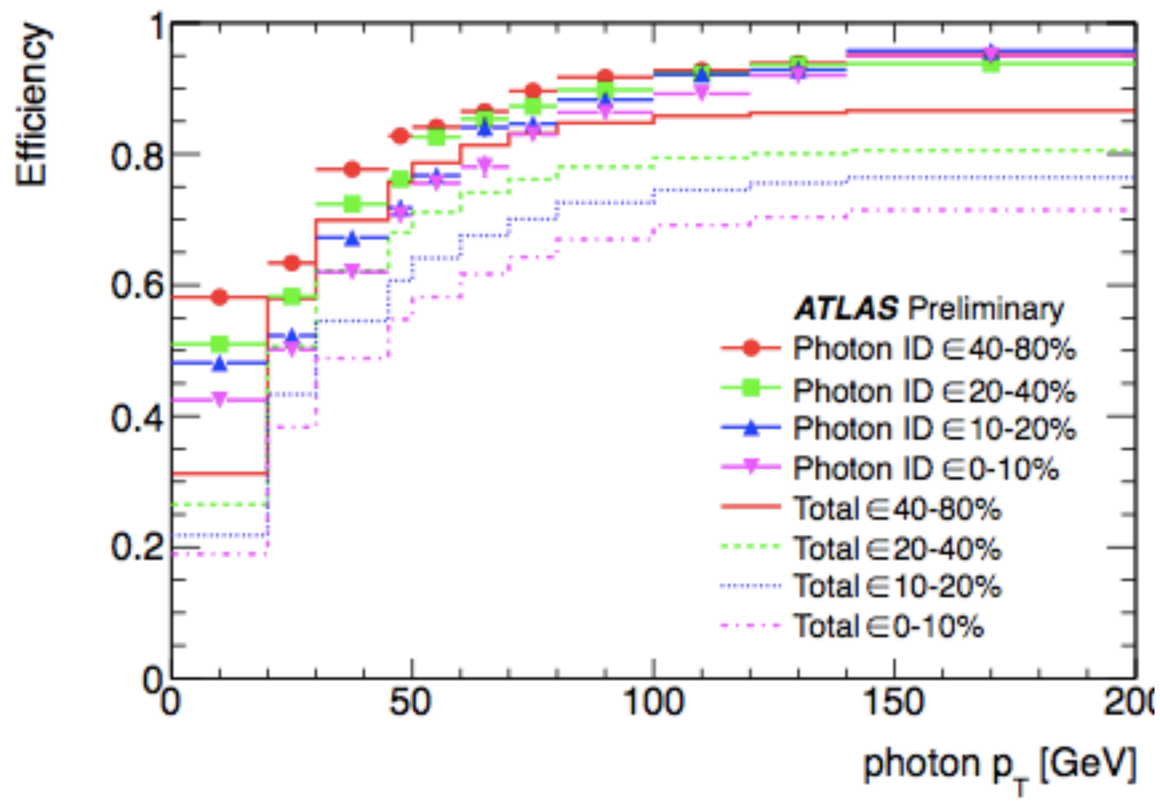


For all event-by-event photon measurements:
Need independent variables (isolation, shower shape)
Data driven technique (double sideband, templates)

ATLAS photon purity, efficiency

Peter Steinberg, QM'12





Purity determined from "double sideband" method:
fraction of di-jet background in photon sample: 20-30% in low p_T bins.

Efficiency controlled mainly by shower shape cuts & isolation selection:
reconstruction & ID quite efficient in central HI,
isolation leads to ~15-20% reduction

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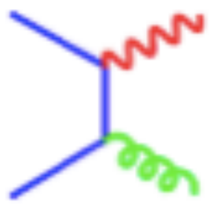
ALICE photon isolation

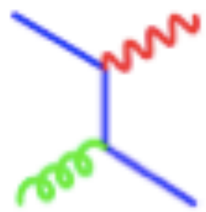
Select **direct photons :**

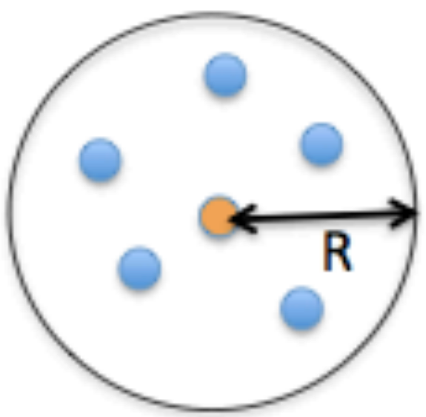
- most of direct photons are isolated, most of decay photons are not (jet)
- isolation parameters : cone radius $R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$, $p_T^{threshold}$

Annihilation



Compton

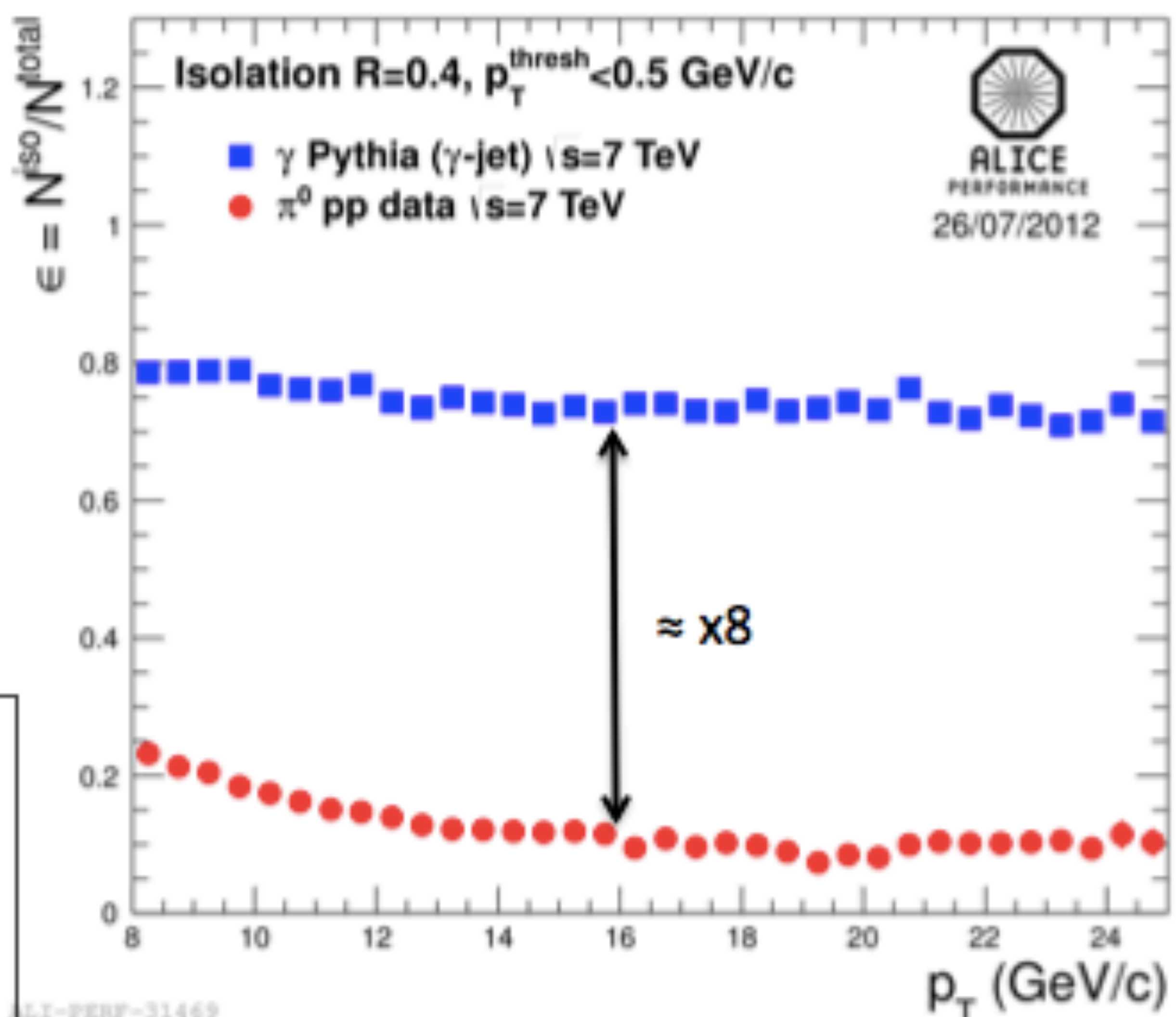




Isolated cluster

⇔

no particle with p_T above 0.5 GeV/c in cone R = 0.4



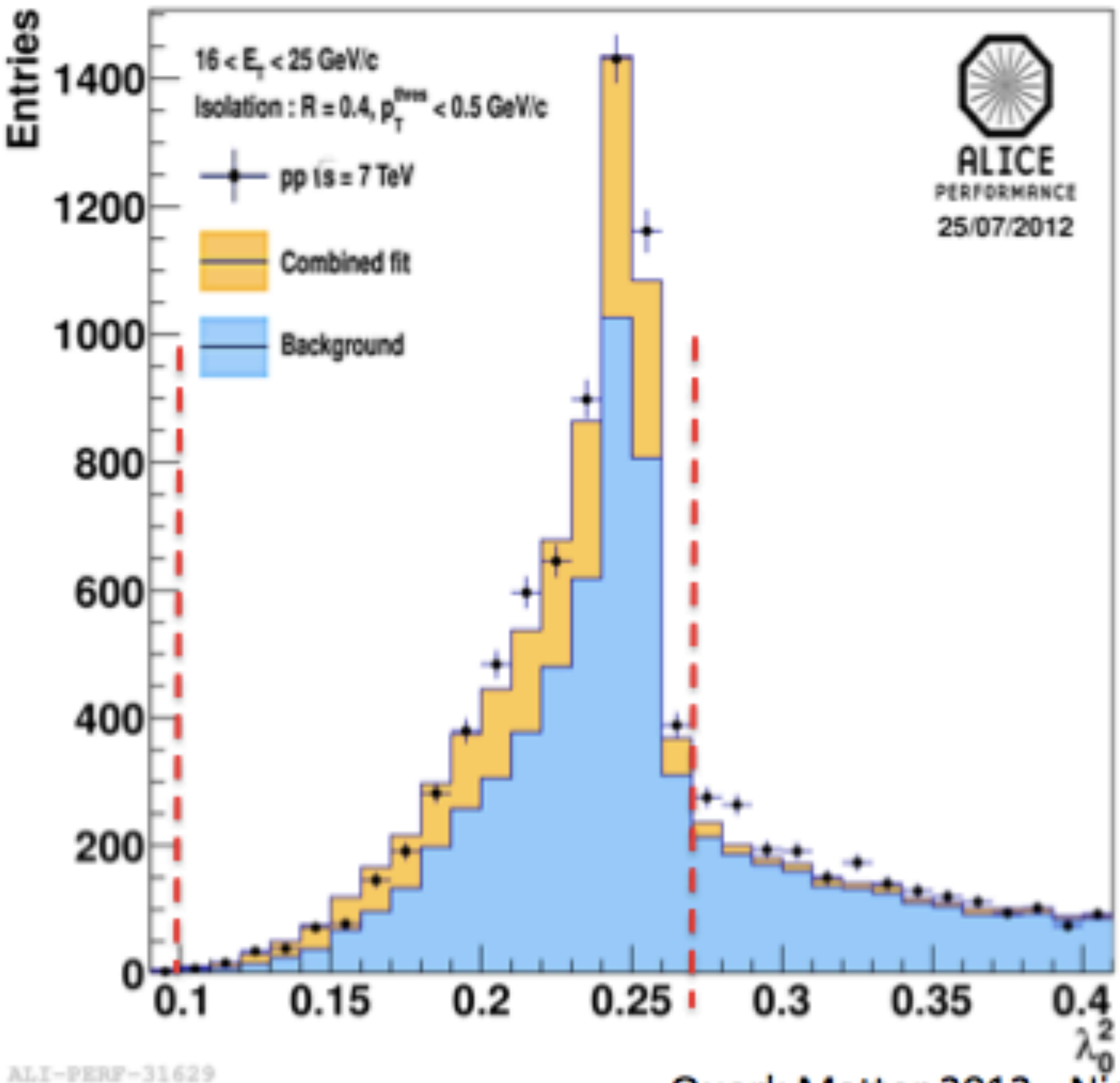
Quark Matter 2012 - Nicolas Arbor

9

ALICE shower shape fit

- Isolated clusters sample = isolated photons + background
- Binned likelihood **fit of the shower shape distribution** :

→ combined signal (MC) and background (data) shower shape to fit data



$$\text{Purity} = \frac{\int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} \blacksquare_{\text{orange}}}{\int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} \blacksquare_{\text{orange}} + \int_{\lambda_0^2=0.1}^{\lambda_0^2=0.27} \blacksquare_{\text{blue}}}$$

p_T bins (GeV/c)	Purity
8-12	0.08 ± 0.01
12-16	0.31 ± 0.05
16-25	0.59 ± 0.04

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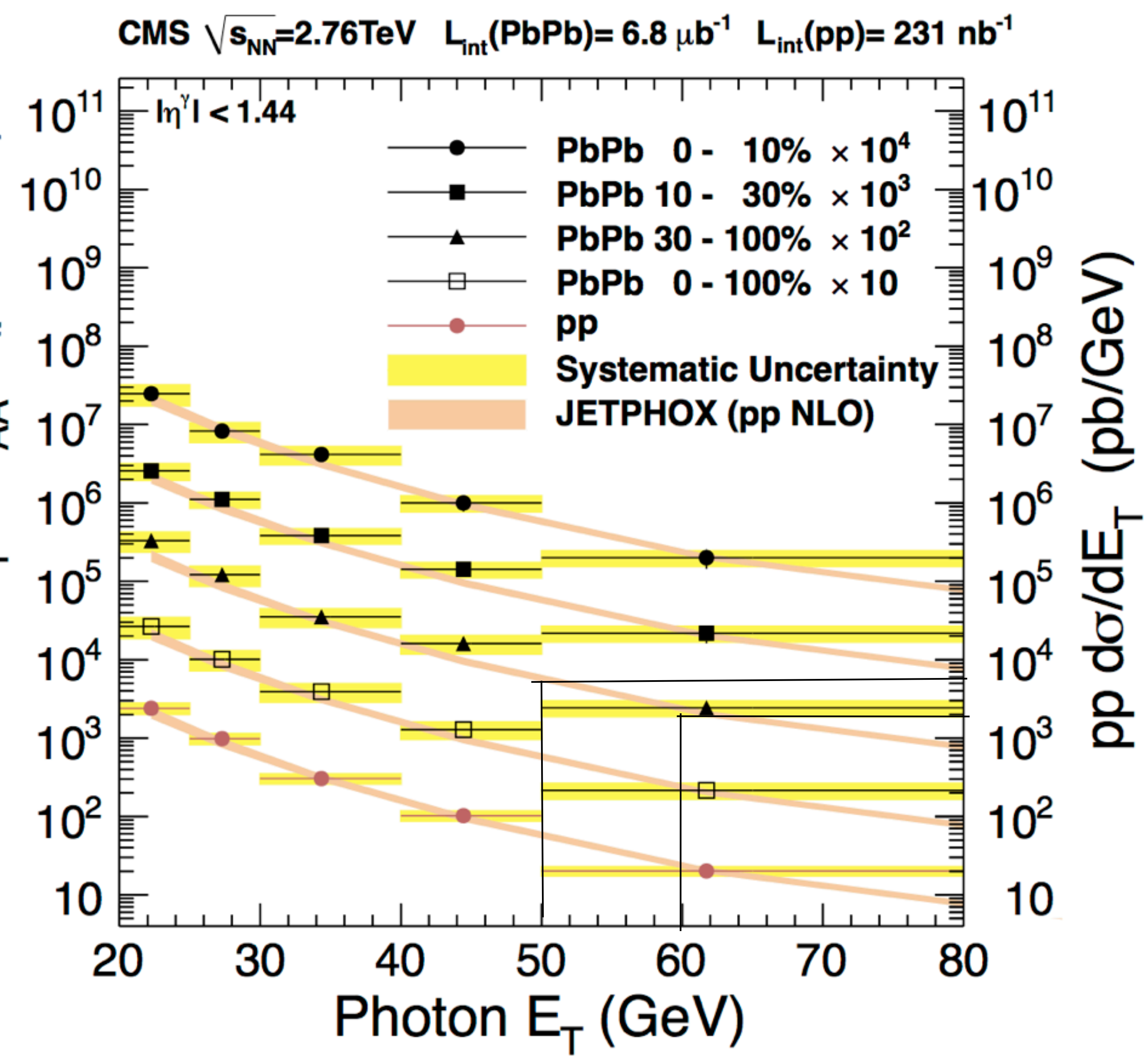
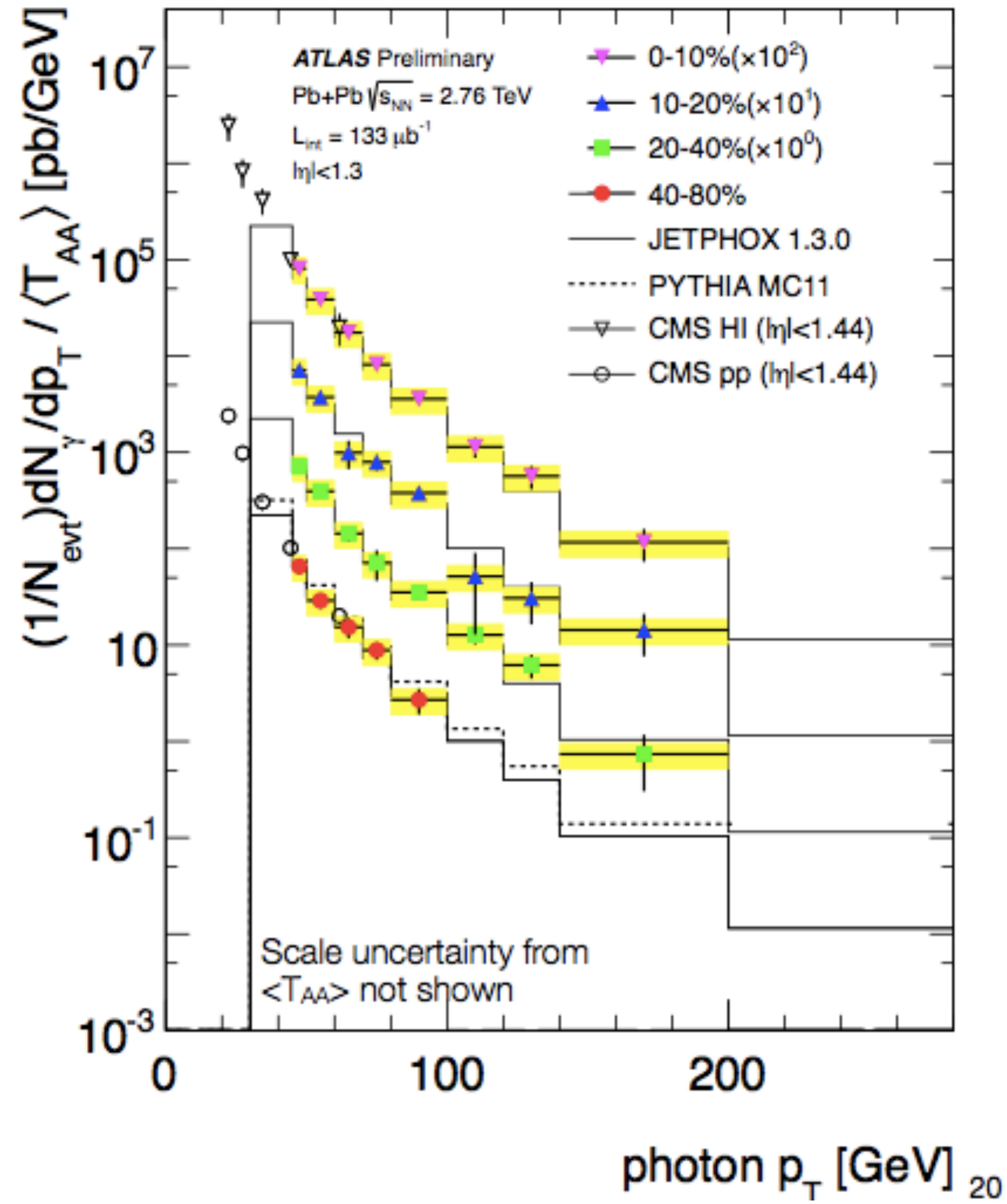
10

Isolated photon spectra

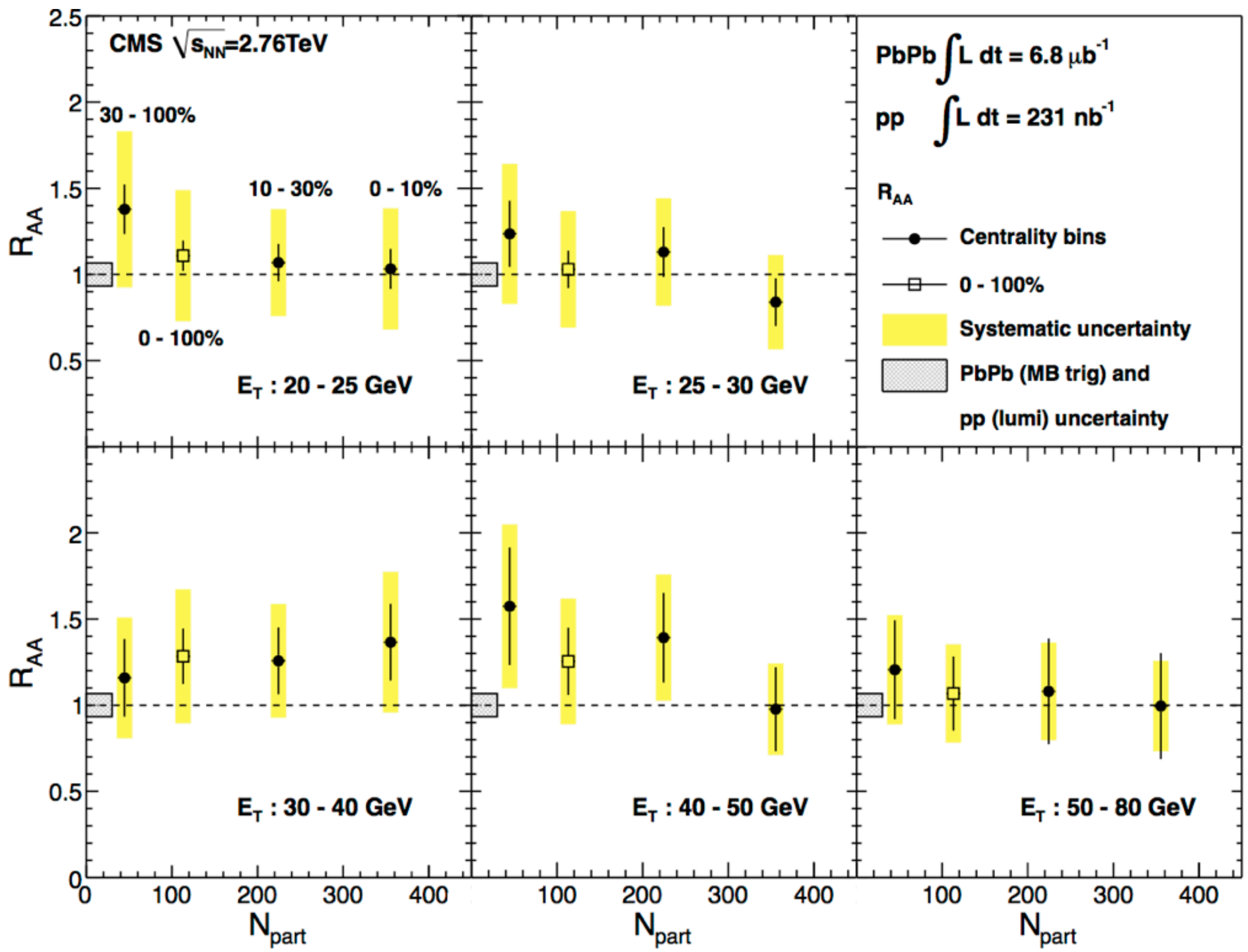


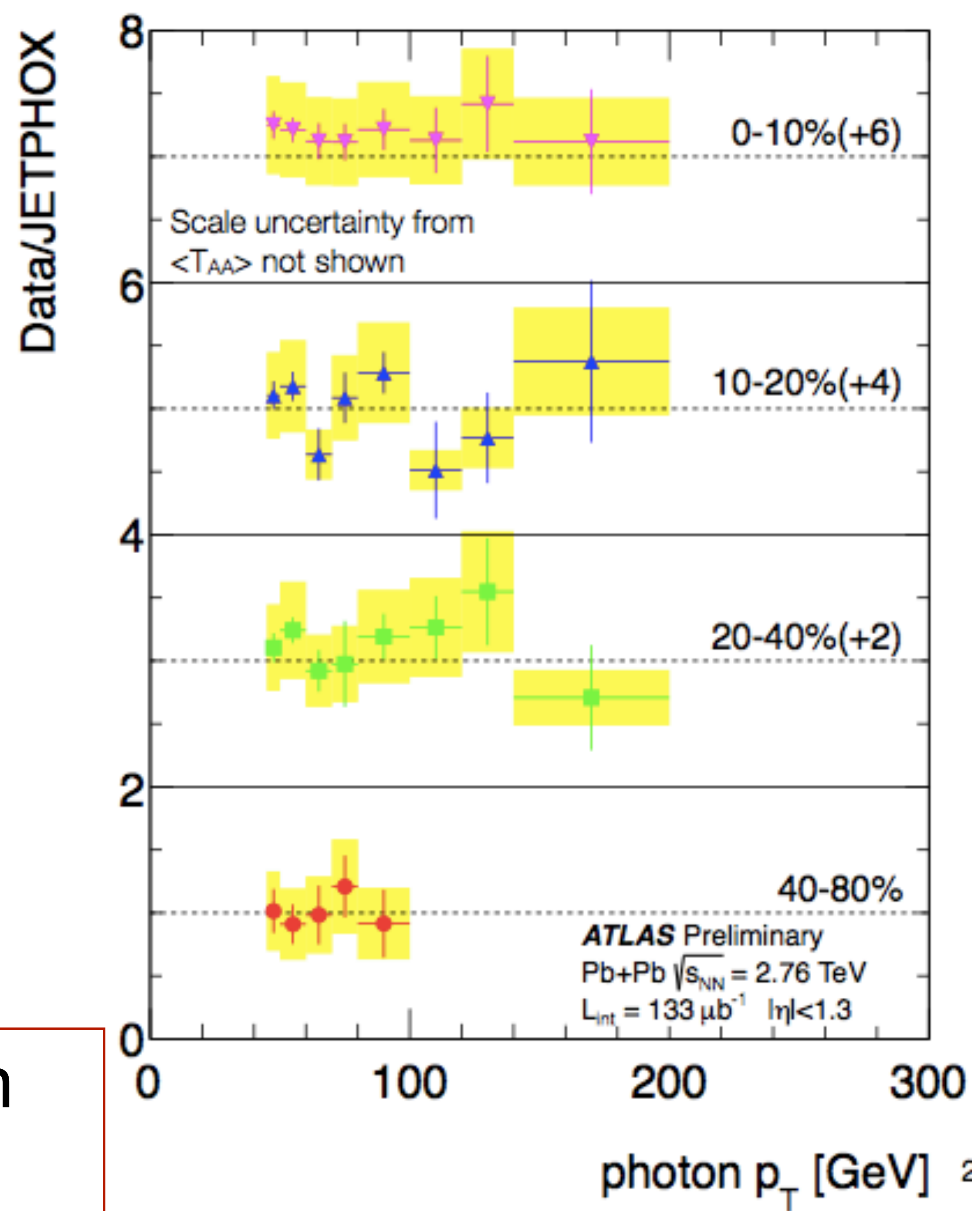


x2-3 hit in statistics per 10GeV increase in p_T

Good agreement in (limited) p_T overlap region

Isolated photon R_{AA}





As for Z^0s, expected N_{coll} scaling seen

Note that even pp measurements typically have 10-15% systematic uncertainties

Direct photons ≡ photons not arising from hadronic decays

~ isolated photons + non-isolated fragmentation/bremsstrahlung photons

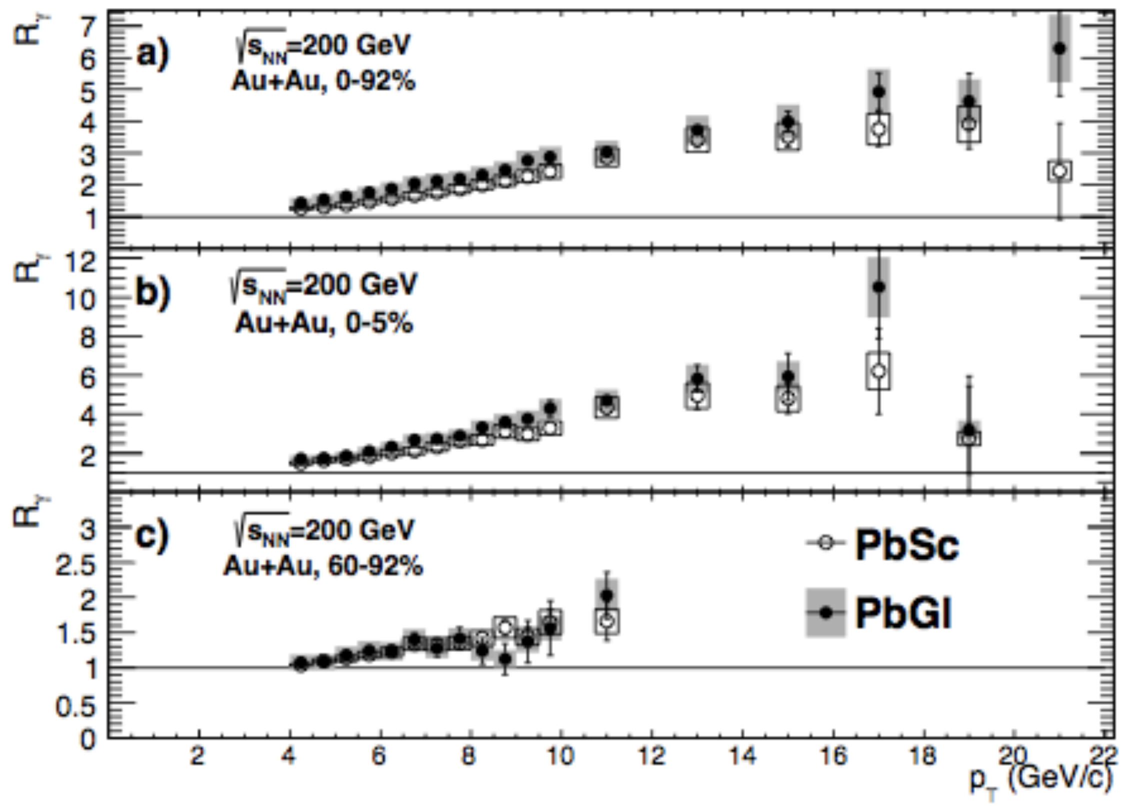
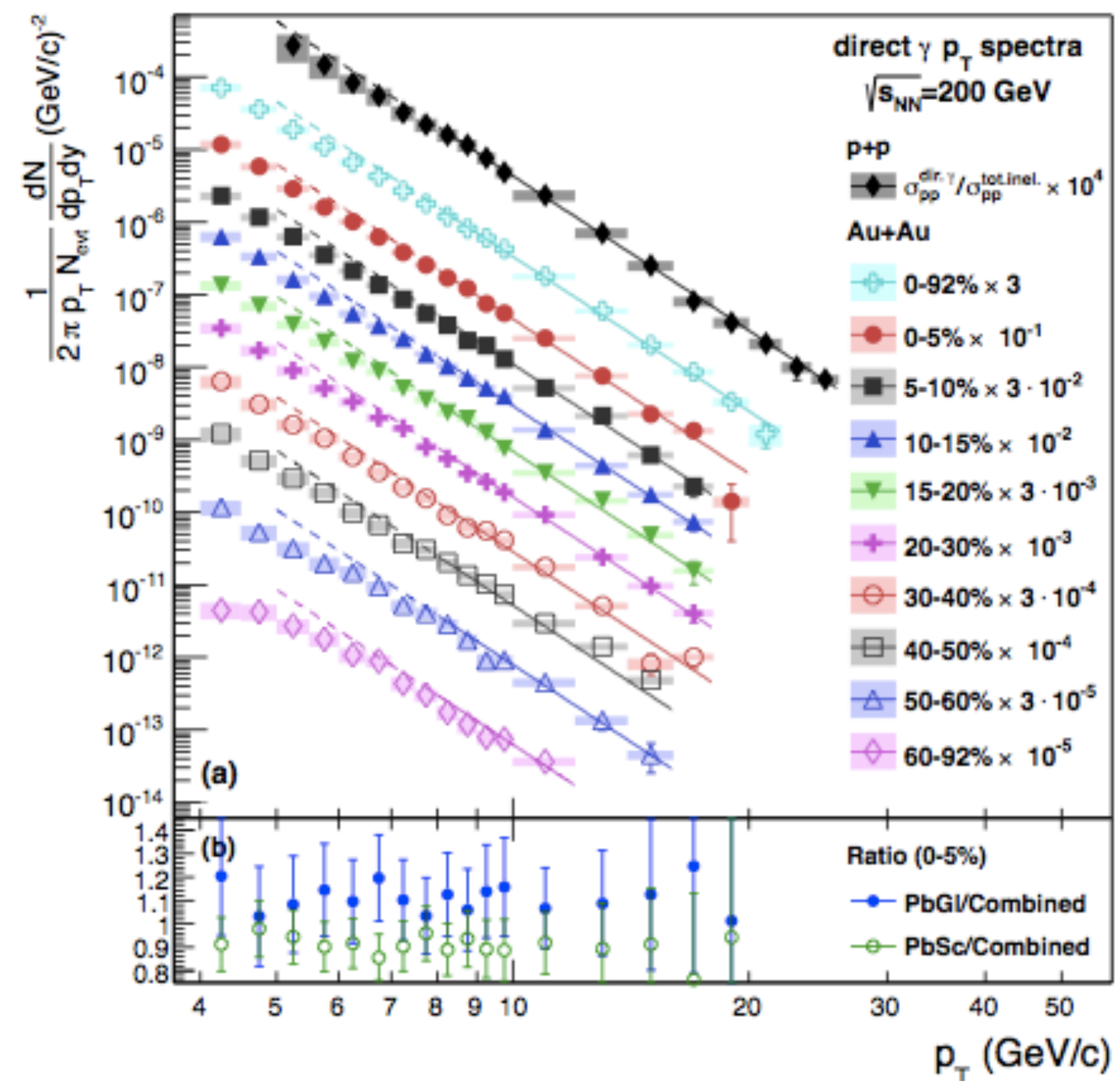


FIG. 1: Ratio R_γ for different centrality selections, for the PbGl and the PbSc analysis. The error bars indicate point-to-point uncertainties, the boxes around the points indicate p_T correlated uncertainties.

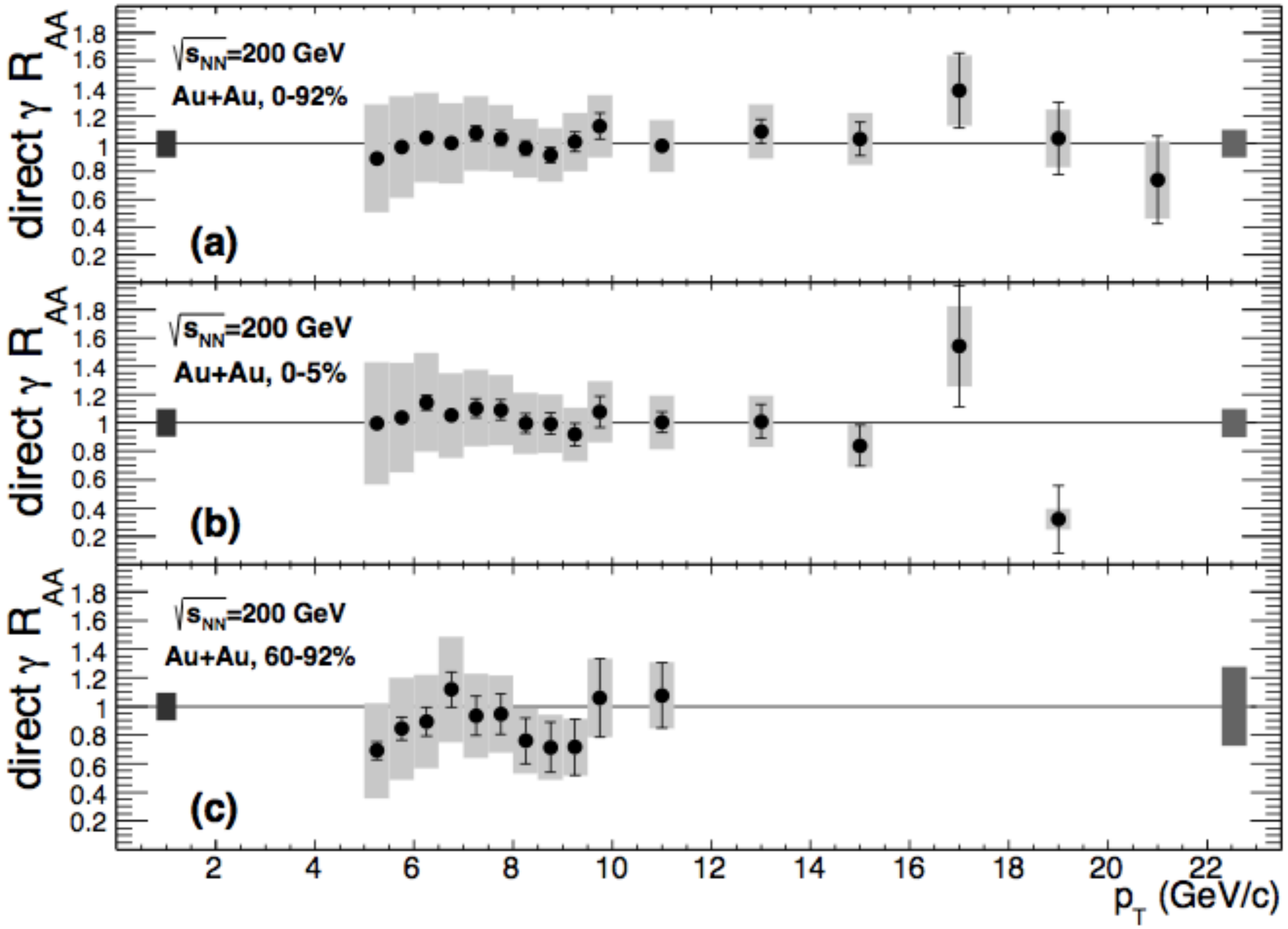


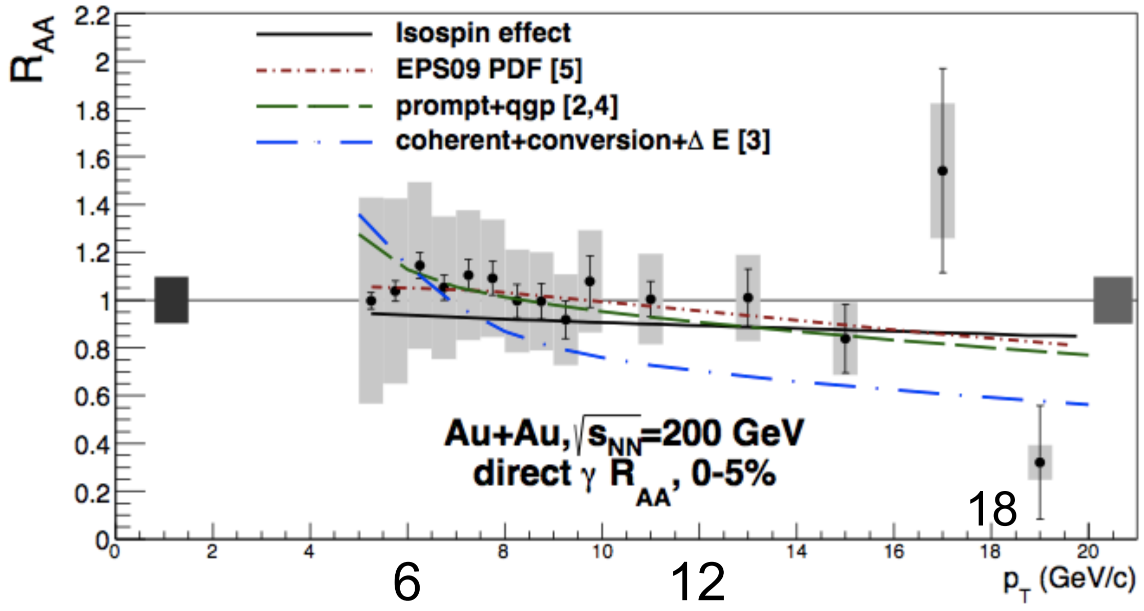
$$R_\gamma = \frac{\gamma_{inclusive}^{data}/\pi^0_{data}}{\gamma_{decay}^{MC}/\pi^0_{MC}}$$

$$\gamma_{direct} = (1 - \frac{1}{R_\gamma})\gamma_{inclusive}$$

In AuAu,derived on a statistical basis from inclusive photons and decay fraction

Direct photon R_{AA}





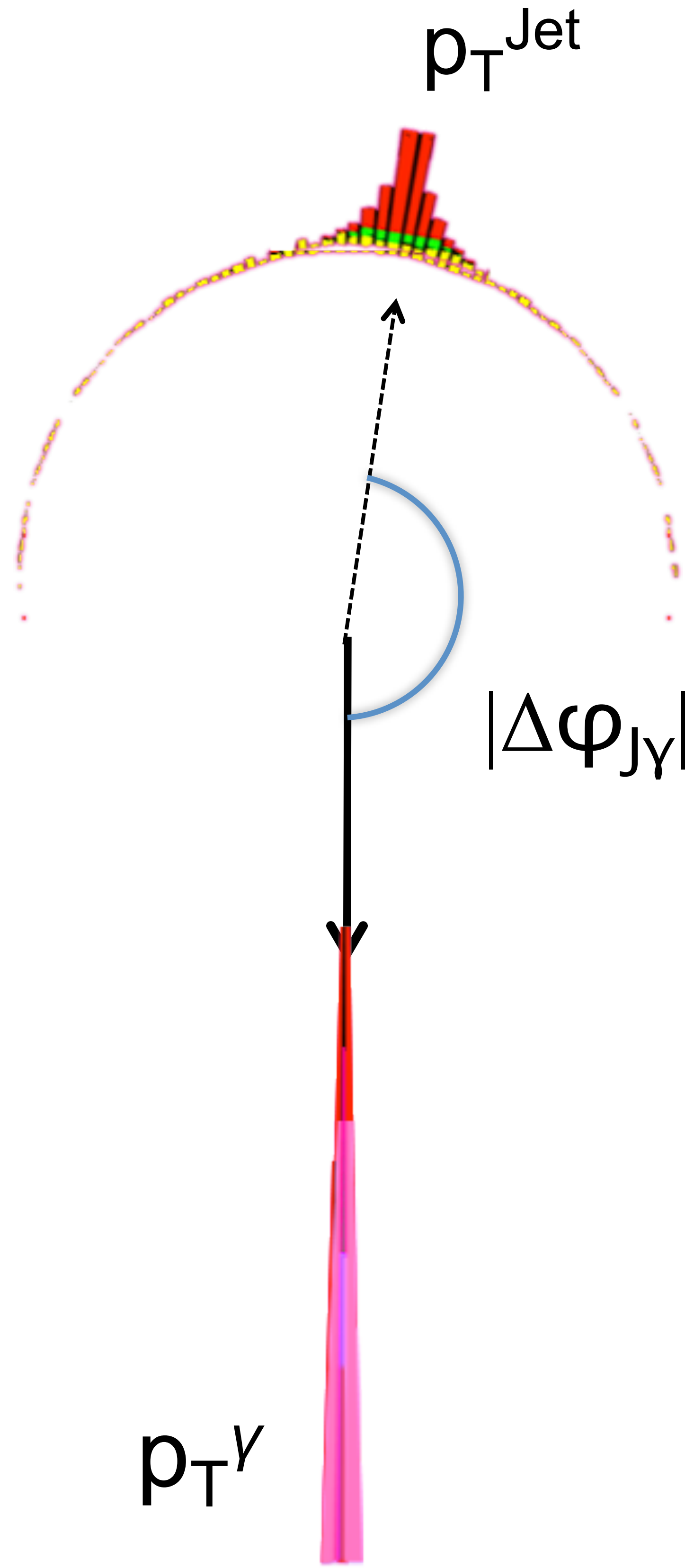
High p_T data compatible with isospin and nPDF effects (~10%)

No evidence of strong nuclear effects is seen

Z^0-jet correlations

Photon (Z^0)-Jet 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)



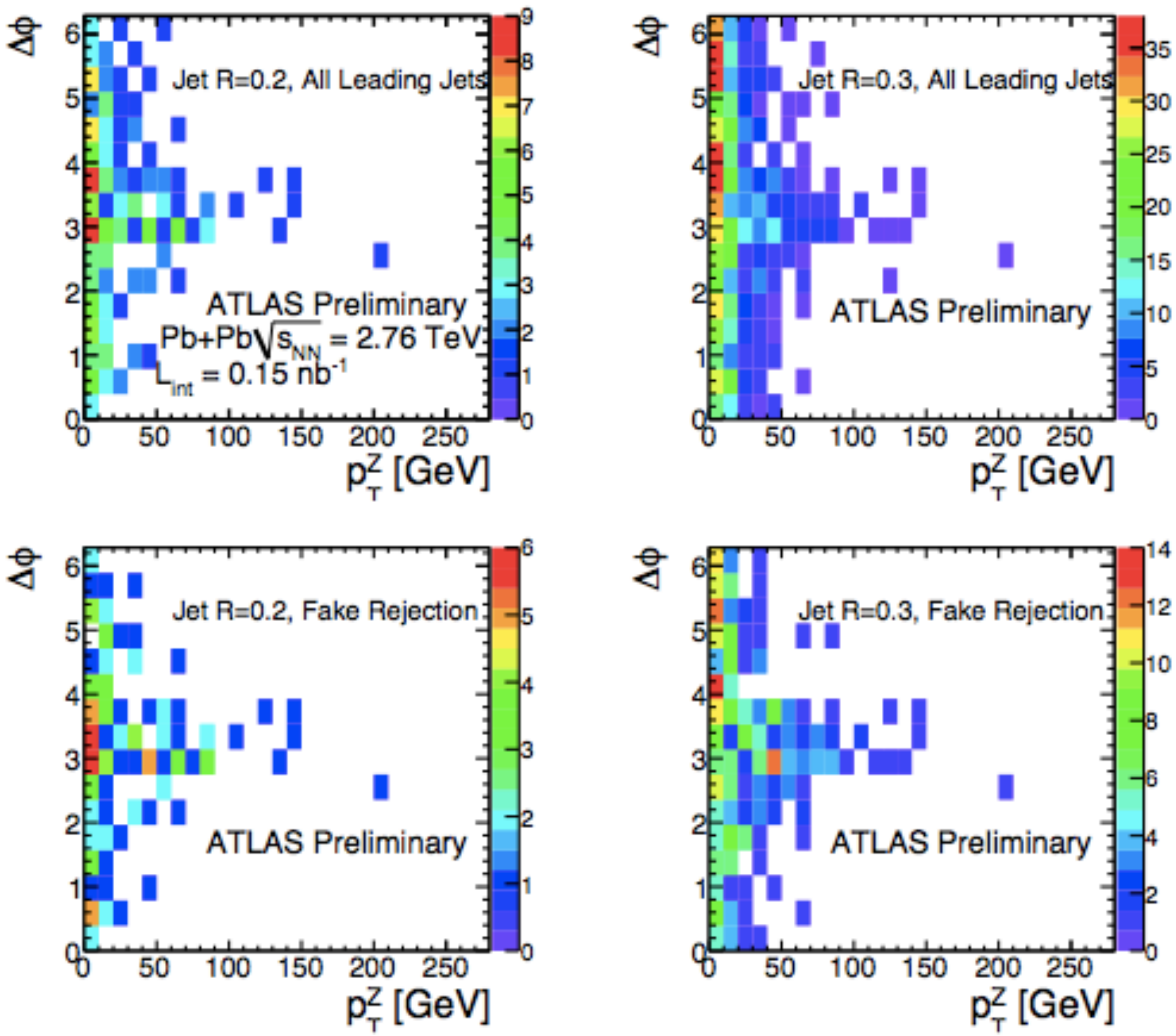
ATLAS Z^0-jet correlations

Peter Steinberg, QM'12

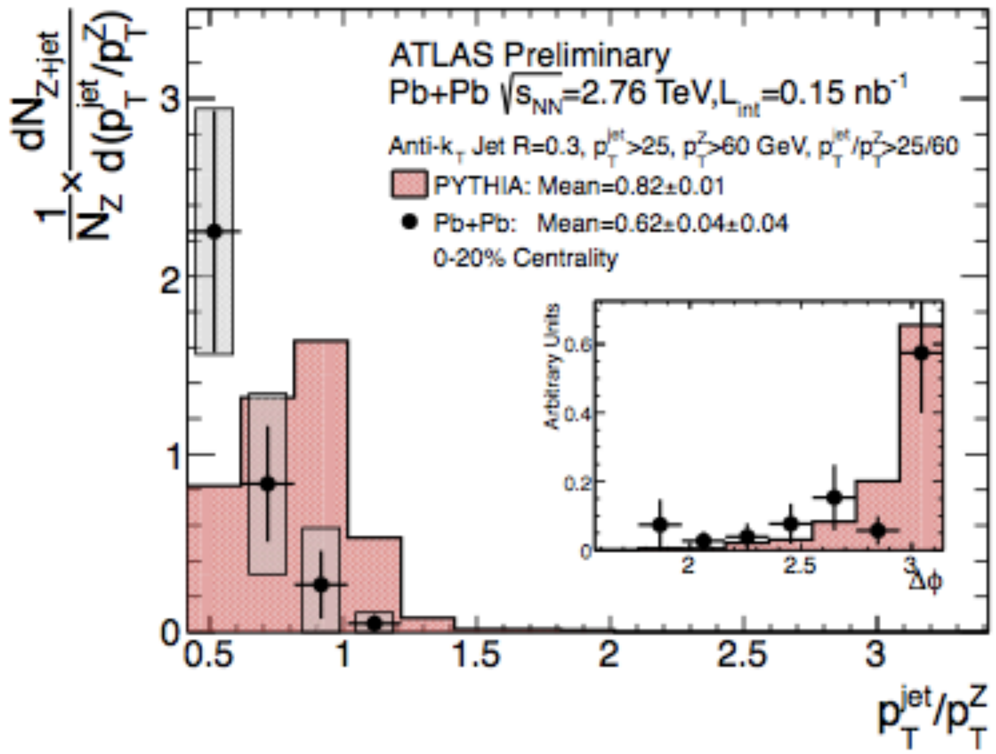
Jets reconstructed using standard iterative background subtraction

Above 50-60 GeV jet and Z are emitted back to back

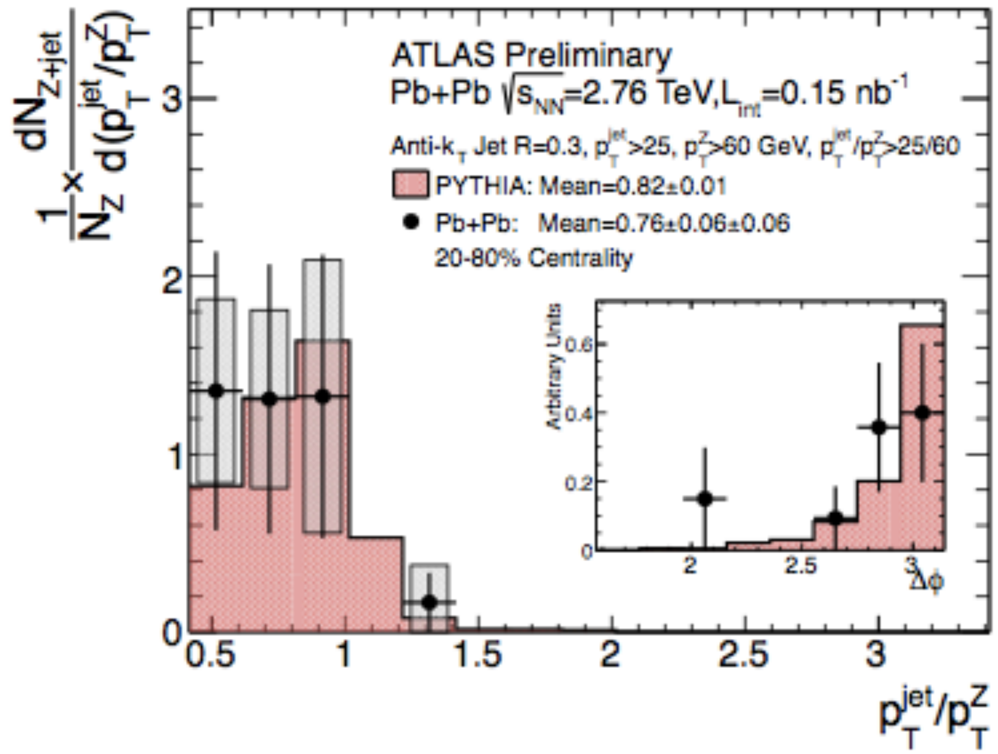
Fake rejection (based on track jet or EM cluster within jet), removes uncorrelated jets (esp. in R=0.3)



ATLAS Z^0-jet correlations



0-20% central

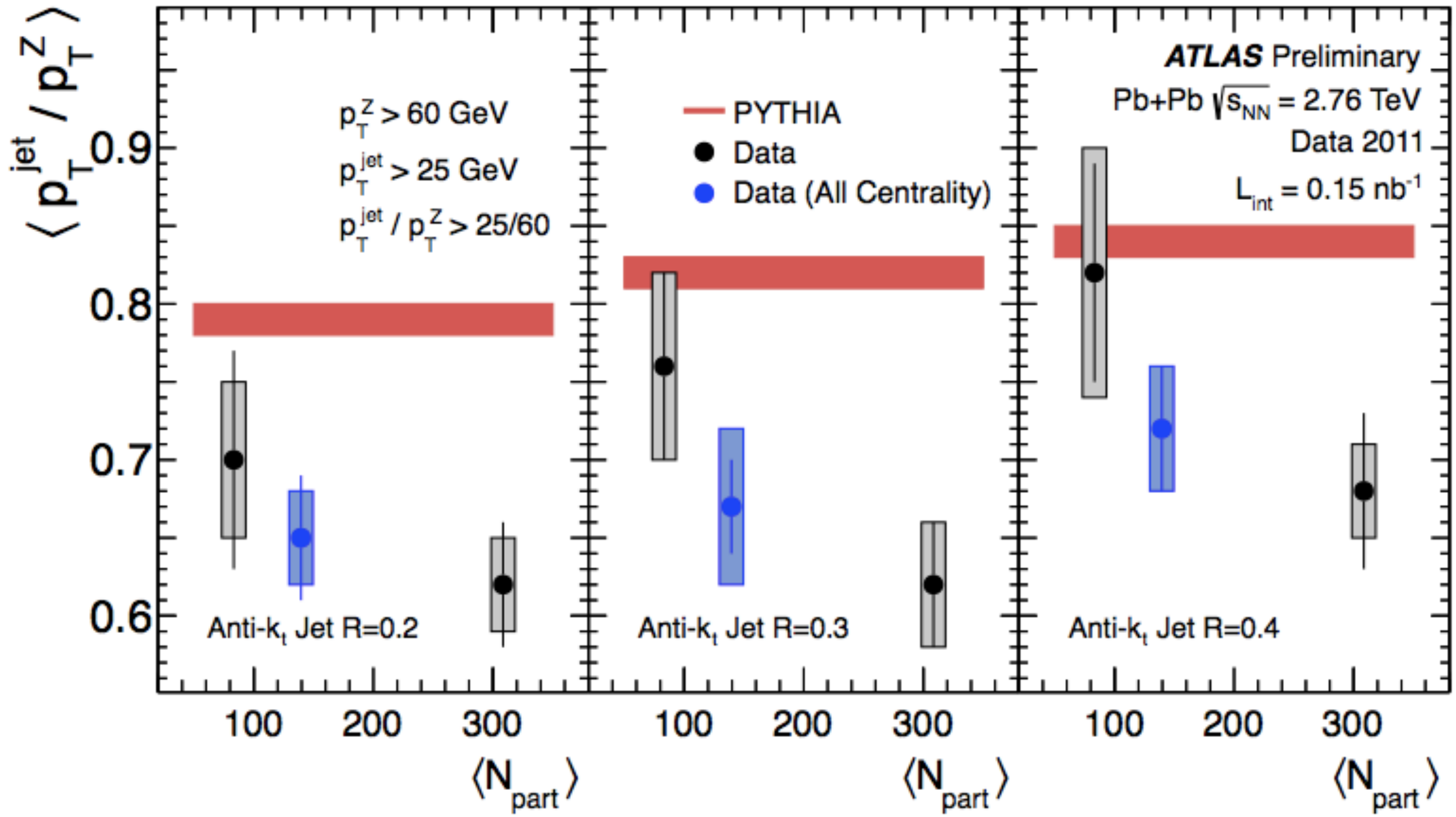


20-80% central

Clear modification of Z^0-jet momentum balance, in particular for central events

Z0-jet momentum balance vs centrality

n.b. three plots contain only two independent data points, total

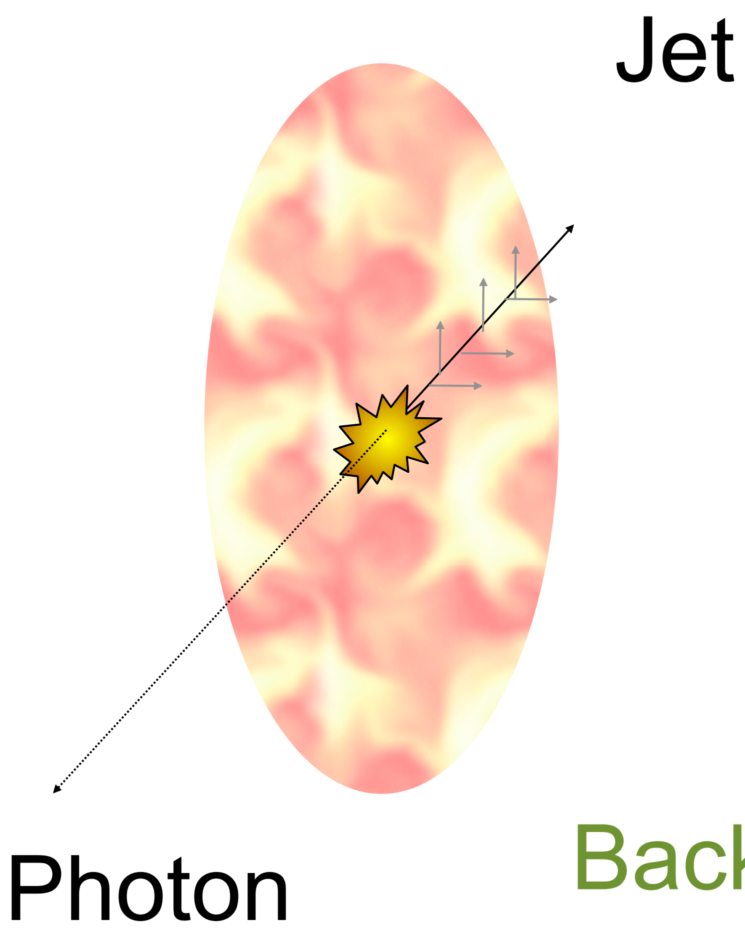


Clear modification of Z^0-jet momentum balance, in particular for central events

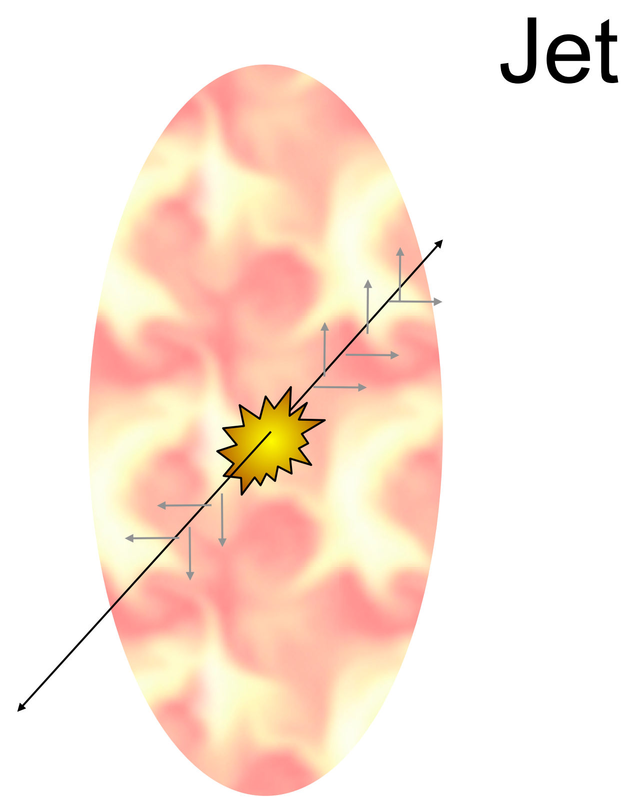
Isolated photon - jet correlations

Background Sources for Photon-Jet Analysis

Signal photon-jet



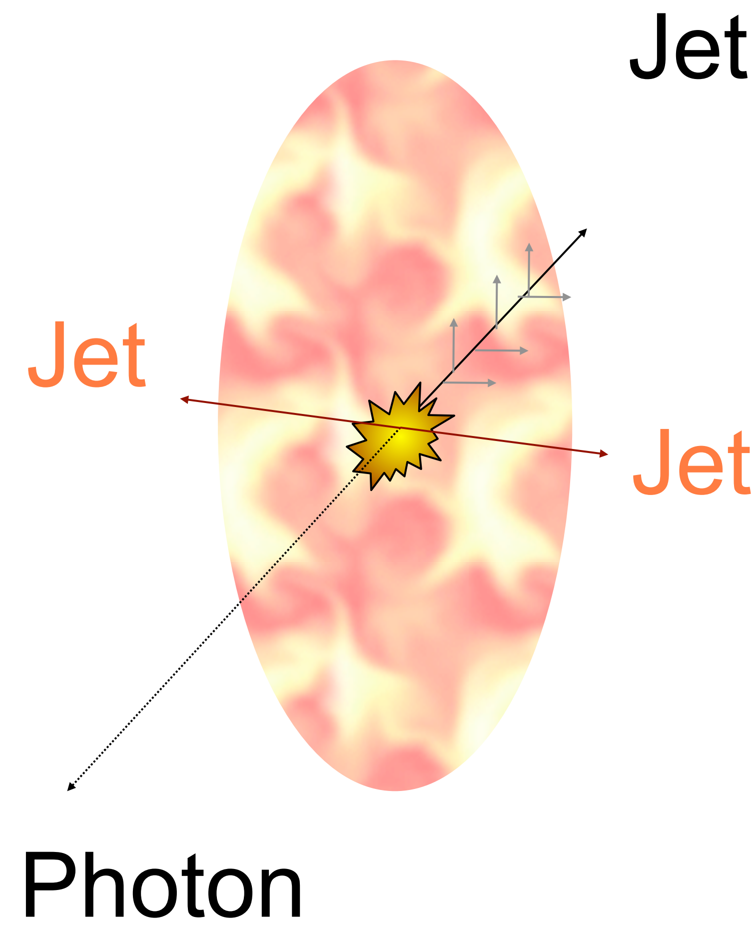
Background from dijet



Background photon

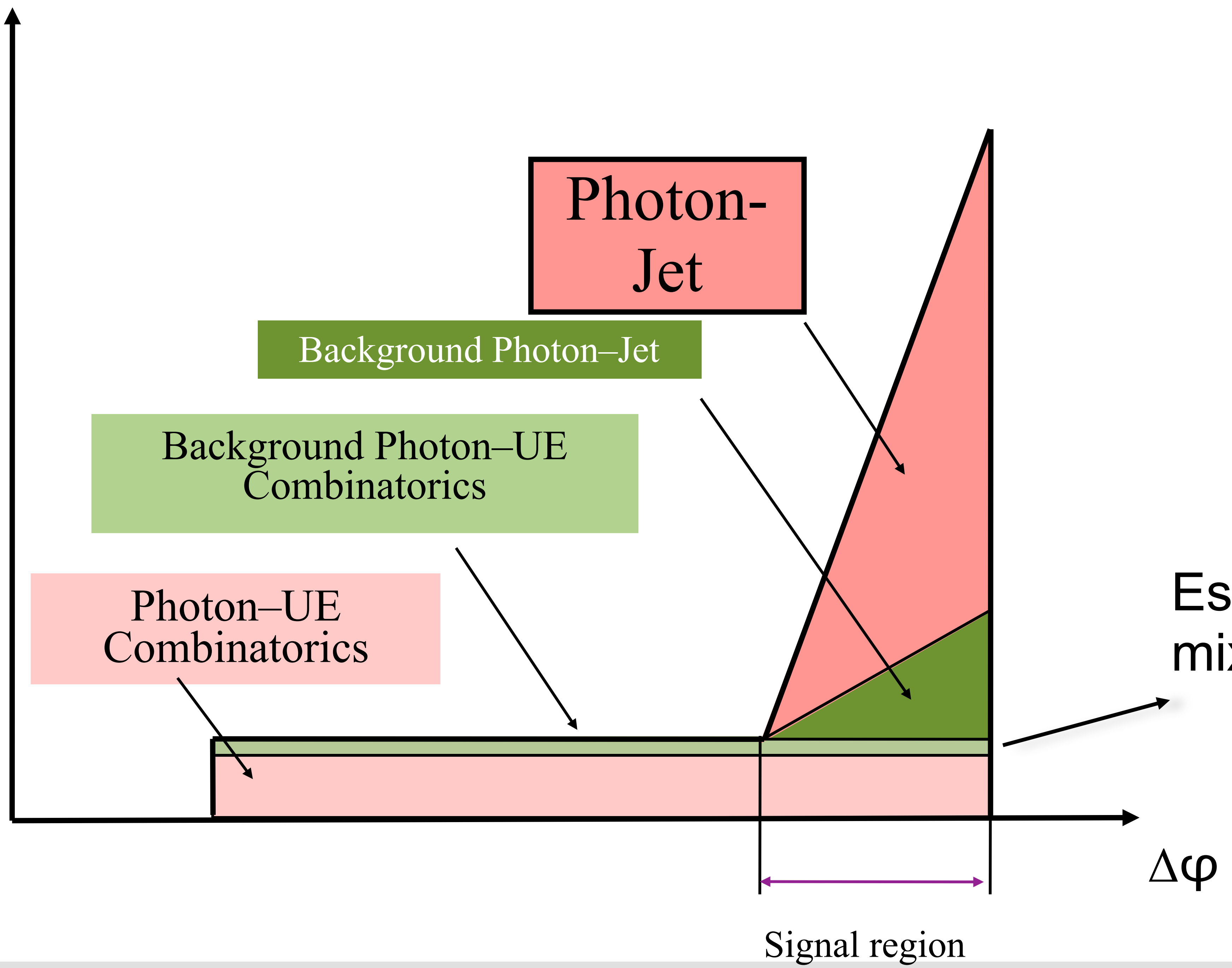
Remove data-driven
using shower shape

Contribution from uncorrelated multiple interaction/fake



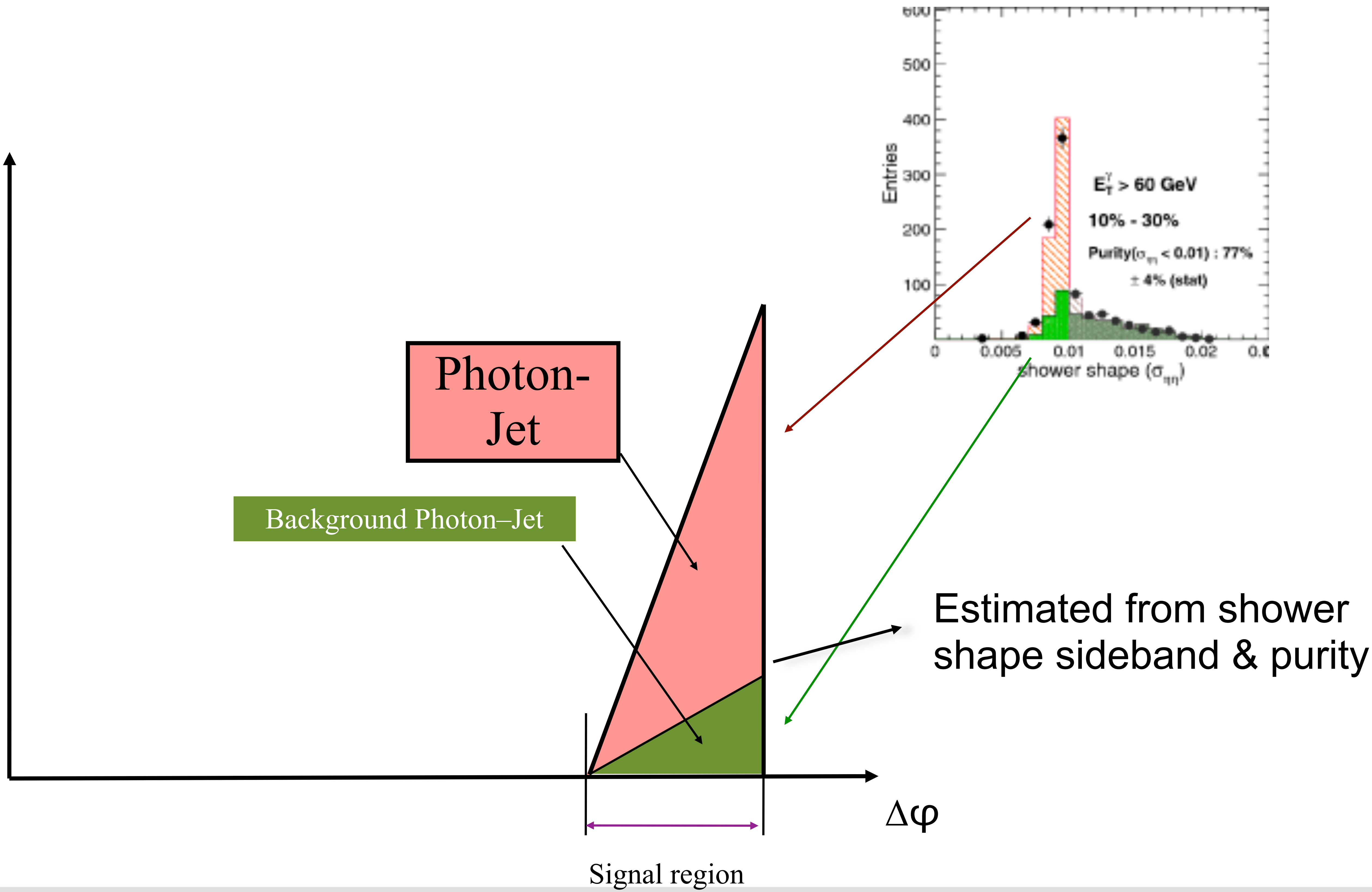
Remove by data-driven template
from event mixing

Background Subtraction, Part I

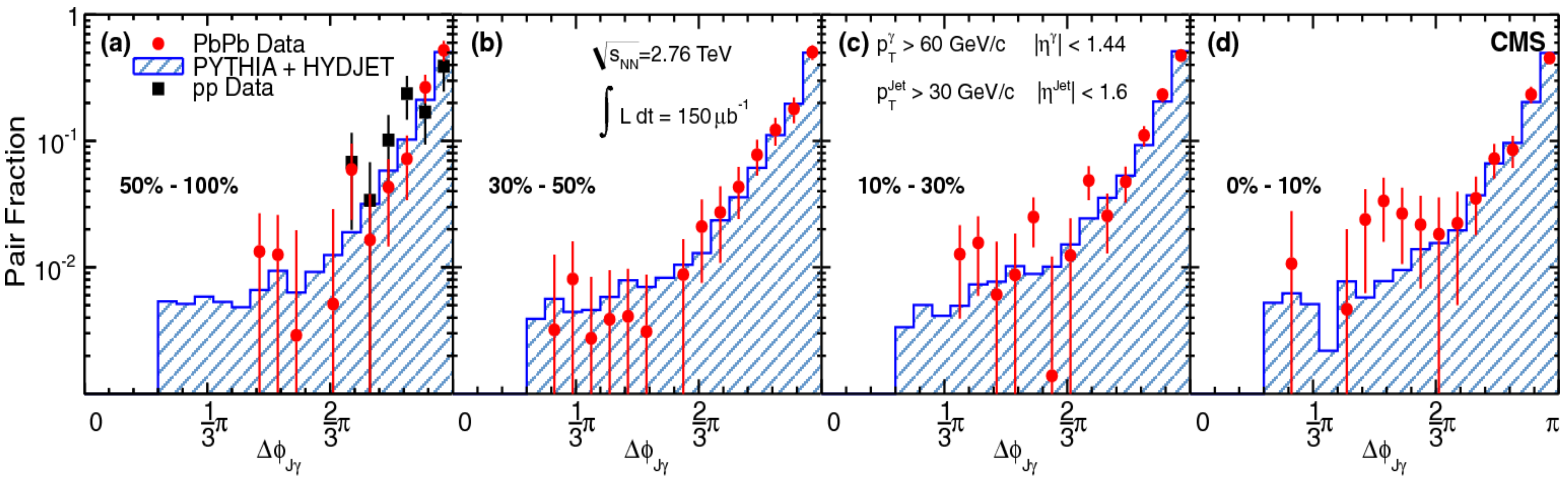


Estimated from event mixing using min-bias data

Background Subtraction, Part II

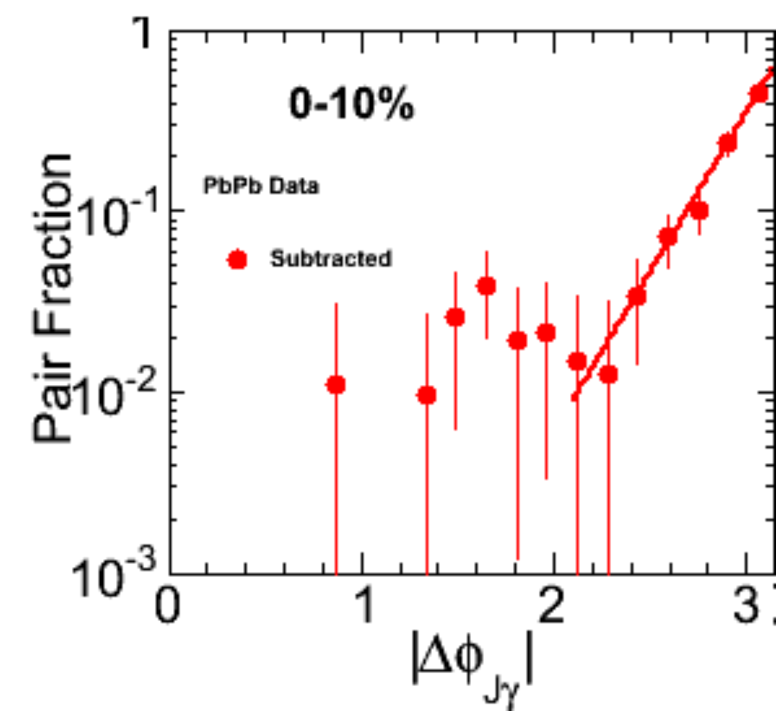


CMS photon-jet angular correlation

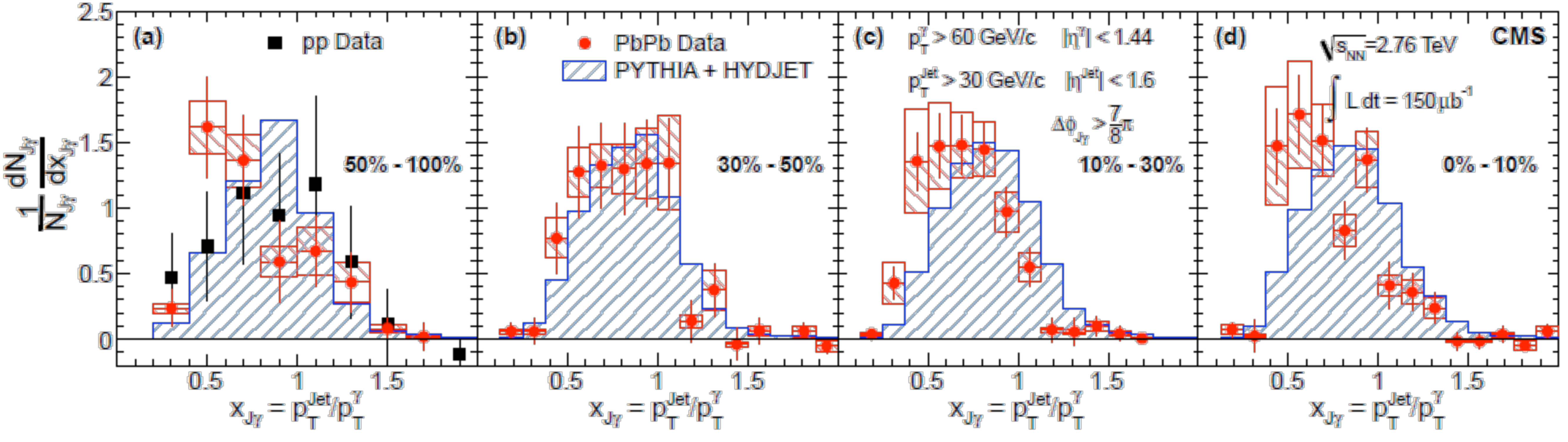


- Distribution is consistent with pp & PYTHIA tune Z2 + Hydjet
- To quantify the centrality dependence, peak region is fit with an empirical formula

$$\frac{1}{N^{\gamma\text{-jet}}}\frac{dN^{\gamma\text{-jet}}}{d\Delta\phi_{J\gamma}} = \frac{e^{(\Delta\phi-\pi)/\sigma}}{(1-e^{-\pi/\sigma})\,\sigma}$$

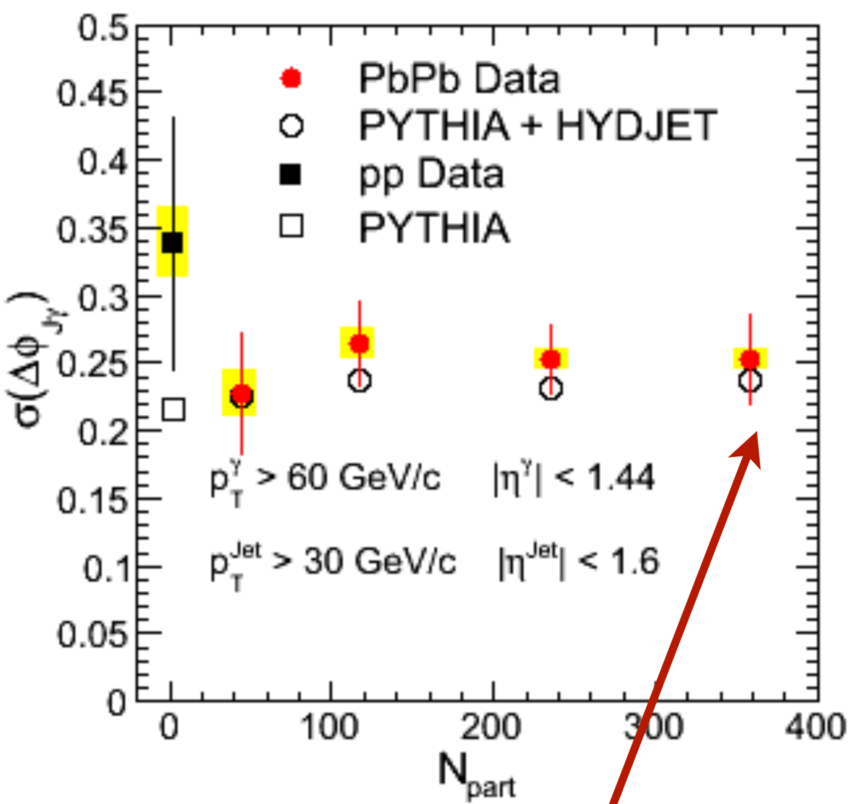


CMS Photon-Jet Momentum Balance

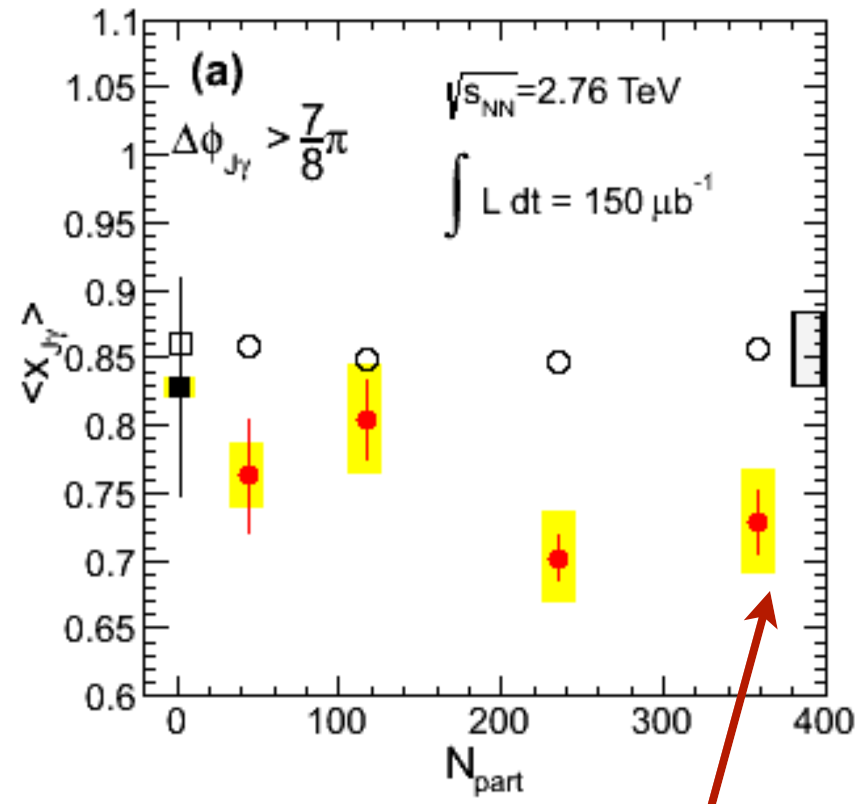


- Momentum ratio shifts/decreases with centrality
- Unitary normalized distribution, points anticorrelated
- Red/blue boxes try to indicate possible, anticorrelated systematic variation

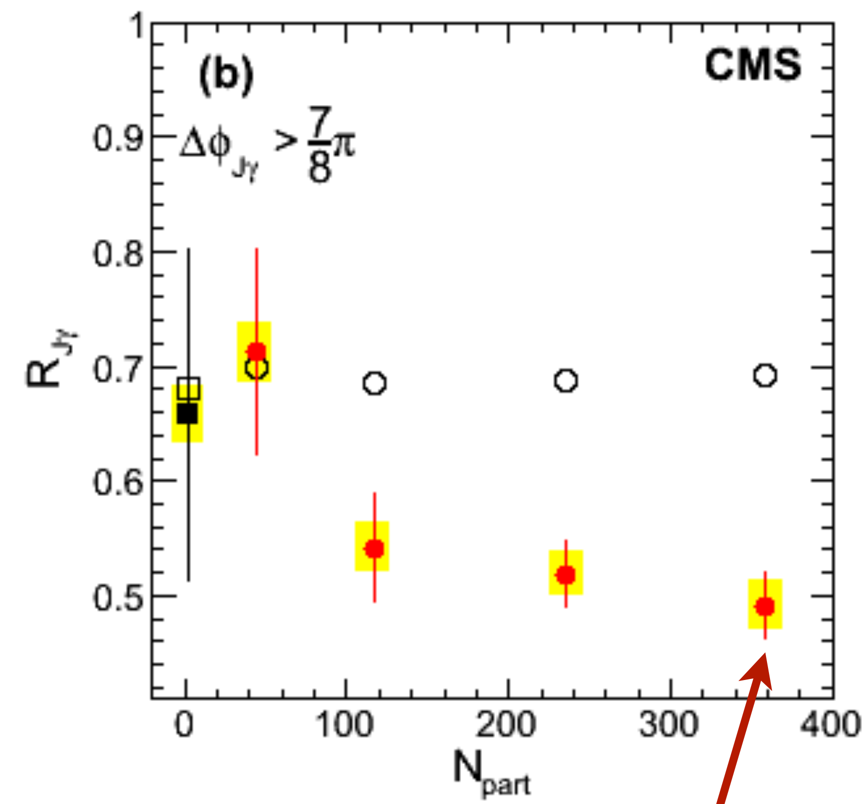
CMS centrality dependence of photon-jet correlations



No modification of photon-jet angular correlation

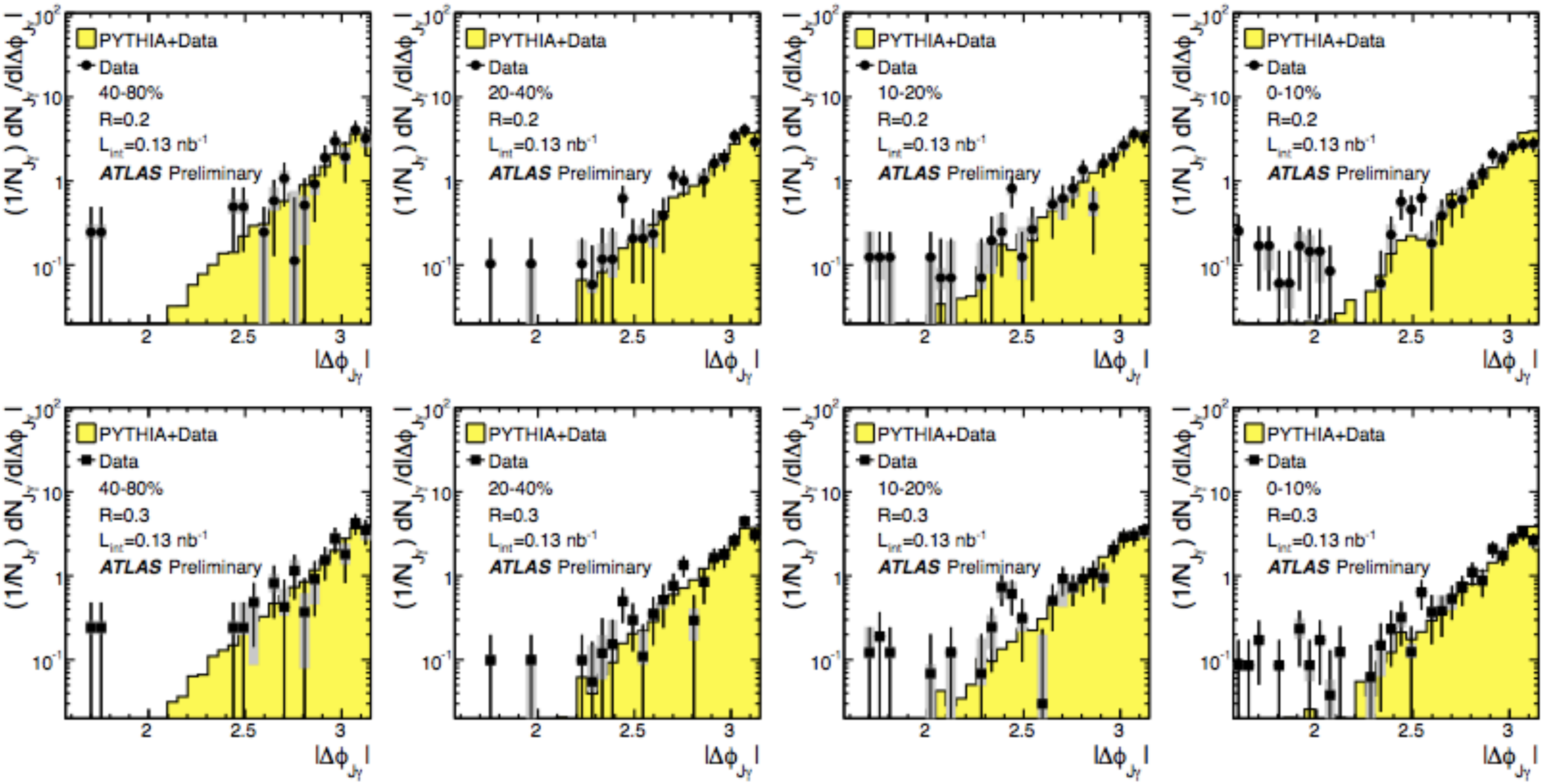


photon-jet momentum balance shifts by 14% of photon momentum



About 20% of photons lose jet partner

ATLAS photon-jet angular correlation

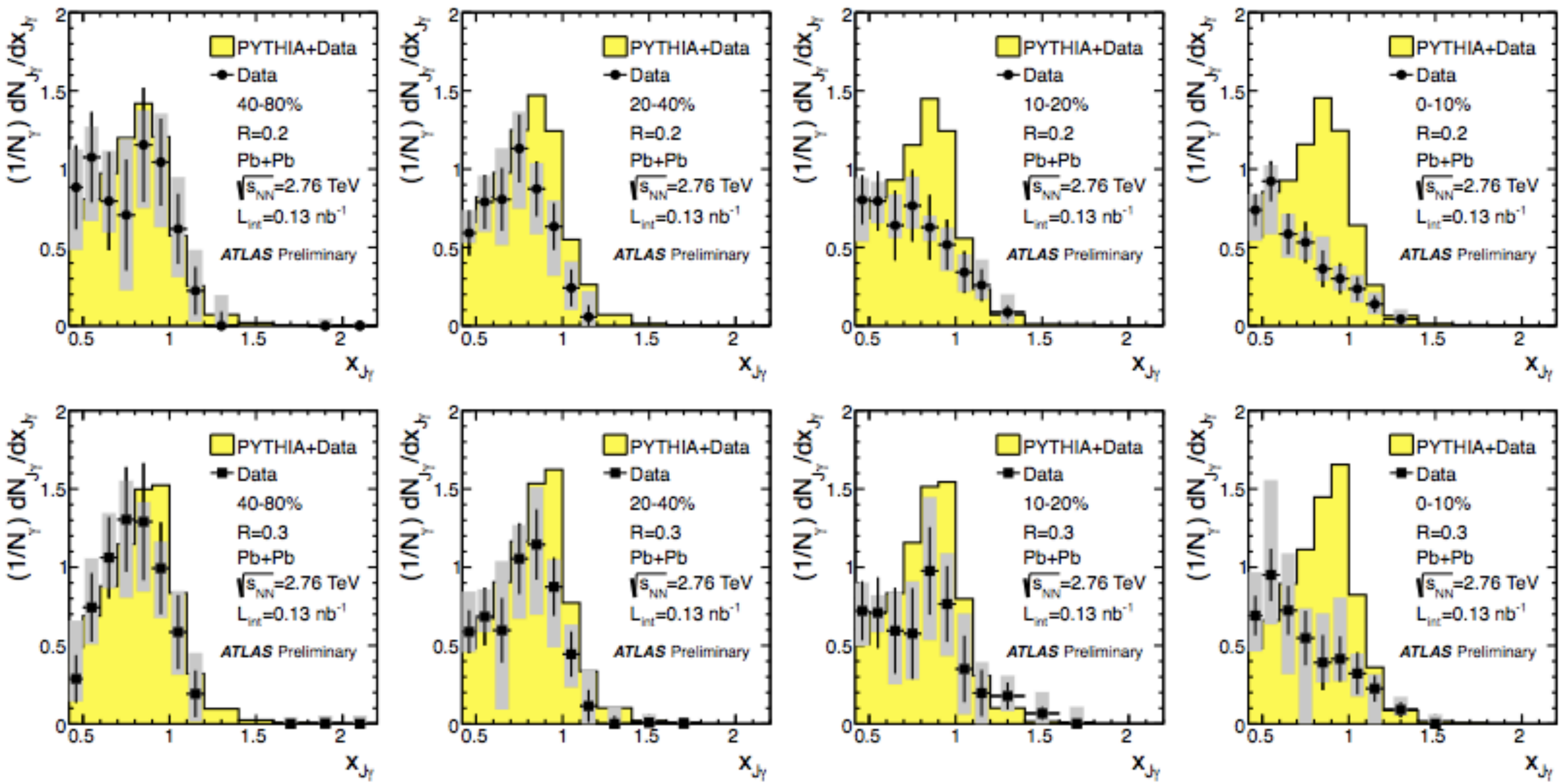


R=0.2

R=0.3

$$60 < p_{\mathrm{T}}^{\gamma} < 90\ \mathrm{GeV},\ |\eta_{\gamma}| < 1.3,\ \ p_{\mathrm{T}}^{\mathrm{jet}} > 25\ \mathrm{GeV},\ |\eta^{\mathrm{jet}}| < 2.1 \text{ and } |\Delta\phi_{J\gamma}| > 7\pi/8.$$

ATLAS photon-jet momentum balance

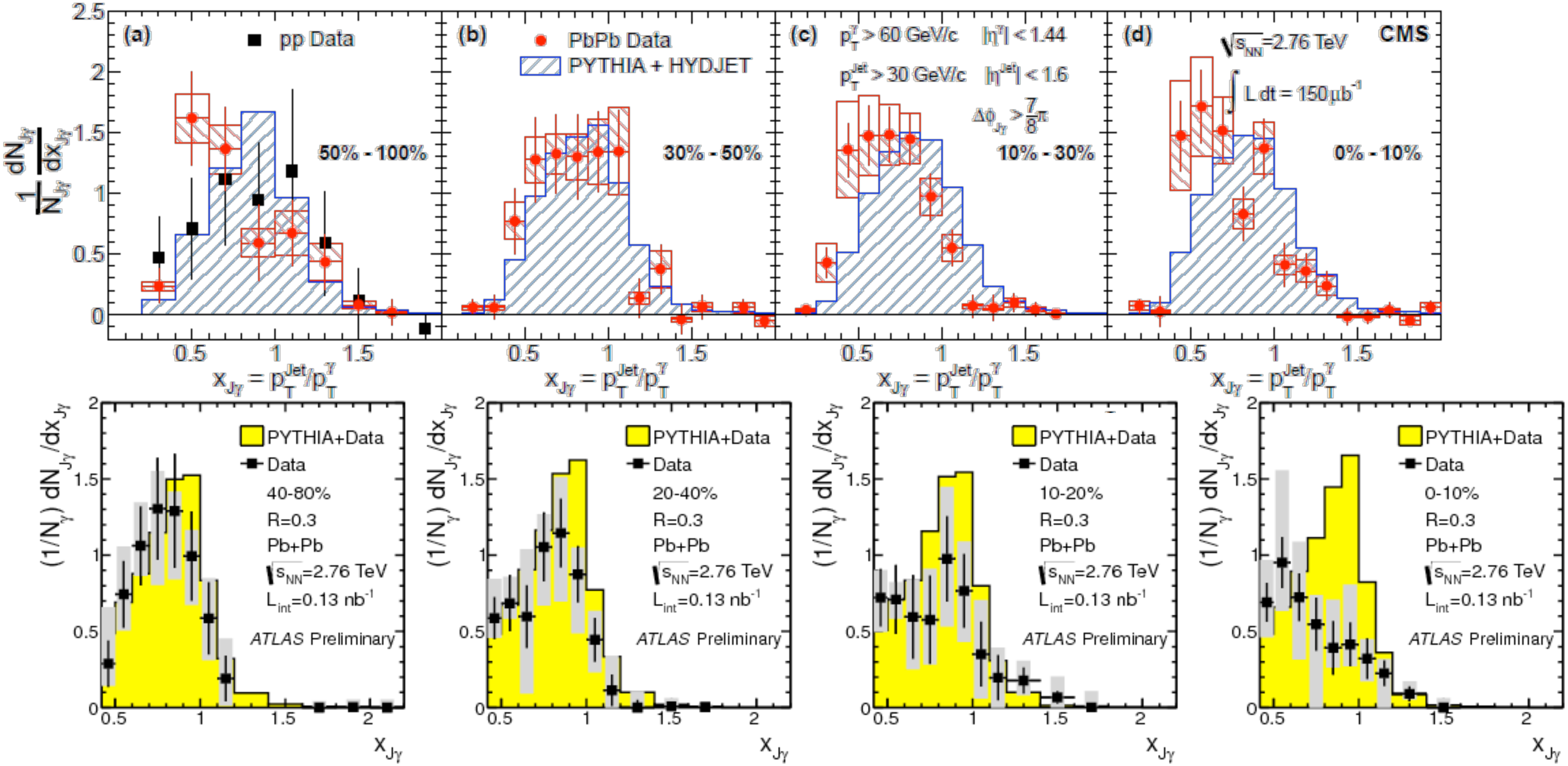


R=0.2

R=0.3

$60 < p_T^\gamma < 90$ GeV, $|\eta_\gamma| < 1.3$, $p_T^{jet} > 25$ GeV, $|\eta^{jet}| < 2.1$ and $|\Delta\phi_{J\gamma}| > 7\pi/8$.

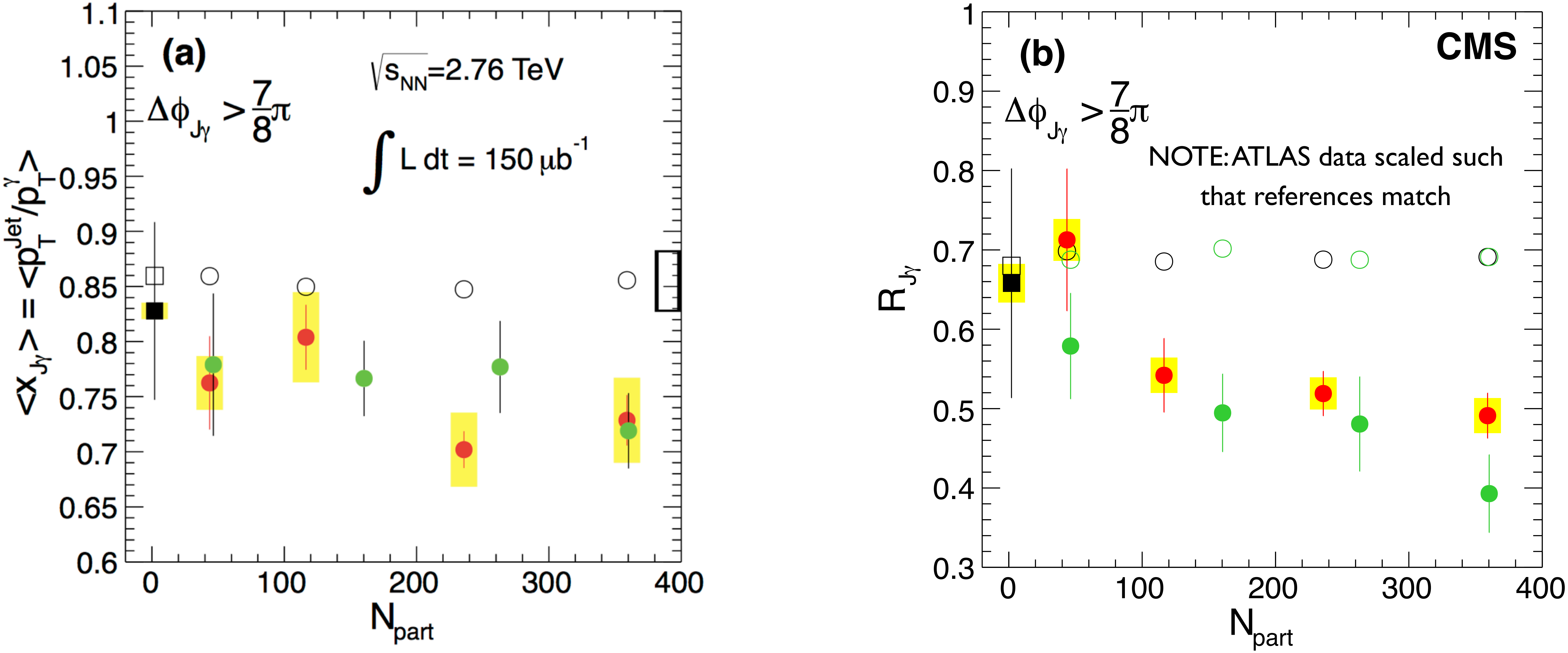
ATLAS/CMS comparison



Qualitative agreement between experiments

(note different normalization vs photon (ATLAS) and photon-jet (CMS))

Photon-Jet Momentum Balance



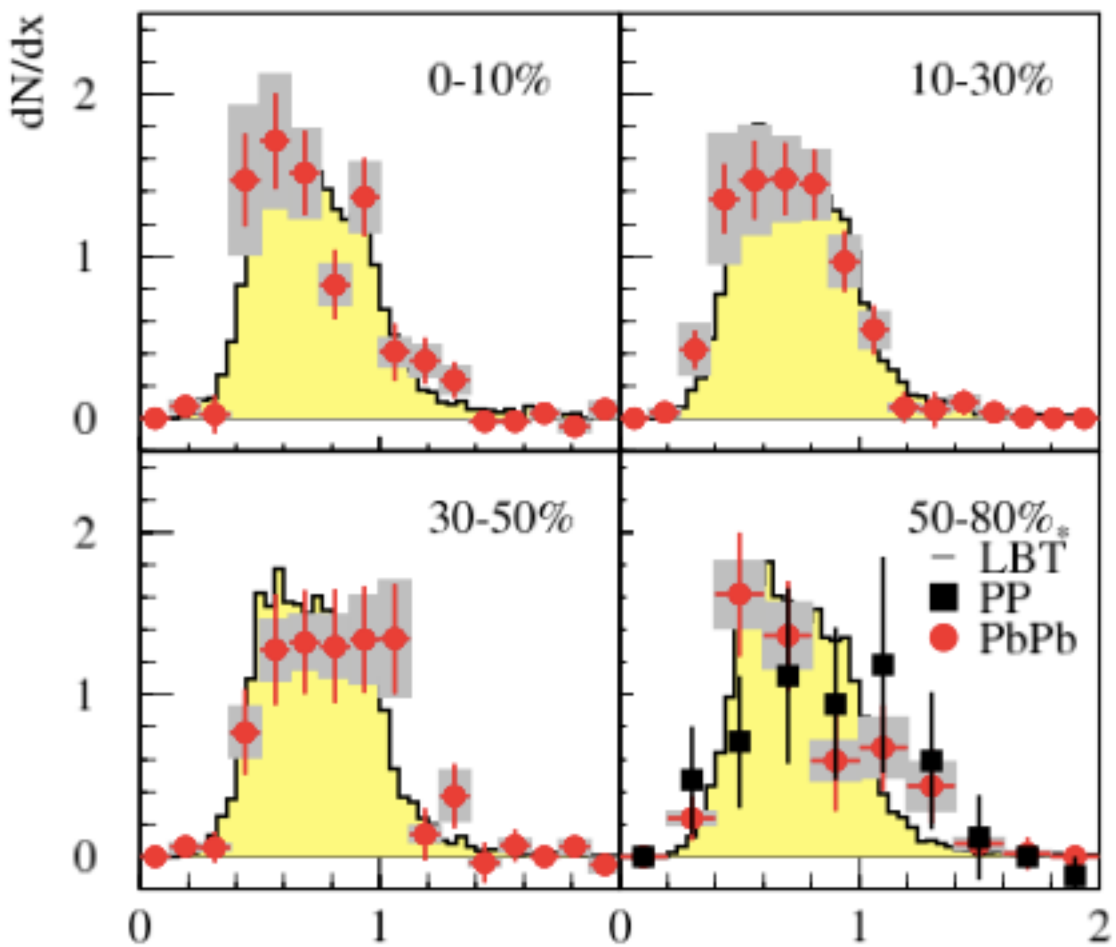
Reasonable agreement between ATLAS and CMS

NOTE: CMS correlates photon w/ associated jet, ATLAS w/ leading jet

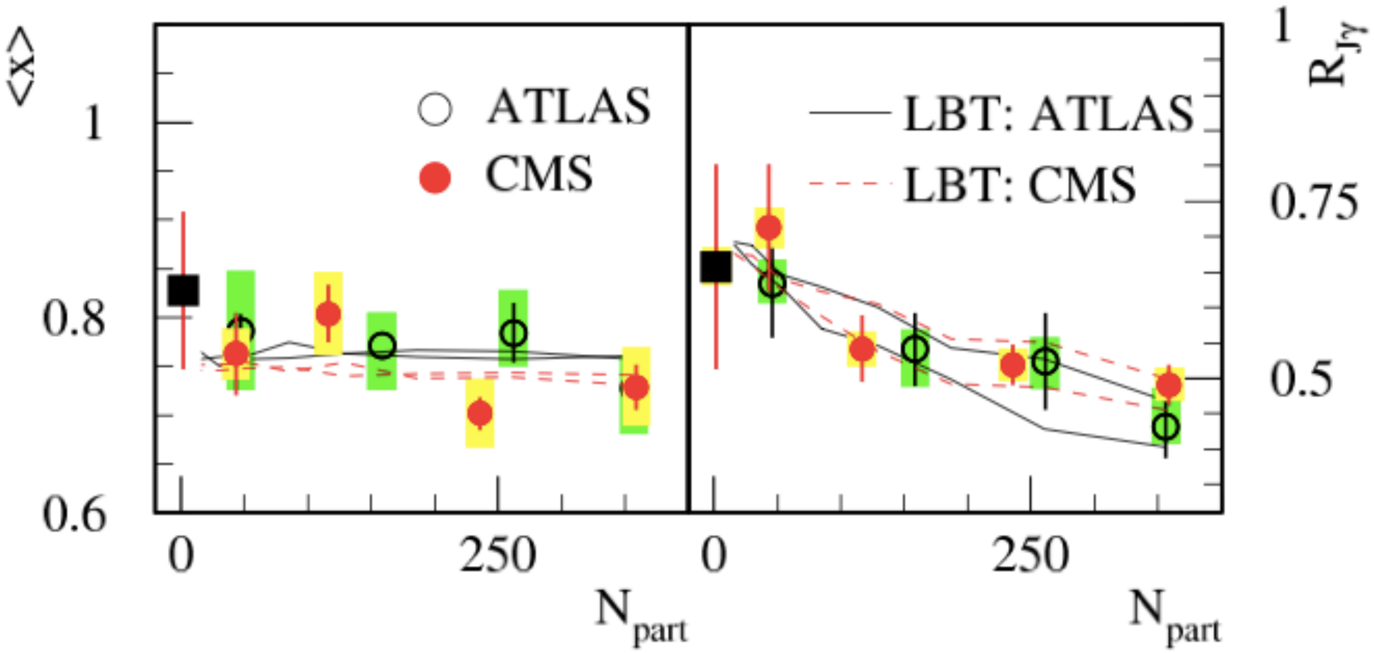
also: ATLAS jet cut 25GeV vs 30 GeV for CMS

ATLAS/CMS vs theory

Wang, Zhu (2013)



Good news: x_{jg} well described by calculation



Not so good news: CMS/ATLAS data require slightly different parameters

In LBT calculations, α_s=0.15–0.23 are used with the CMS cuts (dashed) while α_s=0.2–0.27 for the ATLAS cuts (solid).

photon - hadron correlations

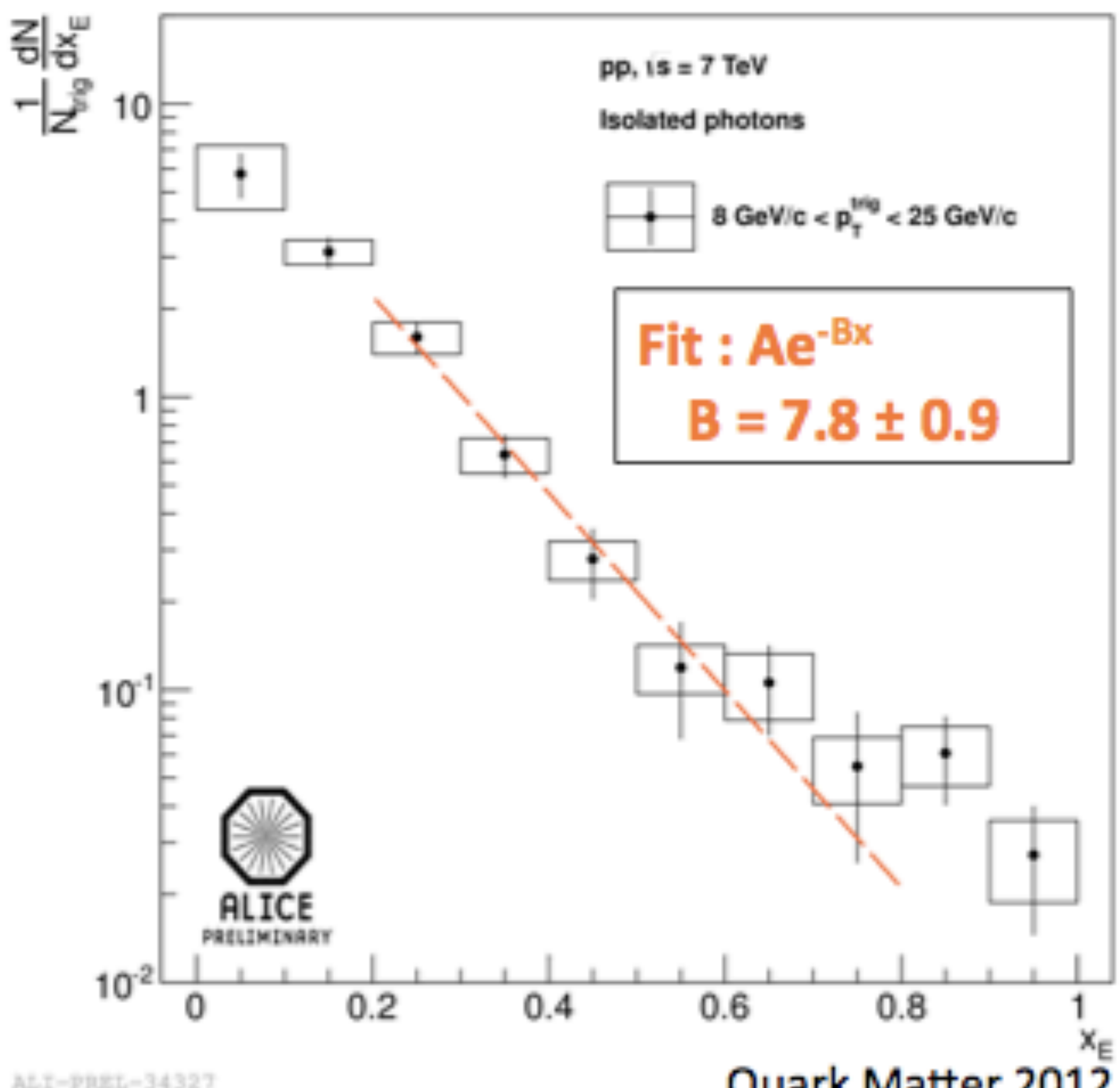
Photon-hadron correlations

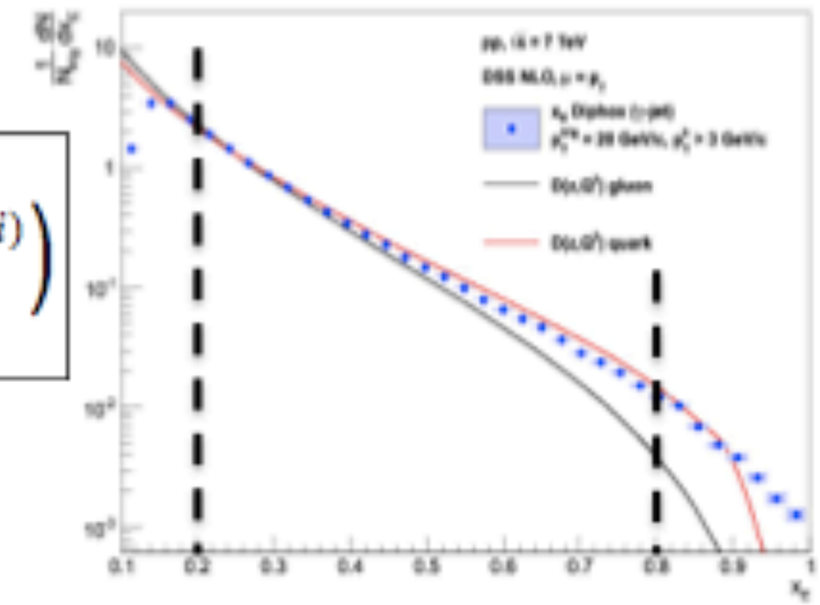
- Jet requirement induces significant kinematic constraints/limitations
  - jet p_T < 25 GeV/c very difficult for central PbPb at LHC
  - large acceptance needed for sufficient statistics
- Alternative is to look at correlations of direct/isolated photons with away-side hadrons
- Extensively used at RHIC; under development in ALICE
-

ALICE photon-hadron correlations

- **Subtract contamination** in p_T bins ($\Delta p_T = 1$ GeV/c)

$$x_E^{\gamma\, iso} = \sum_{i=8}^{25\,GeV/c} \left(\frac{1}{p_i} x_E^{clusters\ iso(i)} - \frac{(1-p_i)}{p_i} x_E^{\pi 0\ iso(i)} \right) - \sum_{i=8}^{25\,GeV/c} \left(x_E^{UE(i)} \right)$$





Exponential shape [0.2-0.8]

Baseline for the study of medium modified parton fragmentation in Pb-Pb

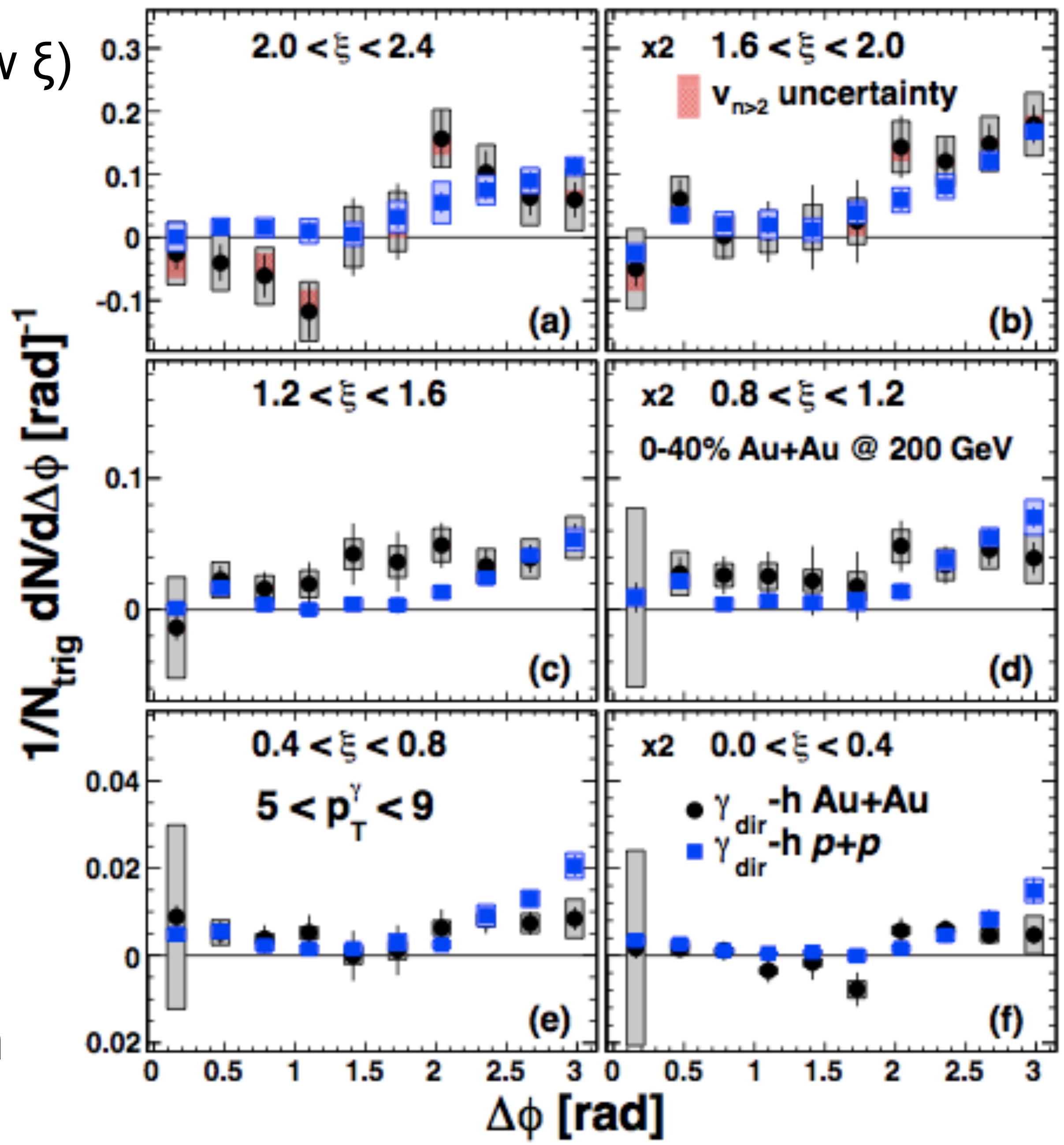
Quark Matter 2012 - Nicolas Arbor

13

PHENIX photon-hadron correlations

Soft fragments (low ξ)

$\xi = ln(1/z_T)$



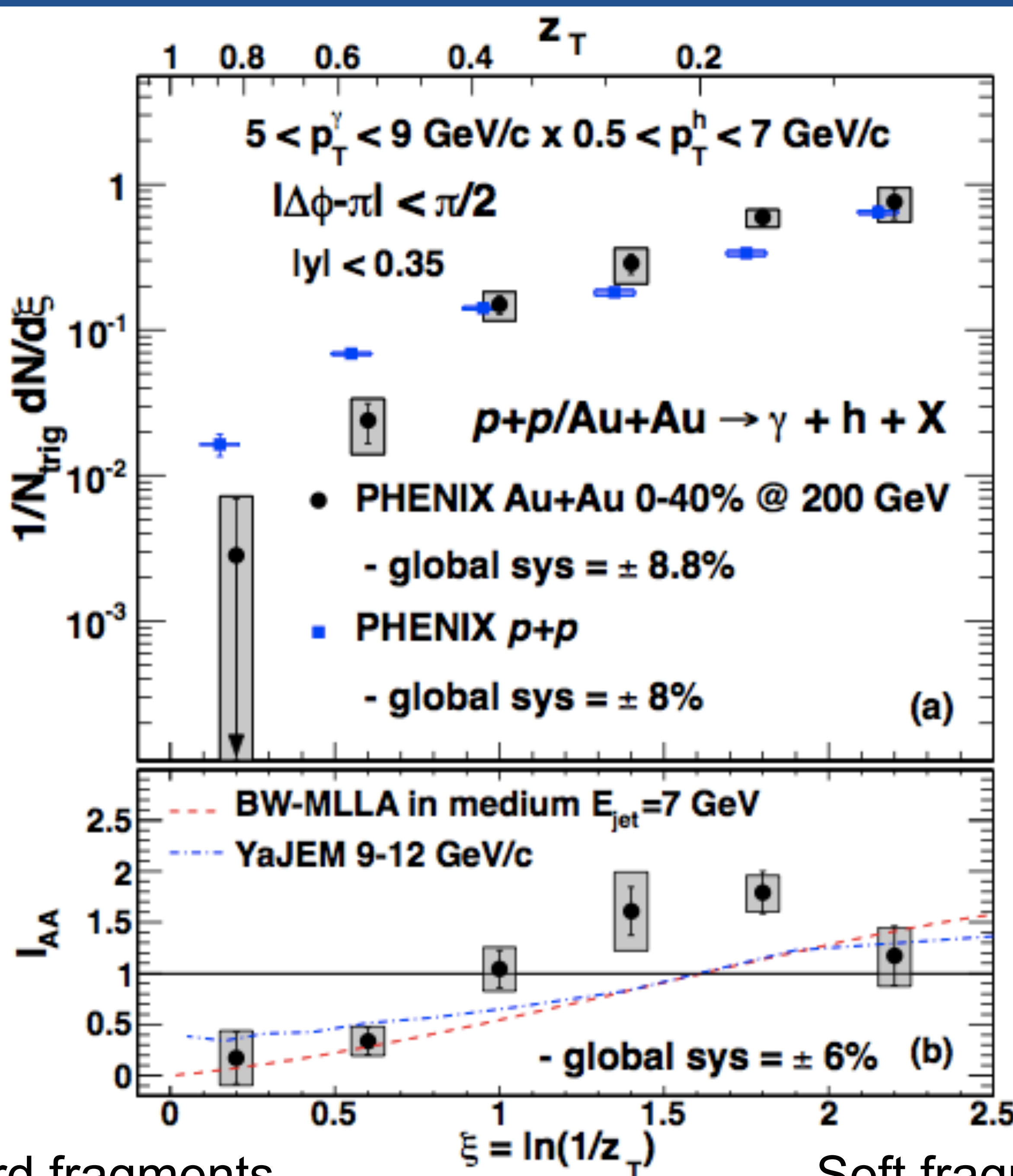
Hard fragments (low ξ)

$$Y_{\rm dir} = \frac{R_\gamma Y_{\rm inc} - Y_{\rm de}}{R_\gamma - 1}$$

Direct photons again derived statistically from inclusive photons

Direct photon-hadron azimuthal correlation

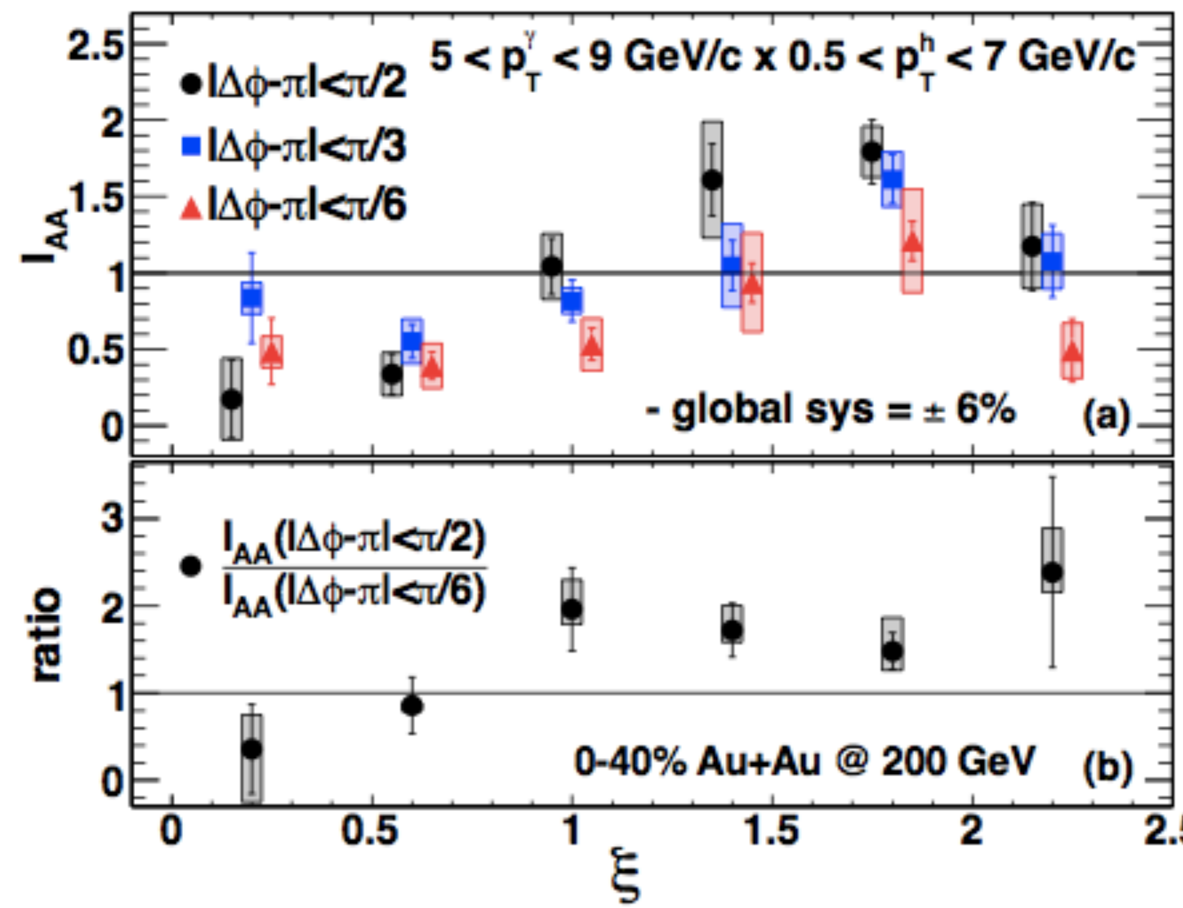
PHENIX photon-hadron correlations



Hard fragments

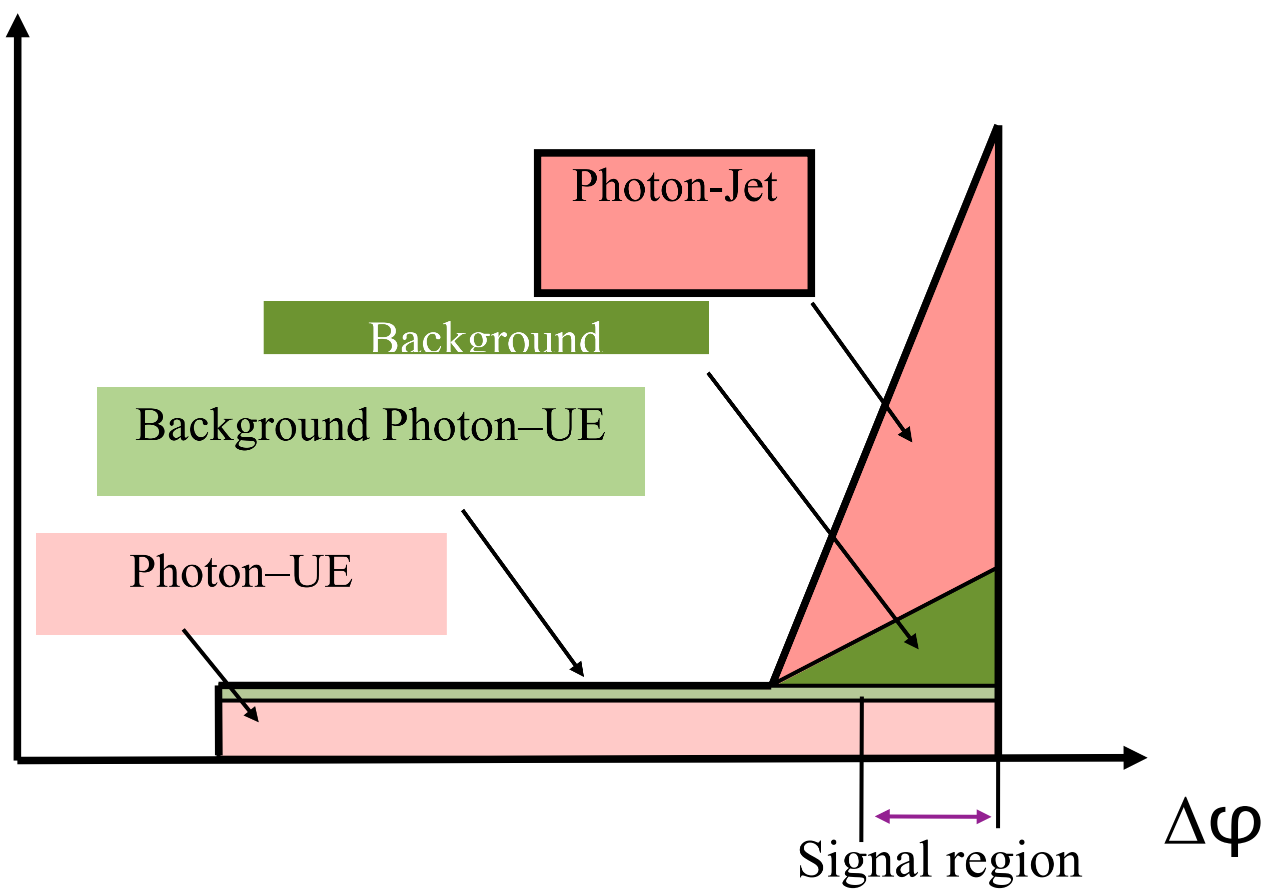
Soft fragments

Distinct softening of fragmentation function in AA vs pp



Soft fragments located at large Δφ to “jet axis”

Photon-hadron correlations



photon-hadron correlations != (photon-jet) hadron correlations

- w/o jet, composition of isolated photon sample is different
- w/o jet, subtraction of photon-UE correlations difficult
  - i.e. associated jet in/out of acceptance
  - multiple hard interactions
- reduced control over initial/final state radiation
  - parton kinematics less well constrained

Future

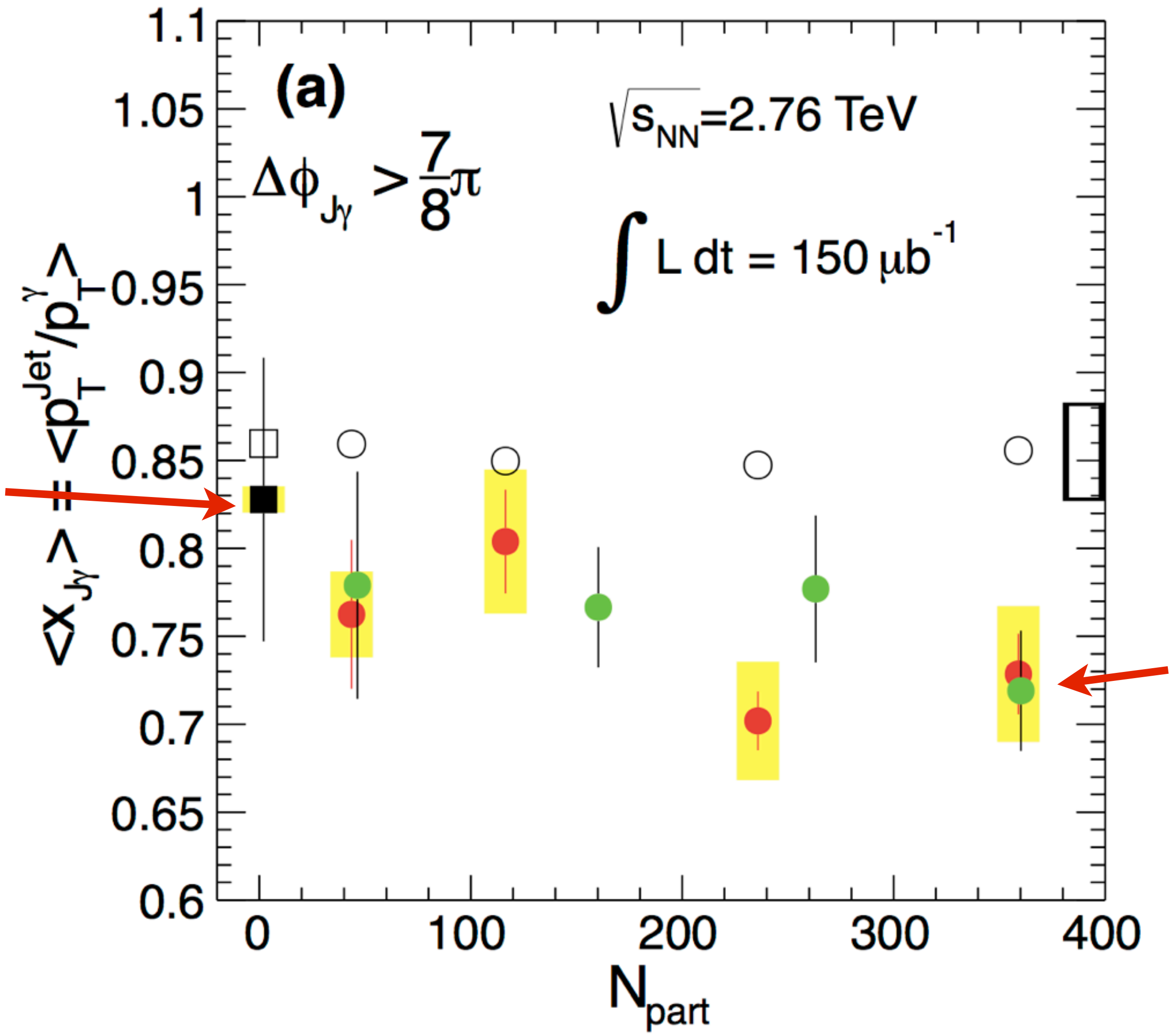
Some remarks about the future

- Next LHC HI run in late 2015
- Next big step at RHIC: sPHENIX
- What can we expect before then?
  - not much for Z^0s - there is only so much one can do with O(50) events
  - still some possibilities for photons

photons at LHC 2013-2015

2011 pp reference to be replaced by 2013 data (x20 higher statistics)

Also pPb (another x5)

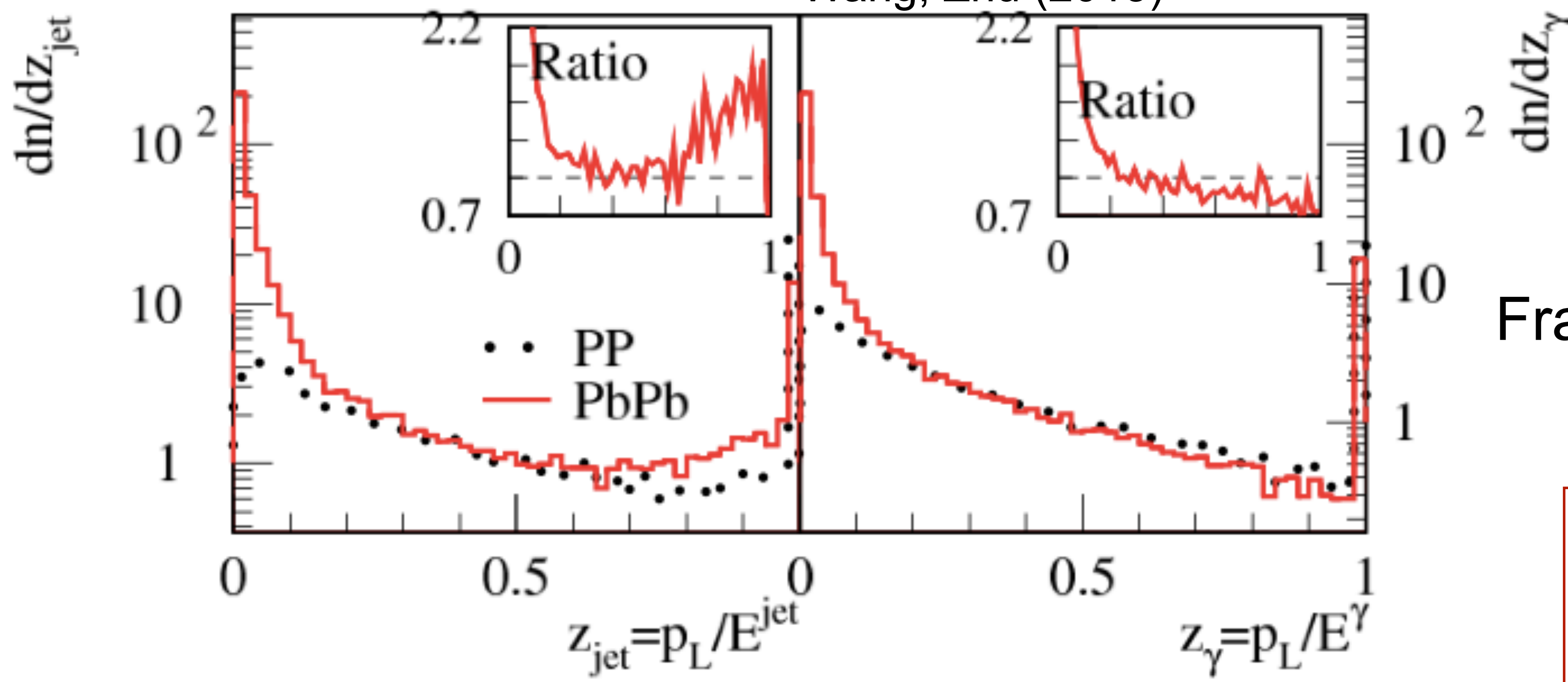


Improve ATLAS/CMS compatibility (i.e. photon-associated jet)

Minor improvements maybe not impossible for jet p_T (20GeV/c)?

photons at LHC 2013-2015

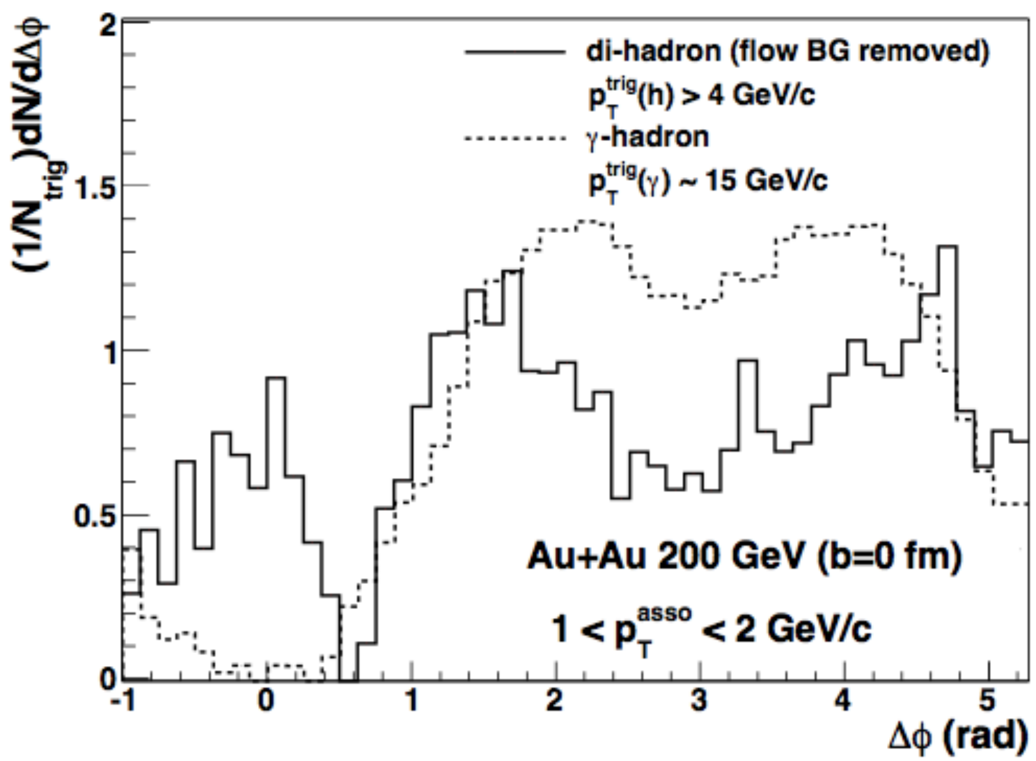
Wang, Zhu (2013)



Softening at high z

Fragmentation functions wrt photon p_T

Statistics should suffice for a first look



photon(-jet) -hadron correlations

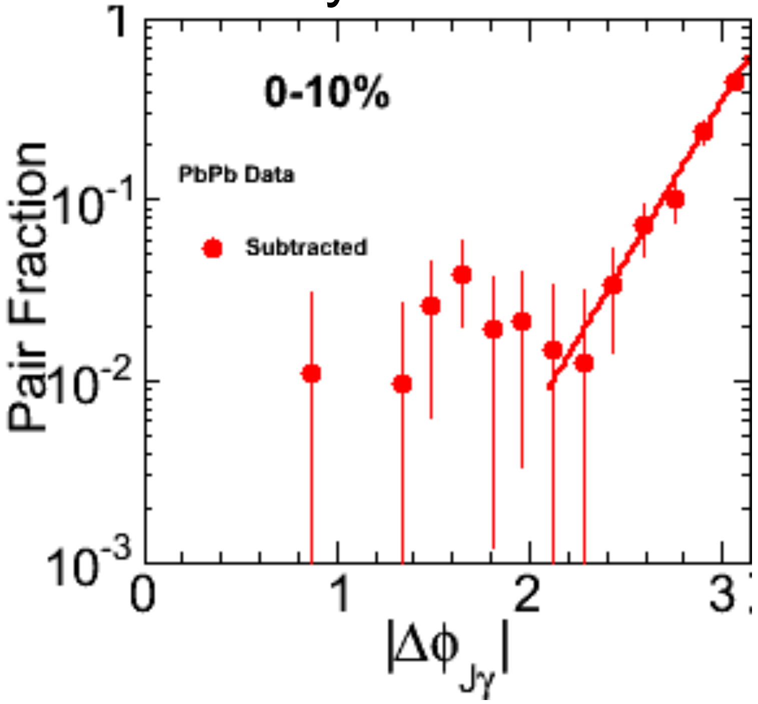
Search for medium response in photon-jet events using

Alleviates some, but not all of v_n bkg subtraction problems (photon isolation...)

Beyond 2015

- LHC luminosity could increase by x5-10
  - limits from machine protection, experiment needs
- x10 would enable
  - high statistics Z^0-jet asymmetry
  - photon-jet with $p_{T,\gamma}$ > 100 GeV/c
    - study of full $x_{j\gamma}$ distribution
    - Path length dependence
    - event-by-event energy loss,
    - event-by-event azimuthal correlations

large angle tail not fully understood



- sPHENIX
  - full complement of photon-jet studies at RHIC
    - needs jets at relatively low p_T (<10GeV/c) for sufficient dynamic range

Summary

- Wealth of results from RHIC and LHC
  - direct photon, isolated photon and Z^0 R_{AA}
  - photon-hadron, photon-jet and Z^0 jet correlations
- General agreement with expectations
  - photon, Z^0 show N_{coll} scaling
    - compatible with expected nuclear effects (nPDFs, isospin)
  - Clear shift in photon/Z^0-jet balance seen
    - compatible with energy loss seen in other measurements
  - softening of fragmentation function (photon-hadron corr’s)
    - also used to study angular distribution of fragments
- Studies will move to precision era
  - High energy, high luminosity running at LHC (2015-)
  - sPHENIX