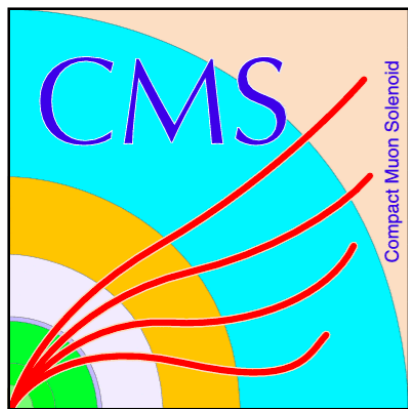


Production of isolated photons in PbPb and pp collisions at 5.02 TeV with the CMS detector



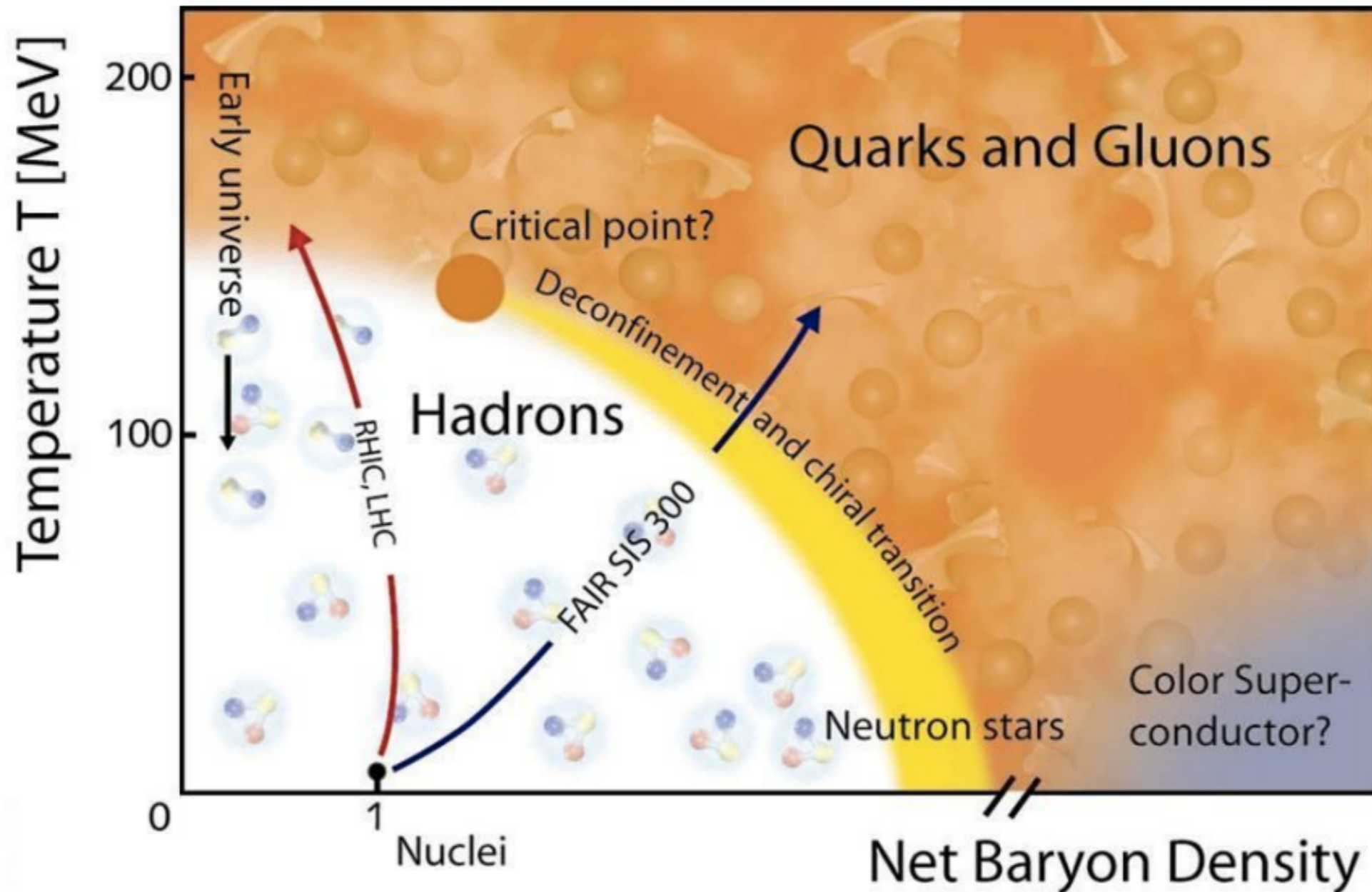
Yeonju Go

July 3-4, 2020

2nd CENuM Joint Workshop
Online



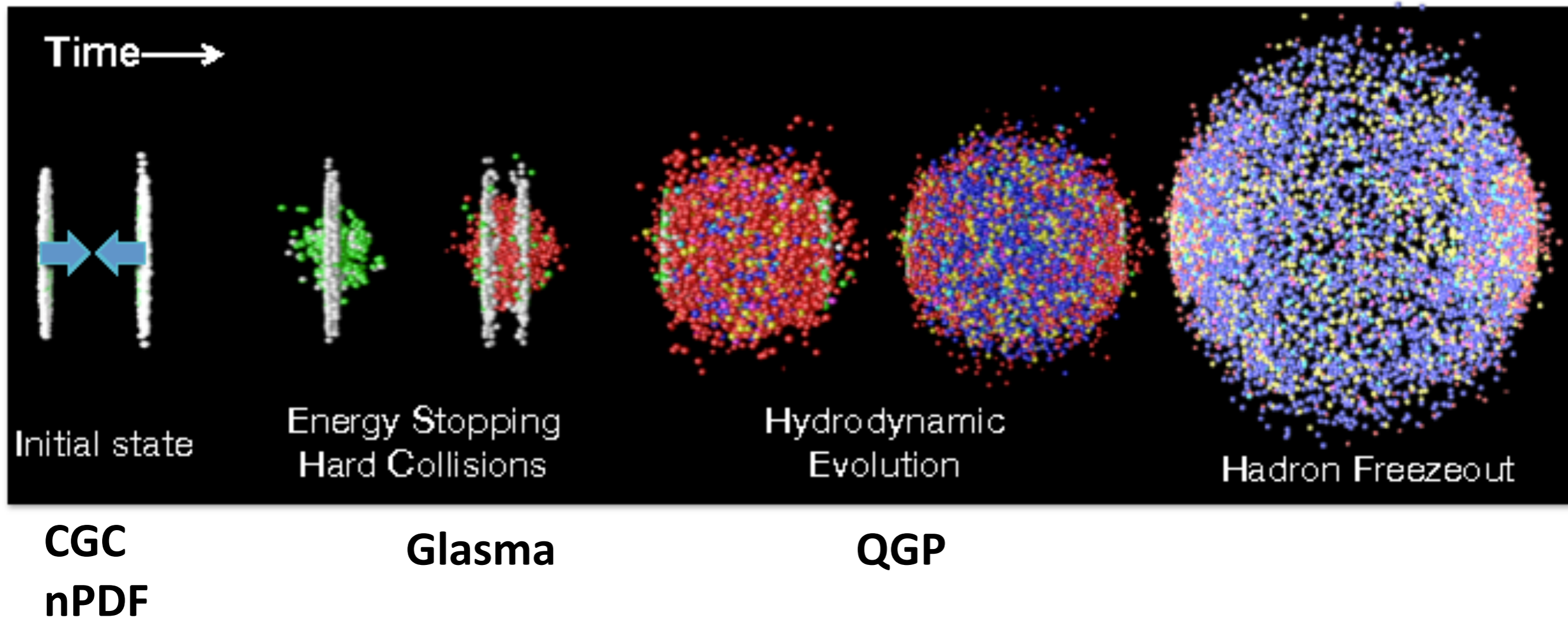
What is Quark Gluon Plasma (QGP)?



● Quark Gluon Plasma (QGP)

- A deconfined state of matter in QCD expected to exist at **extremely high temperature in early universe** and **high ion density in neutron stars**

Evolution of heavy ion collisions



- ◉ In heavy ion collisions, **different stages** in time evolution can be explored using **various probes**: Electroweak bosons, jets, heavy flavors, flows, etc.

Production of prompt photons

- **Direct photon**

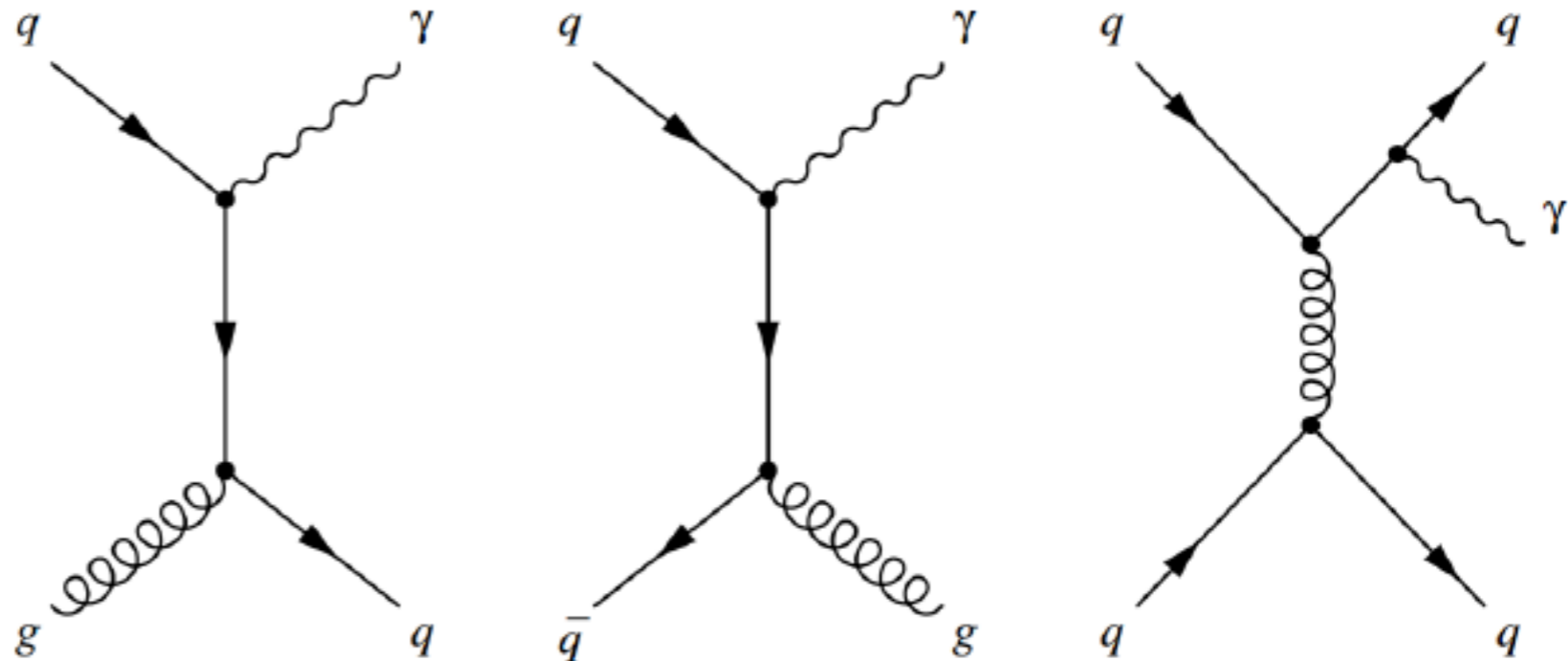
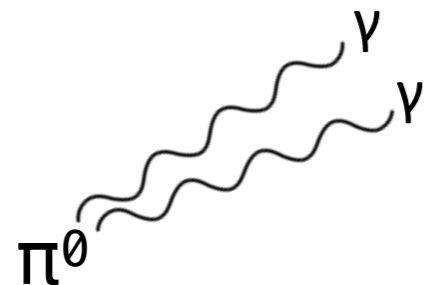
- produced from **primary vertex**
- Processes : Compton scattering, Annihilation

- **Fragmentation photon**

- radiated from partons after the primary hard scattering

- **Decay photon**

- decayed from hadrons, such as $\pi_0 \rightarrow \gamma + \gamma$
- **major background**



Compton scattering

Annihilation

Fragmentation

Direct photons

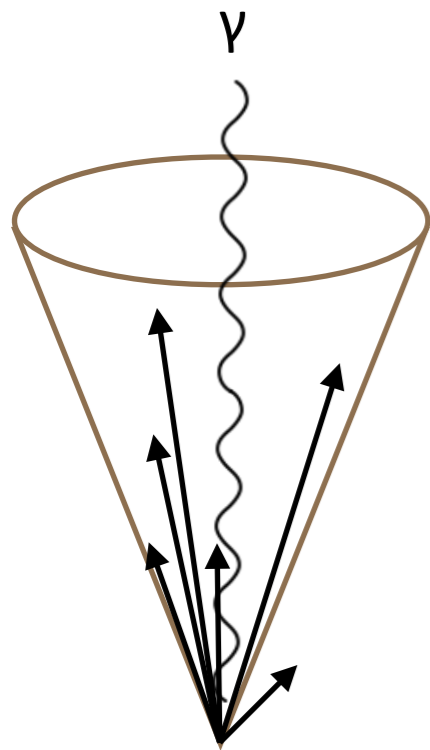
Prompt photons

= Direct + Fragmentation photons

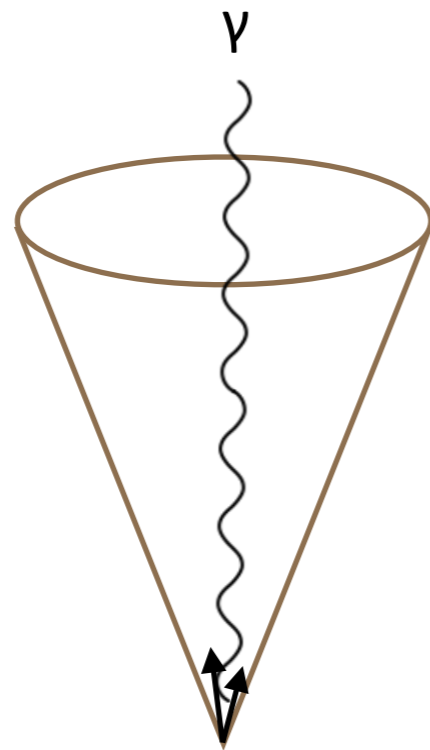
Isolated photons

- **Isolation condition**
 - **suppress significant background photons** from neutral meson decay
 - **suppress fragmentation photon** contribution and contains most of direct photons
- High- p_T isolated photons are sensitive to **gluon distribution** because **quark-gluon Compton scattering** is dominant
- Discrimination between isolated direct and fragmentation photons is arbitrary in experiment

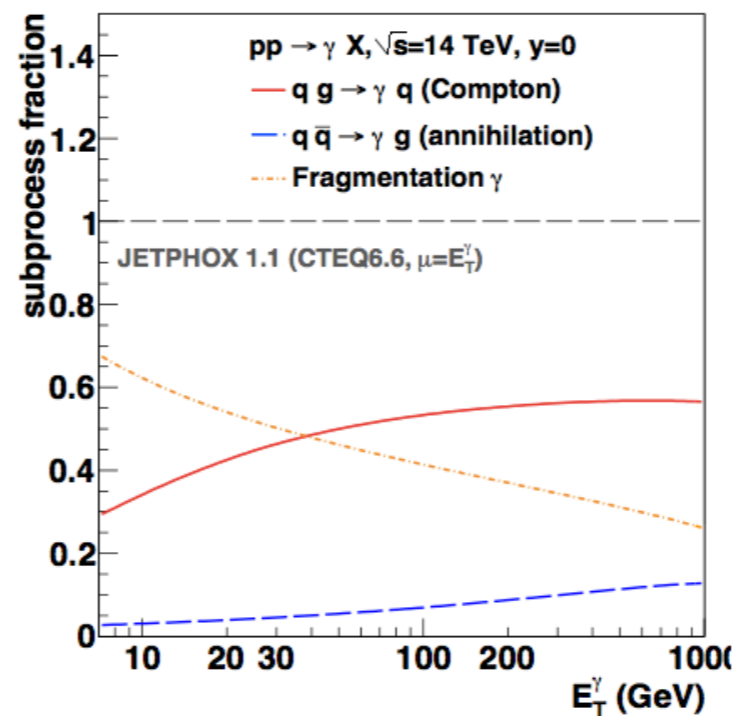
Non-isolated



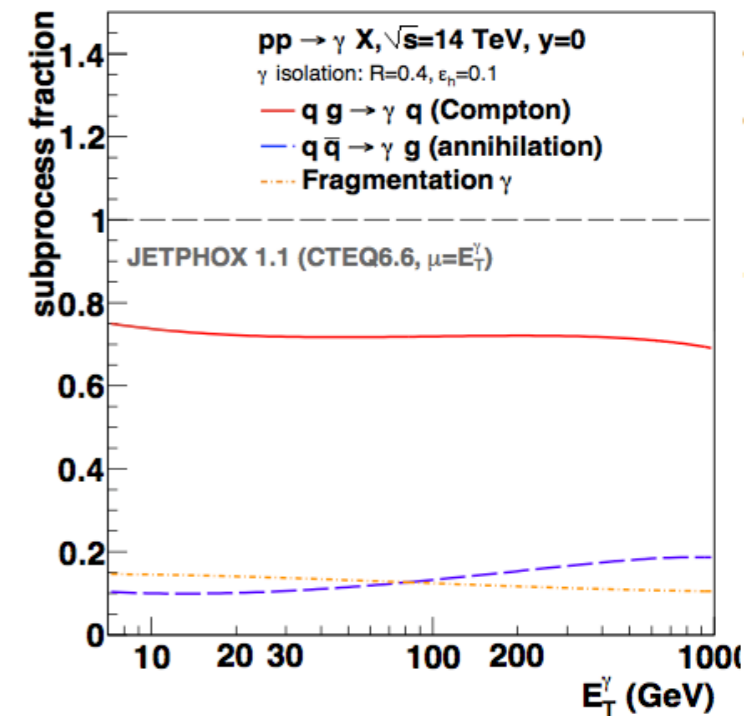
Isolated



Non-isolated



Isolated



Phys.Rev. D82 (2010) 014015

Parton distribution functions

- **QCD Factorization theorem** : hadronic cross section is factorized into PDFs of incoming particles and perturbative partonic cross section

$$\sigma_{AB} = \sum_{a,b=q,g} \hat{\sigma}_{ab} \otimes f_{a/A}(x_1, Q^2) \otimes f_{b/B}(x_2, Q^2)$$

- Hadronic cross section

- Partonic cross section
- perturbative QCD

- Parton distribution
- non-perturbative

- **Parton distribution functions (PDFs)** are **universal**

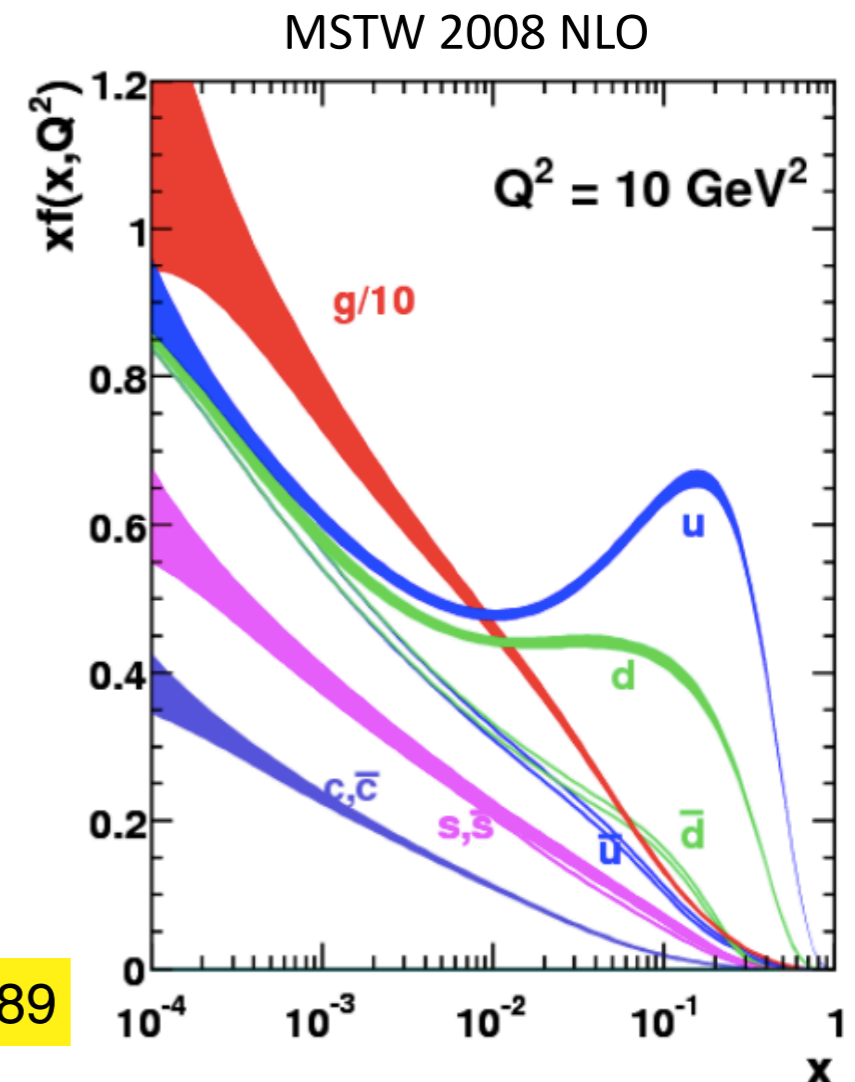
- do not depend on hard scattering processes
- The **Q² dependence** is given by **DGLAP evolution** equations

$$\frac{\partial f_{a/A}}{\partial \ln Q^2} = \sum_{a'=q,g} P_{aa'} \otimes f_{a'/A}$$

splitting functions

- The **x dependence** can be derived by **BFKL equation** and by **fitting experimental data**

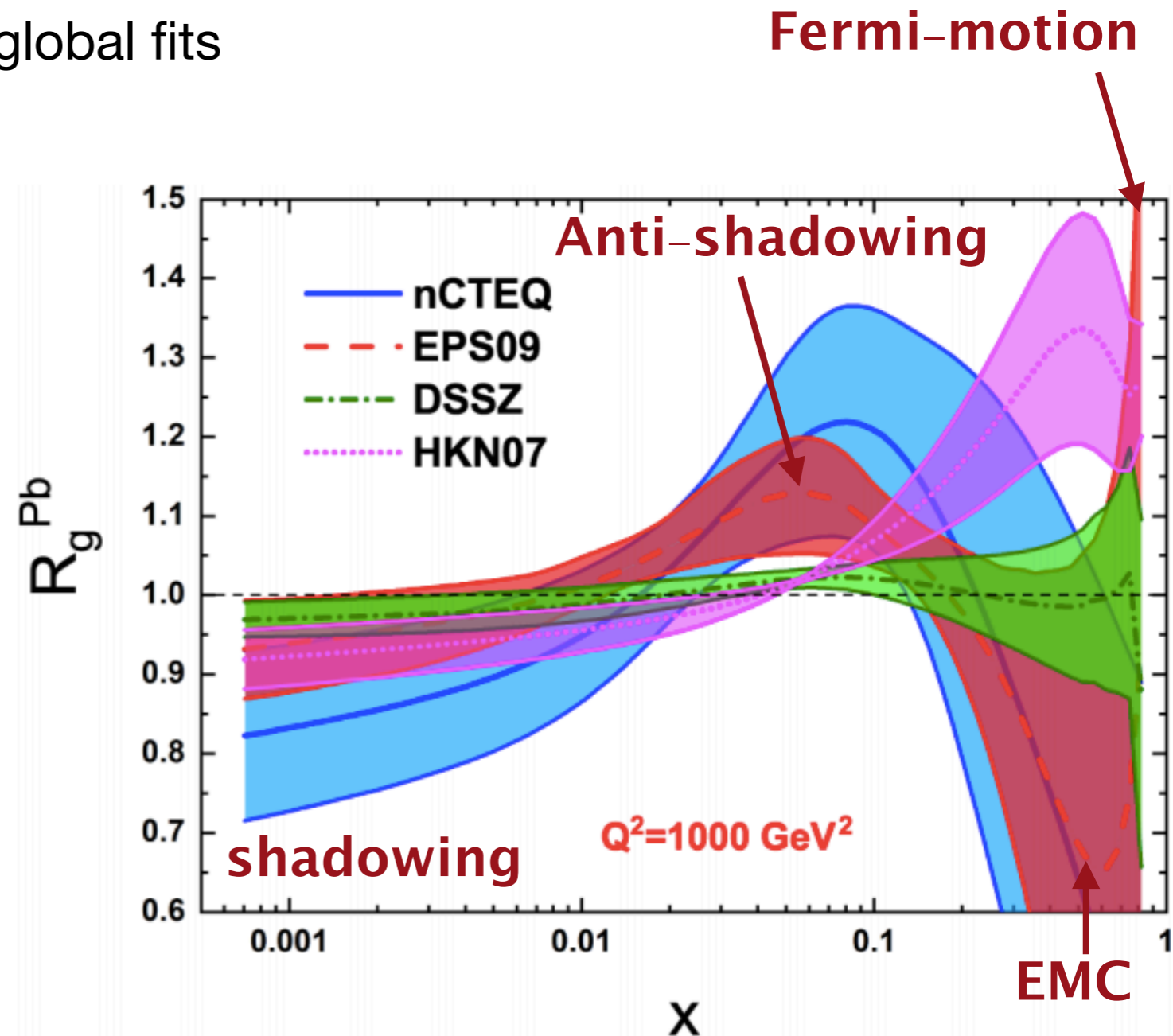
EPJC 63 (2009) 189



Nuclear parton distribution functions

- **Nuclear parton distribution functions (nPDFs):**
modification of PDFs of nucleons **inside nuclei** compared to free proton PDFs
- **Large uncertainty** for gluon in the global fits
- **Discrepancies** between models
 - need data to constraint models

$$R_i^A(x, Q^2) \equiv \frac{\text{nuclear PDF}}{f_i^{P/A}(x, Q^2)} \frac{f_i^P(x, Q^2)}{\text{free nucleon PDF}}$$

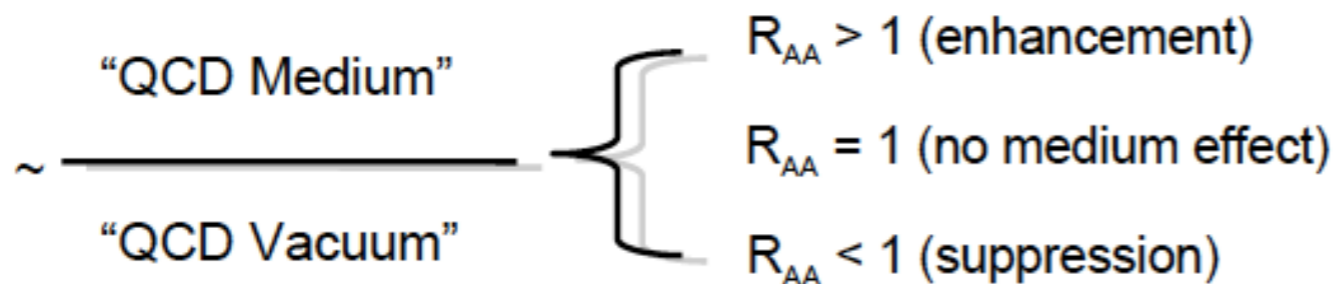


PRC 99, 055206 (2019)

Nuclear modification factor

- Direct comparison of production cross sections of various probes in pp and nuclear collisions allows one to estimate any **nuclear effect**

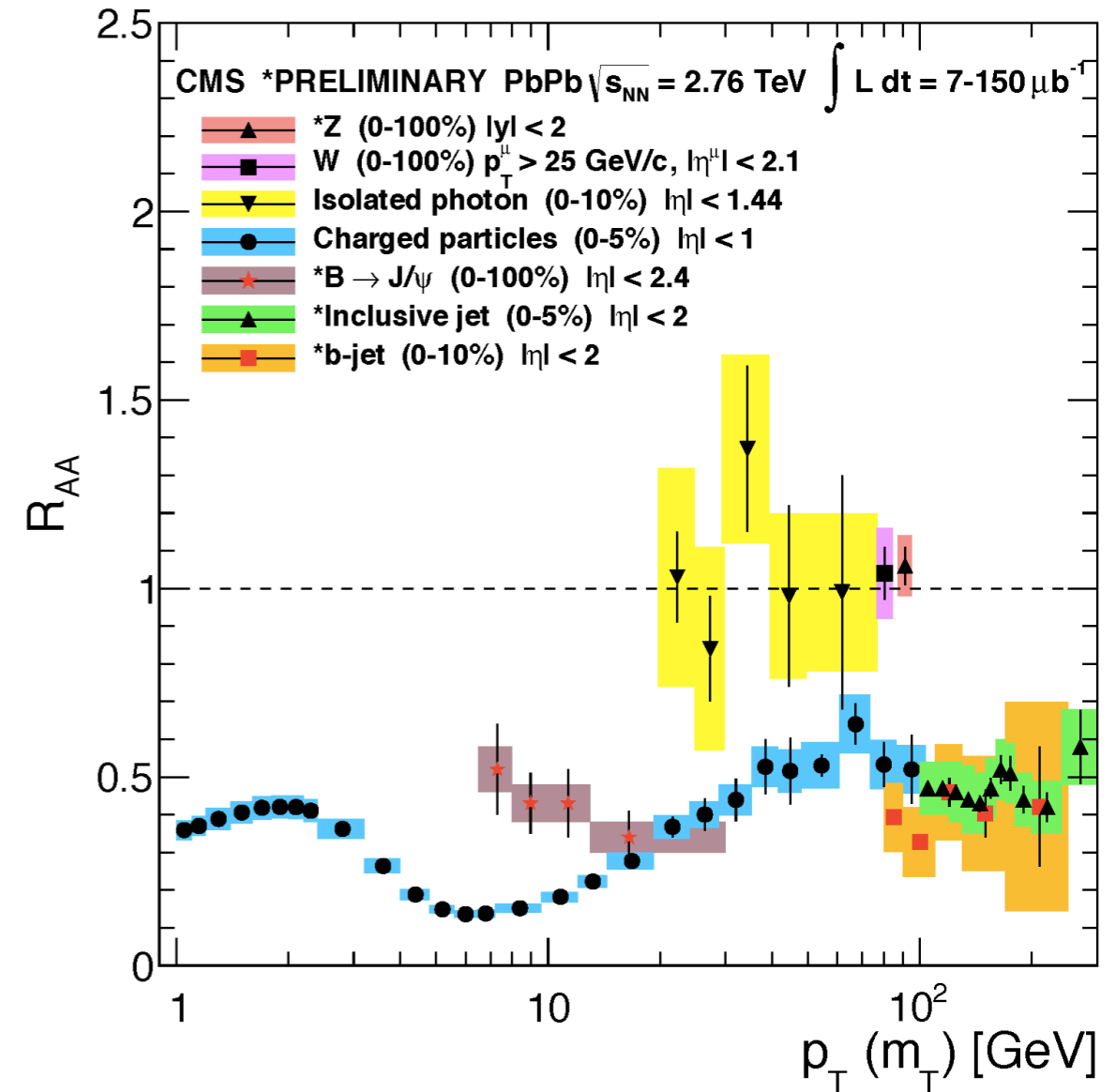
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



- T_{AA} : nuclear overlap function

$$T_{AA} = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per AA collision"



Why prompt photons?

- **Prompt photons**

- **created in early phase** and experience the whole time evolution in heavy ion collisions

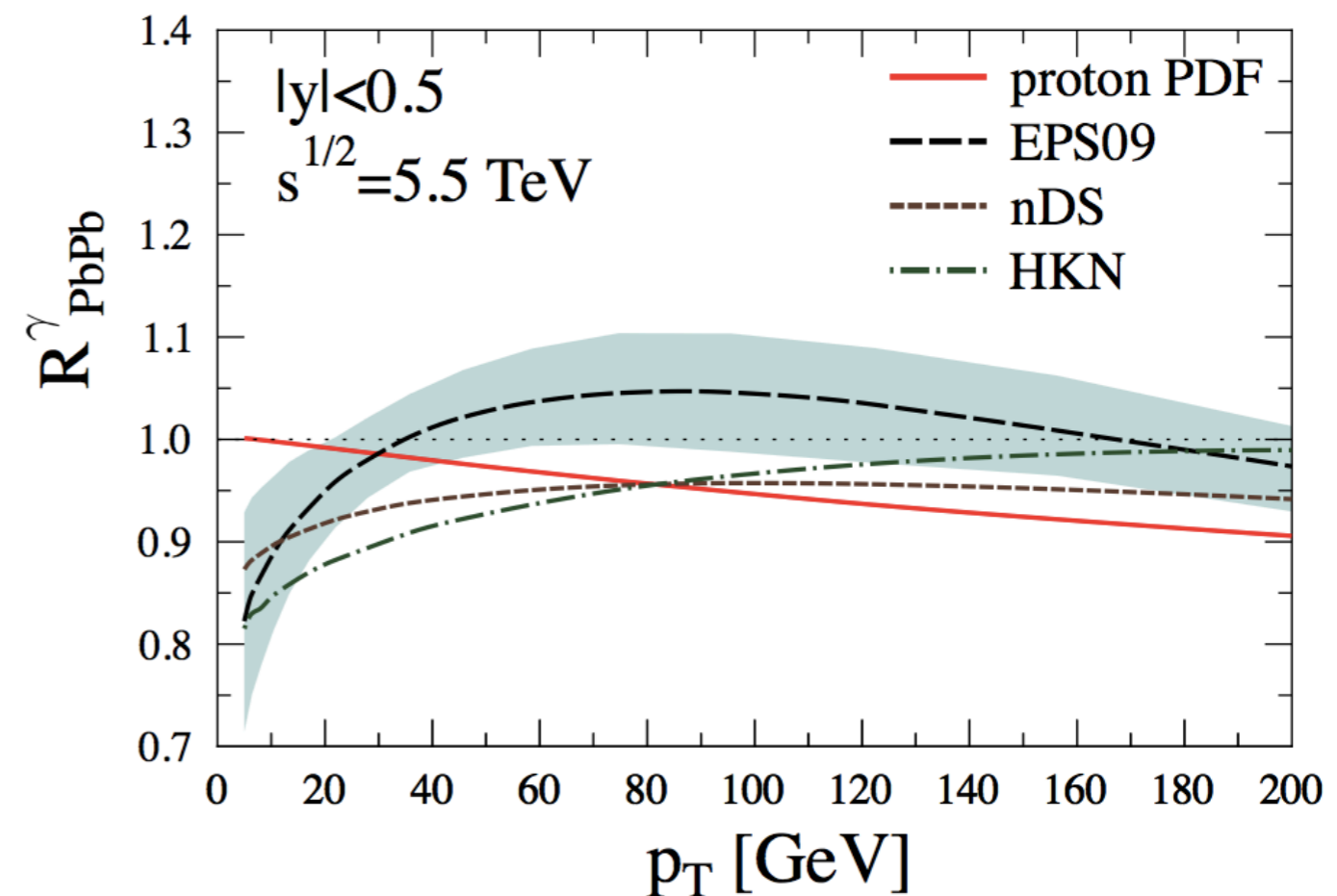
- **Reference for other particles**

- expected to be **un-modified by the QGP** as a clean probe which does not interact with the QCD medium

- **Constrain/help global fits for (gluon) nPDF**

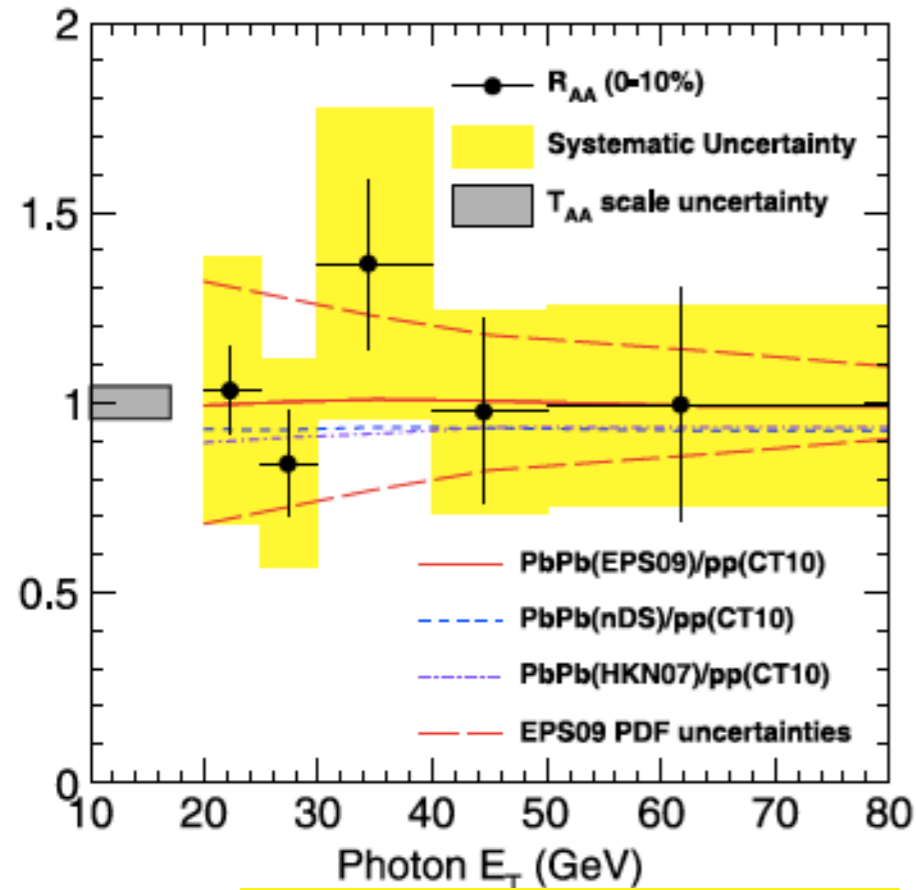
- R_{AA} of prompt photons shows possible **modifications** of the **nuclear parton (gluon) densities**

JHEP04(2011)055

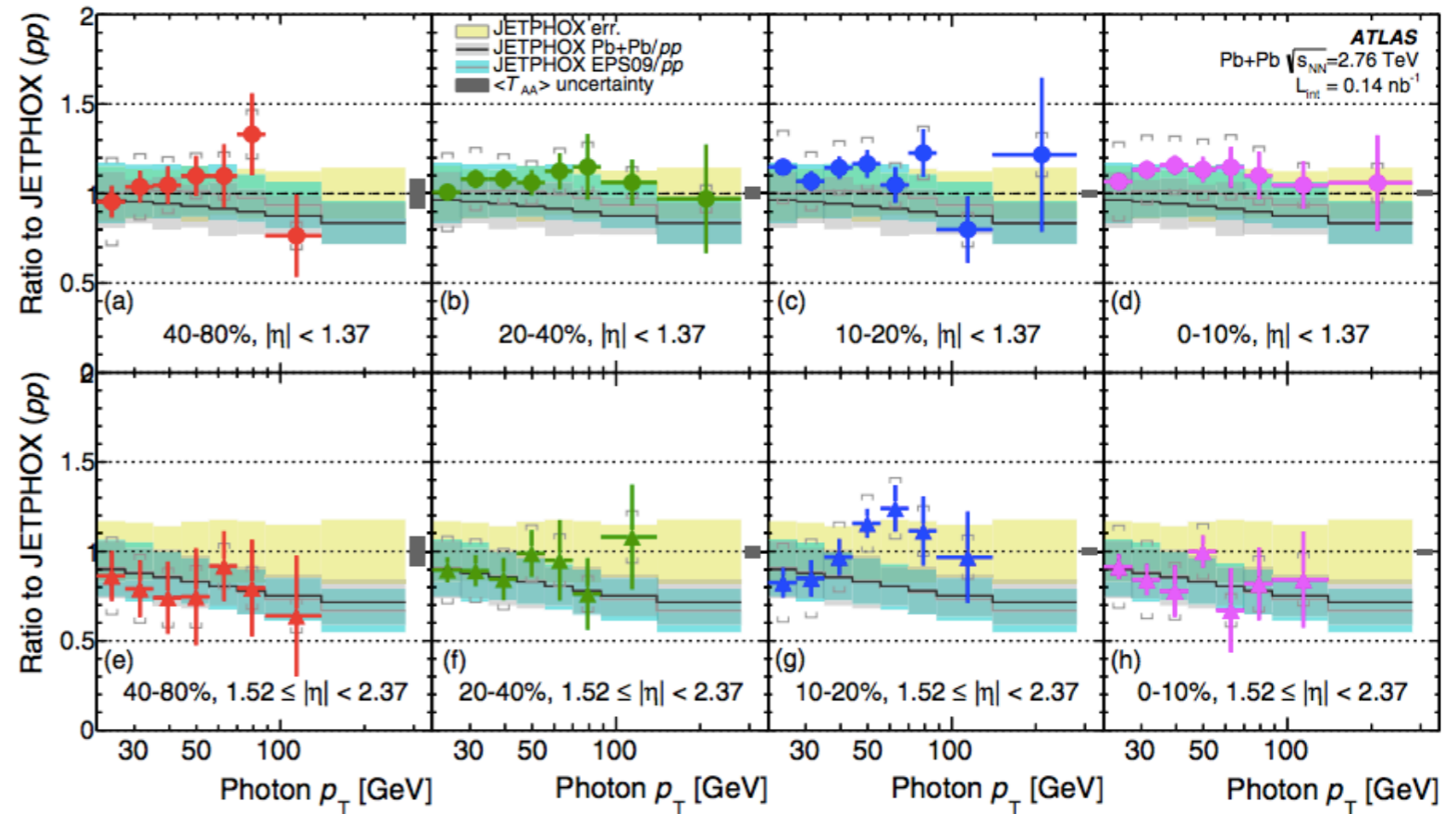


Previous measurement in LHC

CMS $\sqrt{s_{NN}}=2.76\text{TeV}$ $L_{int}(\text{PbPb})=6.8\mu\text{b}^{-1}$ $L_{int}(\text{pp})=231\text{nb}^{-1}$



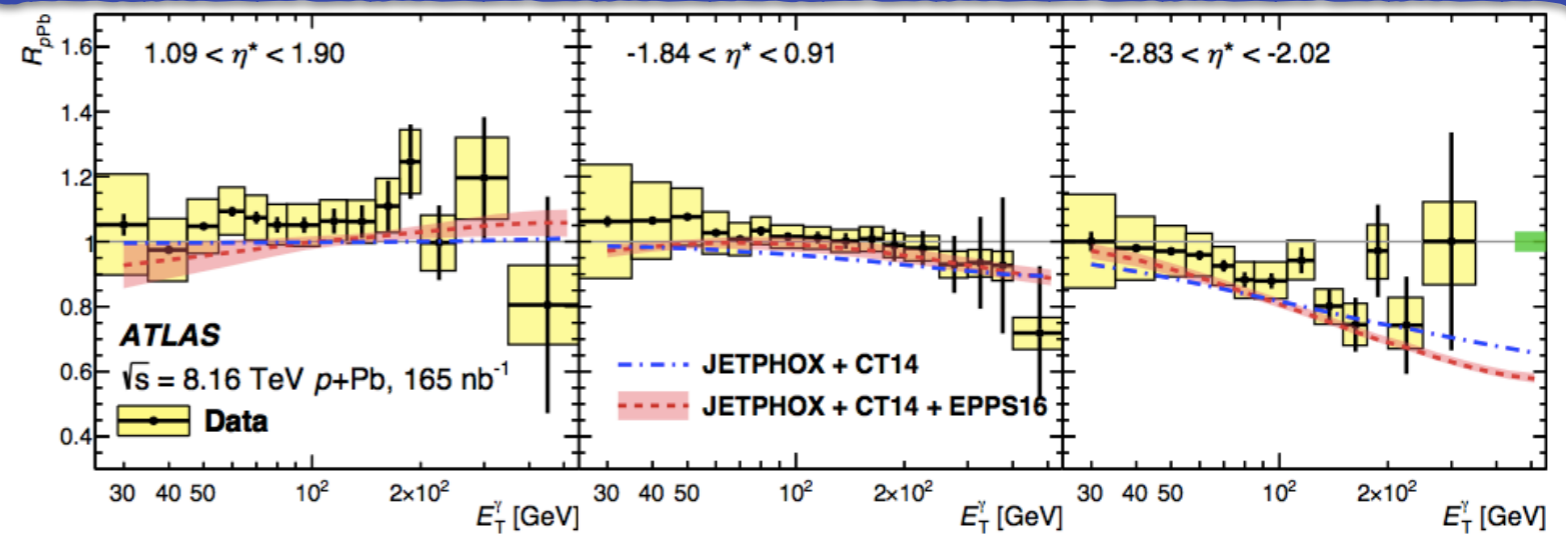
PLB 710 (2012) 256–277



PRC 93 (2016) 034914

PbPb 2.76 TeV

pPb 8.16 TeV



PLB 796 (2019) 230-252

CMS detector

- Tracker, **ECAL** and **HCAL** are used for photon reconstruction, identification and isolation

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

Tracker

SILICON TRACKERS
 Pixel (100x150 μm) $\sim 16\text{m}^2 \sim 66\text{M}$ cha
 Microstrips (80x180 μm) $\sim 200\text{m}^2 \sim 9$.

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
 Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

ECAL : Photon reconstruction

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels

HCAL



$|\eta| < 2.4$

$|\eta| < 5.2$

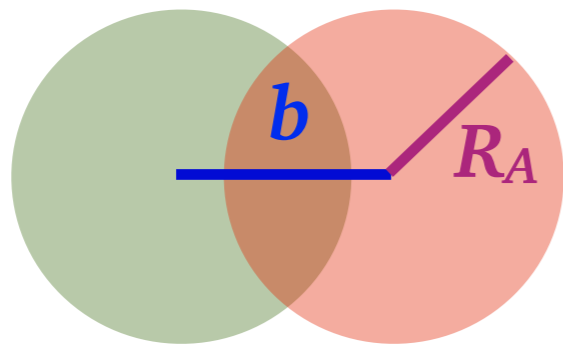
$|\eta| < 3.0$

$|\eta| < 2.5$

HF : Centrality determination

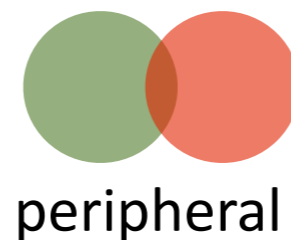
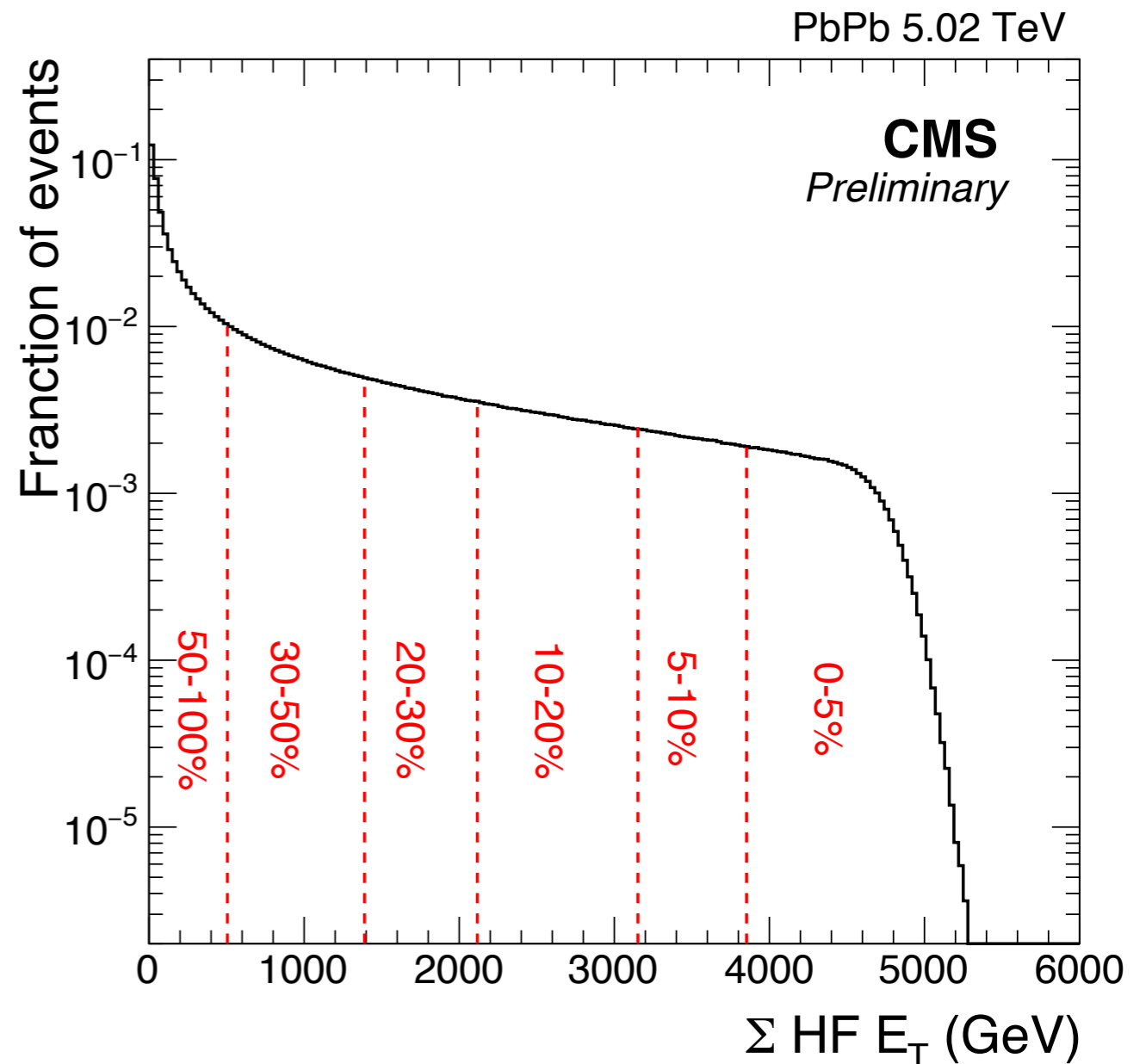
Centrality

- Centrality: a quantity used to determine the impact parameter b between **two colliding nuclei**



$$centrality = \frac{\pi b^2}{\pi (2R_A)^2}$$

- Characterized by **transverse energy sum** in the hadronic forward calorimeter (**HF**)

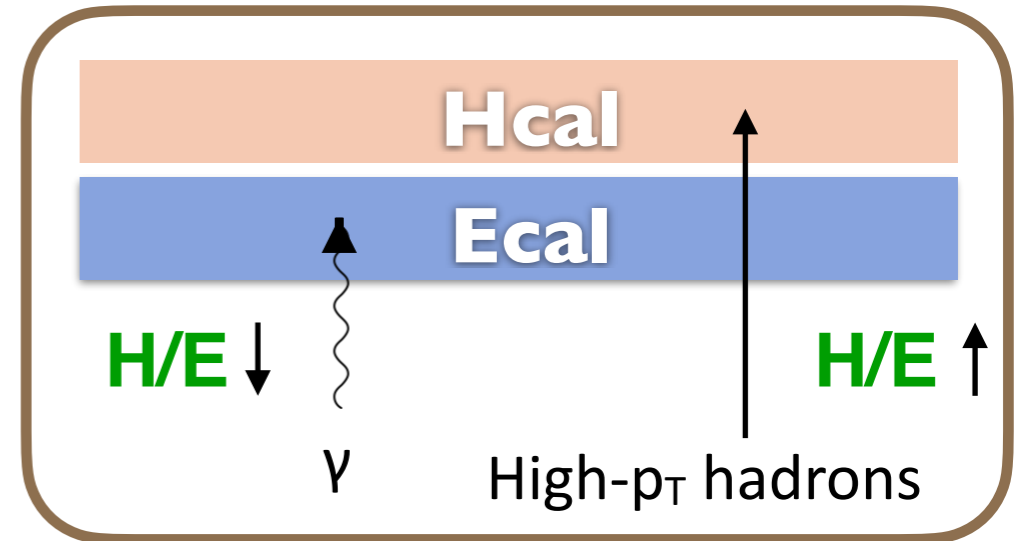
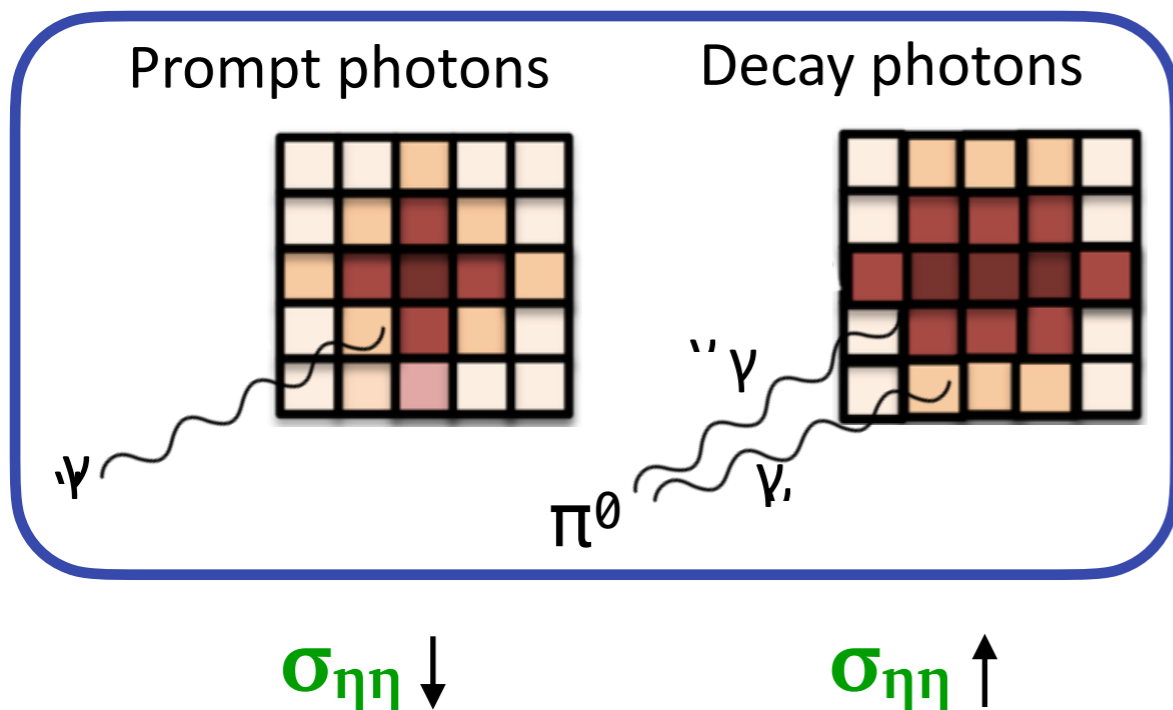


Photon identification and isolation requirement

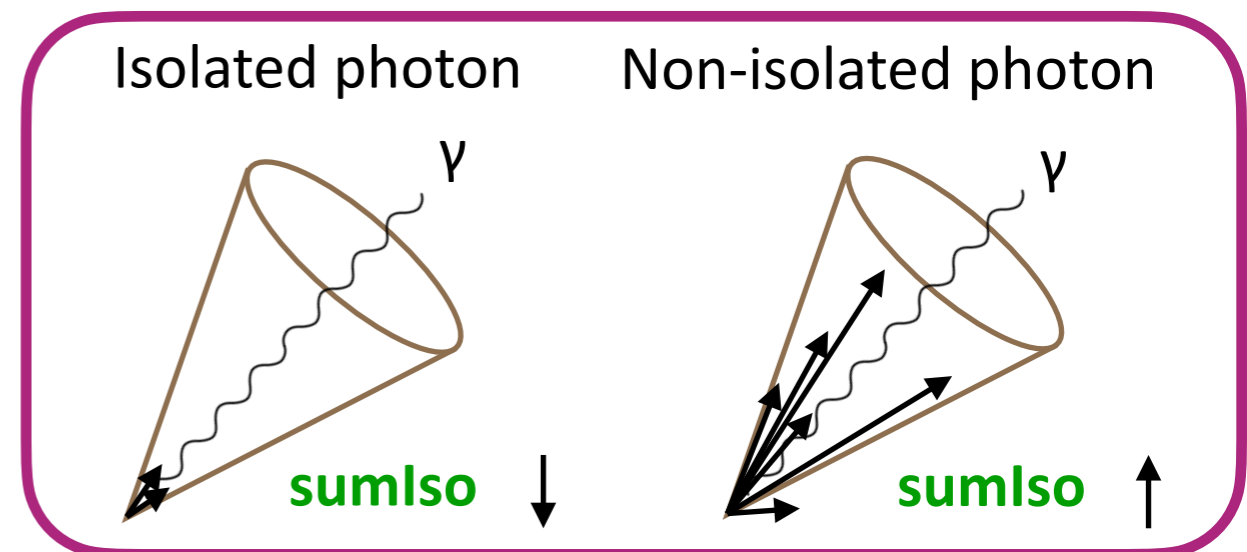
- 1) $H(\text{Hcal})/E(\text{Ecal}) < 0.1$
 - removes high- p_T hadrons
- 2) $\sigma_{\eta\eta}$ (shower shape variable) < 0.01
 - removes decay photons using energy deposit shape

$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5 \times 5} w_i (\eta_i - \eta_{5 \times 5})^2}{\sum_i^{5 \times 5} w_i},$$

$$w_i = \max\left(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}}\right)$$

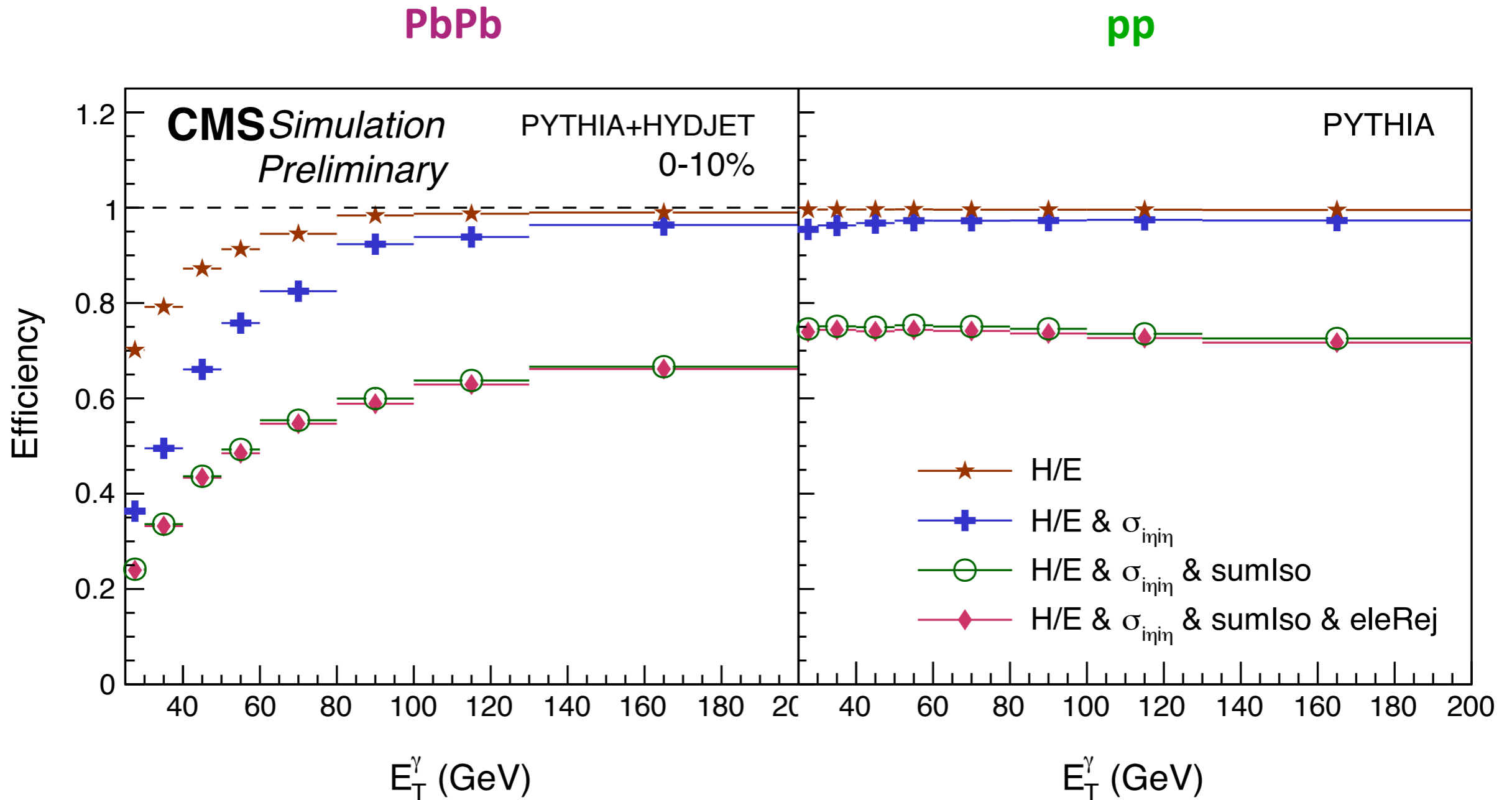


- 3) $\text{sumIso} < 1 \text{ GeV}$
 - sumIso: energy sum around photon candidates
 - $\text{sumIso} = \text{tracker iso} + \text{Ecal iso} + \text{Hcal iso}$
 - $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$
 - underlying event (UE) corrected
 - suppress fragmentation and decay photons



Identification and isolation efficiency

- Efficiencies of different reconstruction selection criteria are estimated **from simulations** as a function of E_T in **different centrality classes**



Purity : template fit method

- After isolated photon selection, there is still **significant contamination** from the neutral meson decays
- Purity is estimated using the **template fit method**

$$\text{purity} = \frac{S}{S + B} \quad (\sigma_{\eta\eta} < 0.01)$$

DATA

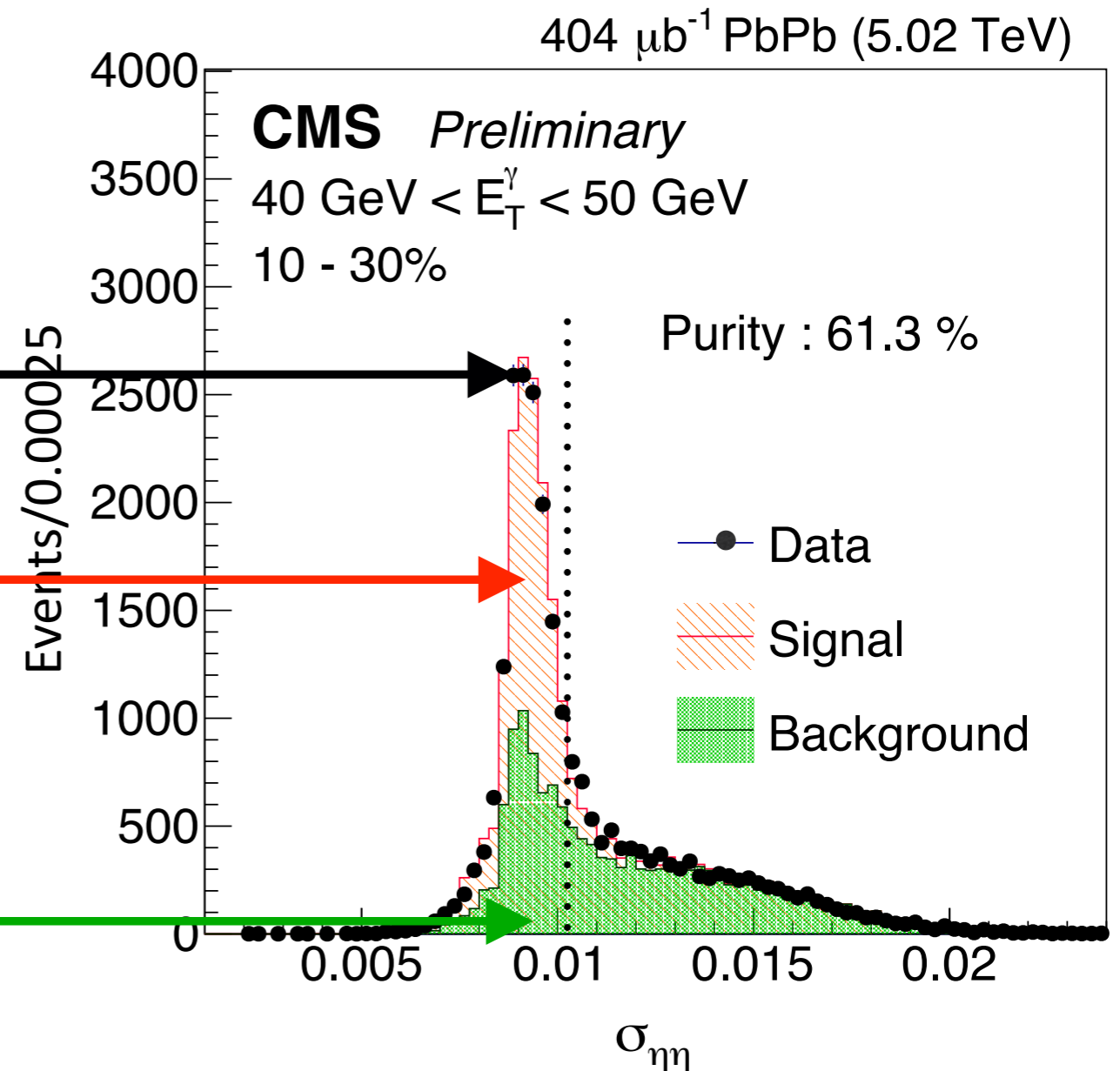
- $H/E < 0.1$
- $\text{sumIso} < 1 \text{ GeV}$

Signal template (from MC)

- Gen-level prompt isolated photons
- $H/E < 0.1$
- $\text{sumIso} < 1 \text{ GeV}$

Background template (from DATA in sideband)

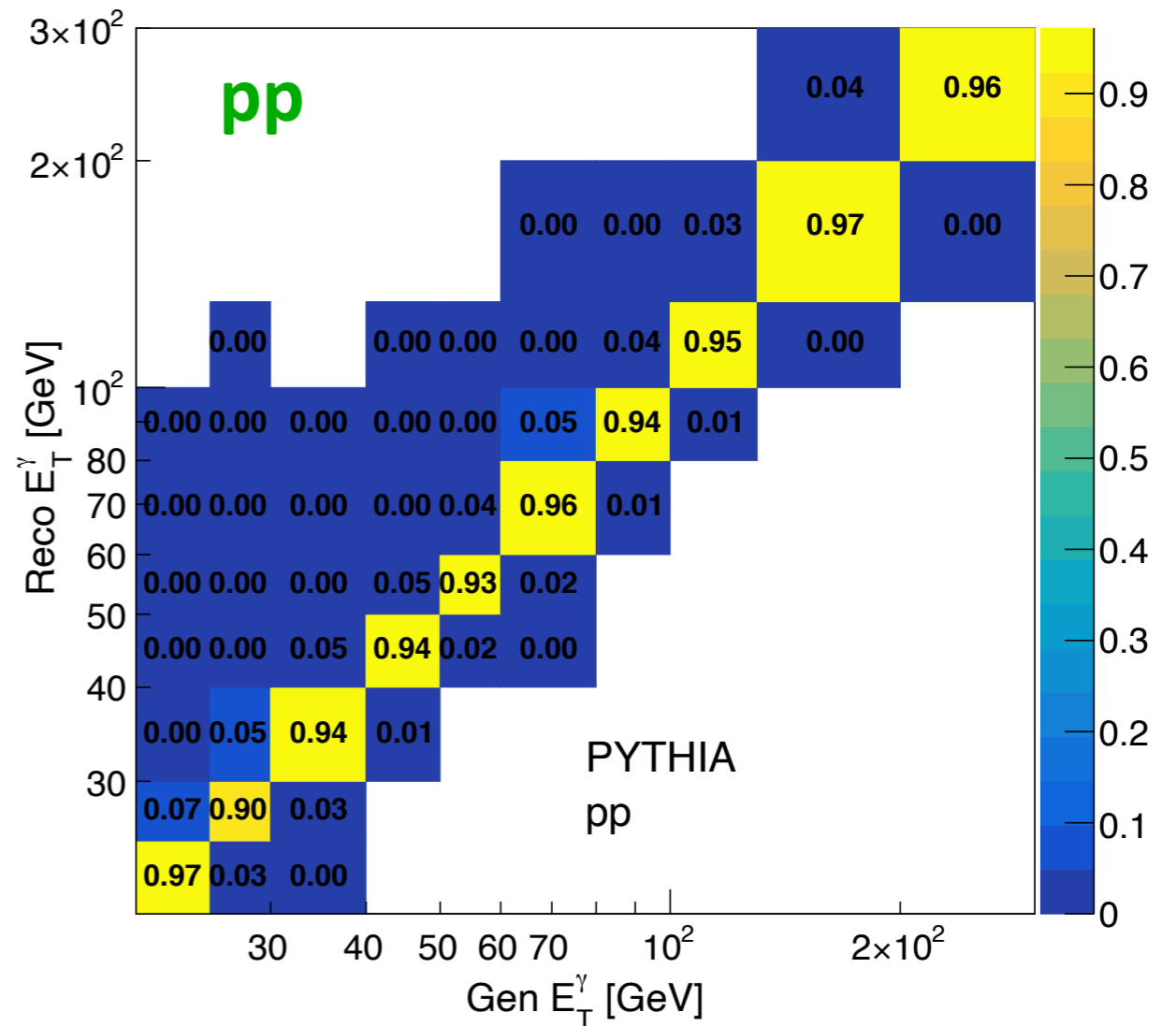
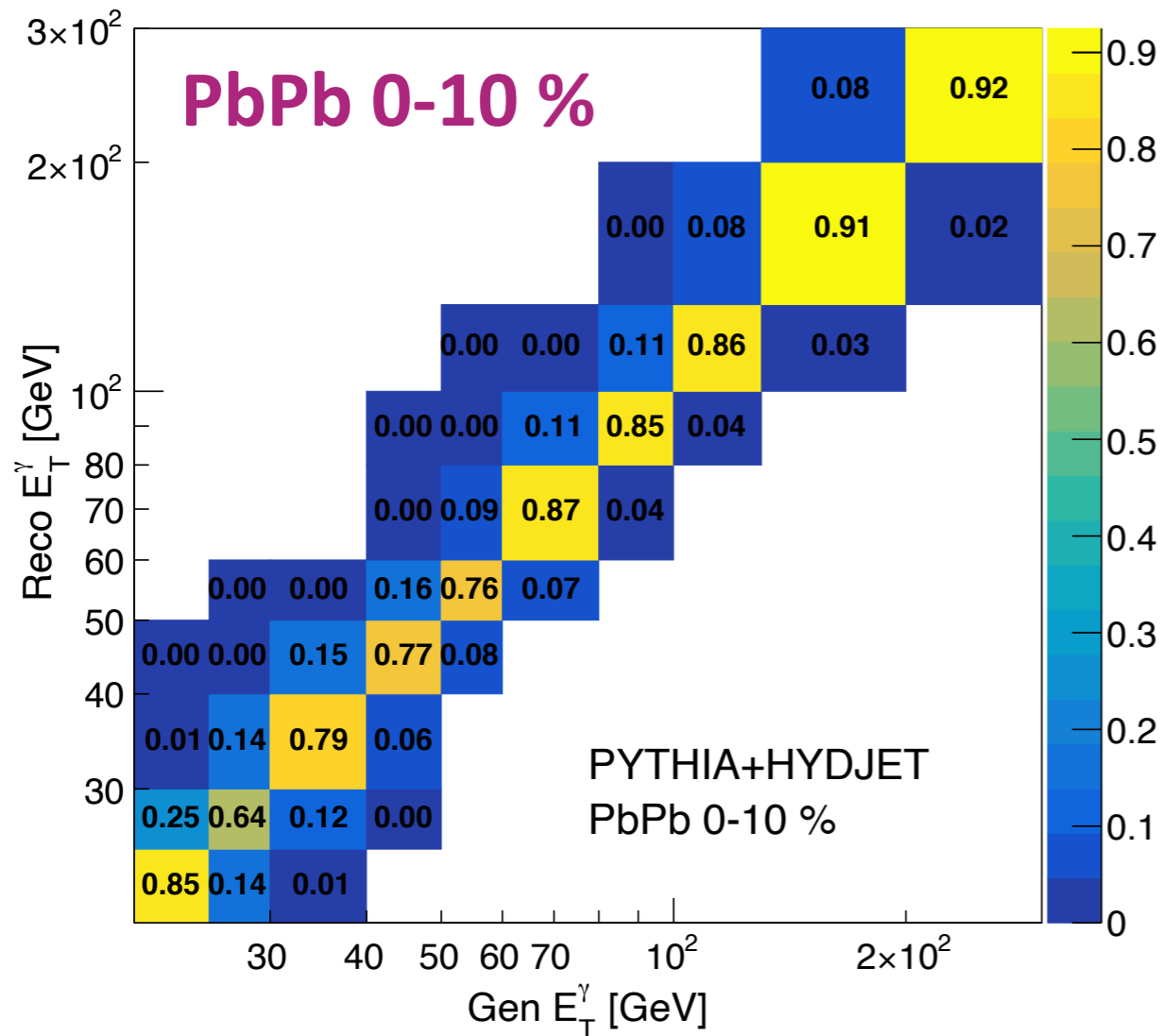
- $H/E < 0.1$
- sideband cut : $1 < \text{sumIso} < 5 \text{ GeV}$



$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5 \times 5} w_i (\eta_i - \eta_{5 \times 5})^2}{\sum_i^{5 \times 5} w_i}, \quad w_i = \max\left(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}}\right)$$

Unfolding

- **Unfolding** is performed to account for **detector resolution**
- Used the matrix inversion method in RooUnfold package



- The systematic uncertainty are estimated for various sources:
 - 1) **Finite size of the MC sample**
 - 2) **E_T distribution of the generated photons**

Systematic uncertainty: cross section

- Summary of the **systematic uncertainties on the cross section** of isolated photons in pp and PbPb collisions
- Purity** is the driving systematic source

Source	pp	PbPb centrality				
		0–100%	0–10%	10–30%	30–50%	50–100%
Purity	4–15%	5–15%	9–16%	11–14%	5–18%	5–17%
Electron rejection	<0.4%	1–3%	1–10%	1–5%	1–3%	0–7%
Pileup	0–11%	—	—	—	—	—
Energy scale	1–2%	3–8%	2–7%	2–10%	2–11%	1–12%
Energy resolution	<0.2%	1–3%	1–7%	1–9%	1–8%	2–6%
Unfolding	<0.2%	1–4%	0–9%	0–5%	0–3%	0–1%
Efficiency	1–2%	0–1%	0–4%	0–2%	0–1%	0–3%
Integrated luminosity	2.3%	—	—	—	—	—
T_{AA}	—	4%	3%	4%	6%	11%
Total	4–16%	6–18%	14–21%	12–18%	10–20%	10–21%

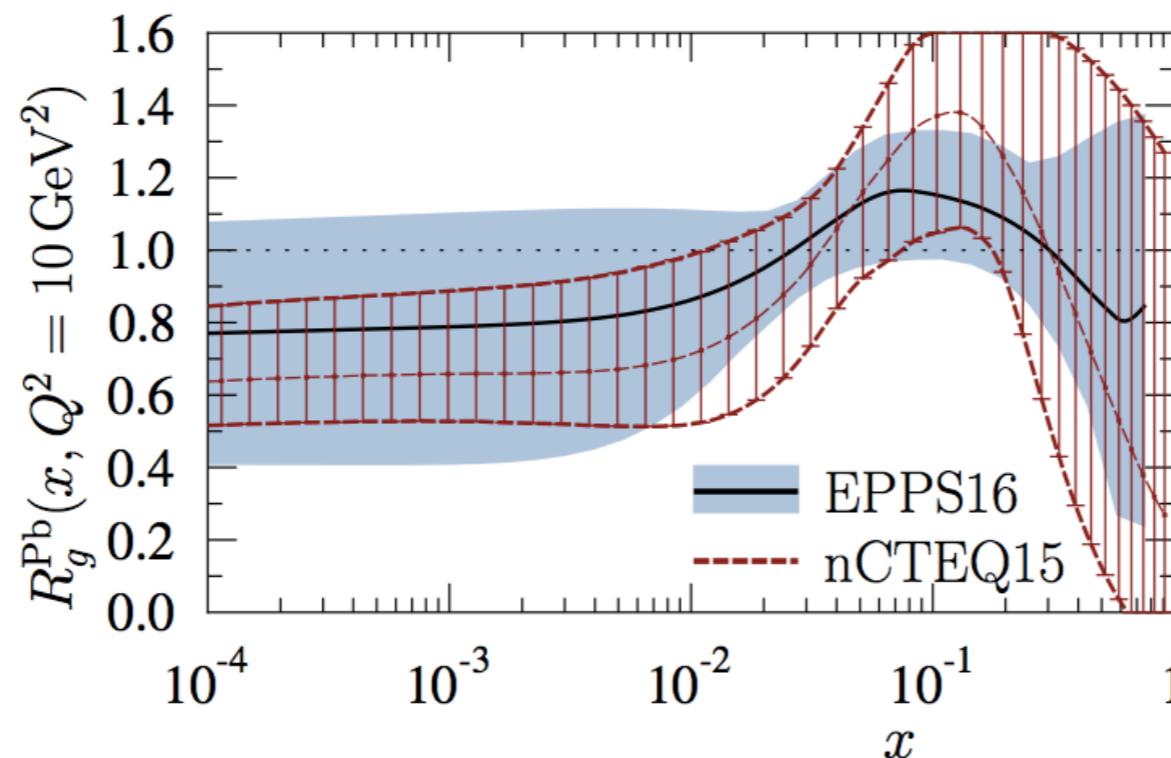
Systematic uncertainty: R_{AA}

- Summary of the **systematic uncertainties on the R_{AA}** of isolated photons in pp and PbPb collisions
- Purity** is the driving systematic source
- The systematic uncertainties from some of the sources are **partially cancelled out** in R_{AA}

Source	PbPb centrality				
	0–100%	0–10%	10–30%	30–50%	50–100%
Purity	6–9%	7–13%	3–12%	4–8%	2–7%
Electron rejection	1–2%	0–10%	1–6%	0–3%	0–7%
Pileup	0–10%	0–10%	0–10%	0–10%	0–10%
Energy scale	2–4%	3–6%	1–9%	2–7%	1–10%
Energy resolution	0–3%	1–7%	0–9%	1–8%	2–6%
Unfolding	1–4%	1–9%	1–5%	0–3%	0–1%
Efficiency	0–2%	0–5%	0–2%	0–1%	0–2%
Integrated luminosity	2.3%	2.3%	2.3%	2.3%	2.3%
T_{AA}	4%	3%	4%	6%	11%
Total	5–12%	10–17%	6–18%	7–15%	7–15%

JETPHOX calculation

- JETPHOX **NLO pQCD** calculations are compared to the data.
- The latest program version of 1.3.1_4
- Scales are set as $\mu_F = \mu_f = \mu_R = E_T$ and varied from $E_T/2$ to $2E_T$
- Parton to photon fragmentation function : **BFG-II**
- Isolation requirement: **$R=0.4, E_T^{\text{had}} < 5 \text{ GeV}$**
- PDF of free proton : **CT14** (56 PDF error sets)
- Nuclear PDF : **EPSS16** (97 nPDF error sets), **nCTEQ15** (33 nPDF error sets)

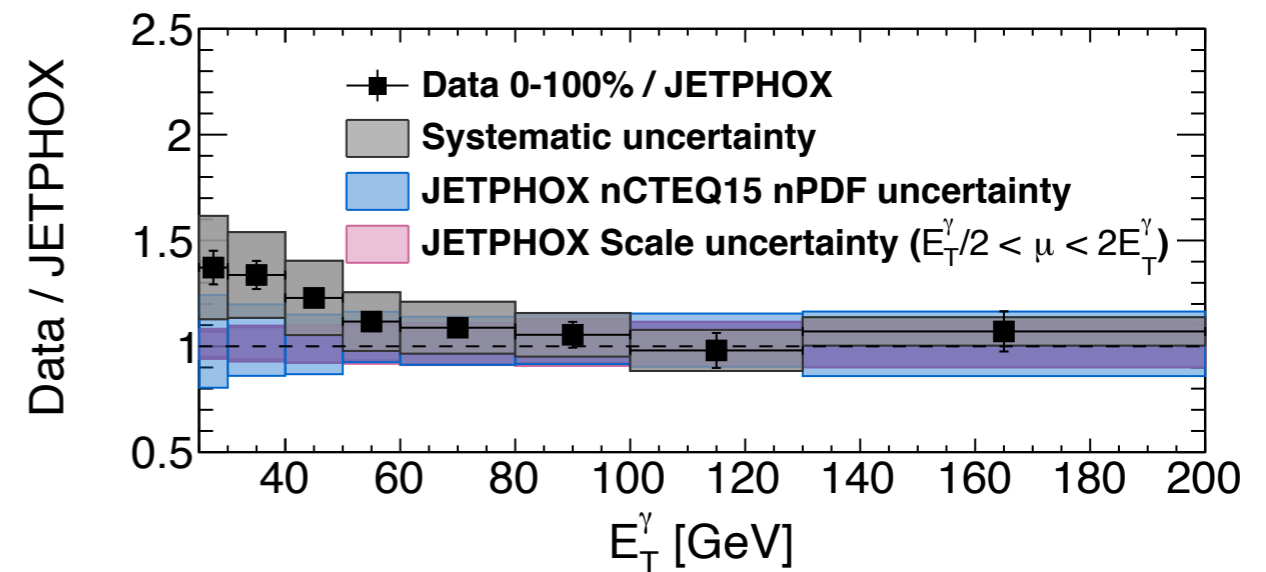
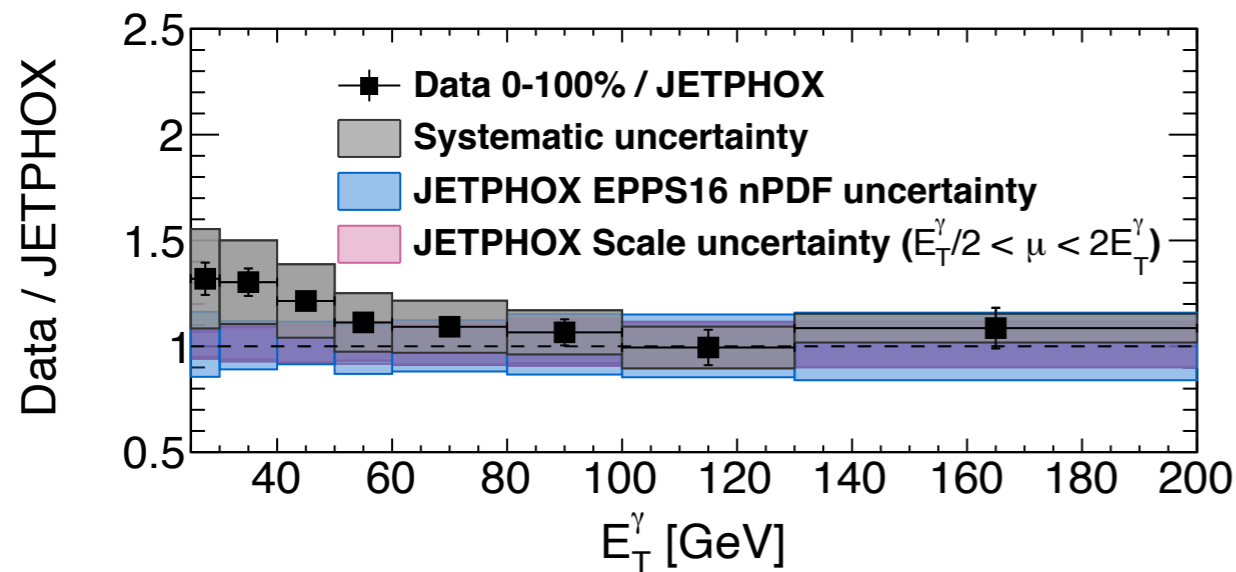
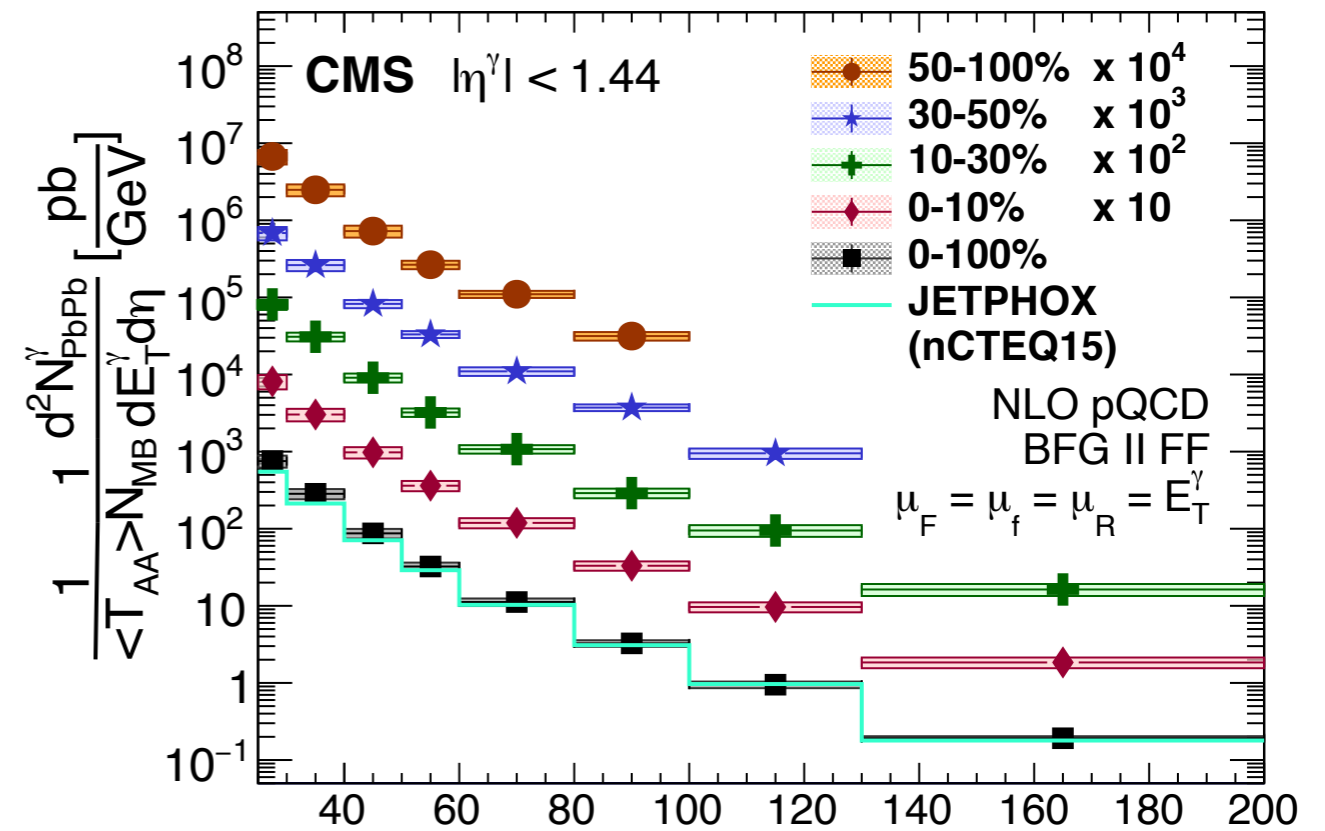
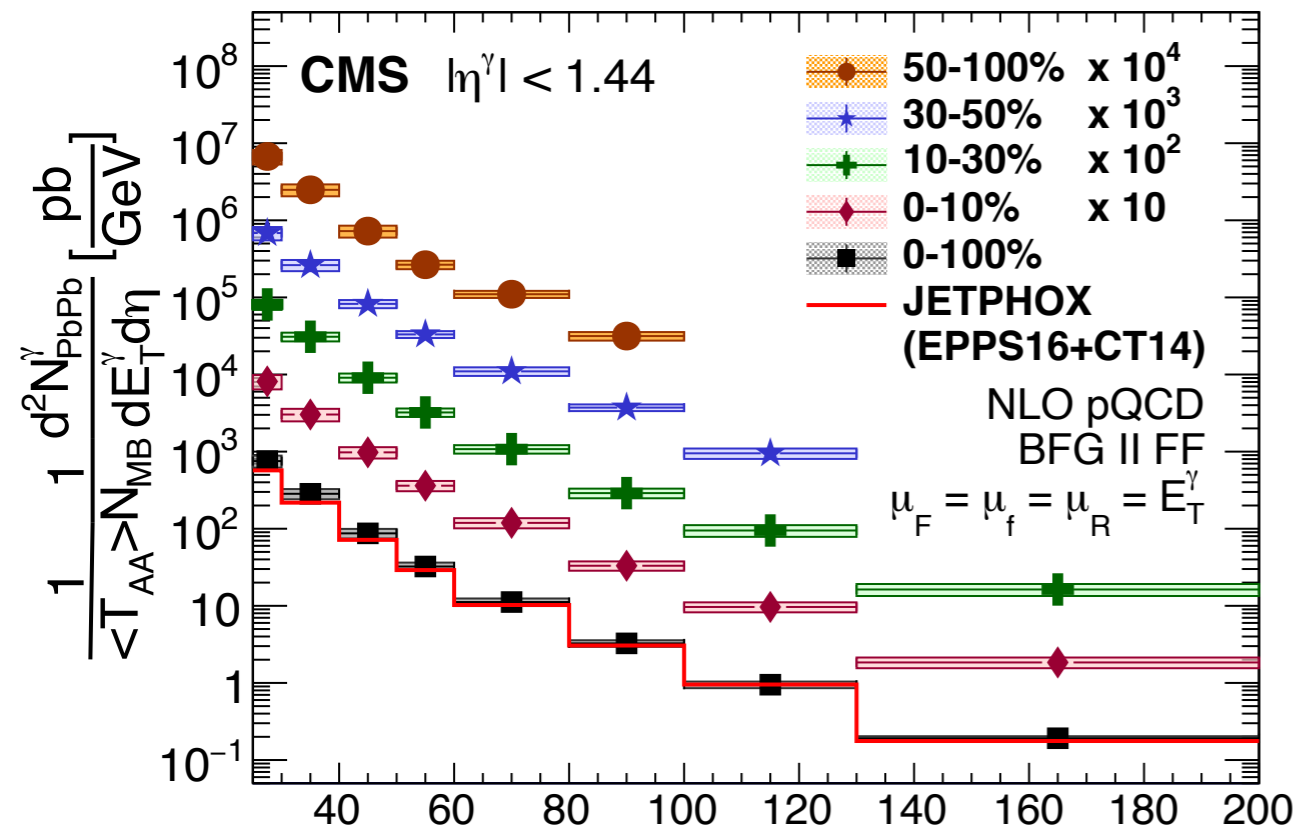


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Cross section of isolated photons (PbPb)

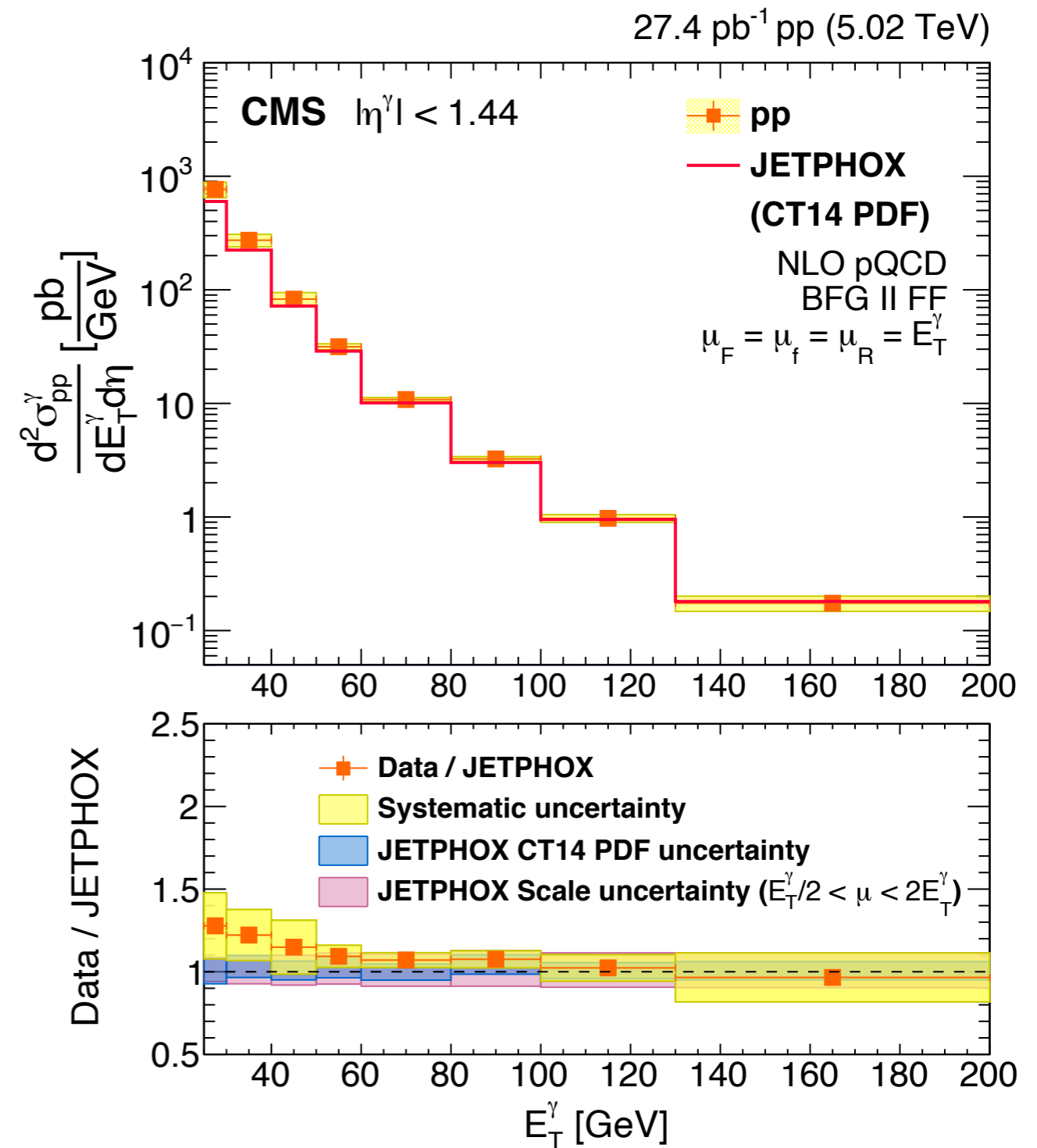
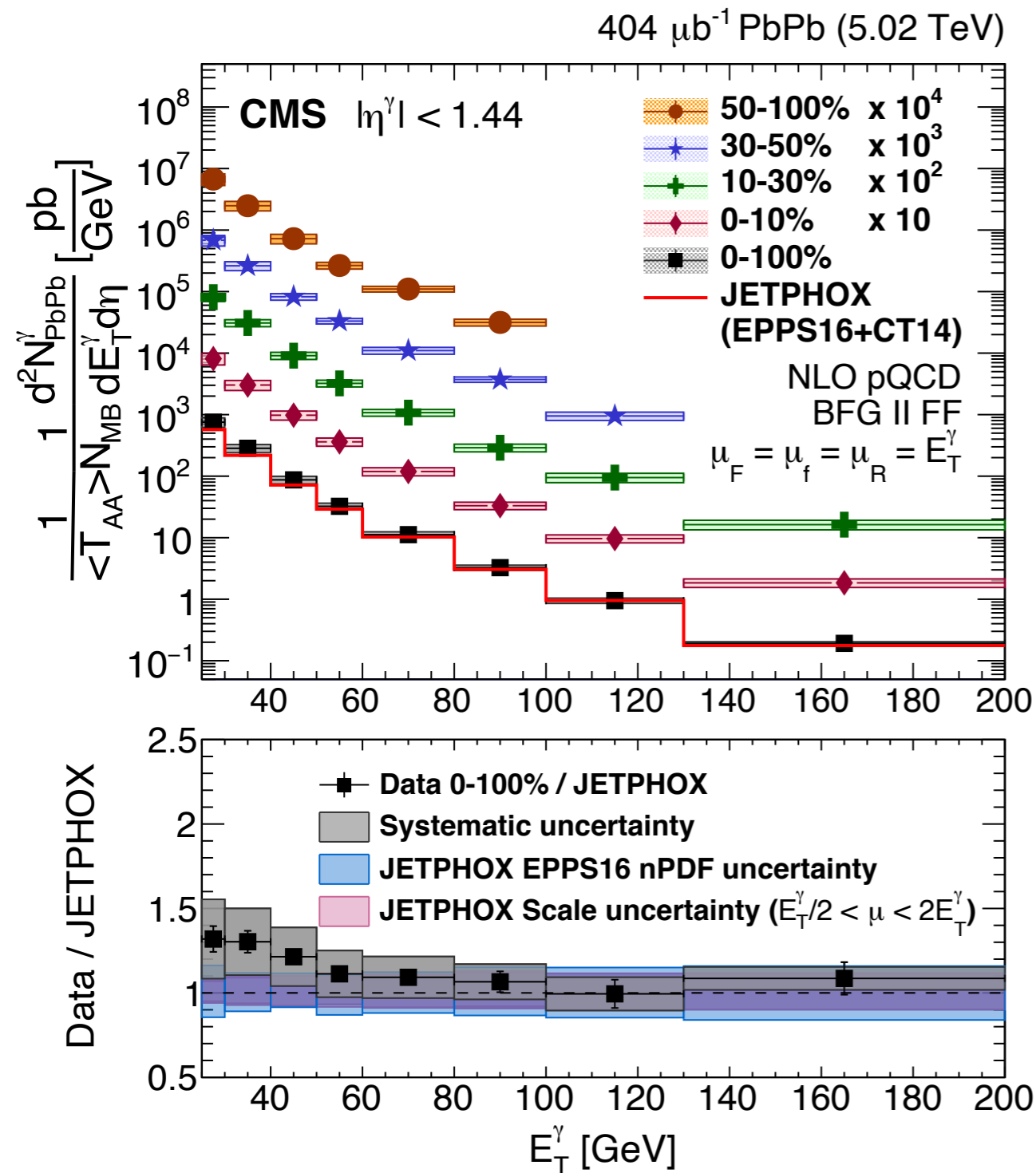
404 μb^{-1} PbPb (5.02 TeV)

404 μb^{-1} PbPb (5.02 TeV)



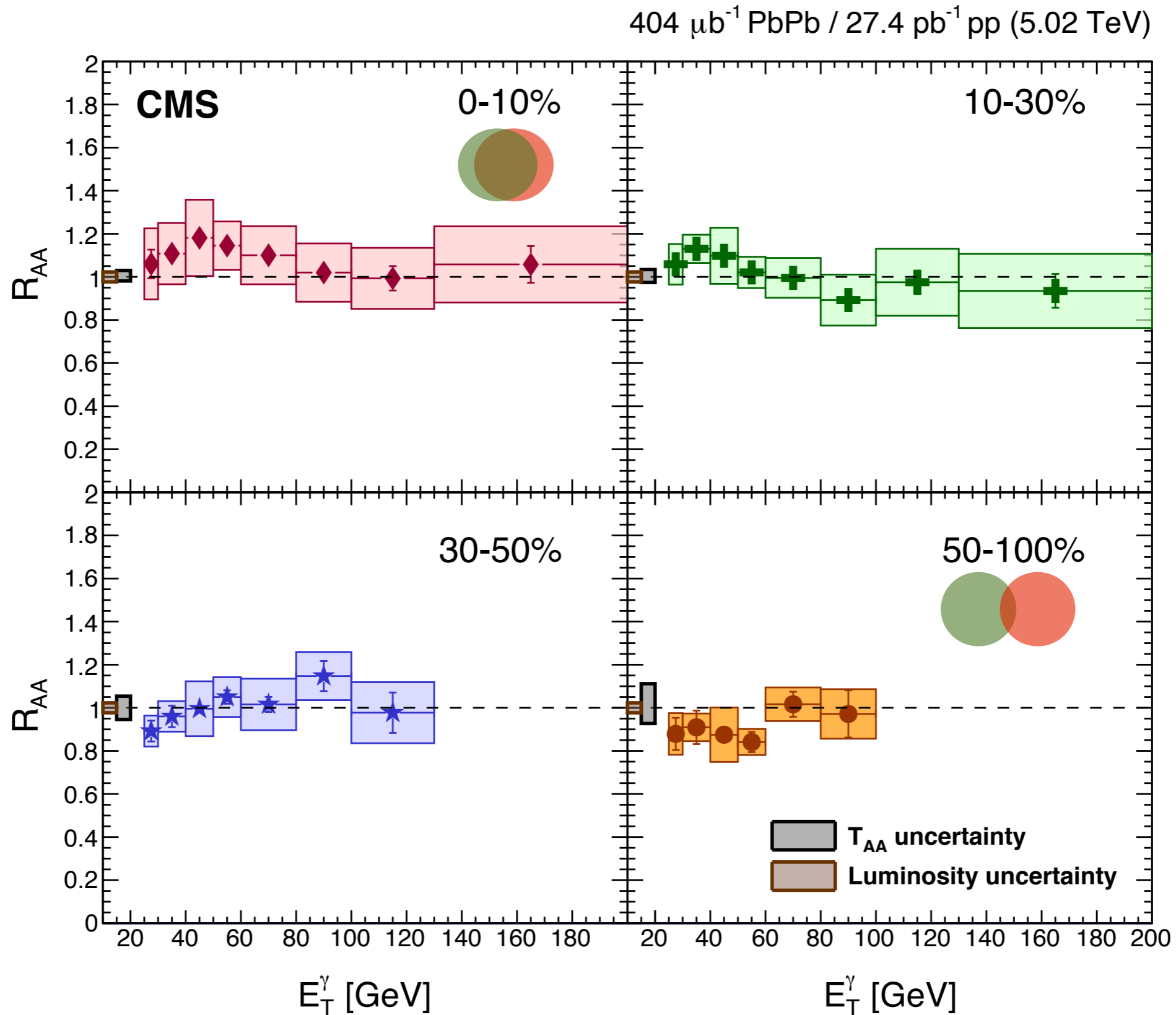
• **JETPHOX predictions are consistent with the data in both pp and PbPb**

Cross section of isolated photons (PbPb)



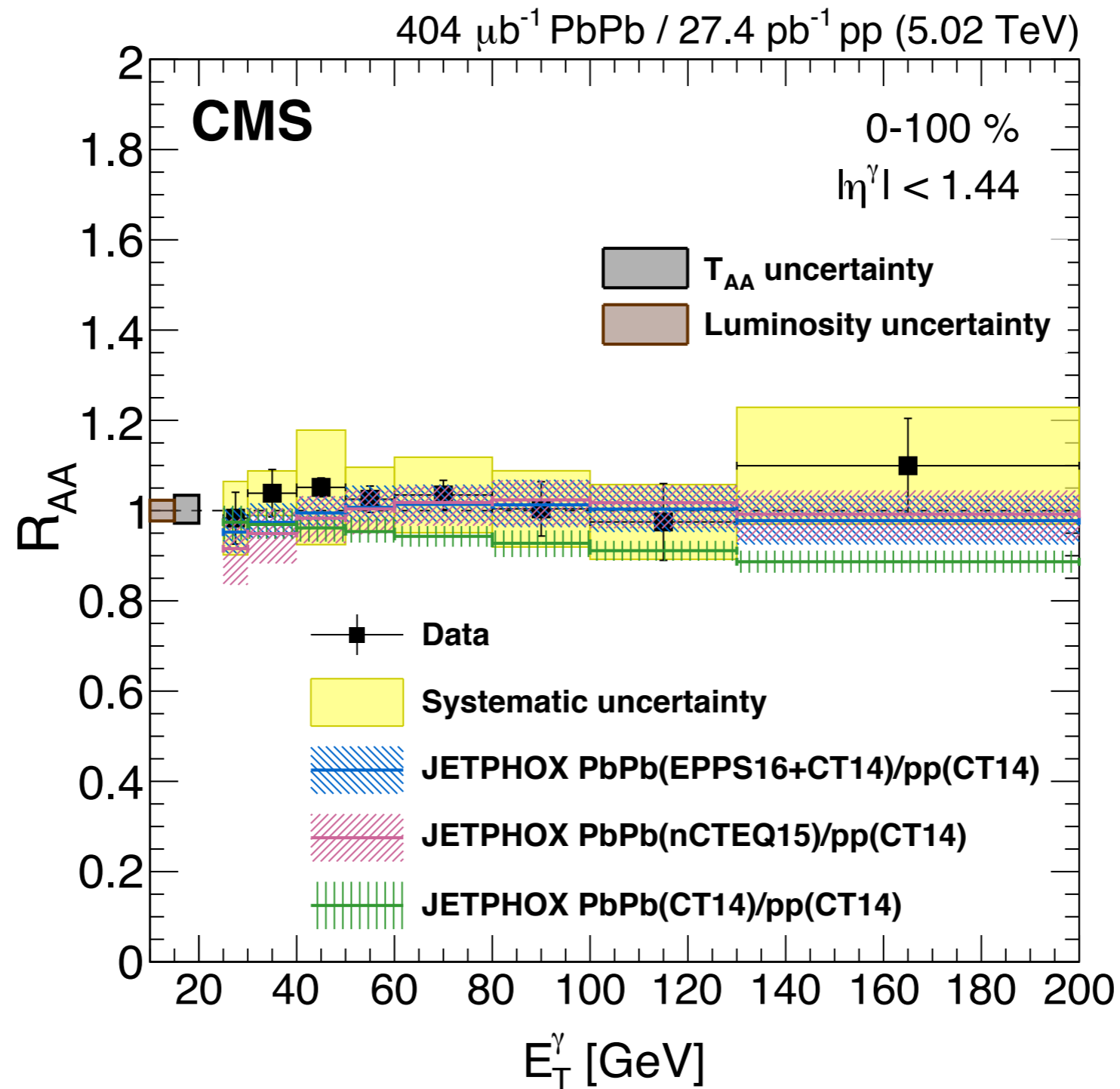
◉ **JETPHOX predictions are consistent with the data in both pp and PbPb**

Nuclear modification factor



- **No significant modification** is found in R_{AA} for various collision centralities

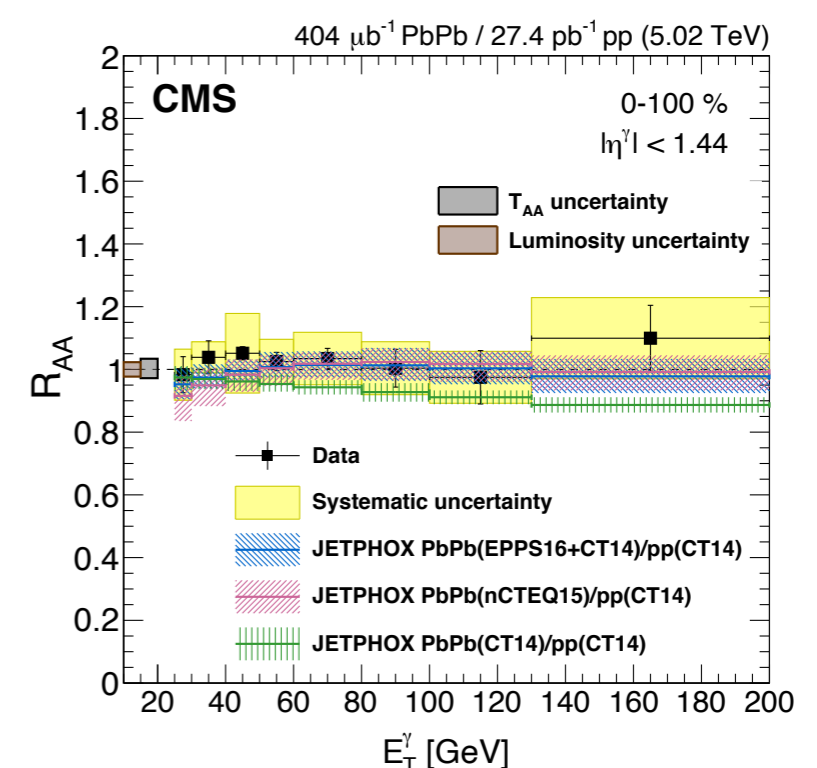
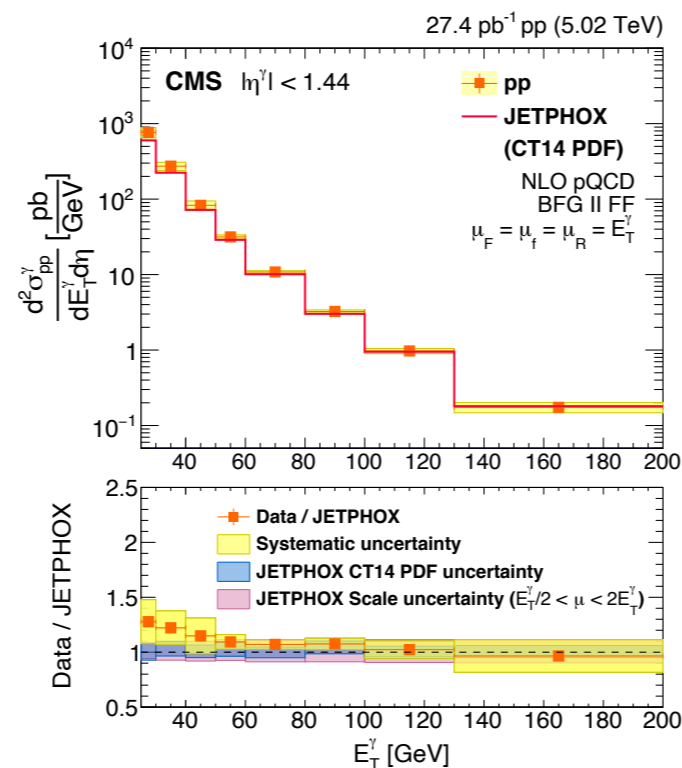
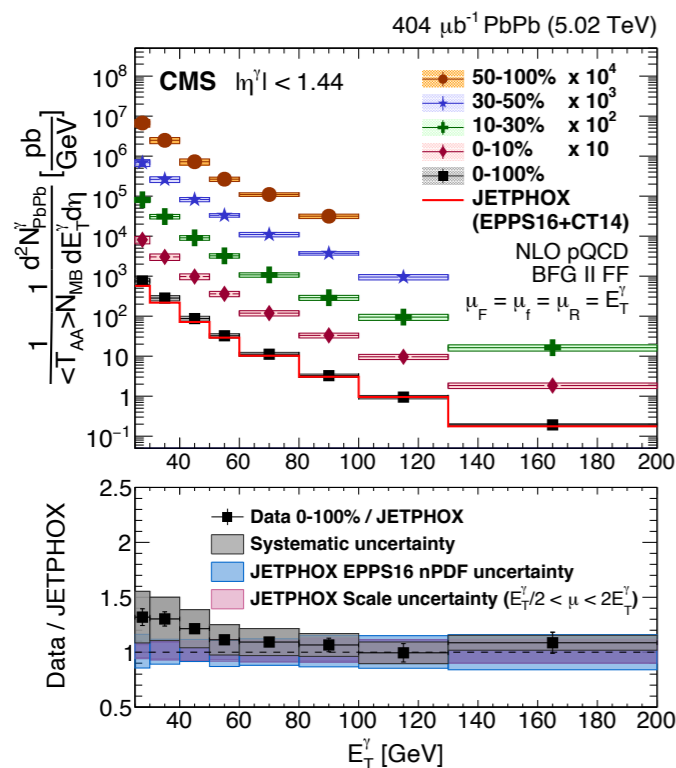
Comparison with predictions



- Both **EPPS16** and **nCTEQ15** describe the data well within the uncertainty

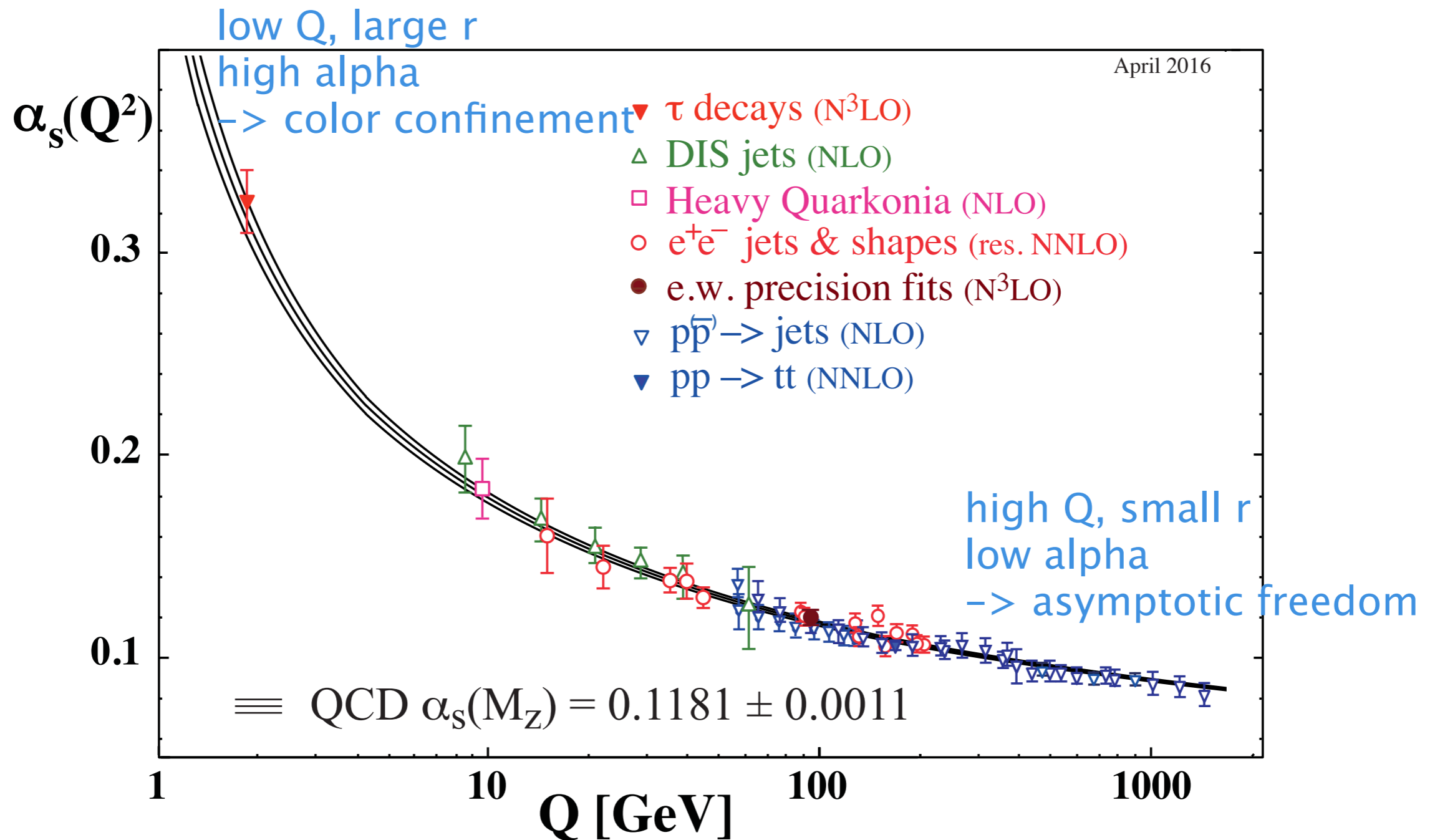
Conclusion

- **High- p_T isolated photons** are **valuable probes** for understanding **nPDF** and the **in-medium effect**
- The **nuclear modification factor** and **cross sections** have been measured for isolated photons in PbPb and pp at 5.02 TeV
 - **significantly improved accuracy** compared to the previous CMS data
 - measured in a higher E_T range ([20,80] GeV \rightarrow [25,200] GeV)
- The **NLO JETPHOX** prediction is found to be **consistent with the data**
- **No significant modification** of isolated photons is found in R_{AA}
- The results can help to constrain the nPDFs global fits.



BACK UP

Strong coupling constant



- The coupling constant decreases logarithmically as the interaction energy gets higher: **running** coupling constant
- Two distinctive features of QCD: **color confinement** and **asymptotic freedom**

Prompt photons in various collision systems

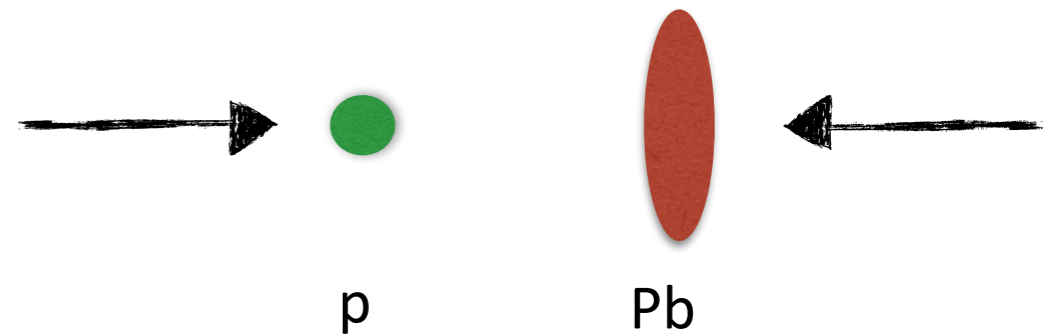
● **pp collisions**

- pQCD benchmark
- reference for larger systems



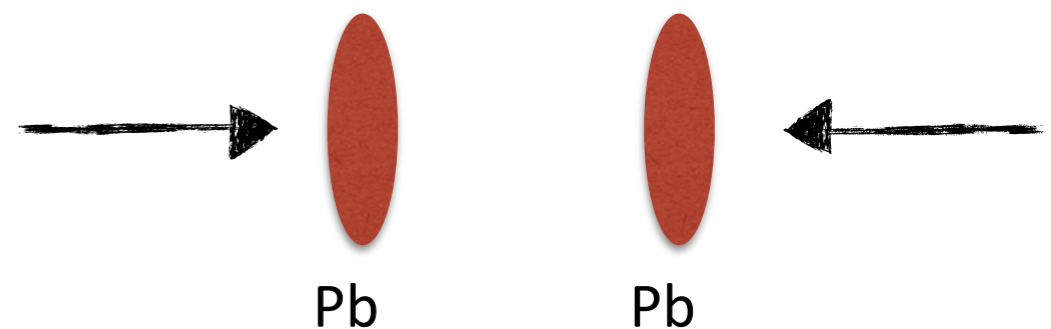
● **pPb collisions**

- study cold nuclear matter (CNM) effect
- PDF modification:
(anti)shadowing, gluon saturation

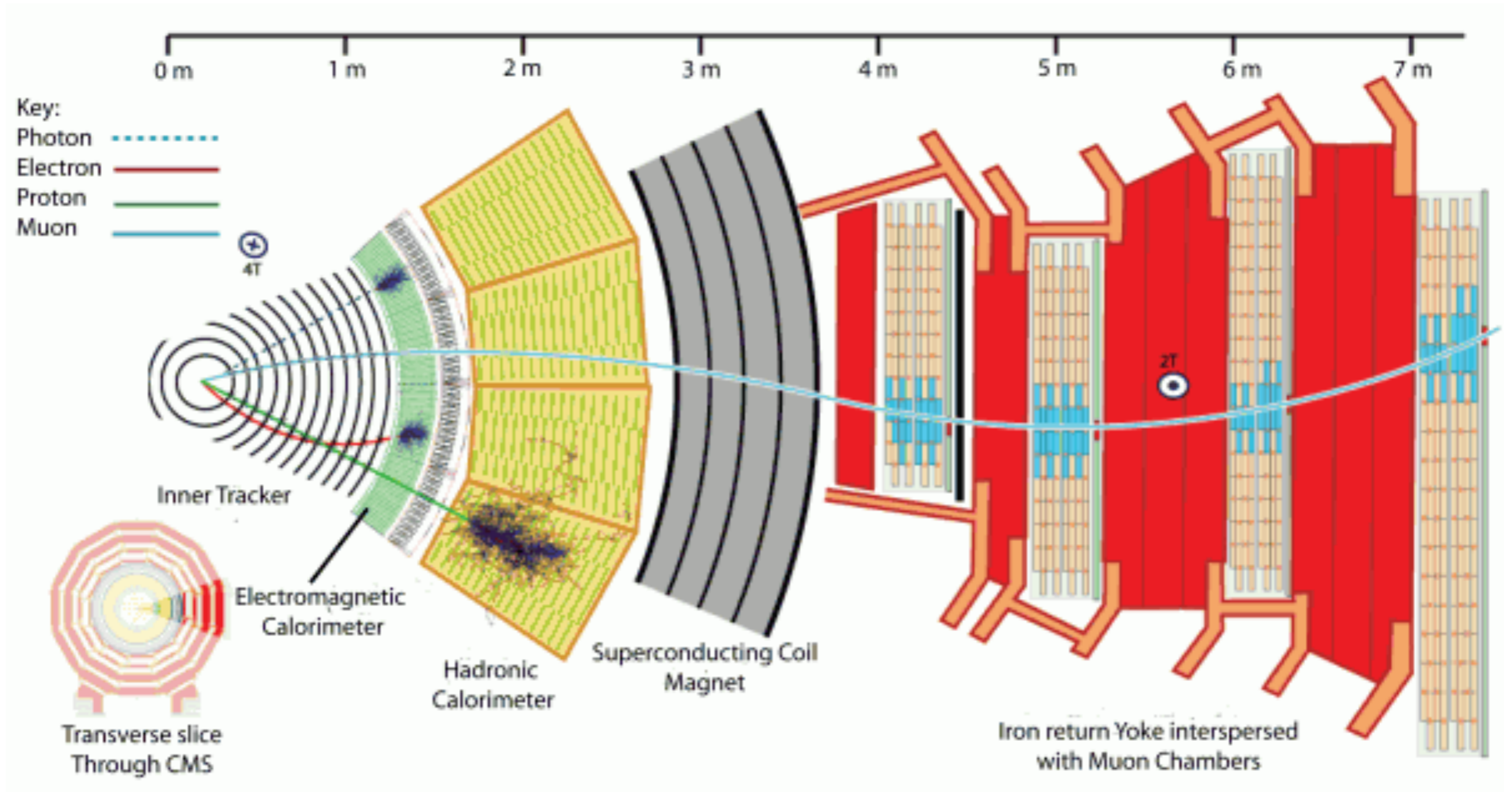


● **PbPb collisions**

- study hot nuclear matter effect (QGP)



CMS detector

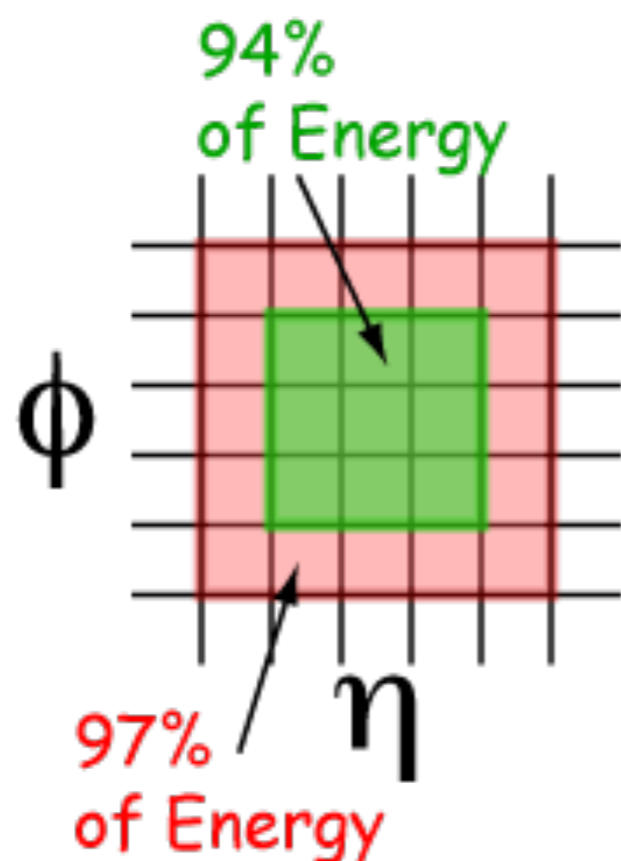


- **Tracker**, **ECAL** and **HCAL** are used for photon **reconstruction, identification and isolation**

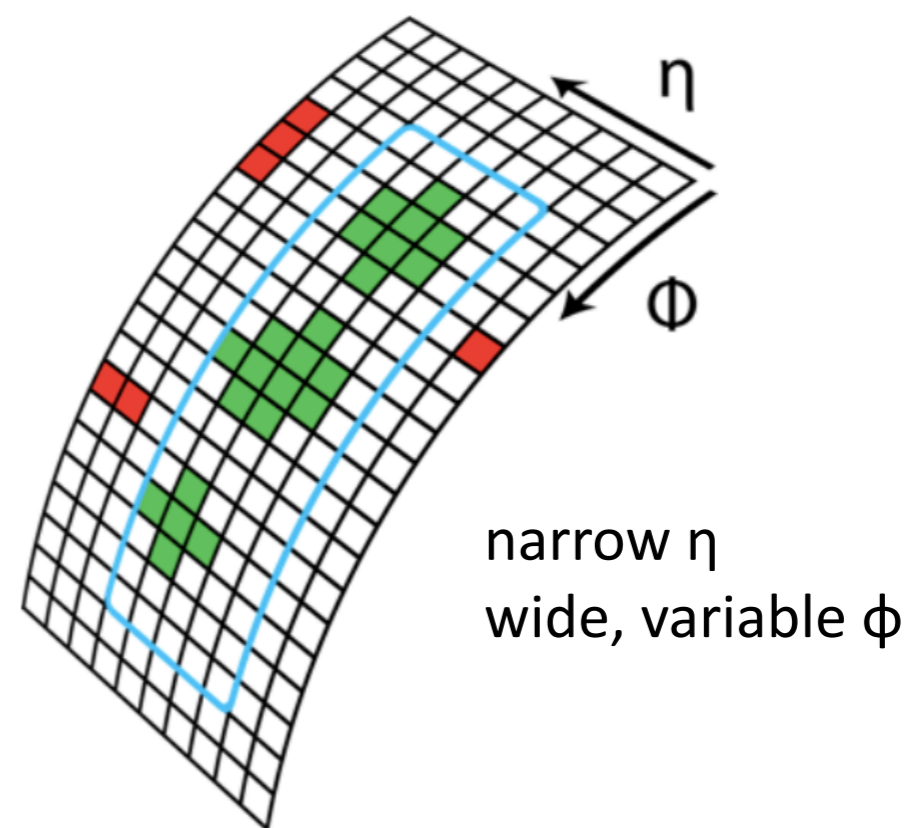
Photon reconstruction

- Energy deposits in ECAL crystals are aggregated in “**superclusters**”
- Almost full (97%) energy of **unconverted photons** is limited in 5x5 crystals
- Energy of **converted photons** and **their radiation (Bremsstrahlung)** is spread in ϕ

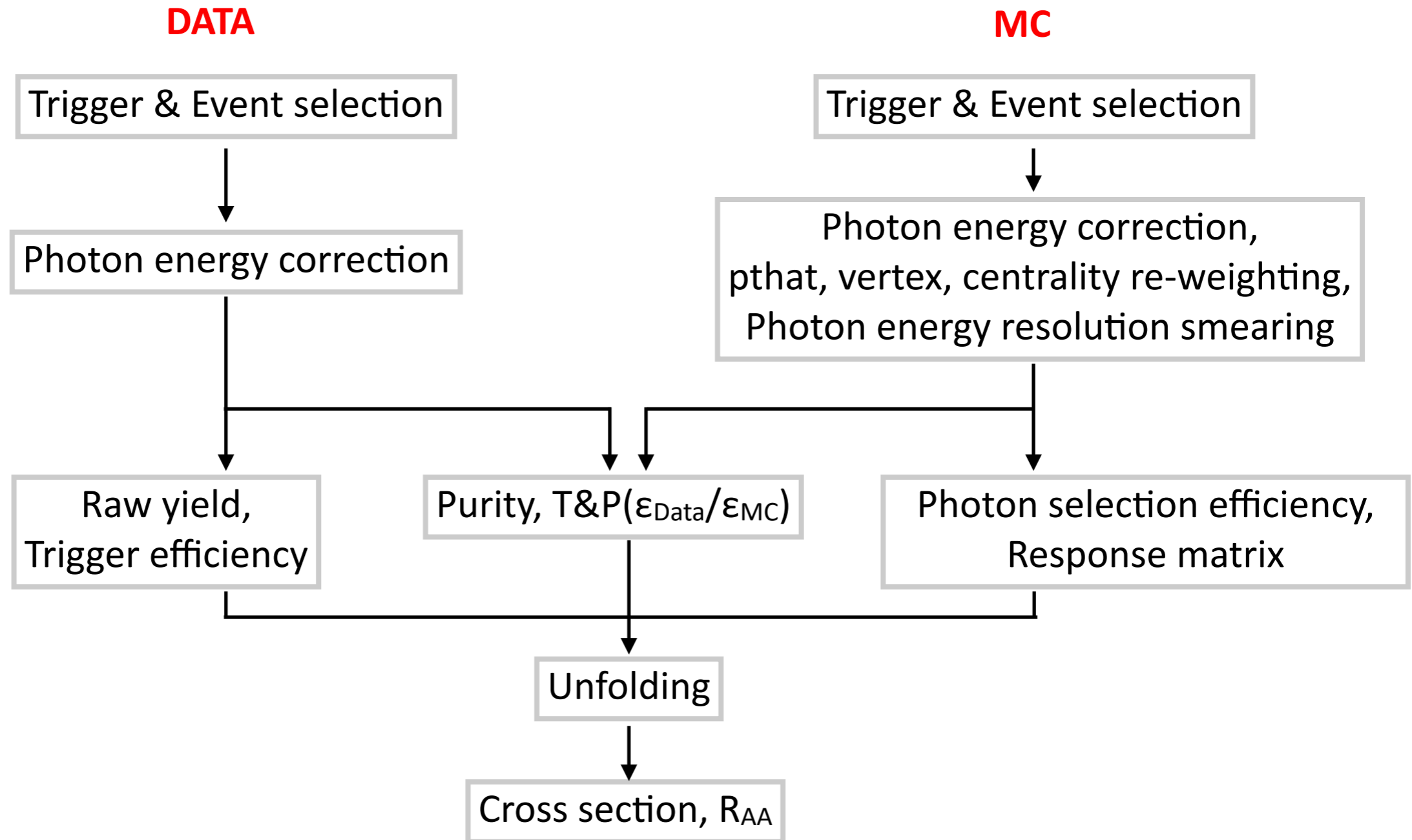
Un-converted photons



Converted photons



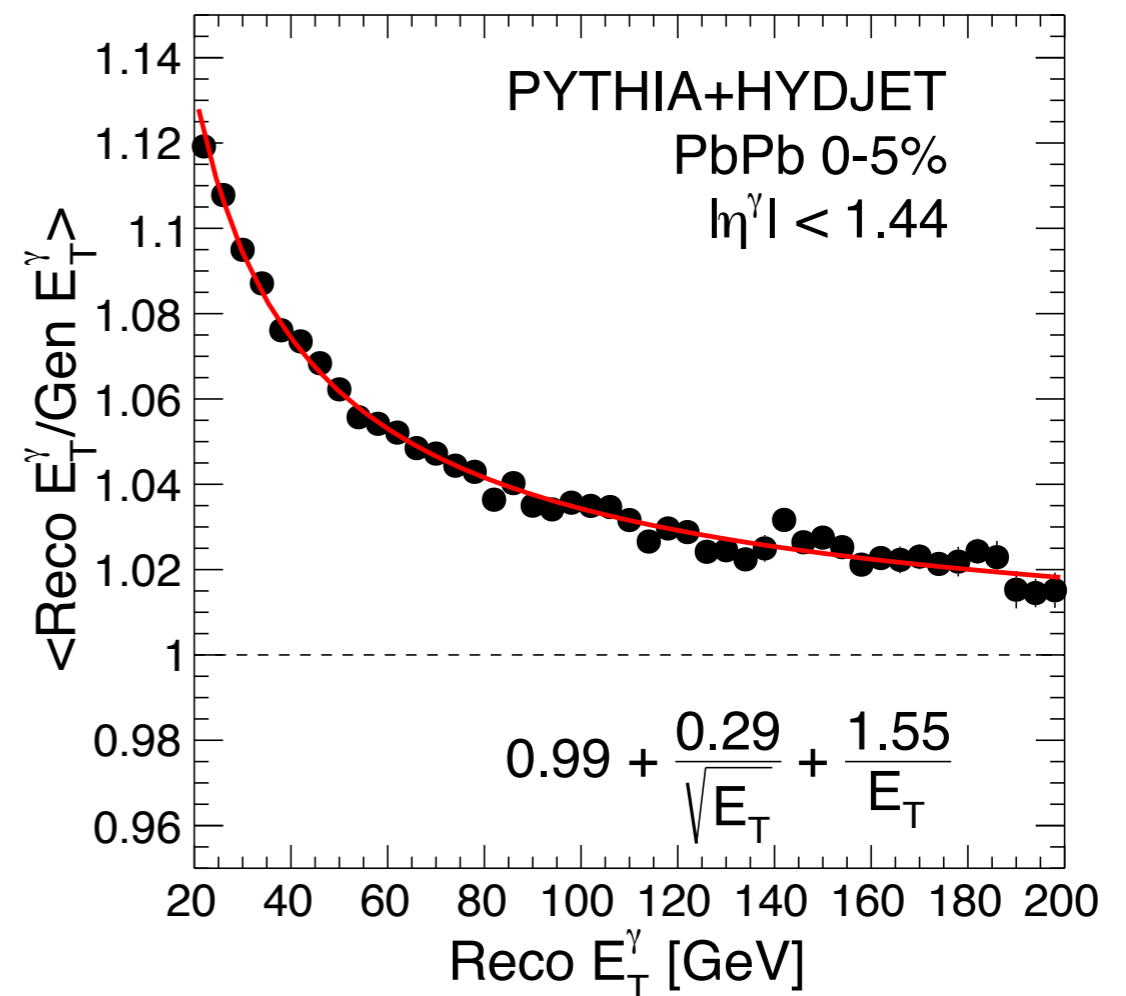
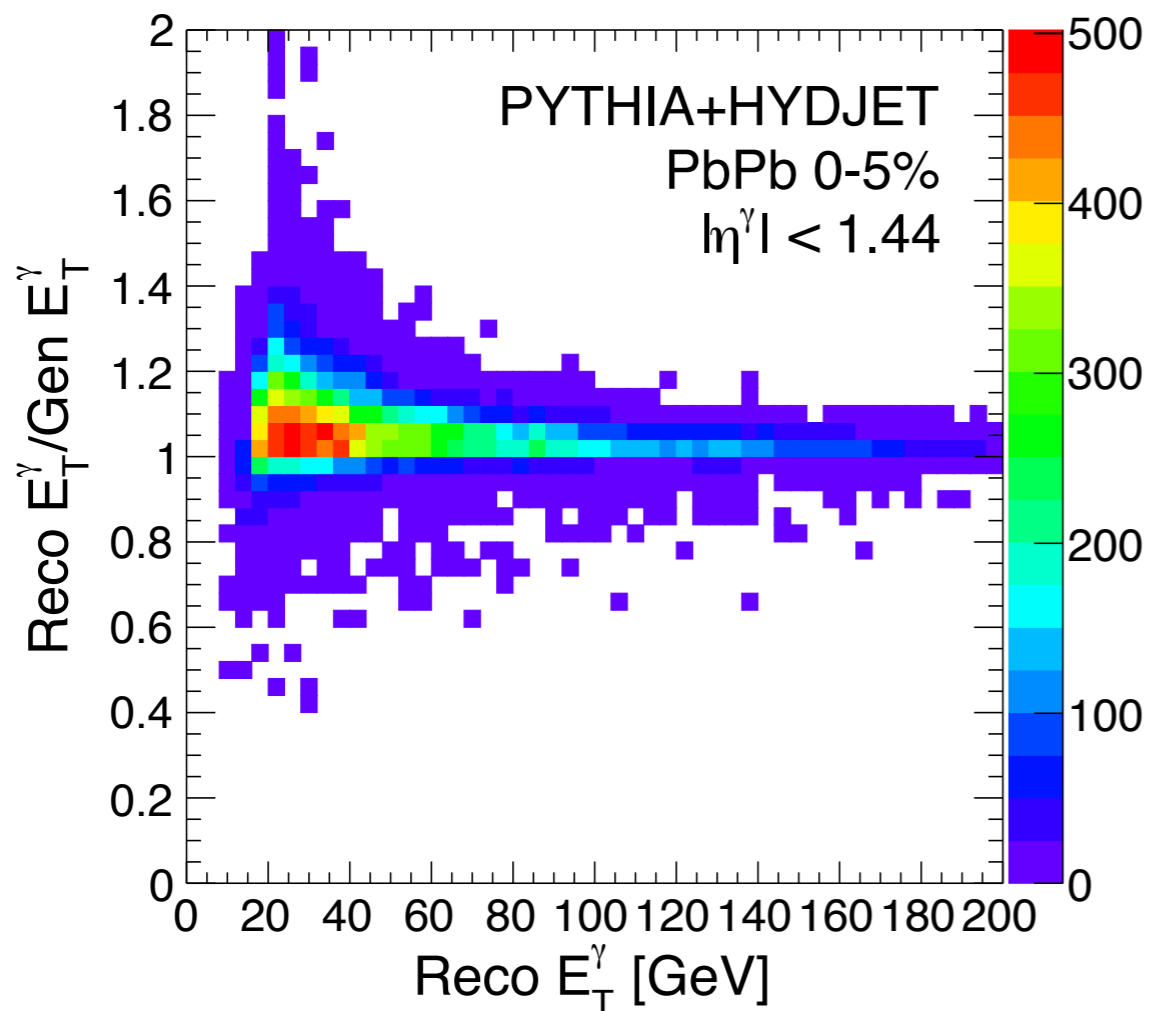
Analysis flow chart



* Below conditions are applied on Efficiency, Purity and Yield calculation

- 1) signal photon selection condition (H/E , $\sigma_{\eta\eta}$, $\text{sum}l_{\text{iso}}$)
- 2) electron rejection
- 3) noise mask (spike rejection, hotspot rejection)

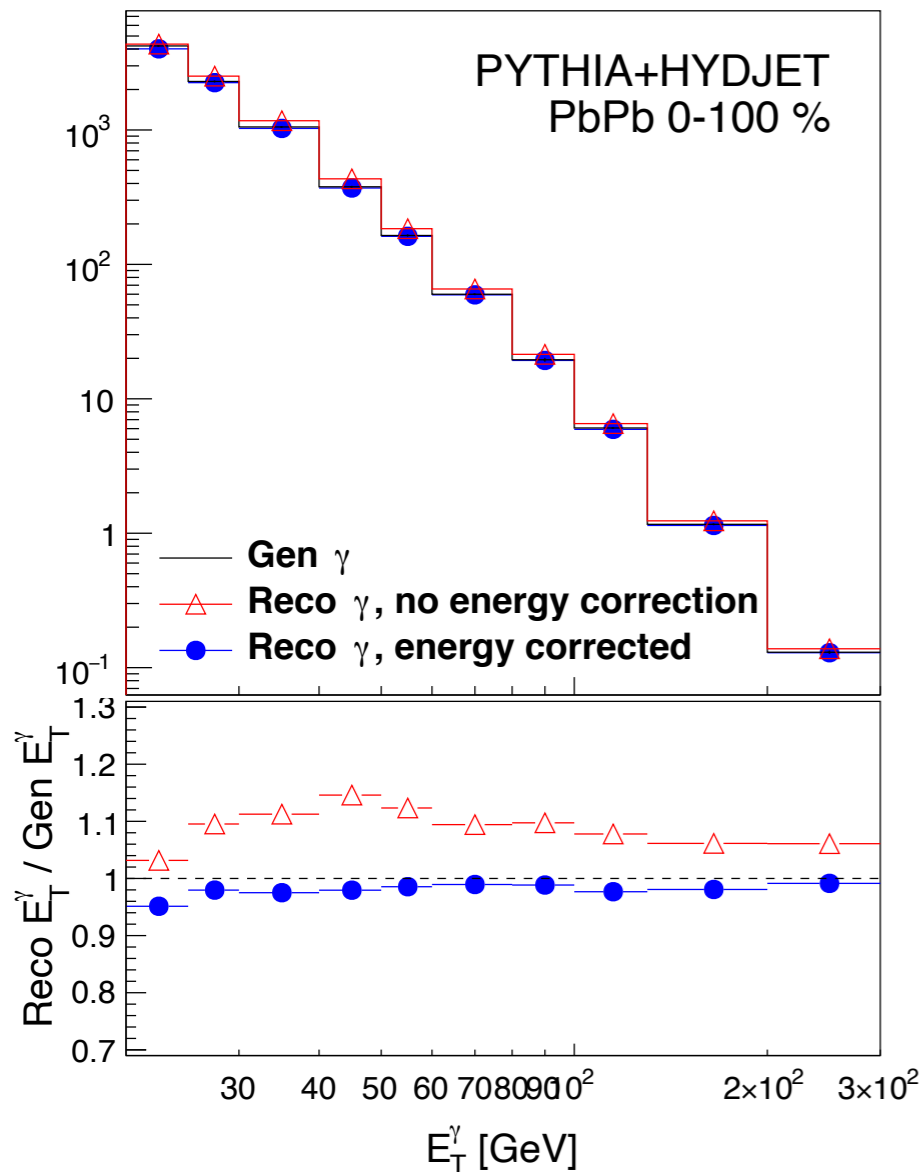
Photon energy correction



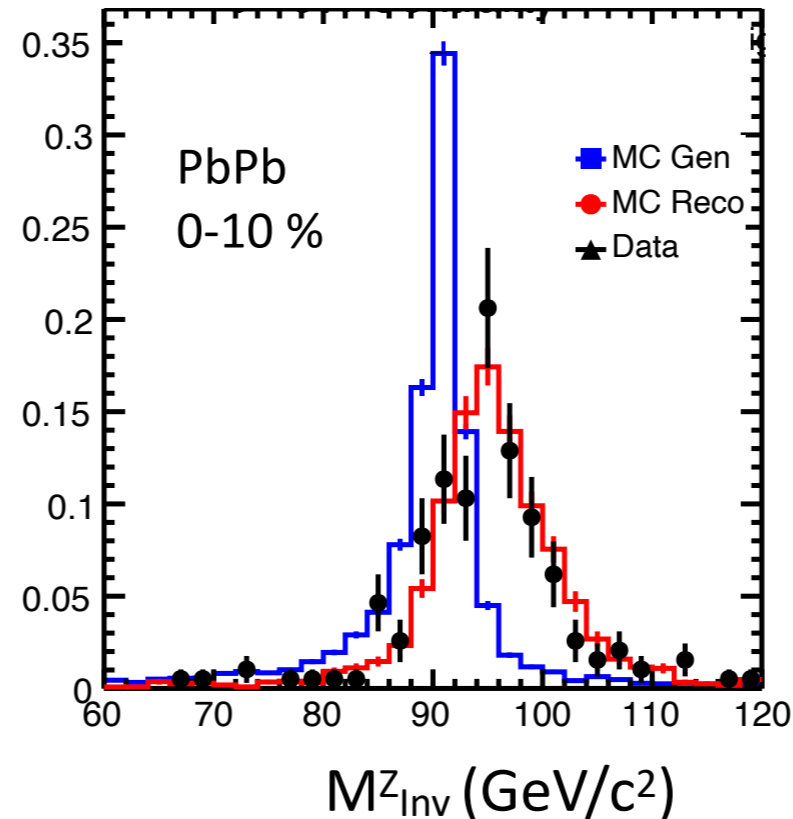
- **Energy of the reconstructed photons is corrected**

- photon energy scales as a function of E_T are determined by simulation in 7 different centrality intervals

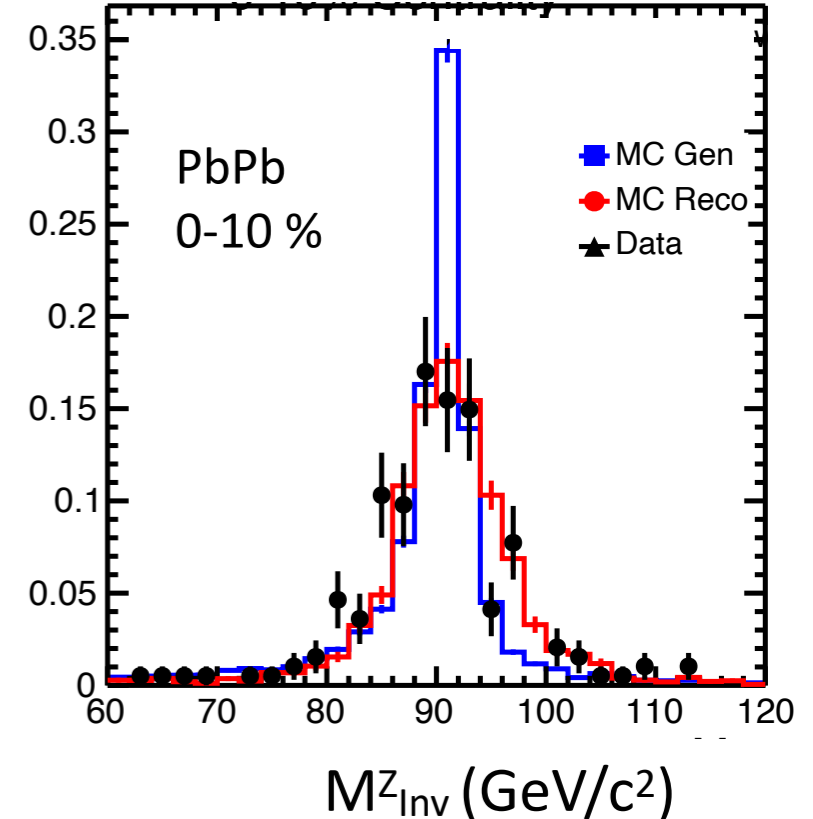
Validation: photon energy correction



Before energy correction



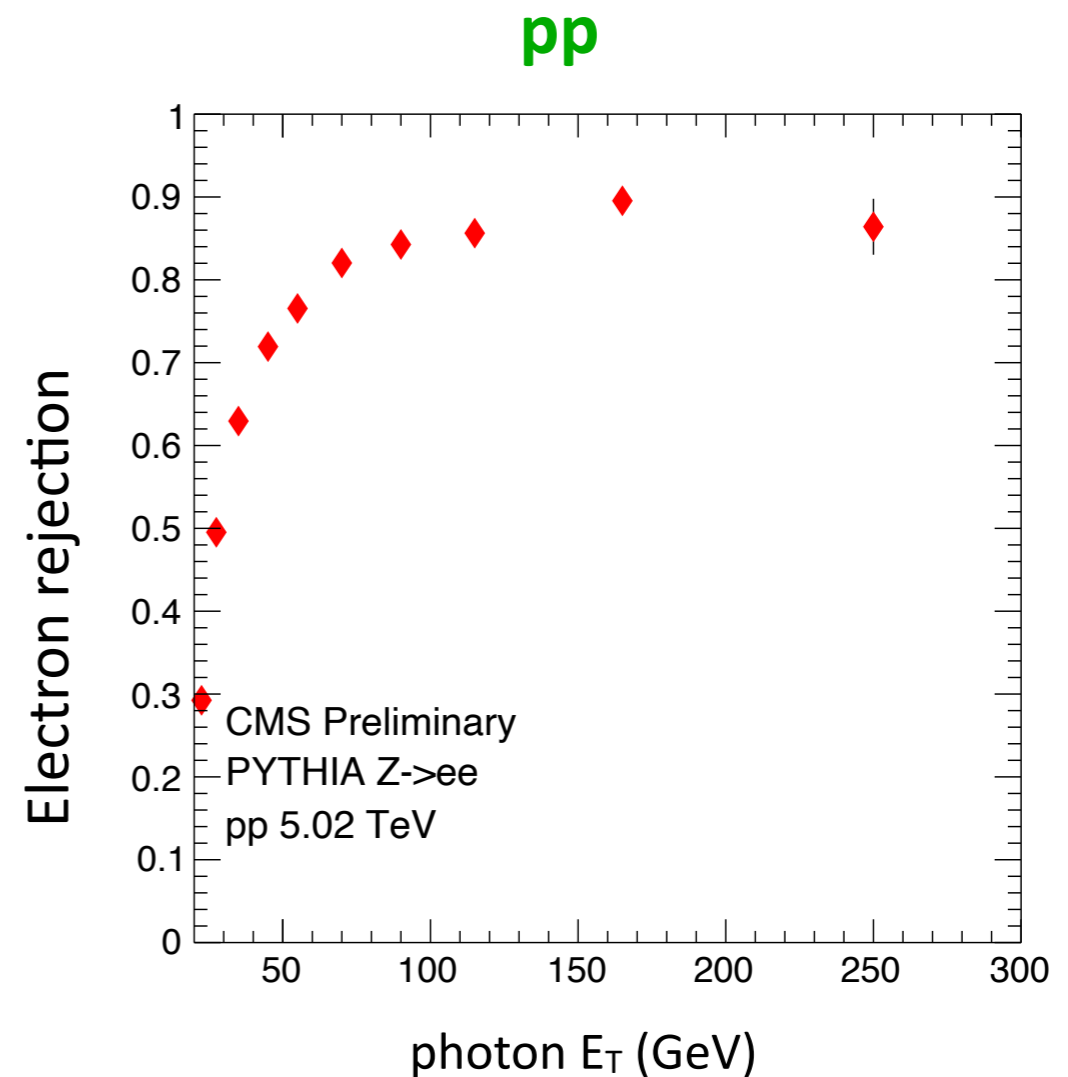
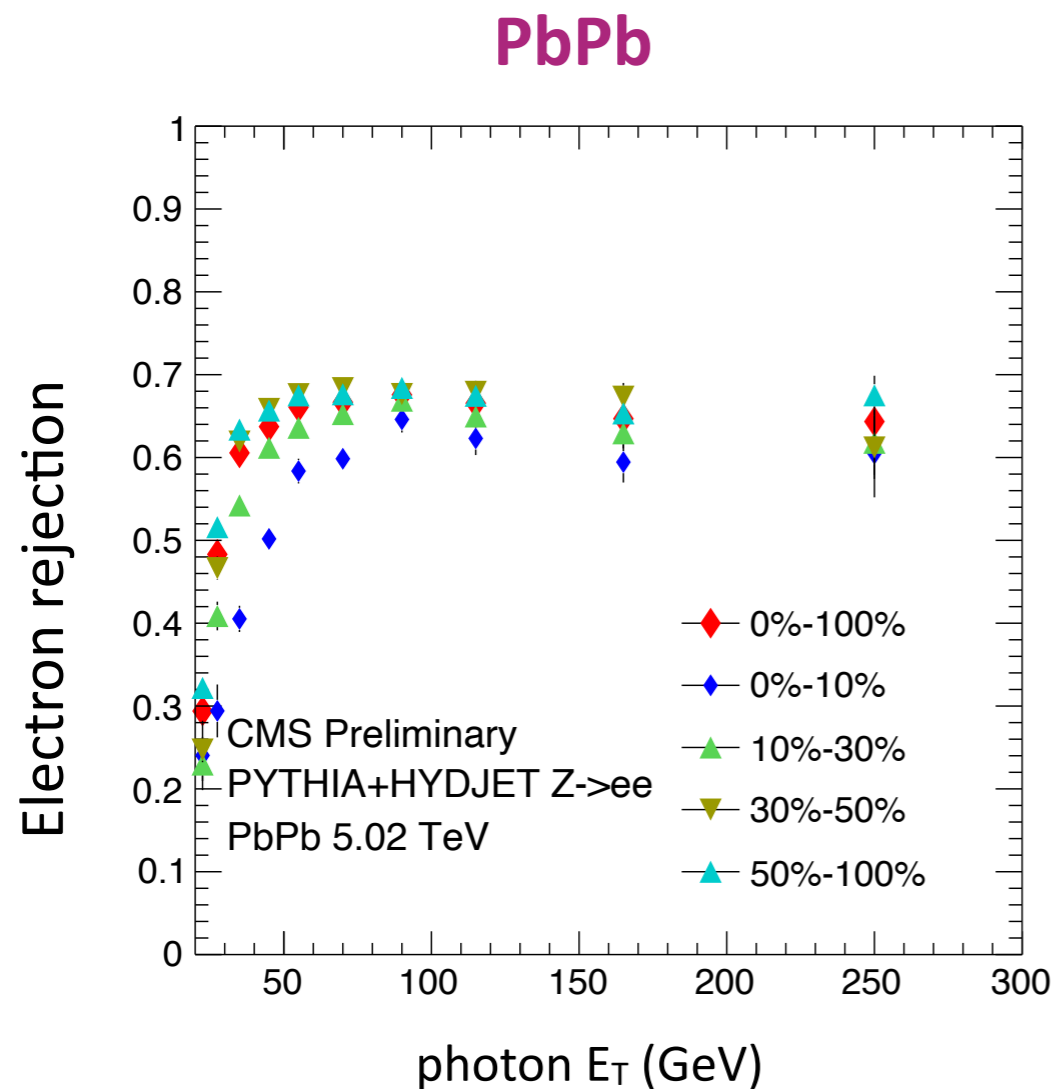
After energy correction



- Validation: Z mass is reconstructed well after the energy correction
- Systematic uncertainty: residual difference btw data and MC

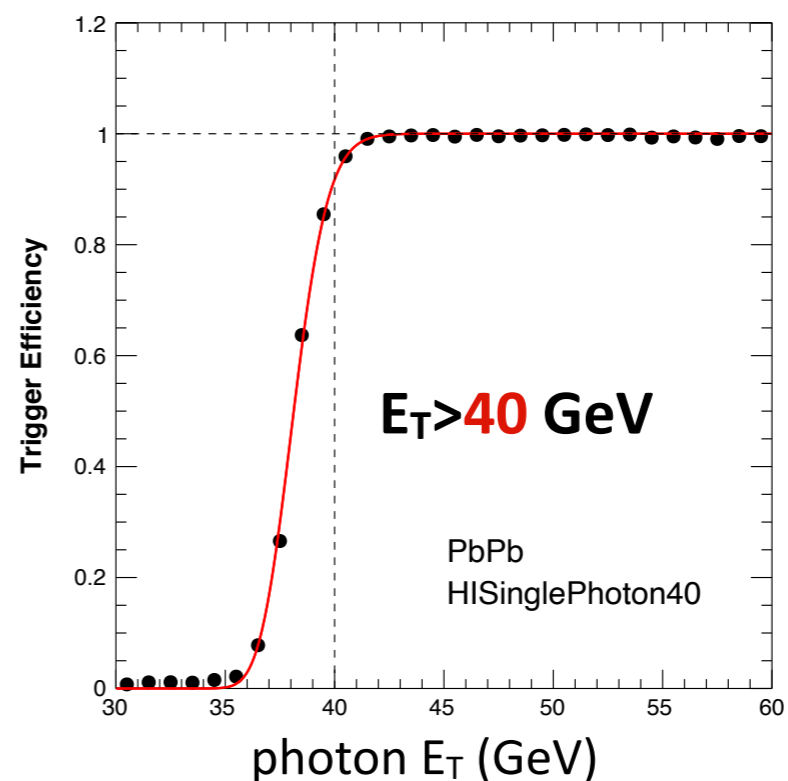
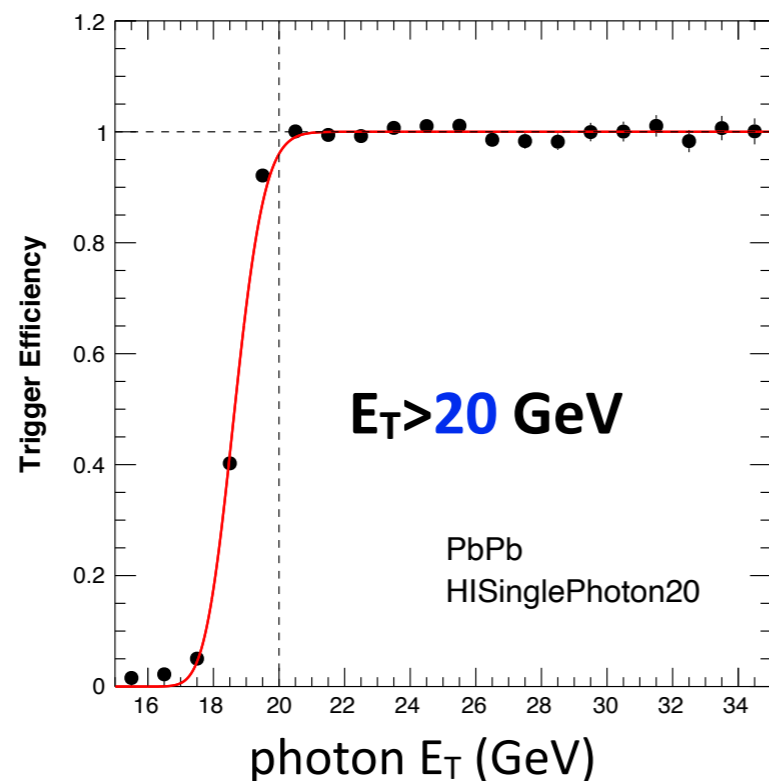
Electron rejection

- Electrons **mis-identified as photon are rejected** by matching photon candidates to electron candidate when $|\Delta\eta| < 0.03$ and $|\Delta\phi| < 0.03$
- $\epsilon_{\text{electron rejection}} = N_{\text{rejected mis-identified electrons}} / N_{\text{mis-identified electrons}}$**
- Remaining electron contribution is **statistically subtracted** and considered as **systematic source**: $(1 - \epsilon_{\text{electron rejection}}) / \epsilon_{\text{electron rejection}}$

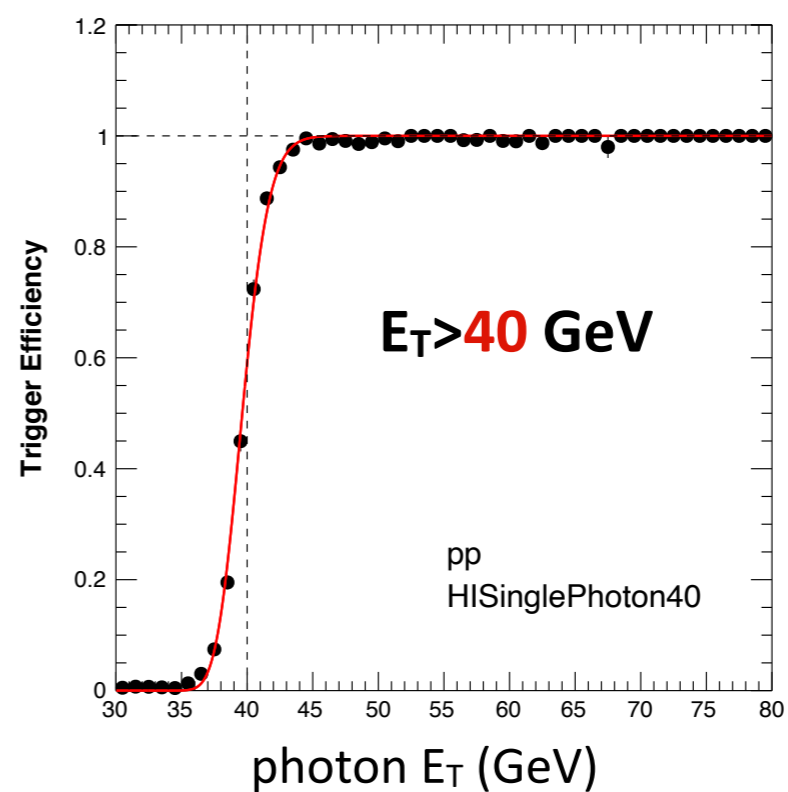
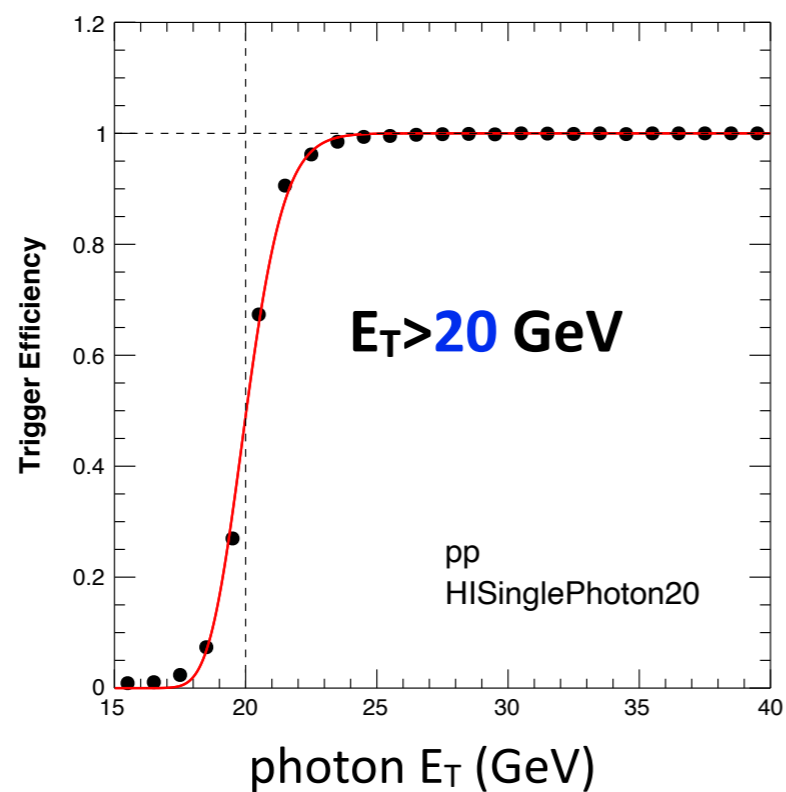


Trigger efficiency

PbPb

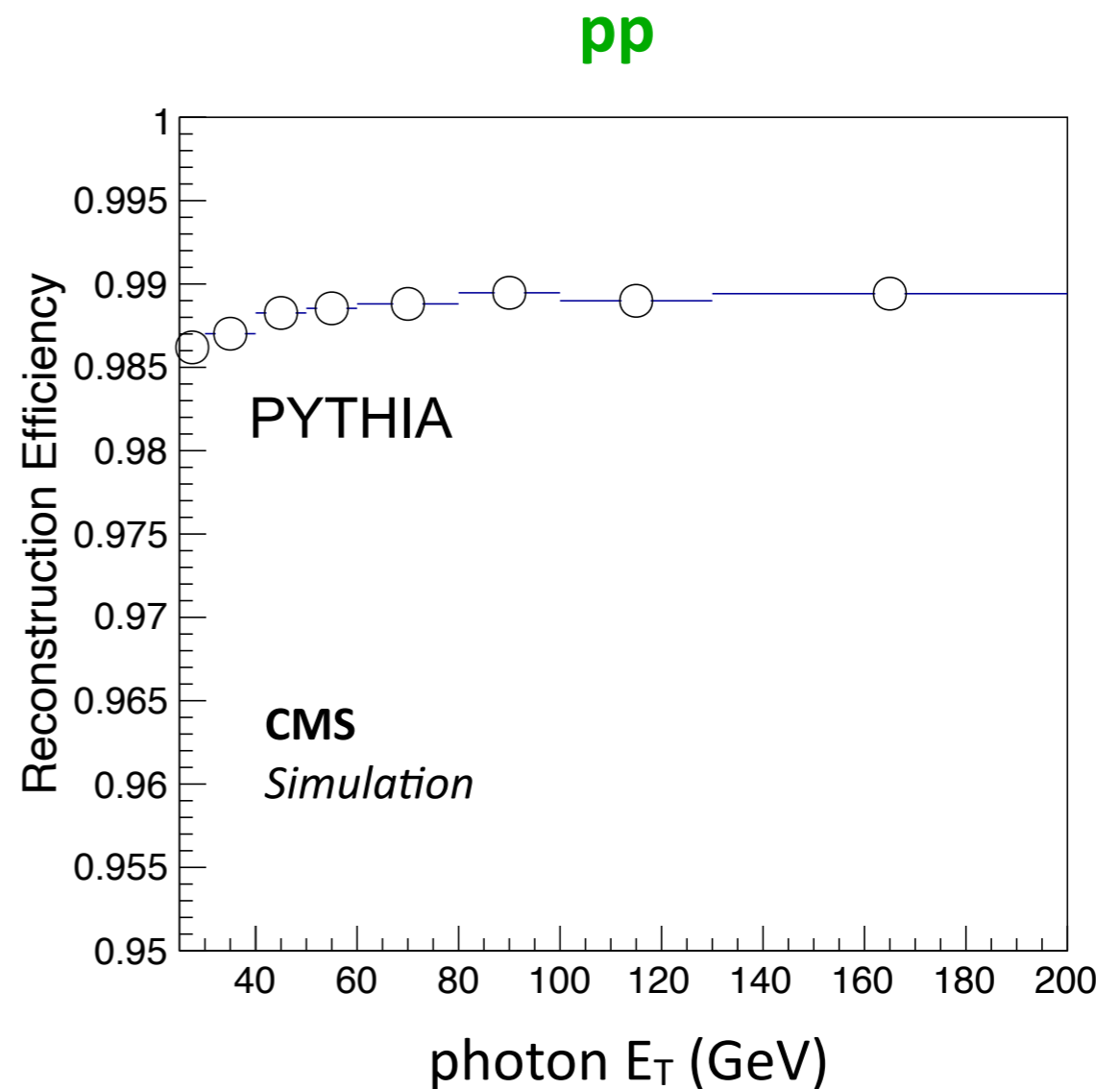
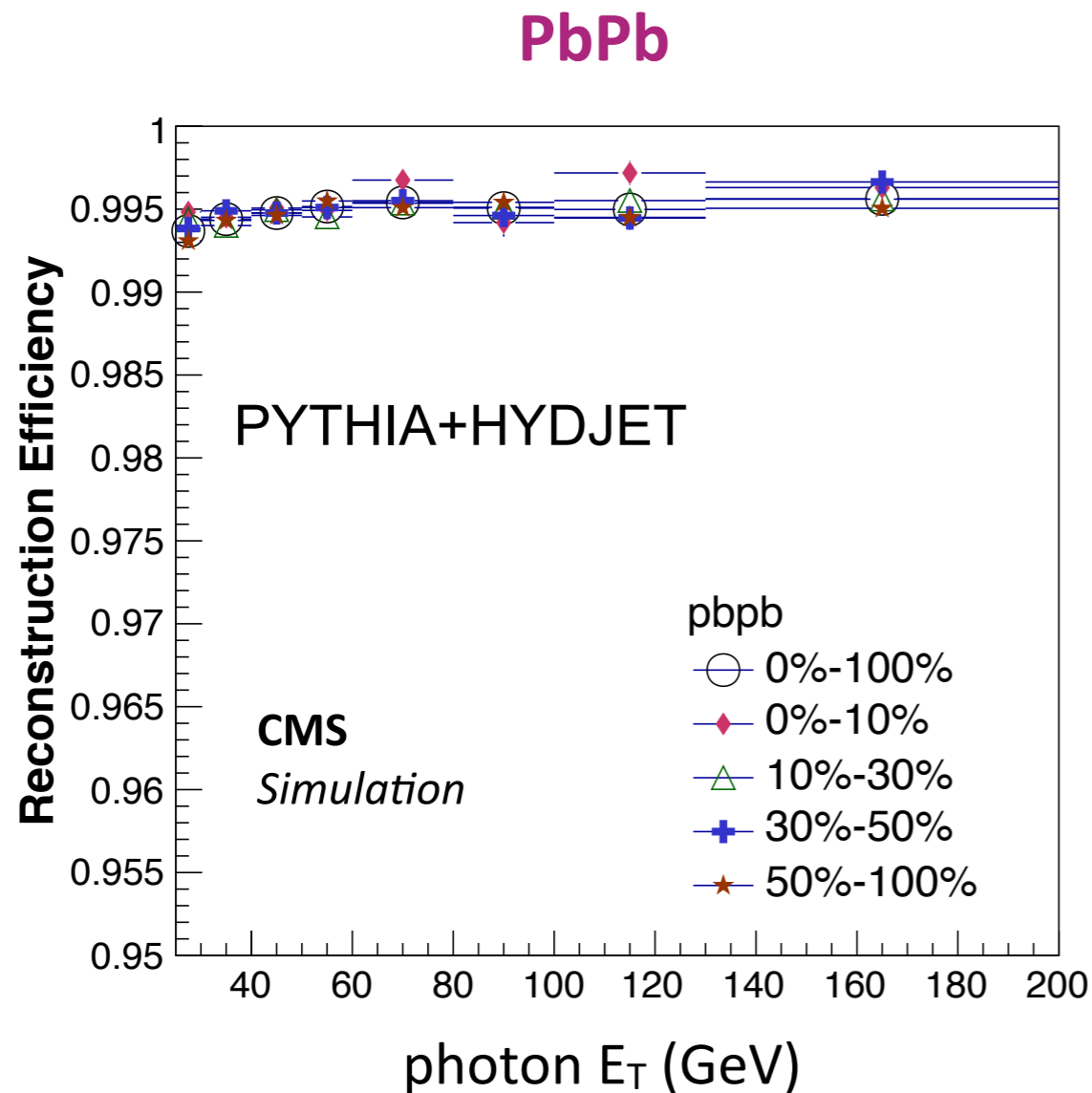


pp



- Trigger efficiency is derived from data as a function of corrected photon energy

Reconstruction efficiency

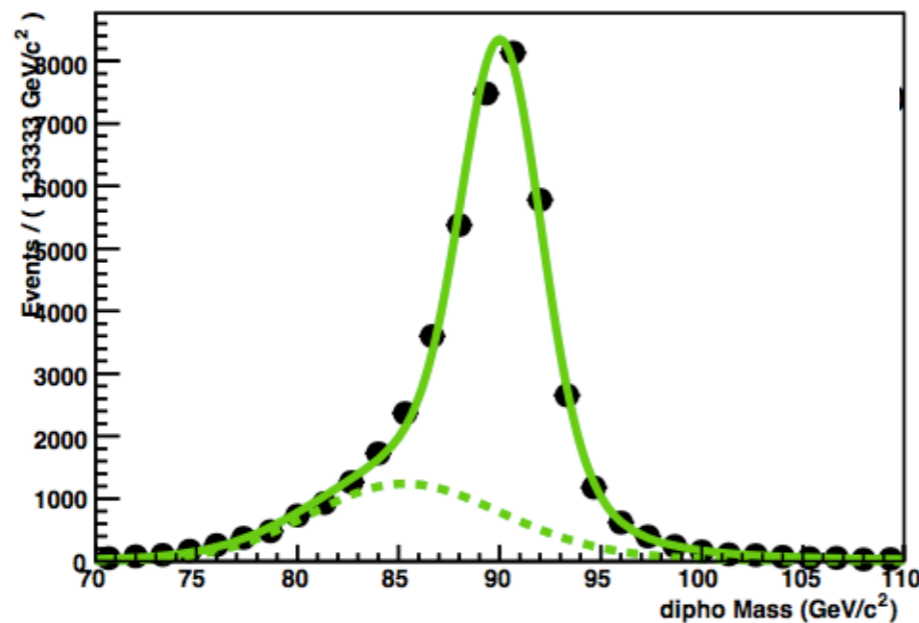


- **Reconstruction efficiency** = $N_{\text{generated and reconstructed photons}} / N_{\text{generated photons}}$
 - generator-level isolation energy < 5 GeV inside a cone of $dR = 0.4$
 - generated and reconstructed photon matching in $dR < 0.15$
- **Reconstruction efficiency is $\sim 99\%$** for pp and PbPb in all centrality classes

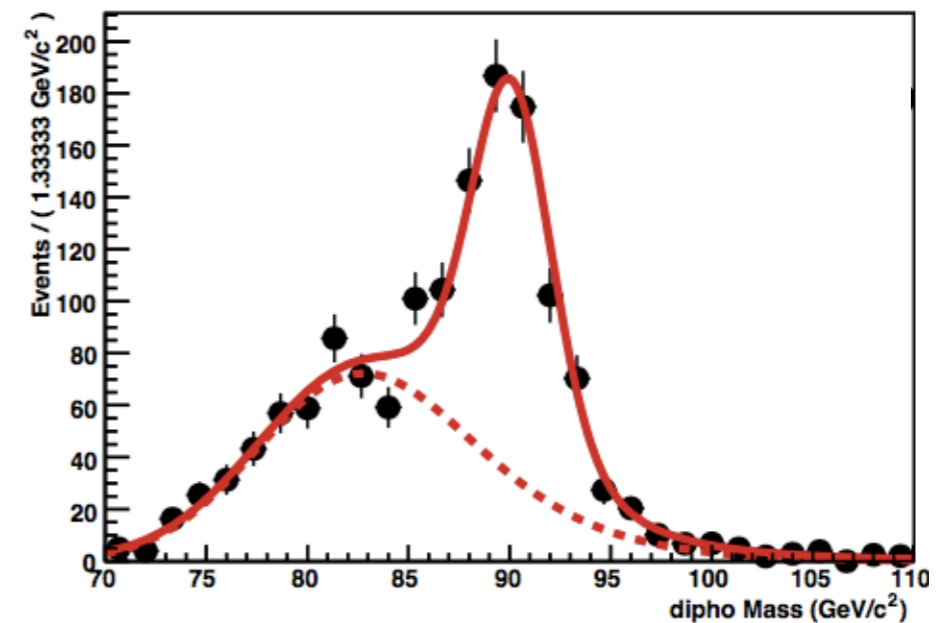
Tag-and-Probe method

- Scale Factor (SF) = $\epsilon_{\text{DATA}}/\epsilon_{\text{MC}}$
 - to compensate the discrepancy between data and MC
- Using the **tag-and-probe** method with **Z \rightarrow ee** events

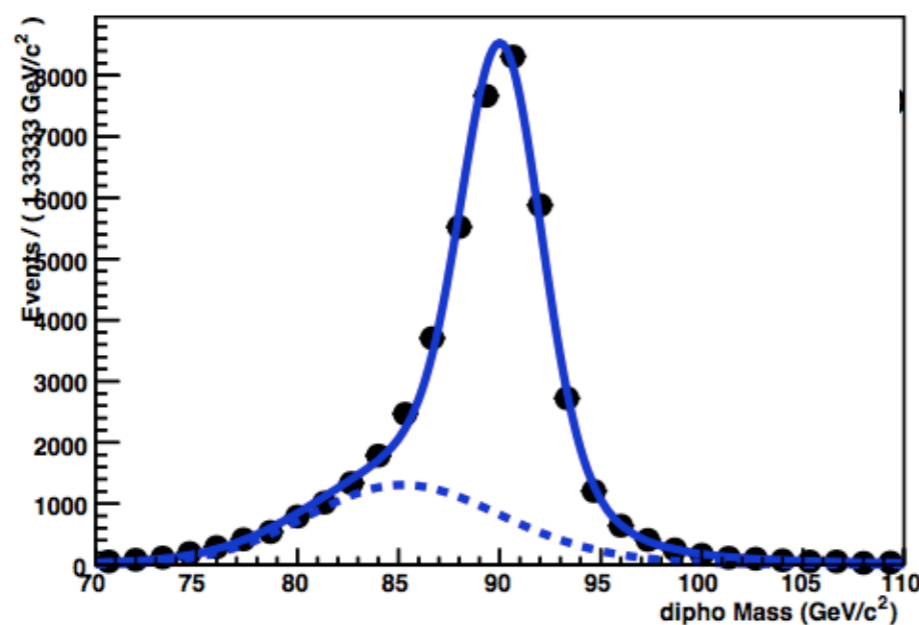
Passing Probes



Failing Probes



All Probes



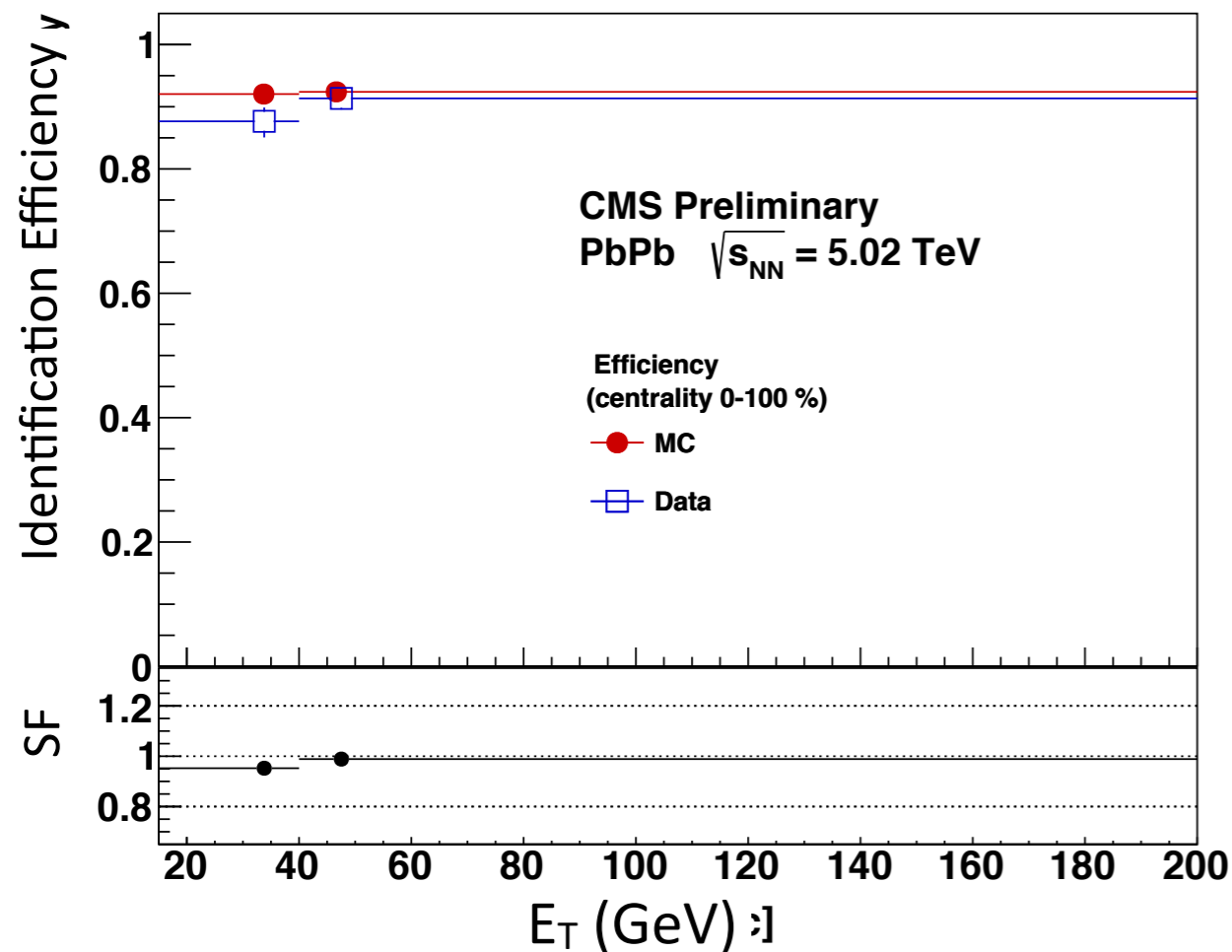
$\alpha_{\text{Fail}} = 84.8 \pm 0.9$
 $\alpha_{\text{Pass}} = 90.0 \pm 0.3$
 $\beta_{\text{Fail}} = 0.155 \pm 0.007$
 $\beta_{\text{Pass}} = 0.165 \pm 0.003$
 $\text{effBkg} = 0.937 \pm 0.008$
 $\text{efficiency} = 0.980 \pm 0.001$
 $f_{\text{SigAll}} = 0.74 \pm 0.04$
 $\gamma_{\text{Fail}} = 0.24 \pm 0.02$
 $\gamma_{\text{Pass}} = 0.372 \pm 0.008$
 $\text{mean} = 90.09 \pm 0.05$
 $\text{numTot} = 46023 \pm 210$
 $\text{sigma} = 1.69 \pm 0.05$
 $\text{width} = 1.6 \pm 0.1$

pp MC
 ID efficiency
 $30 < \text{probe } E_T < 40 \text{ GeV}$

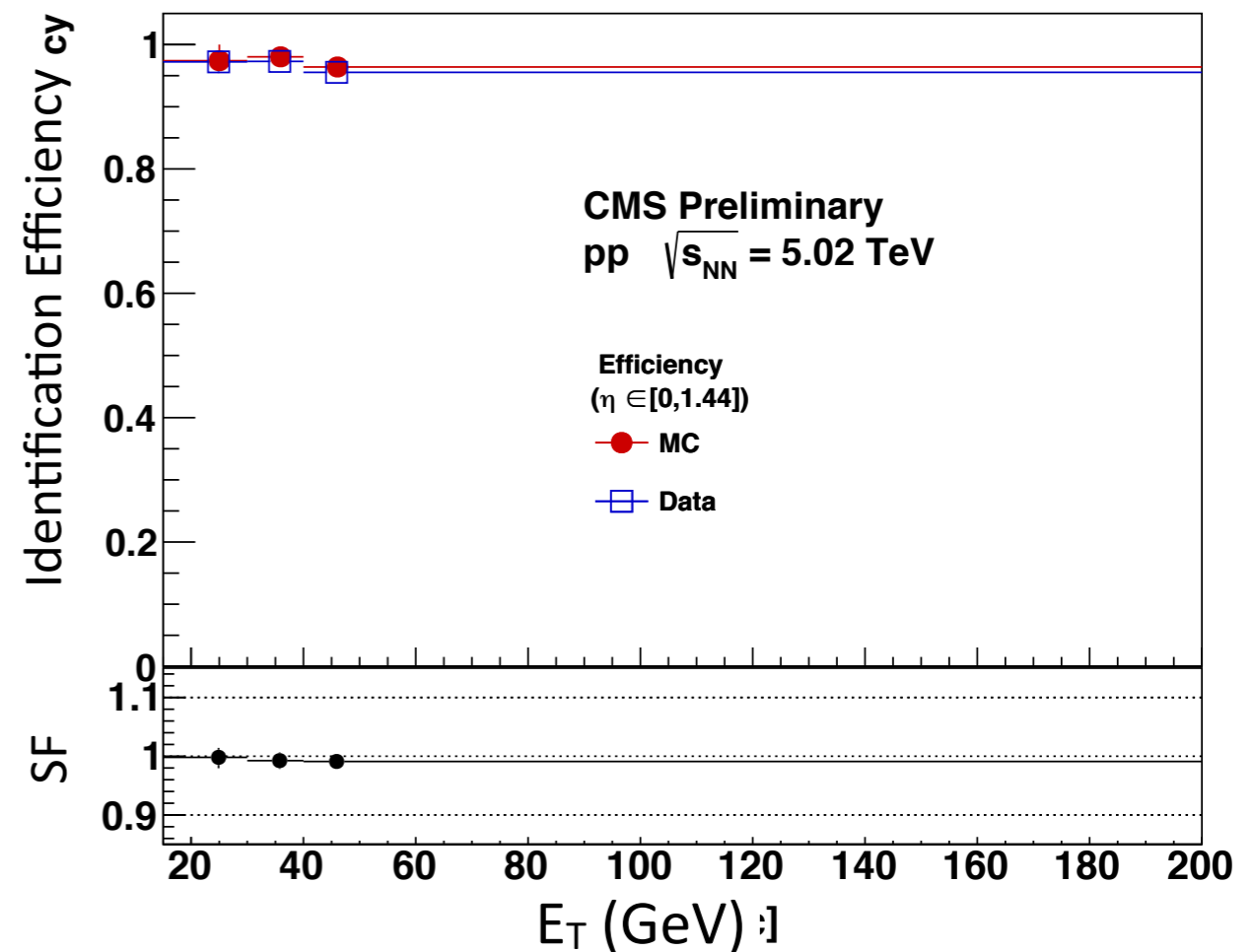
Efficiency scale factor (SF)

- Scale Factor (SF) = $\epsilon_{\text{DATA}}/\epsilon_{\text{MC}}$
 - to compensate the **discrepancy between data and MC**
- Using the **tag-and-probe** method with **Z->ee** events

PbPb



pp



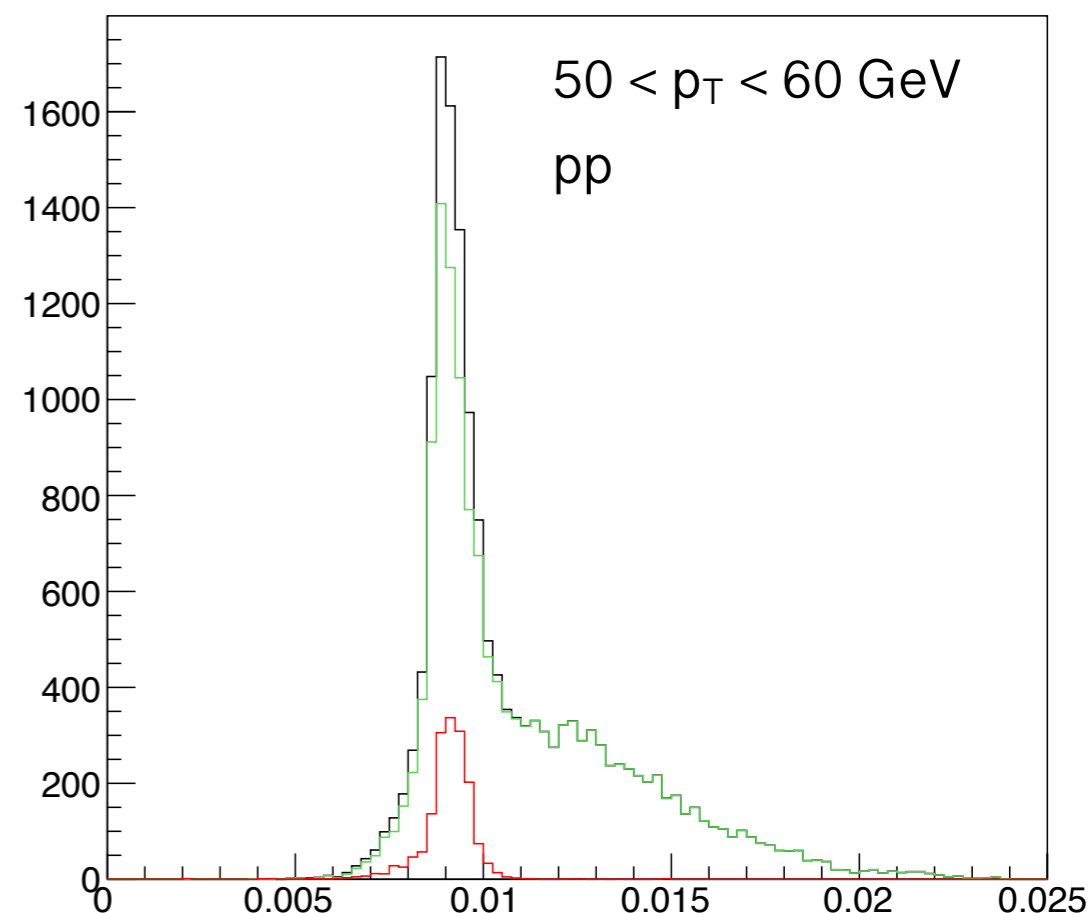
- Total efficiency**
= **Trigger ϵ x Reconstruction ϵ x Identification and Isolation ϵ x Scale factor (SF)**

Signal contamination removal in purity background template

- Take signal contamination shape from signal MC in sideband region.
- Determine $N_{true,sb}$, normalization of true(signal) photons in sideband, using:
 - $N_{data,sig}$: # of events in signal region from data
 - p : photon purity
 - $p \cdot N_{data,sb}$: # of signal photons in signal region taken from MC, normalized to match data
 - $f_{true,sig}$: relative fraction of signal photons in signal
 - $f_{true,sb}$: relative fraction of signal photons in sideband
- Subtract signal photon shape in sideband region with norm $N_{true,sb}$ from sideband template

$$N_{true,sb} = \frac{f_{true,sb}}{f_{true,sig}} p N_{data,sig}$$

- bkg template before signal subtraction
- signal contamination in sideband
- bkg template after signal subtraction



Purity : signal subtraction in bkg template

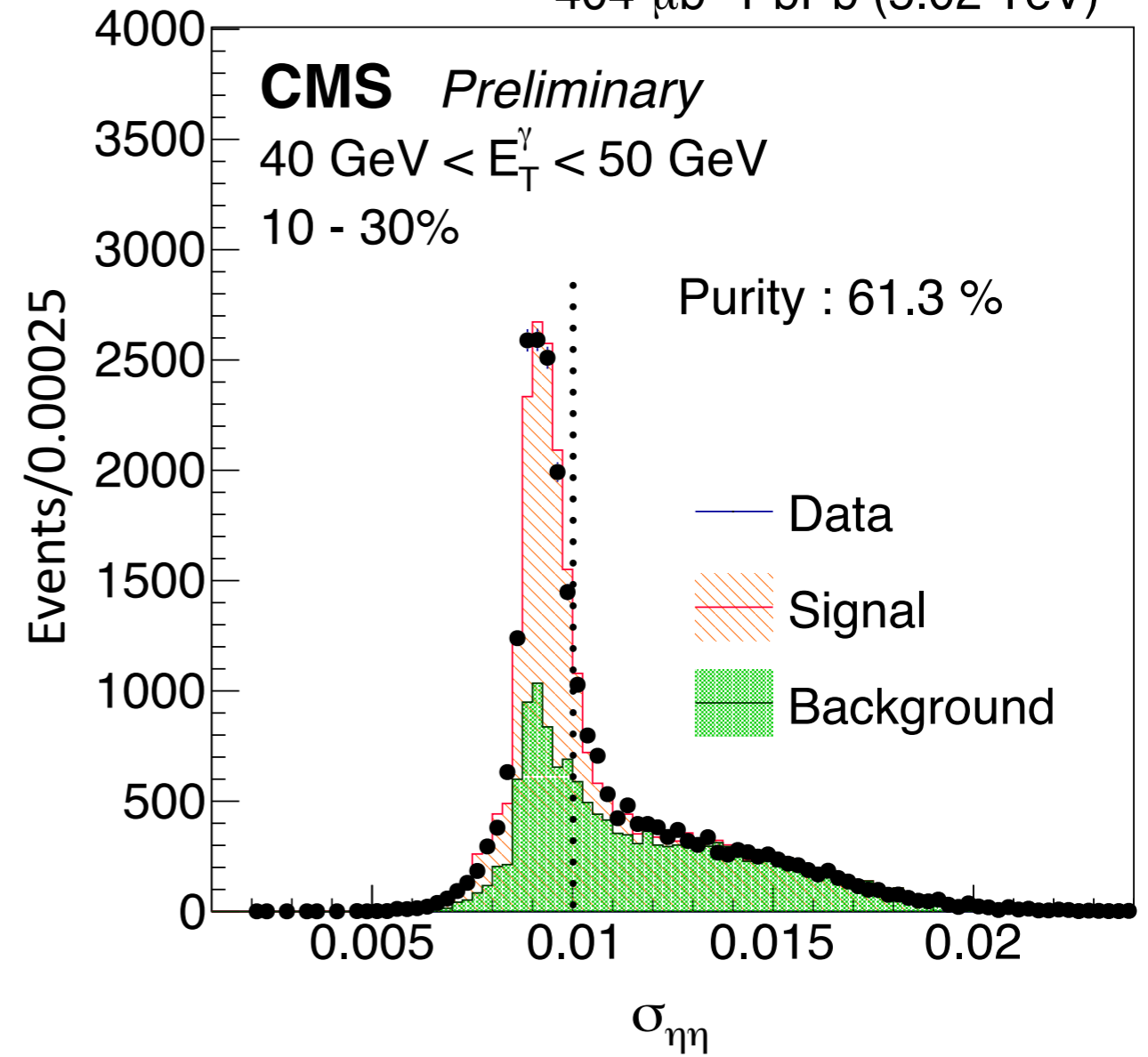
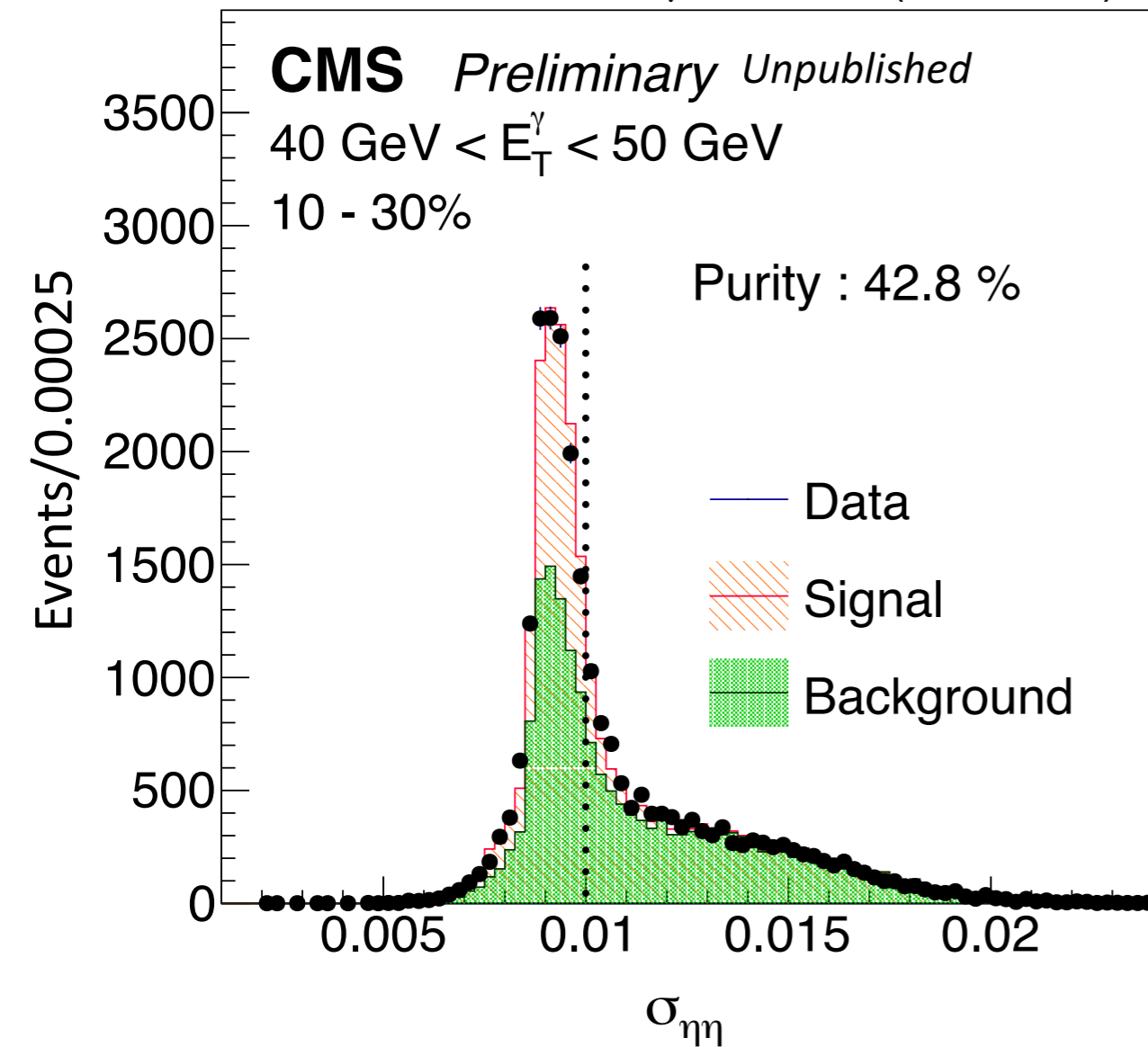
- Signal contamination in the background template is **subtracted**

Before signal subtraction in background template

After signal subtraction in background template

404 μb^{-1} PbPb (5.02 TeV)

404 μb^{-1} PbPb (5.02 TeV)

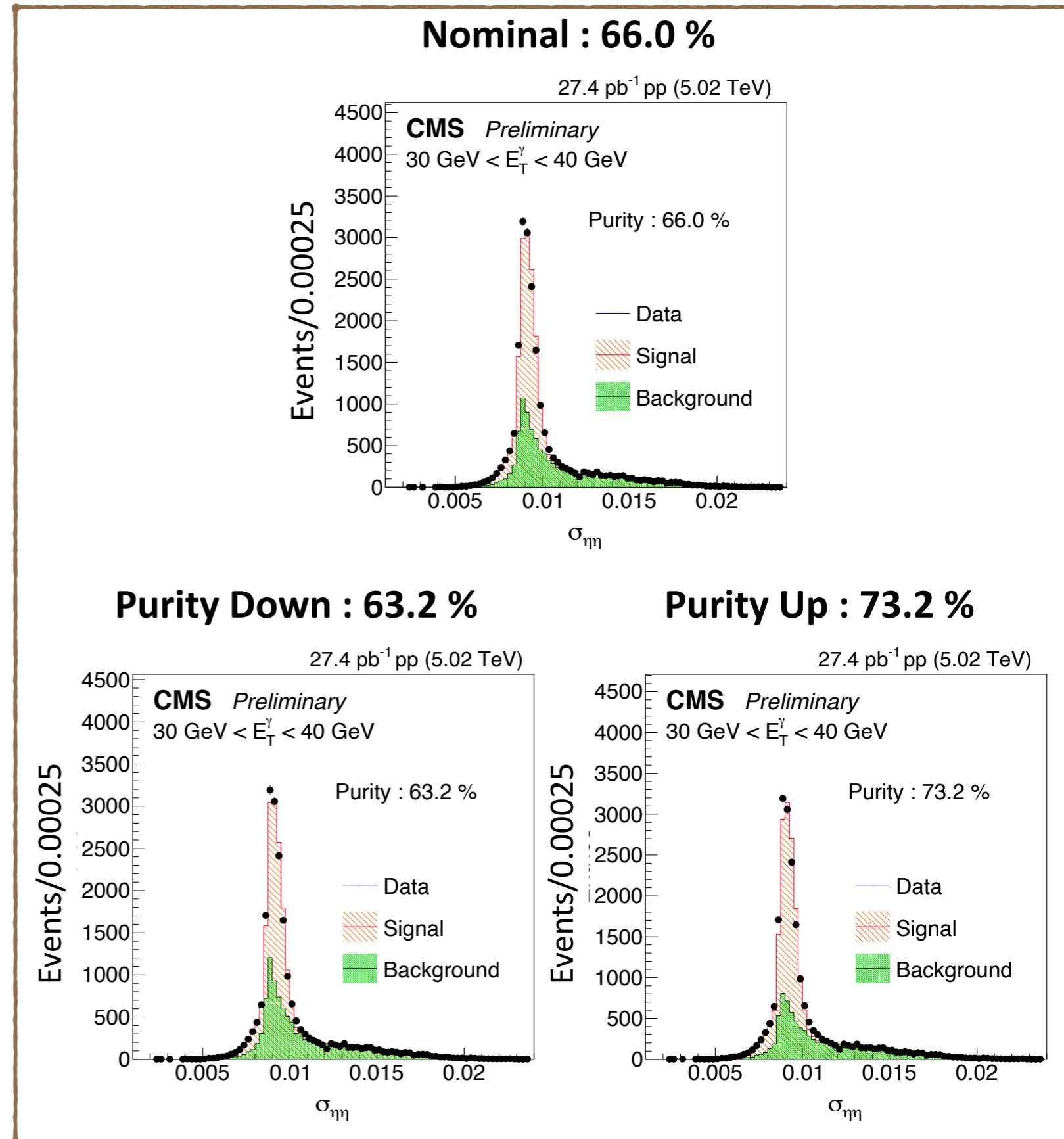
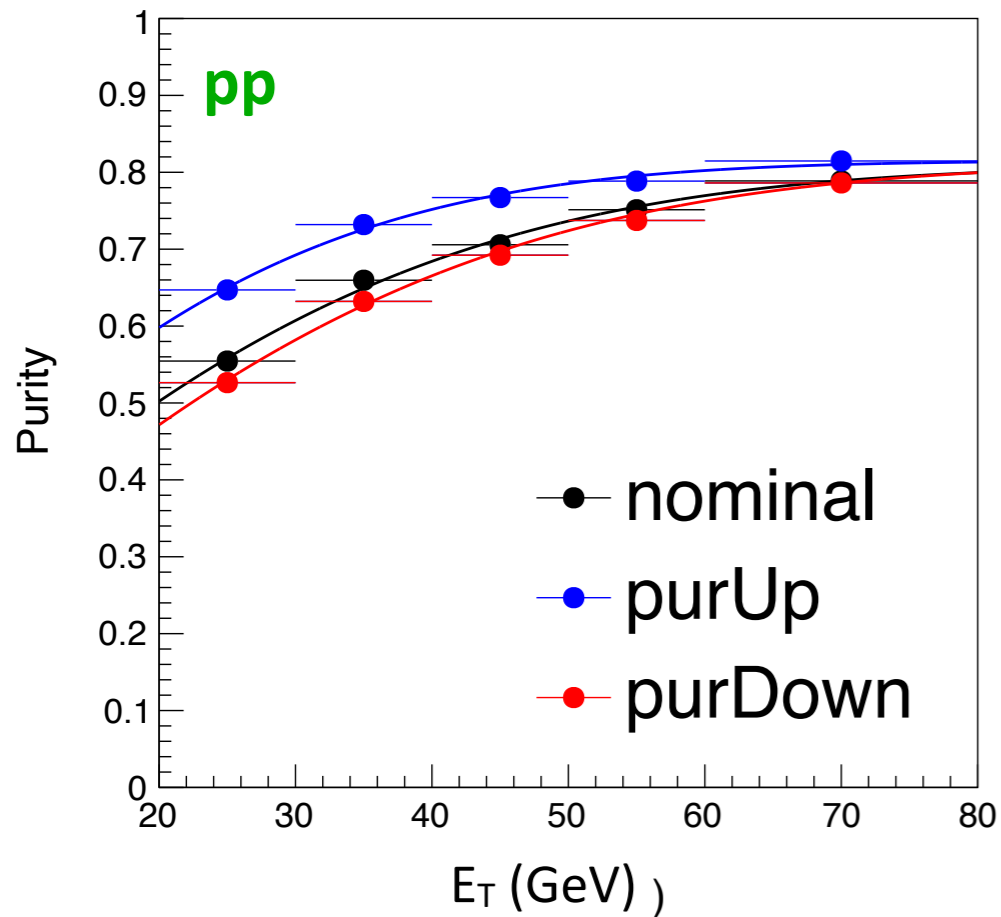


- Peak in the background template decreases in magnitude -> **higher purity**

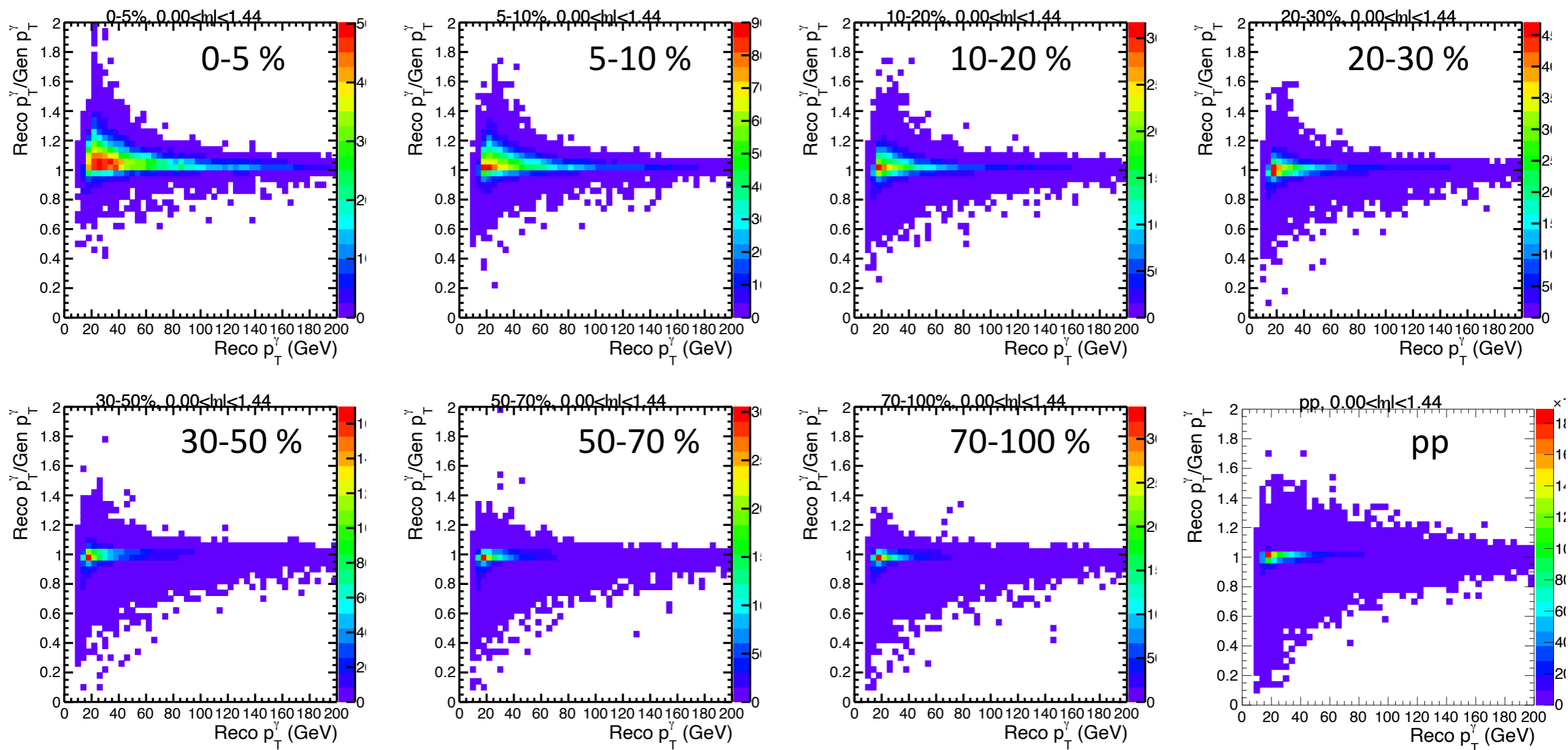
Purity : systematic

○ Purity systematics

- sideband range change
- quote maximal deviation between variations

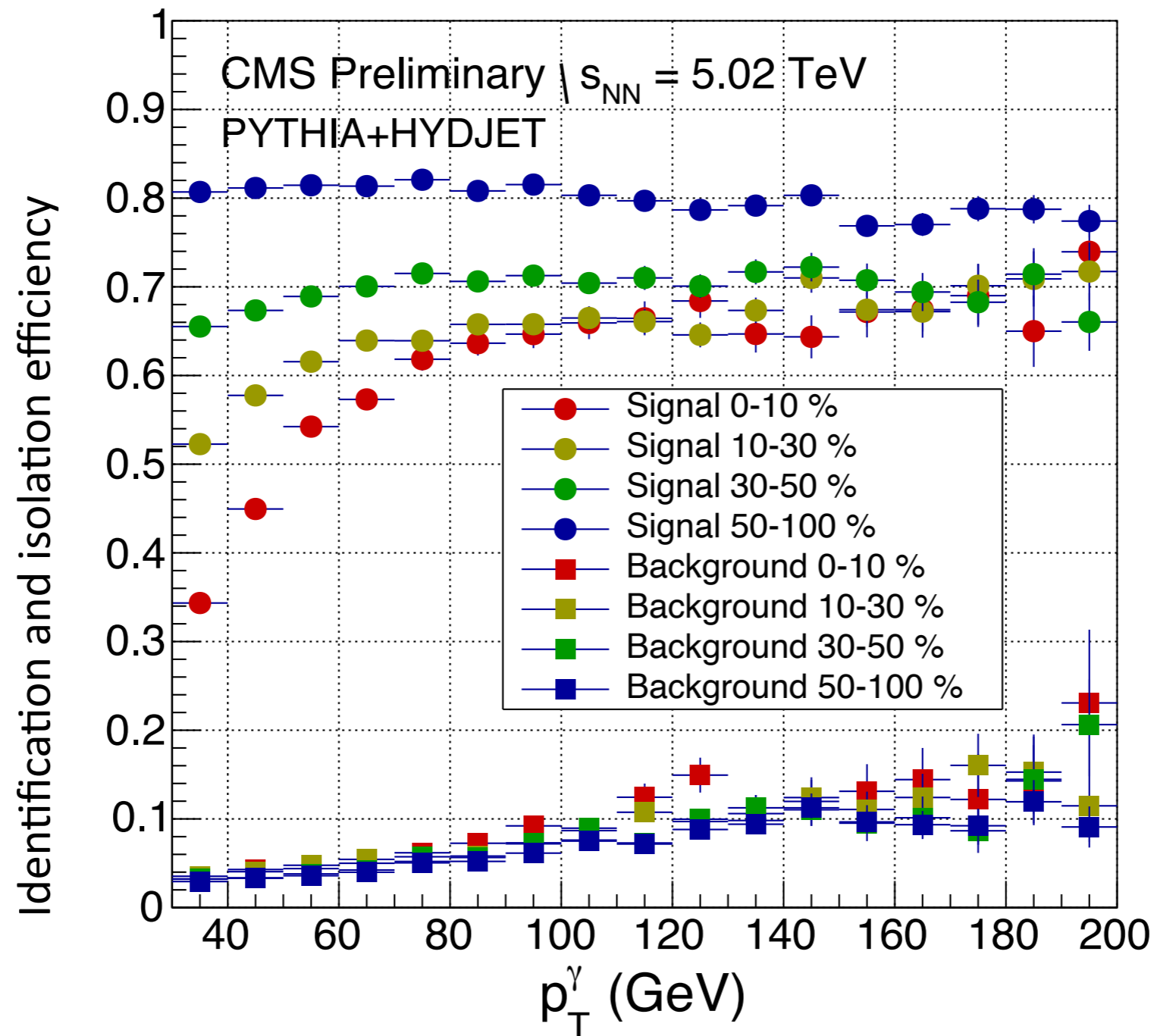


Photon energy correction



- Photon energy scales are derived as a function of E_T in different centrality classes.

Background photon rejection



- Over 80 % of background photons are rejected by identification and isolation requirements though the whole p_T ranges.

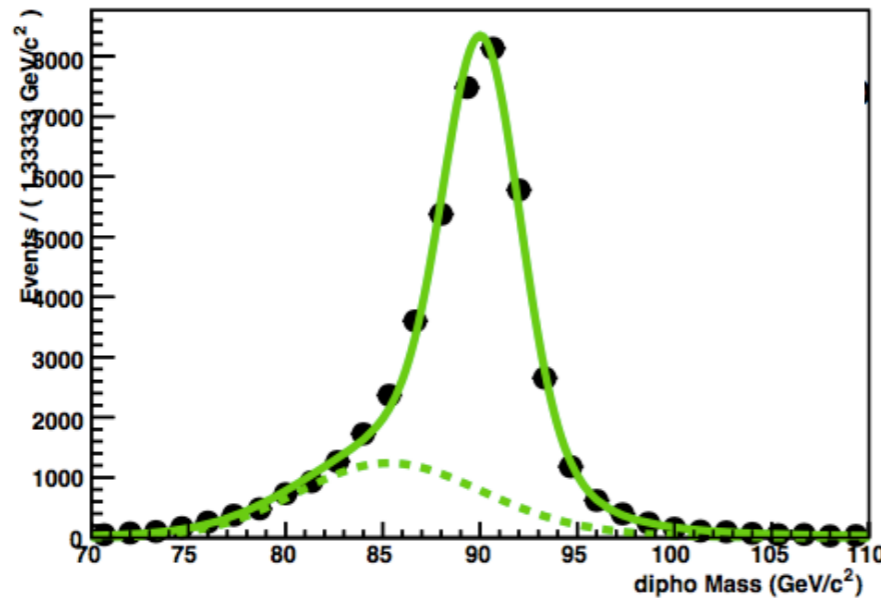
Tag and Probe

- Signal function : Voigtian
- Background function: 3rd order Chebychev. pol.
- Mass range : [80,100]

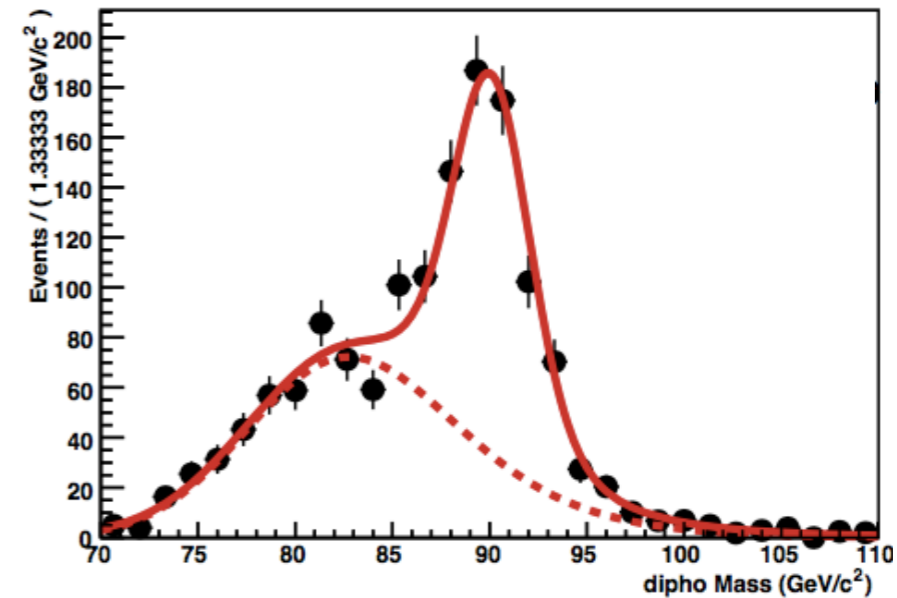
- Tag : ID + ISO + Electron tight WP
- All probes : no cut
- Passing probe : ID cut

pp MC
ID efficiency

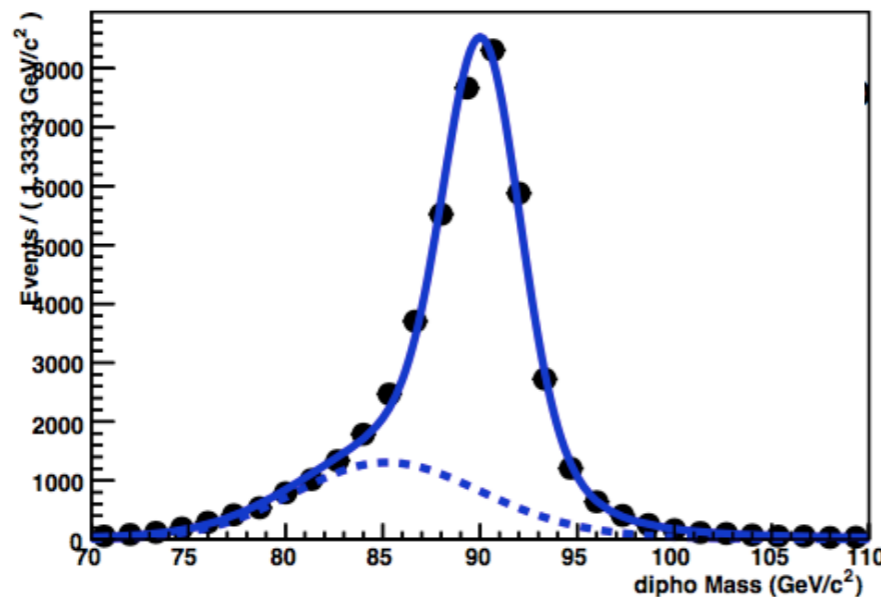
Passing Probes



Failing Probes



All Probes



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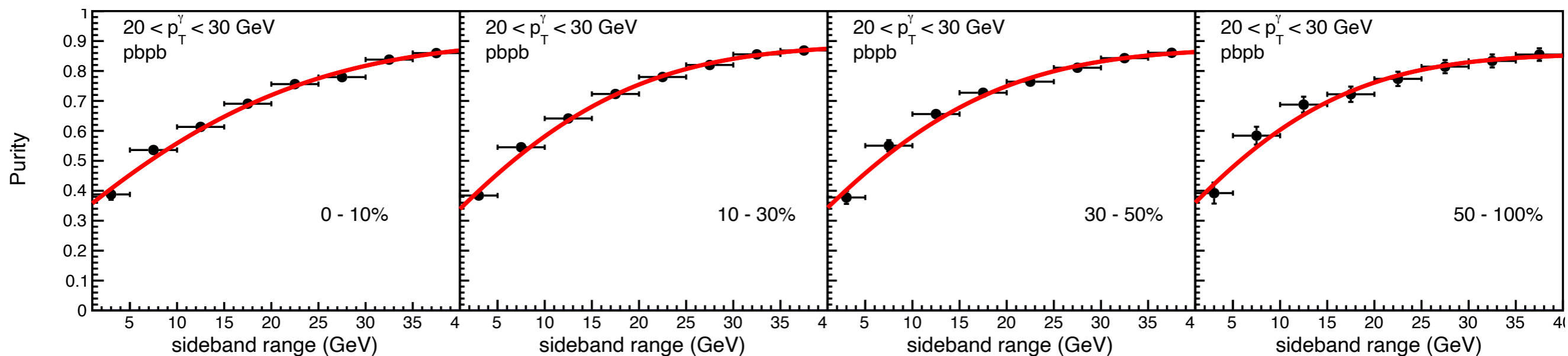
Global numbers

- **pp total integrated luminosity** : 27.4 pb⁻¹ with an uncertainty of 2.3%
- Number of minimum bias events in PbPb (**N_{MB}**) : 2.72×10^9
- **Event selection efficiency** in PbPb : $(99 \pm 2)\%$
- **T_{AA}** from Glauber model simulation
 - uncertainties estimated by varying Glauber model parameters

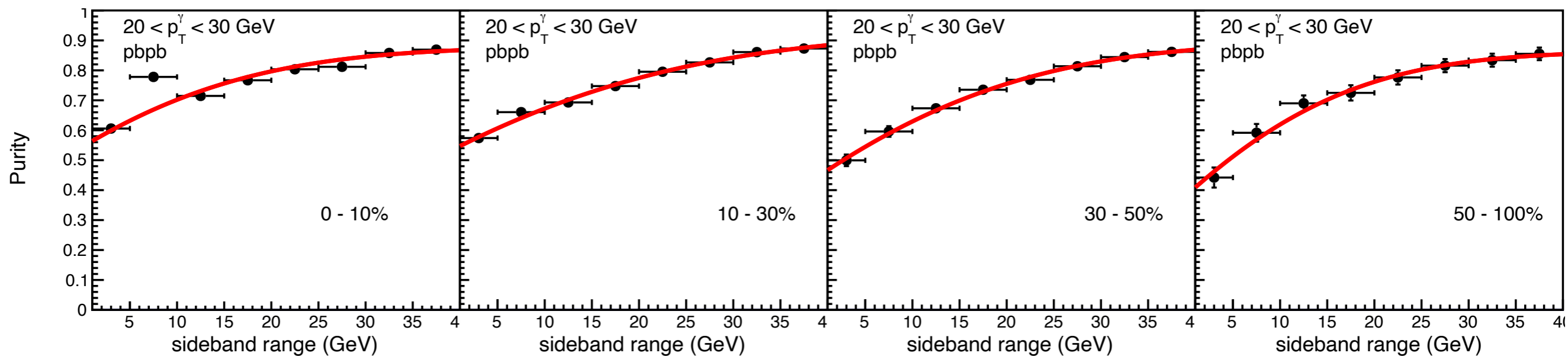
Centrality	T_{AA} [mb ⁻¹]
0–10%	$23.22^{+0.43}_{-0.69}$
10–30%	$11.51^{+0.30}_{-0.39}$
30–50%	$3.82^{+0.21}_{-0.21}$
50–100%	$0.44^{+0.05}_{-0.03}$

Purity: sideband dependence

Before signal subtraction in background template



After signal subtraction in background template



- Determination of purity is sensitive to sideband ranges.

rapidity vs. pseudorapidity

pseudo rapidity

$$\eta \equiv -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] \quad \theta = 2 \arctan(e^{-\eta})$$

$$\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L} \right)$$

rapidity

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$$

nPDF models

- The PDF global analysis aims at finding the best possible parameter values
-> a large set of experimental data from various hard processes are optimally described

arxiv:1802.05927

EPS09

DSSZ

nCTEQ15

EPPS16

Order in α_s	LO & NLO	NLO	NLO	NLO
NC DIS lA/l_d	✓	✓	✓	✓
DY pA/pd	✓	✓	✓	✓
RHIC pions dAu/pp	✓	✓	✓	✓
νA DIS		✓		✓
πA DY	DATA as input			✓
LHC pPb W, Z			LHC DATA as input	
LHC pPb jets				✓

- **EPS09** & **nCTEQ15**: hint of anti-shadowing of gluon nPDF
- **DSSZ**: modification of parton-to-pion fragmentation function in heavy ion collisions and no gluon anti-shadowing
- **EPPS16**: LHC data from Z/W/dijets at 5 TeV pPb as input