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

Yeonju Go

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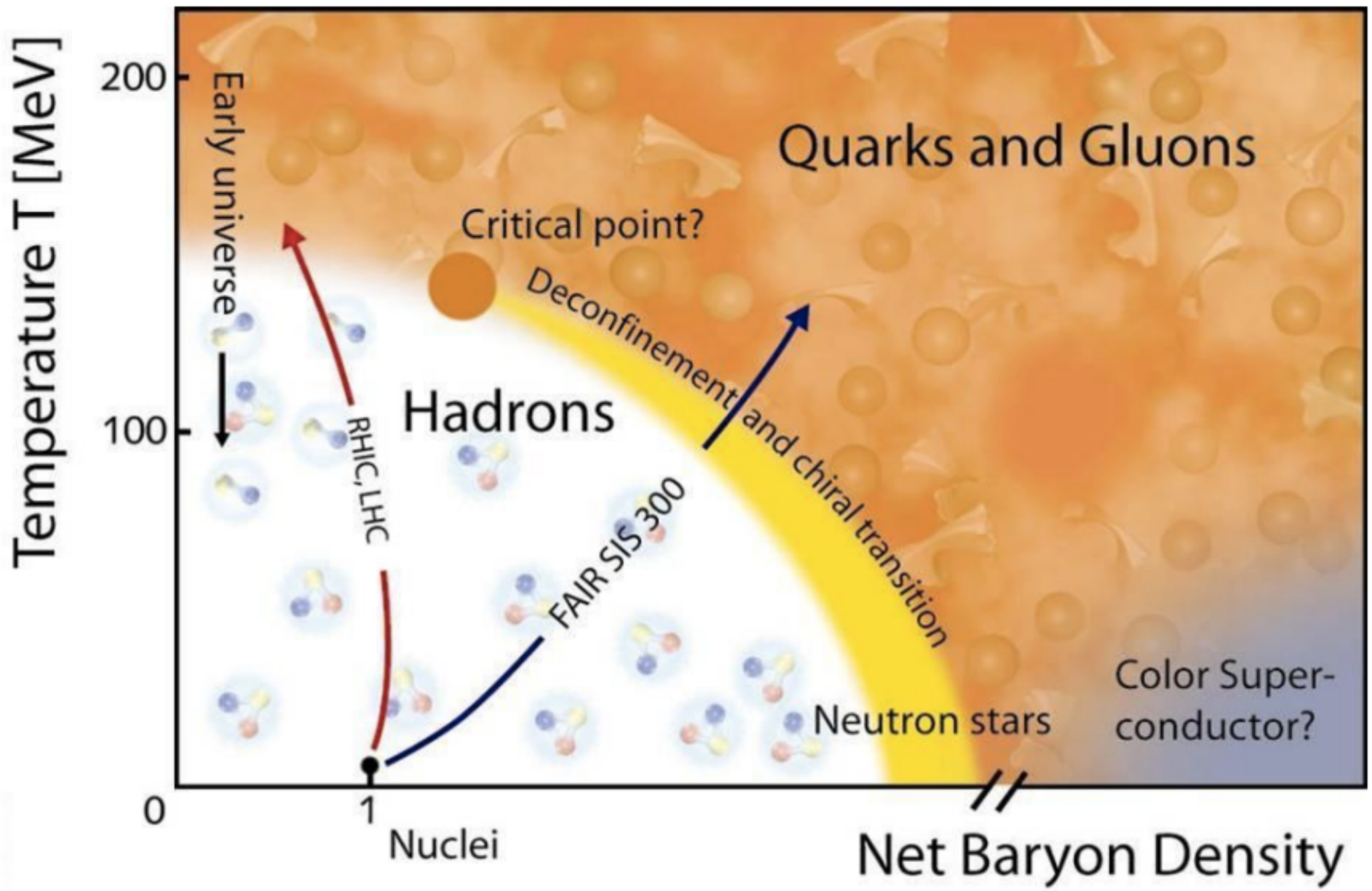
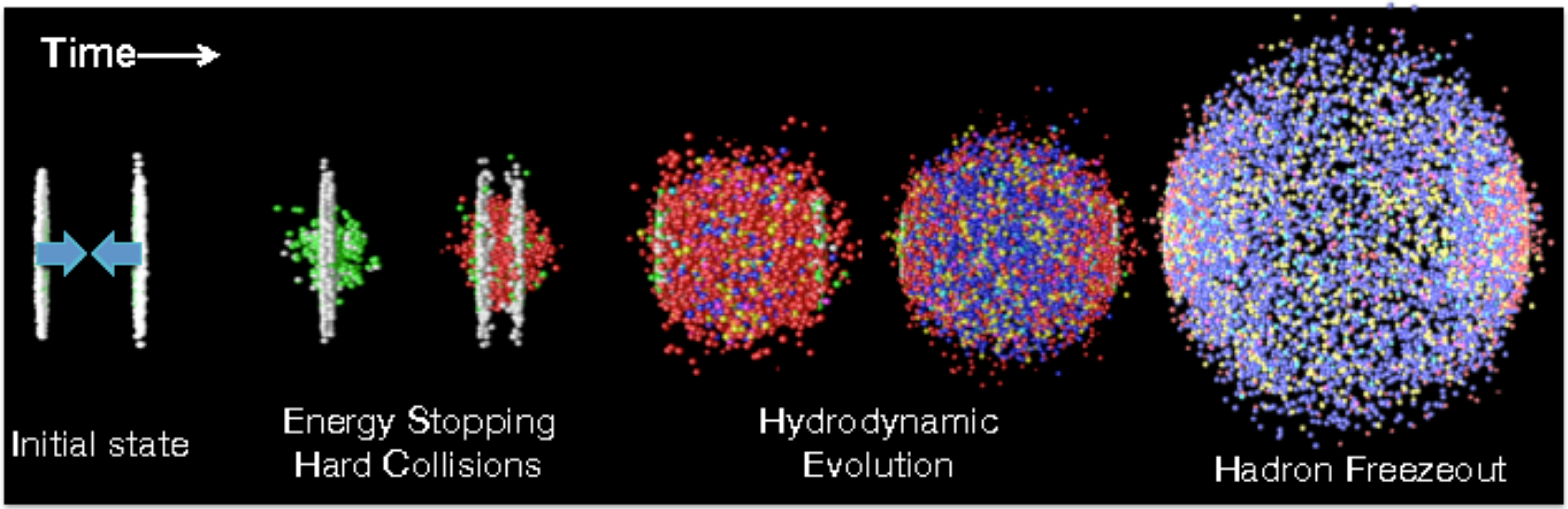
2nd CENuM Joint Workshop
Online

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



CGC
nPDF

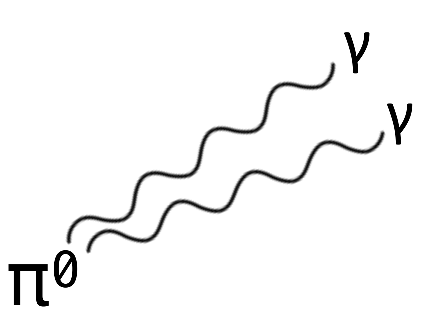
Glasma

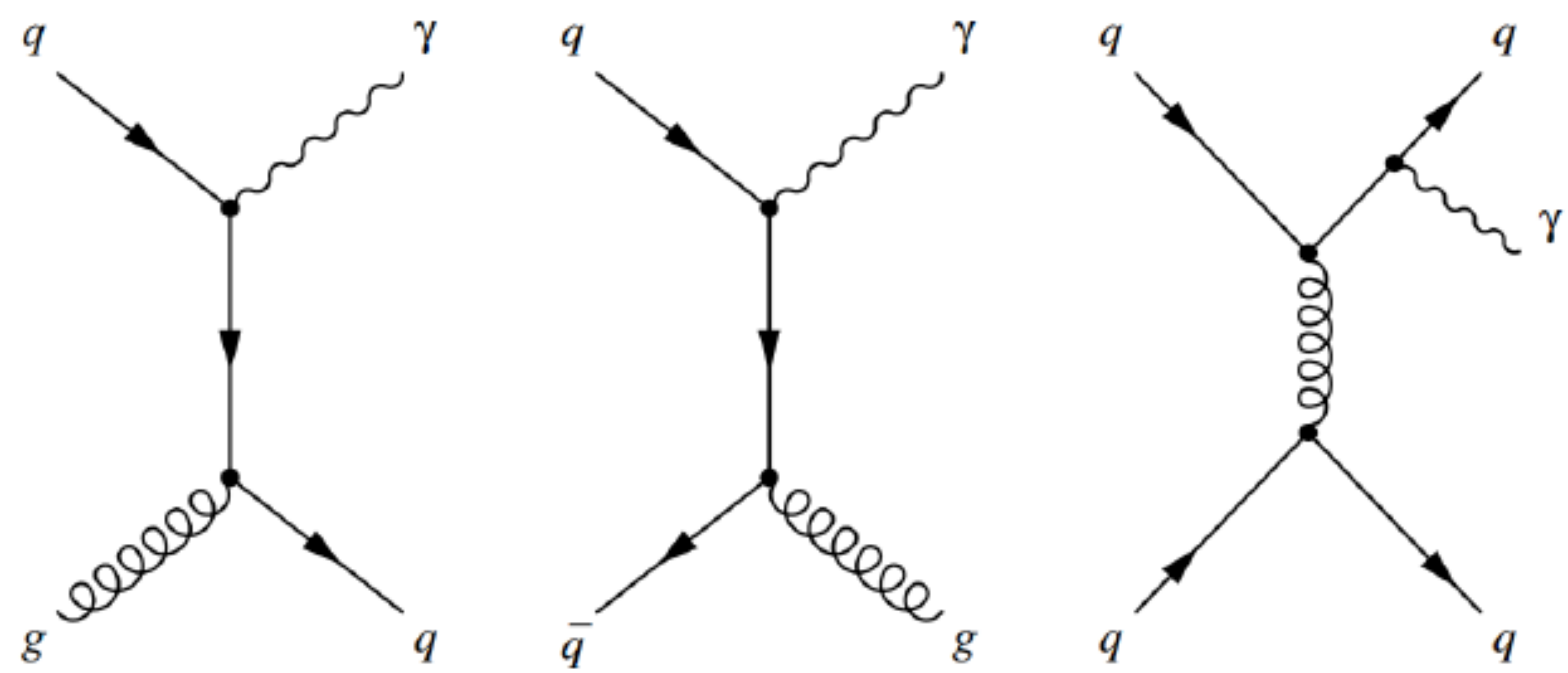
QGP

- **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

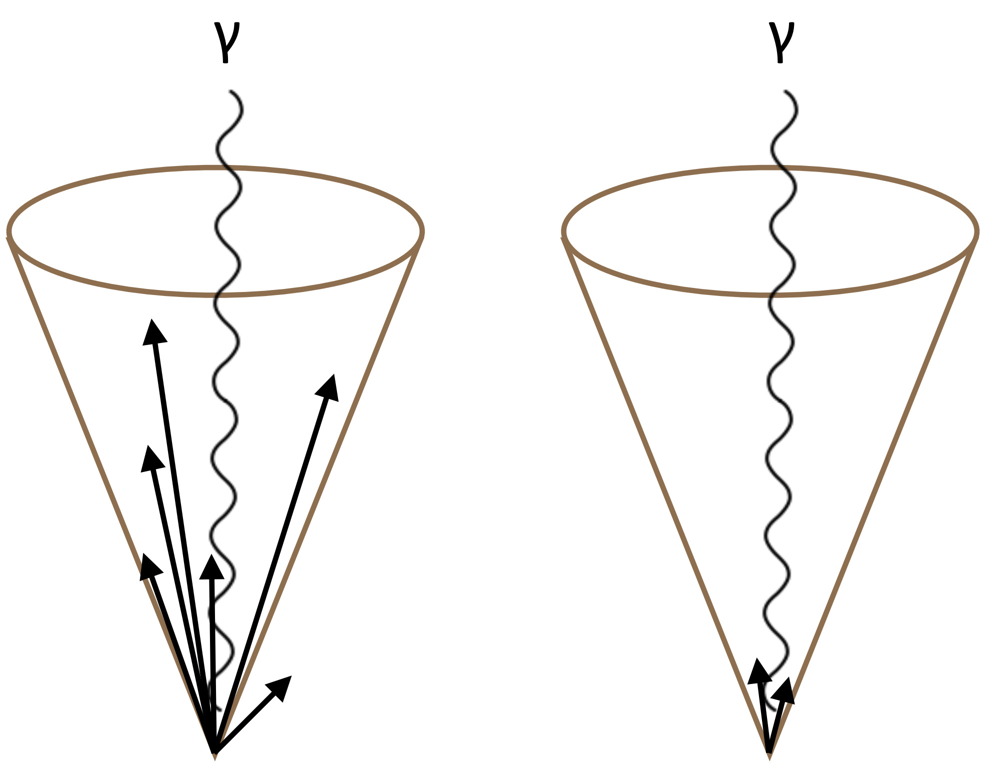
Isolated photons

- **Isolation condition**
  - **suppress significant background photons** from neutral meson decay
  - **suppress fragmentation photon** contribution and contains most of direct photons

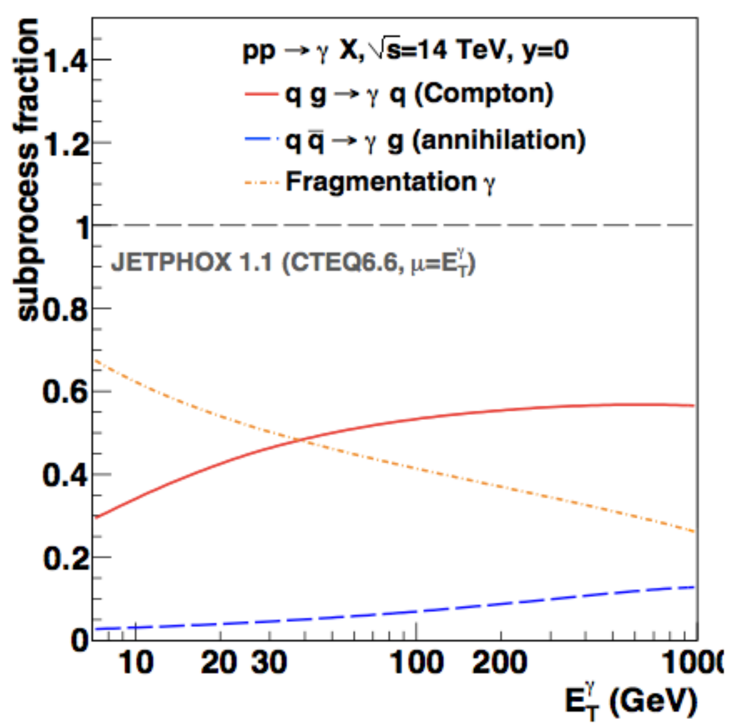
- High-p_T isolated photons are sensitive to **gluon distribution** because **quark-gluon Compton scattering** is dominant

- Discrimination between isolated direct and fragmentation photons is arbitrary in experiment

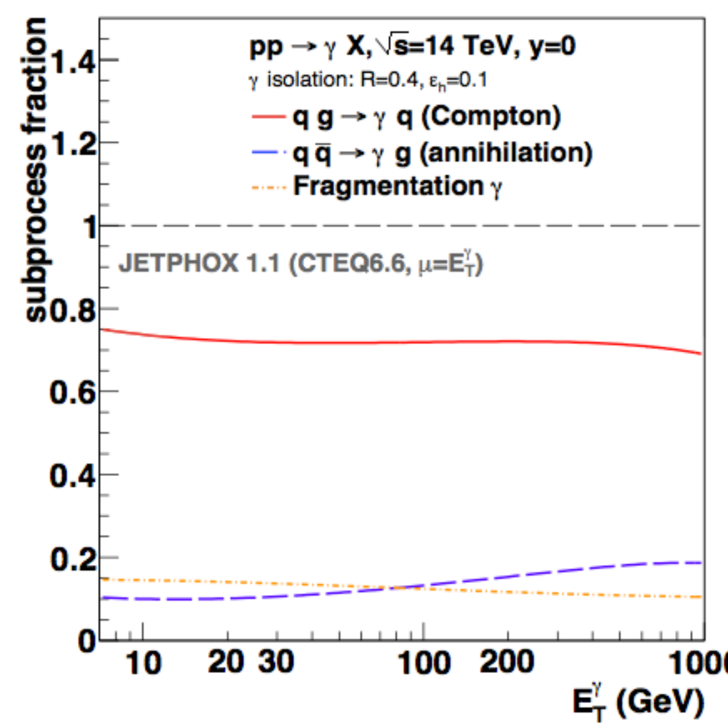
Non-isolated Isolated



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

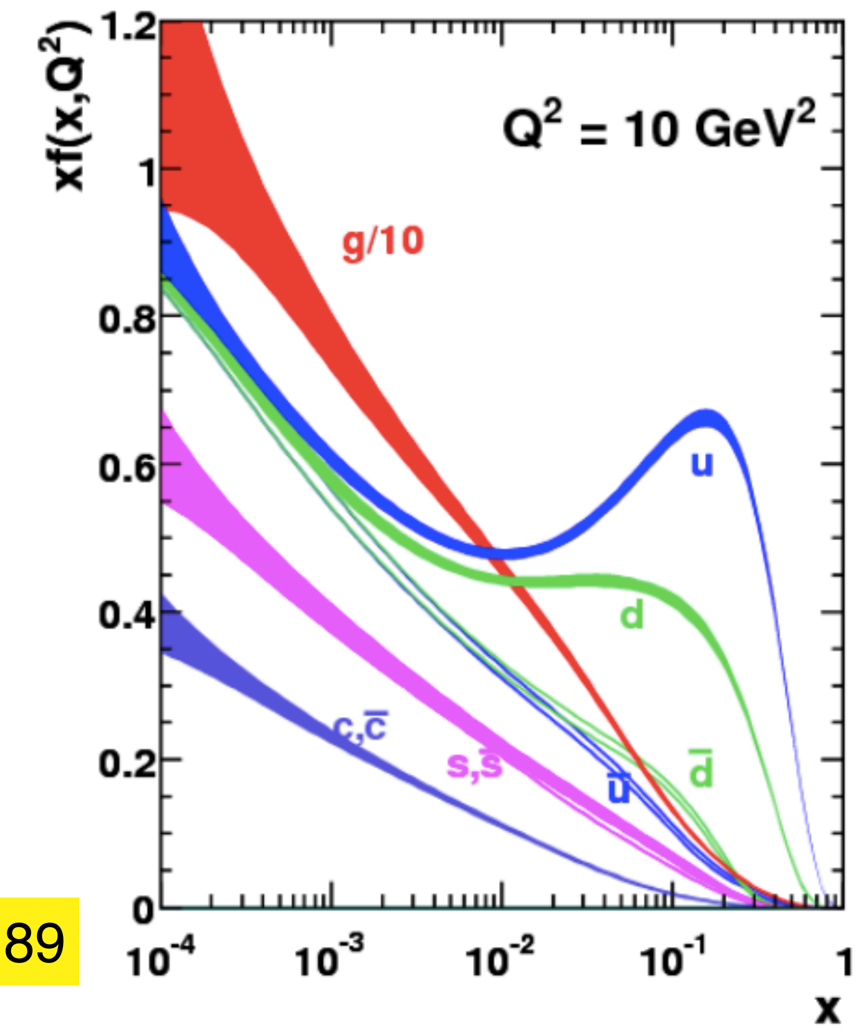
- **Parton distribution functions (PDFs)** are **universal**
  - do not depend on hard scattering processes
  - The **Q^2 dependence** is given by **DGLAP evolution** equations

splitting functions

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

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

MSTW 2008 NLO



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

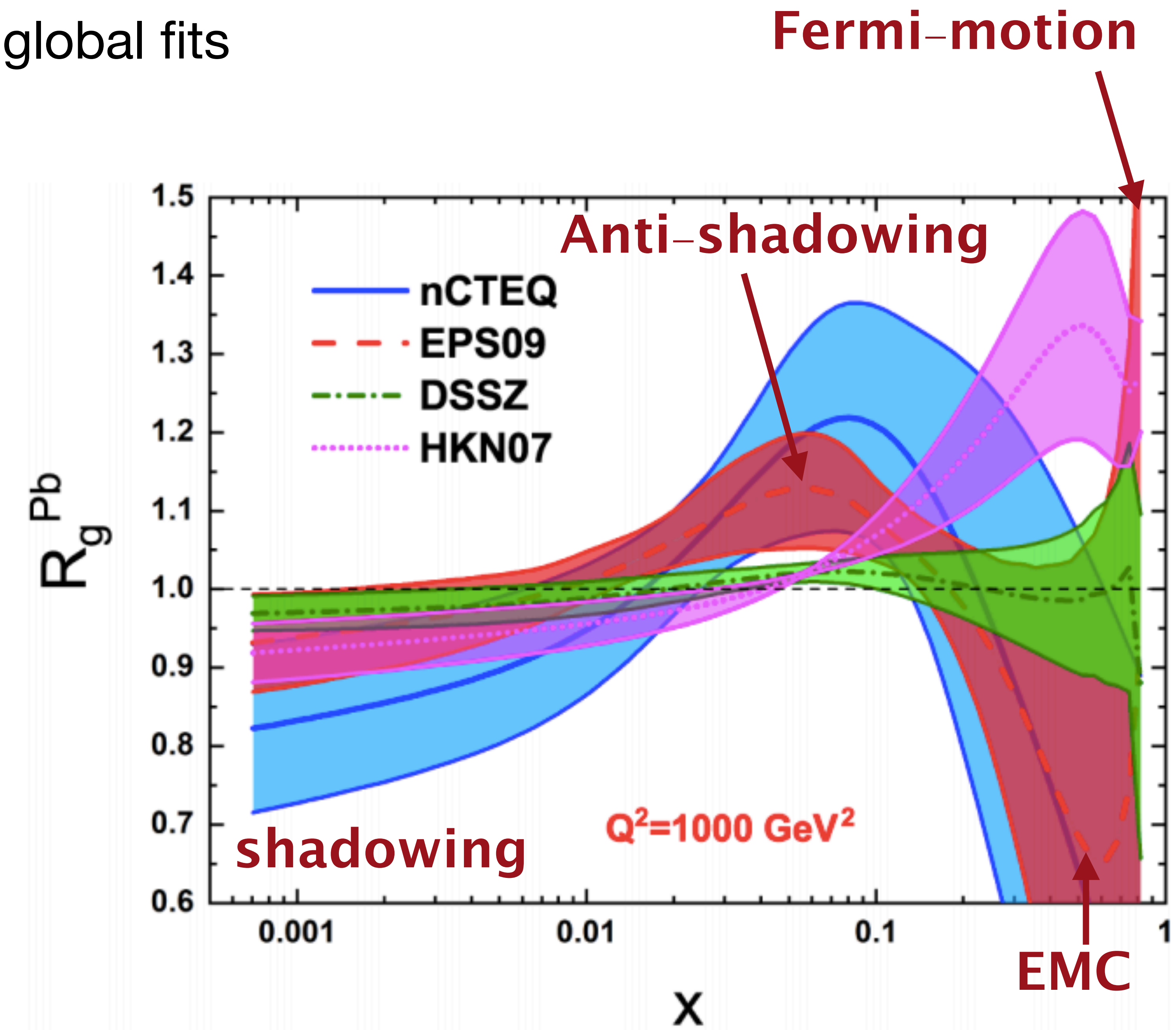
- **Large uncertainty** for gluon in the global fits

- **Discrepancies** between models
  - need data to constraint models

nuclear PDF

$$R_i^A(x,Q^2) \equiv \frac{f_i^{p/A}(x,Q^2)}{f_i^p(x,Q^2)}$$

free nucleon PDF



PRC 99, 055206 (2019)

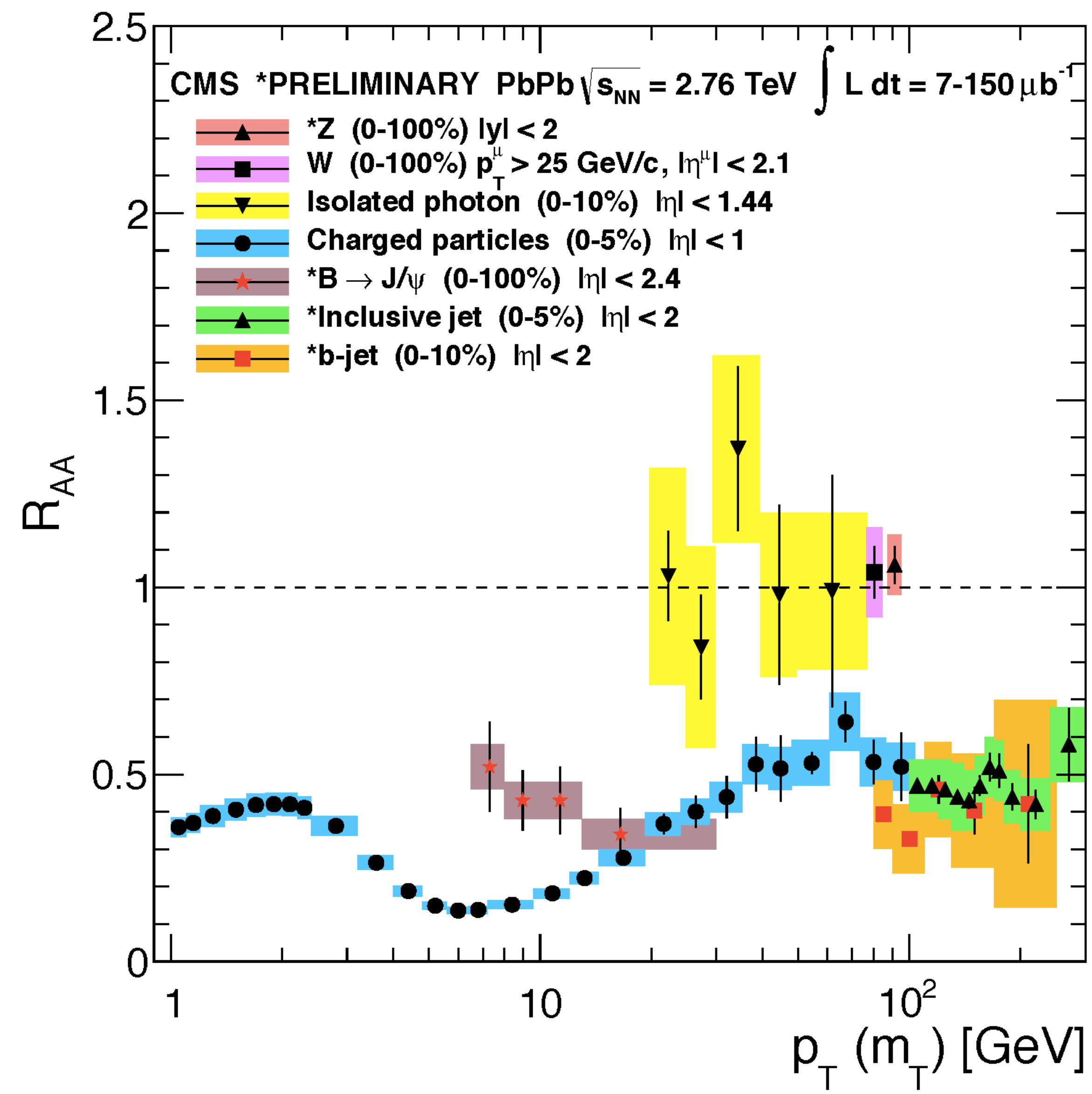
Nuclear modification factor

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

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

~ "QCD Medium" / "QCD Vacuum"

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effect)
- $R_{AA} < 1$ (suppression)



- T_{AA} : nuclear overlap function

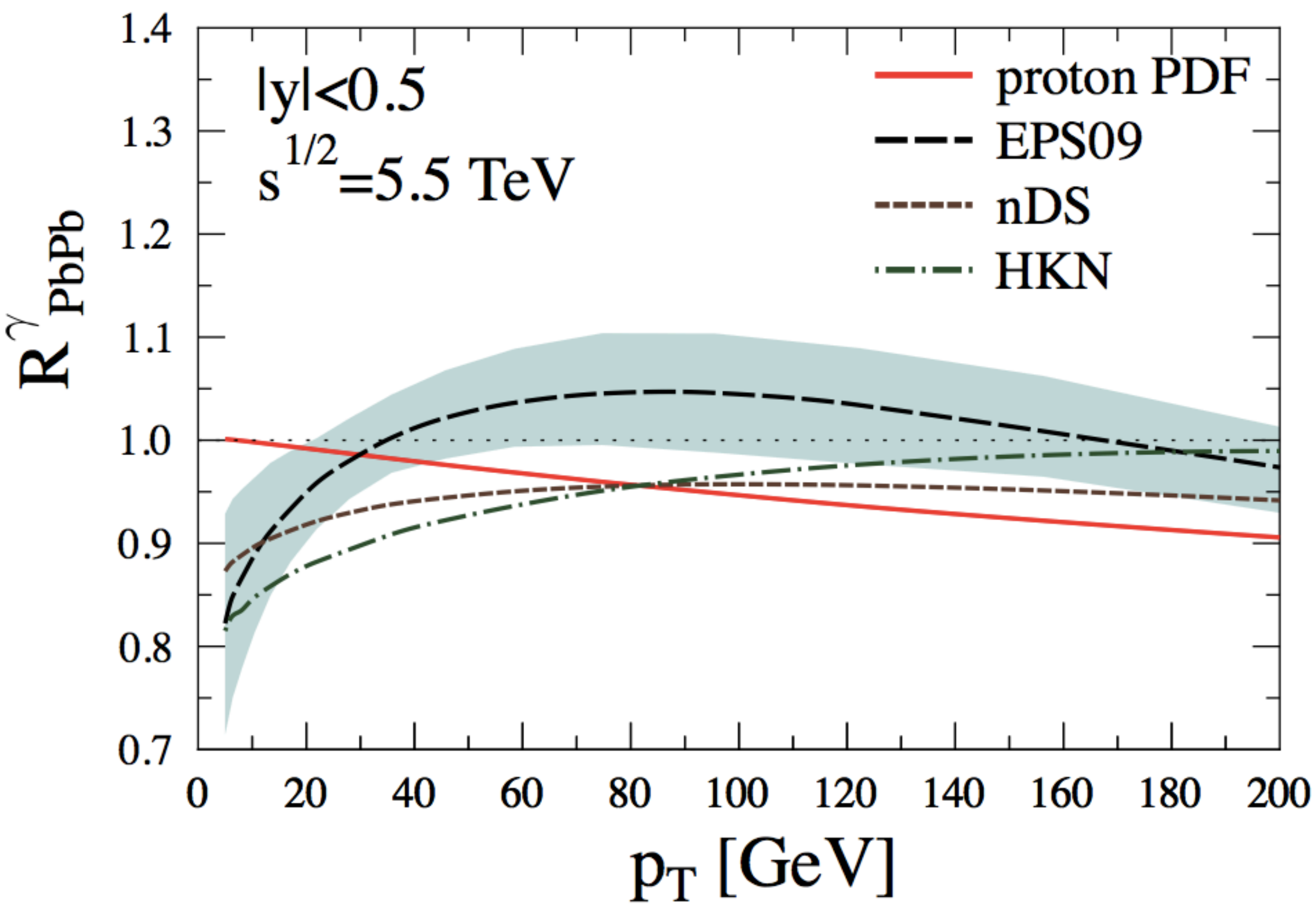
$$T_{AA} = \frac{\langle N_{coll} \rangle}{\sigma_{pp}^{inel}}$$

"NN equivalent integrated luminosity per AA collision"

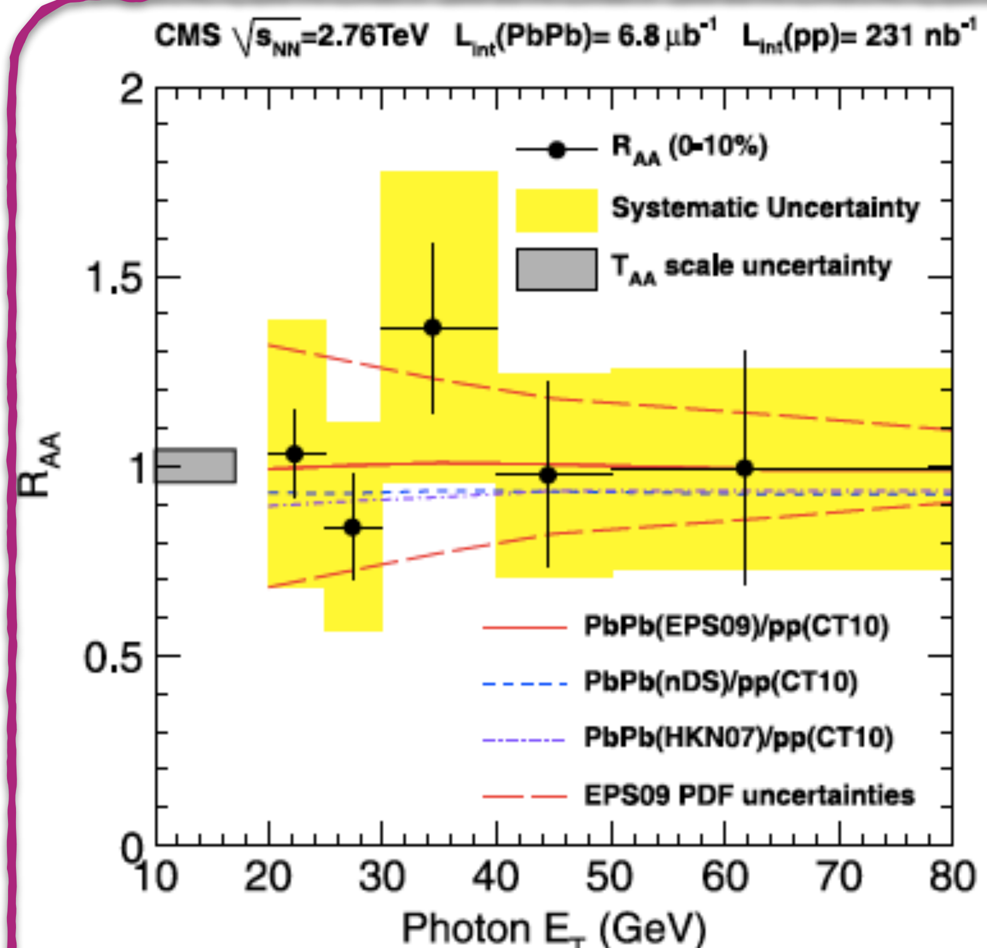
Why prompt photons?

- **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**

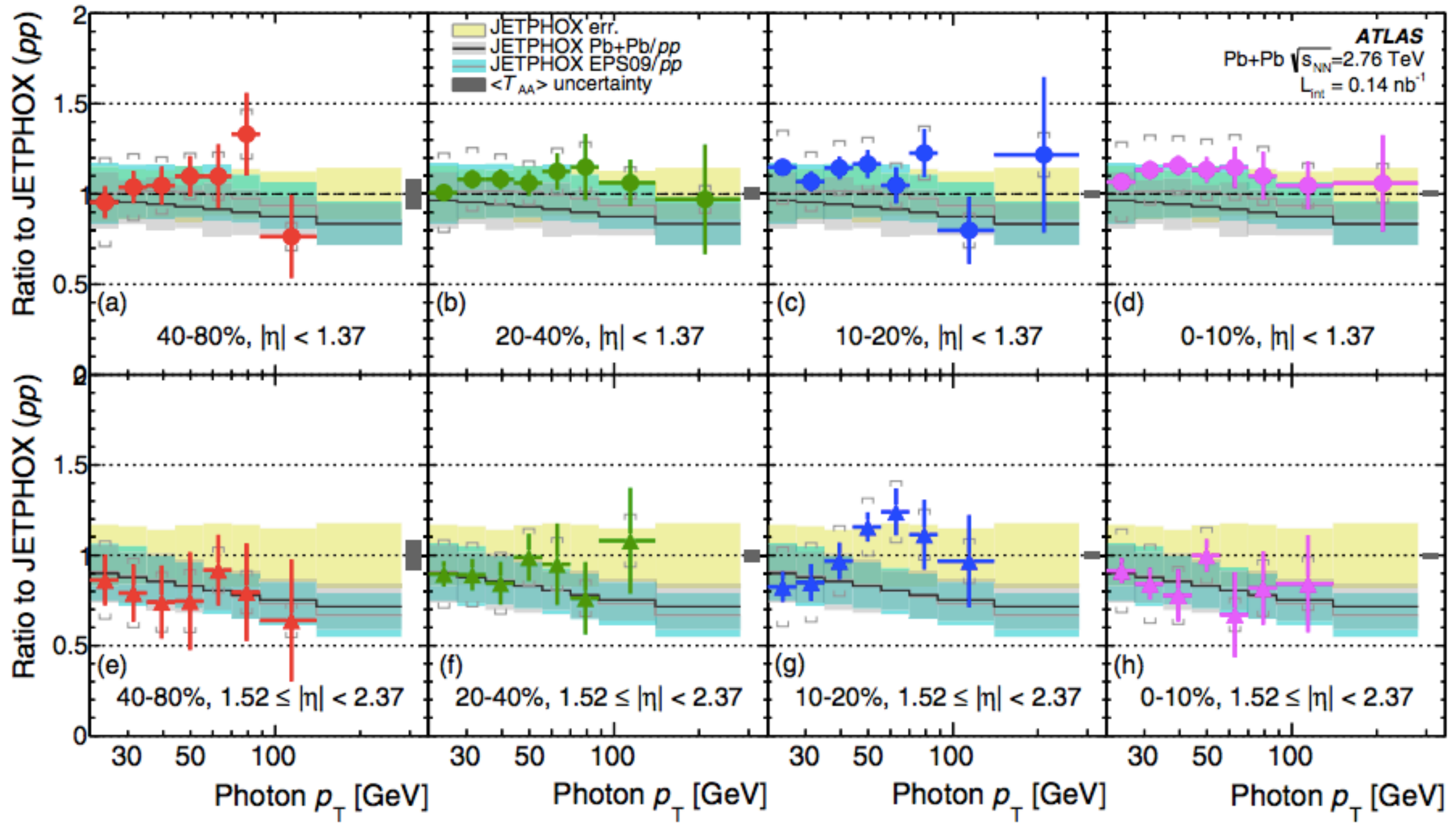
JHEP04(2011)055



Previous measurement in LHC



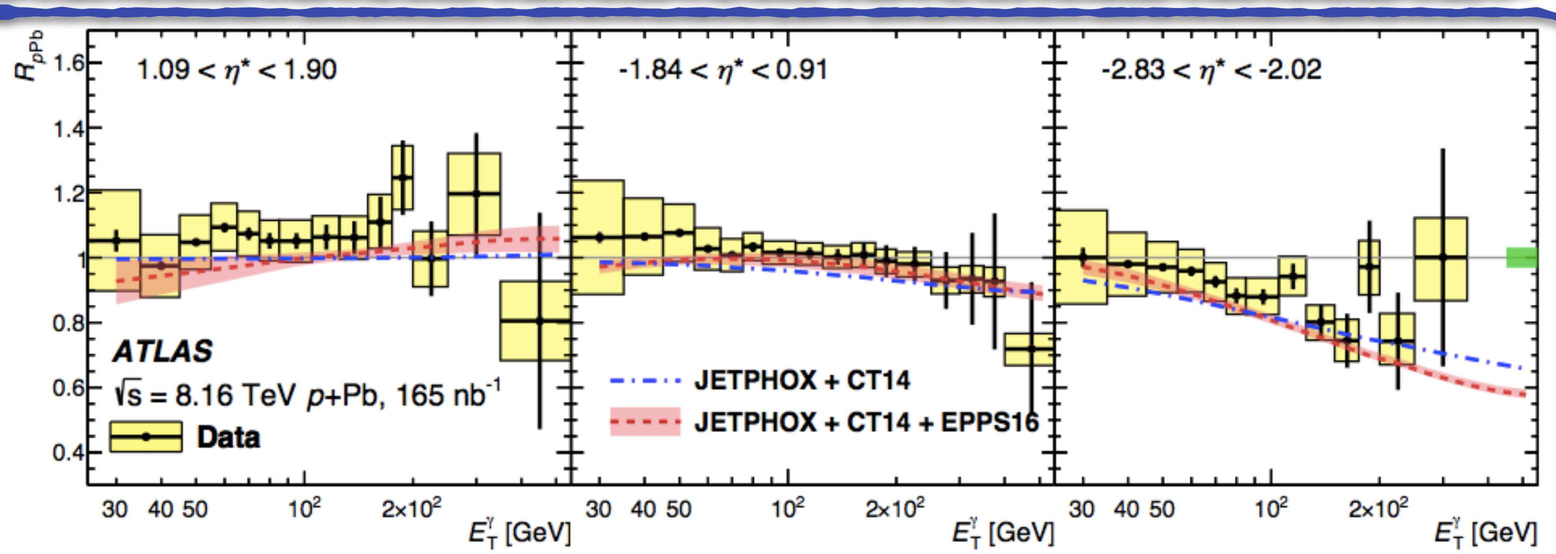
PLB 710 (2012) 256–277



PRC 93 (2016) 034914

PbPb 2.76 TeV

pPb 8.16 TeV



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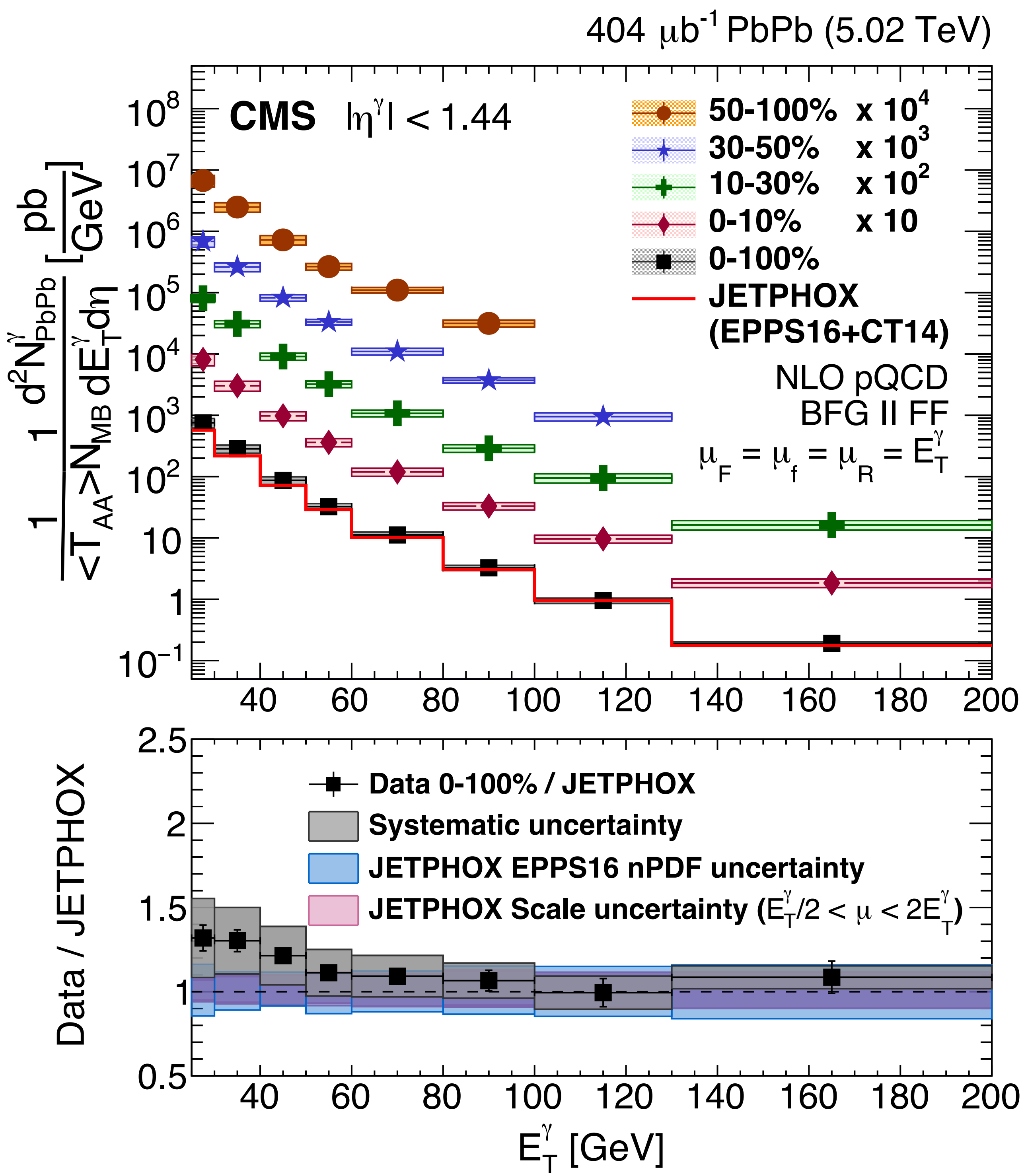
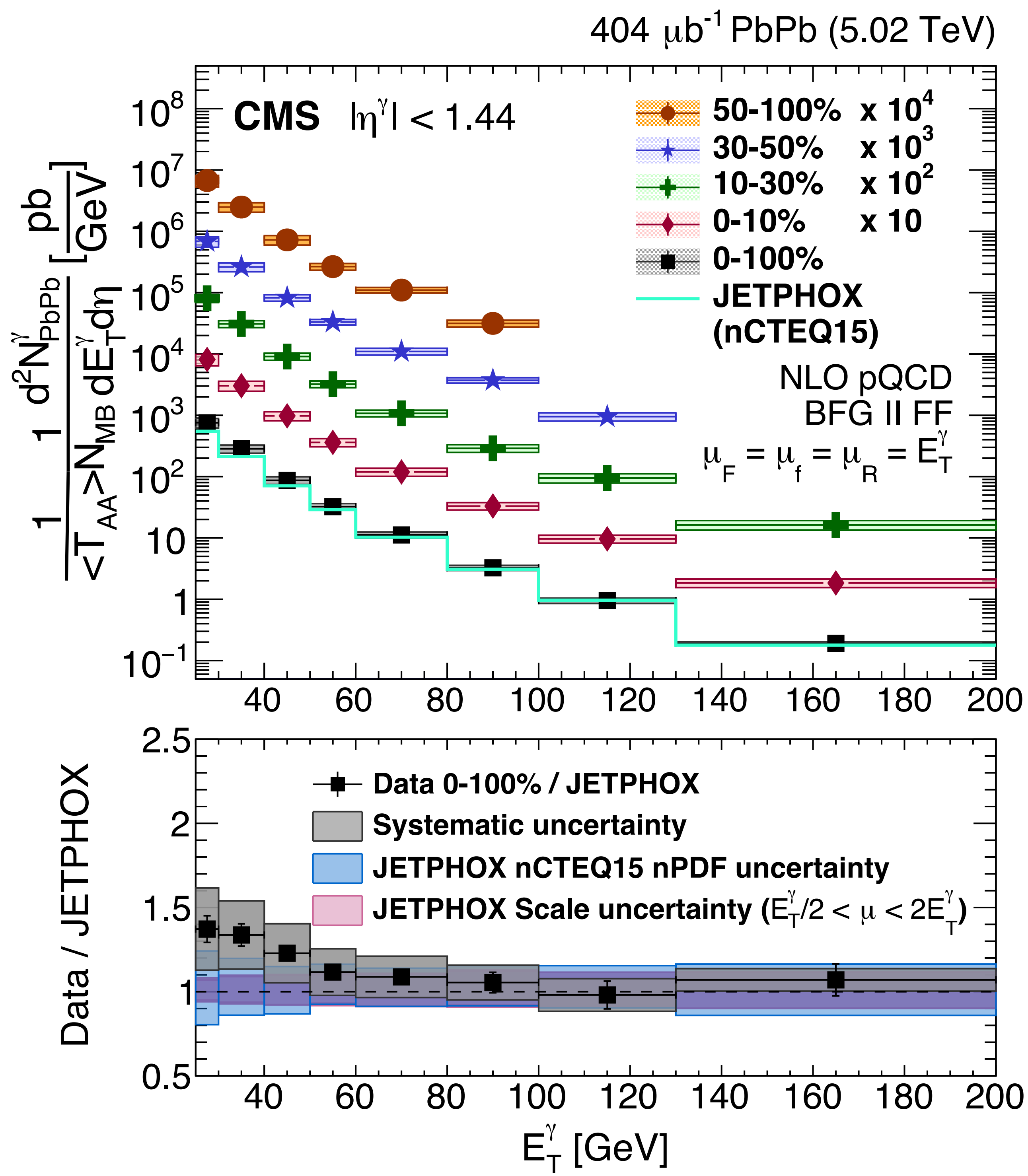
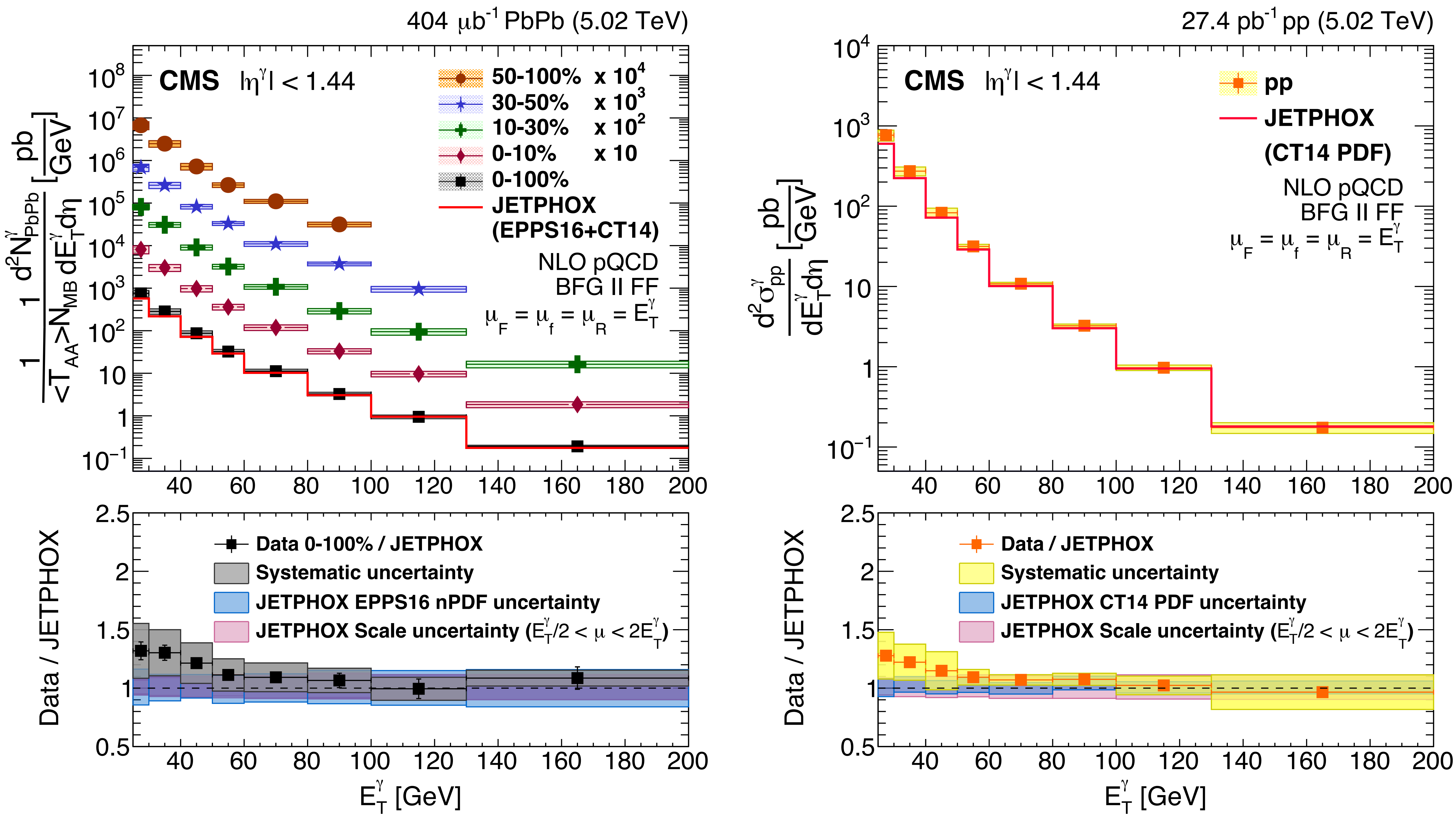
Cross section of isolated photons (PbPb)





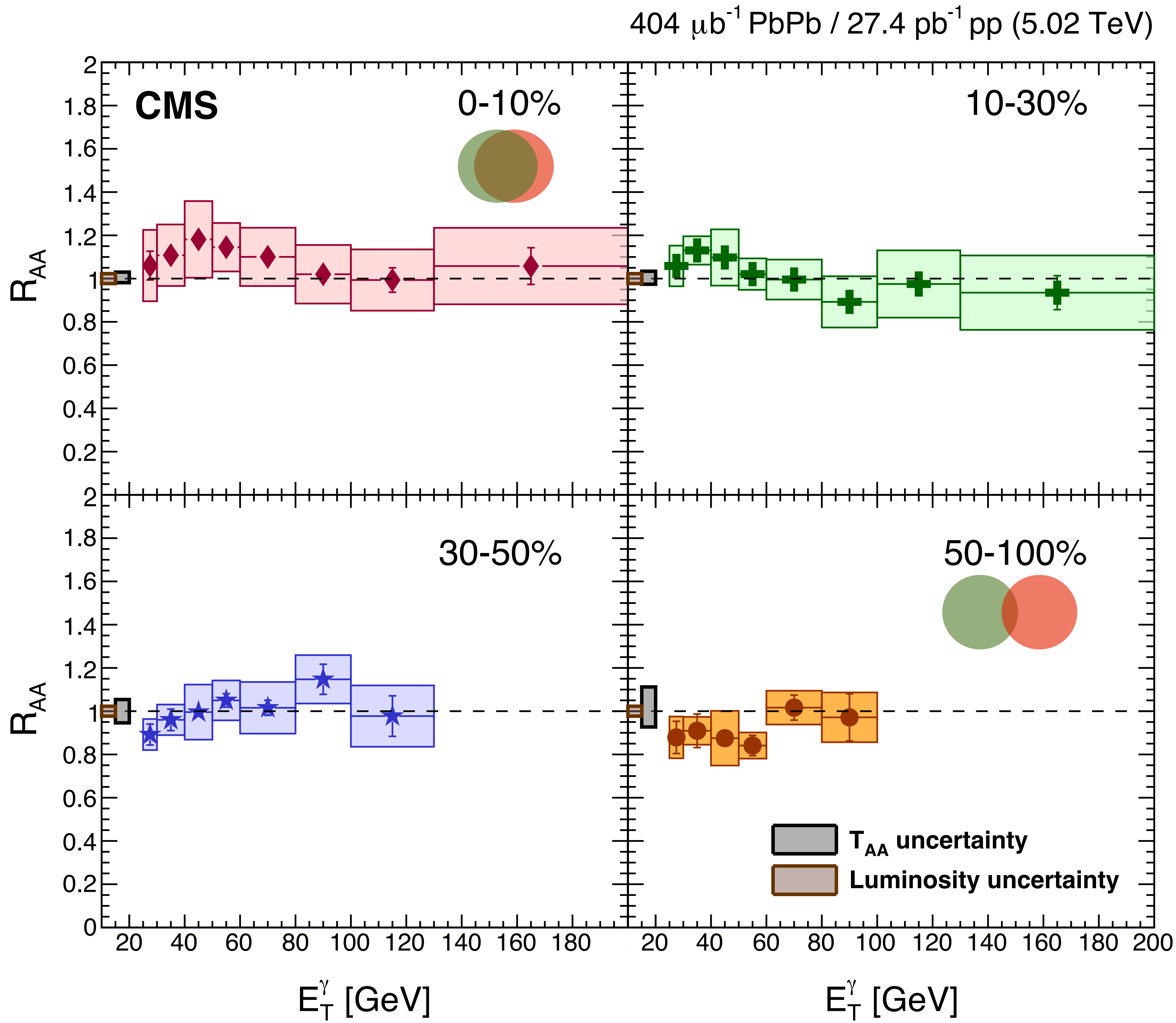
- **JETPHOX predictions** are **consistent with the data** in both pp and PbPb

Cross section of isolated photons (PbPb)



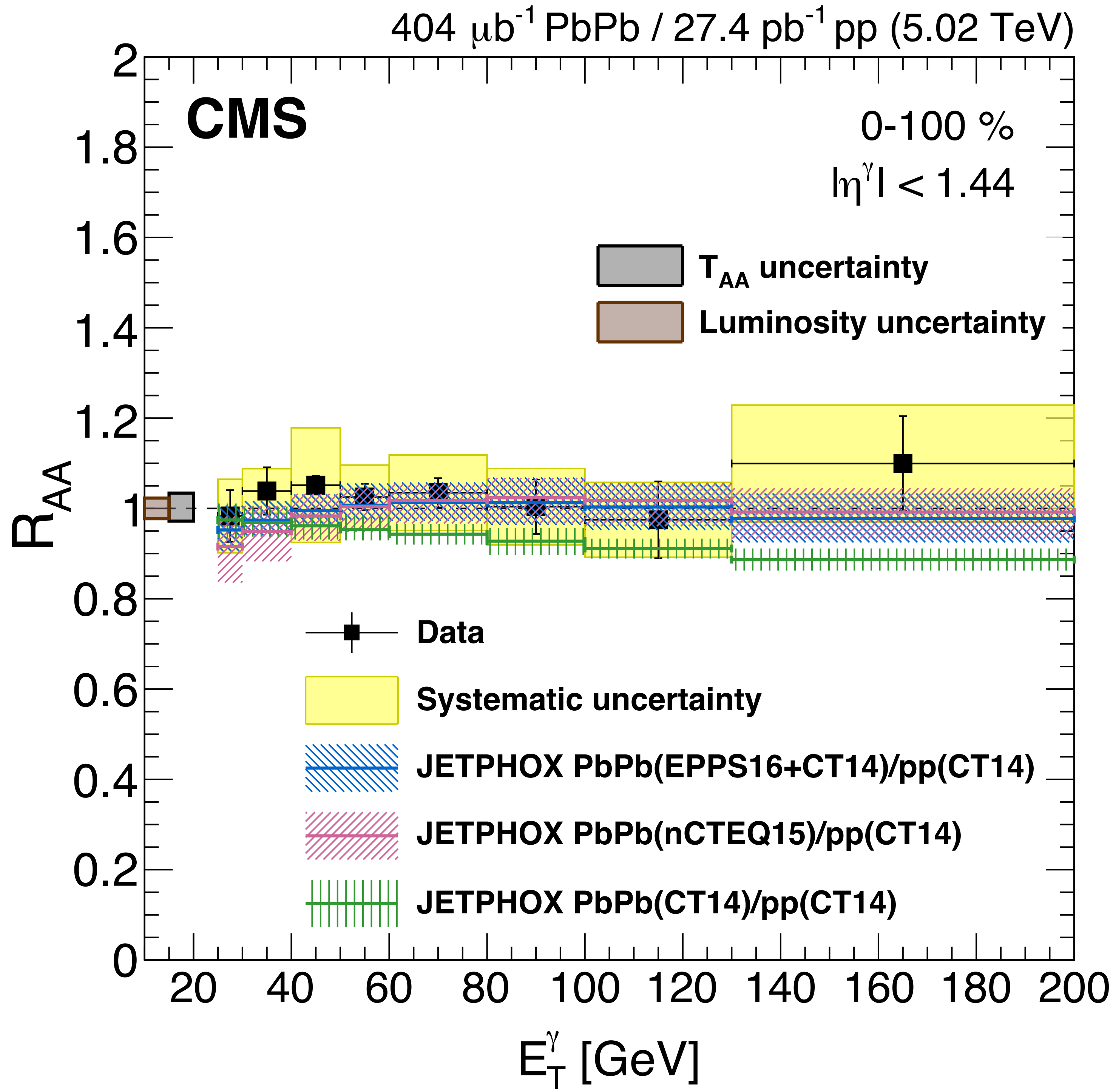
- **JETPHOX predictions** are **consistent with the data** in both pp and PbPb

Nuclear modification factor



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

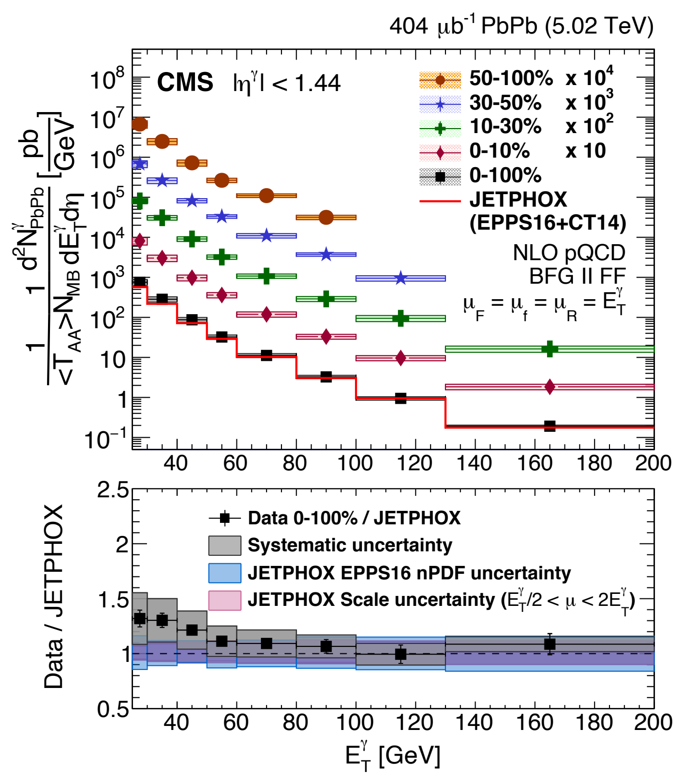
Comparison with predictions

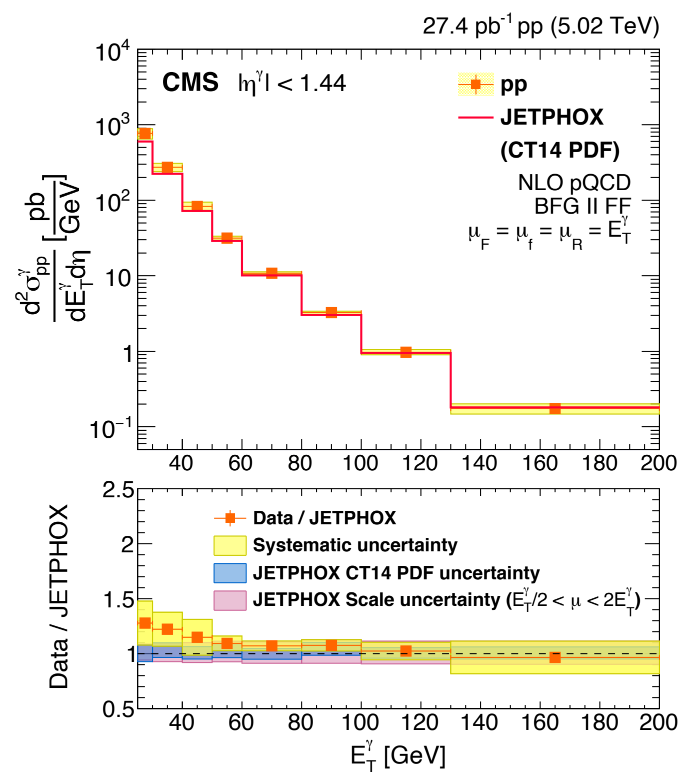


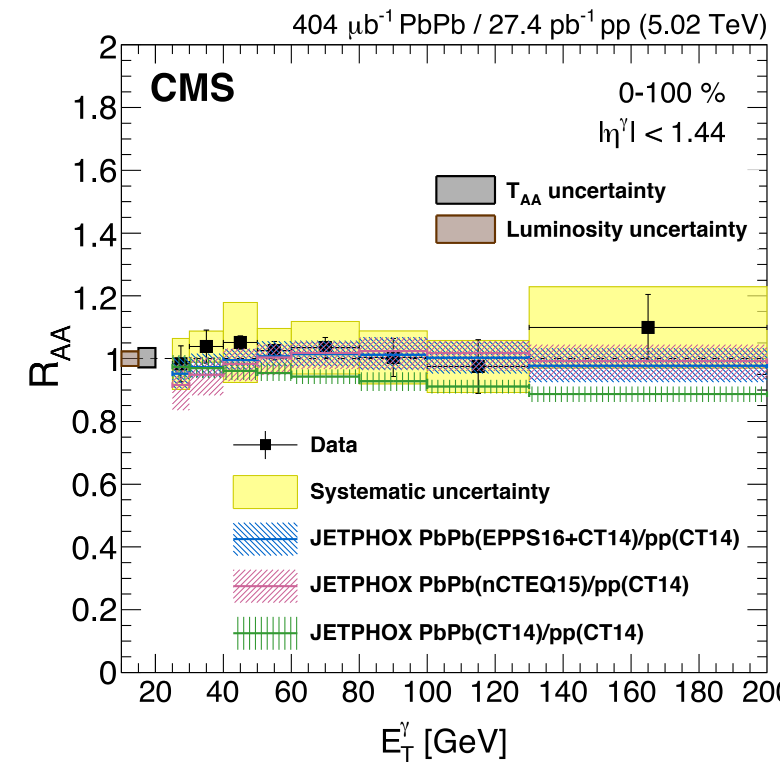
- Both **EPPS16 and nCTEQ15 describe the data well** within the uncertainty

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 -> [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.

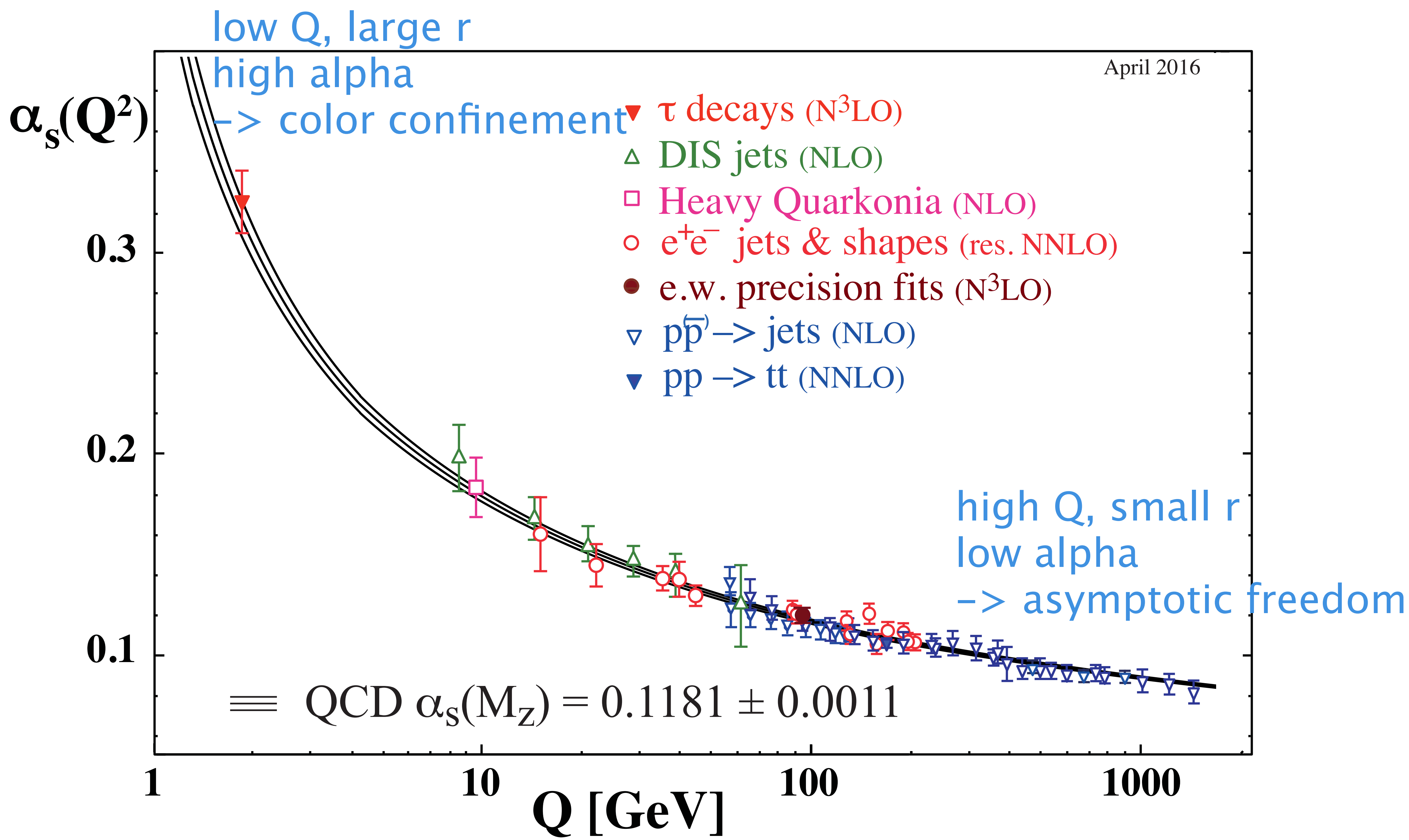






BACK UP

Strong coupling constant

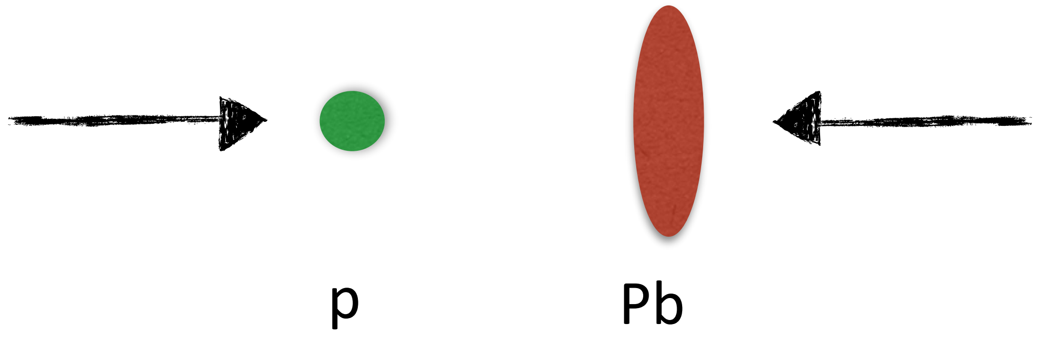


- The coupling constant decreases logarithmically as the interaction energy gets higher: **running** coupling constant
- Two distinctive features of QCD: **color confinement** and **asymptotic freedom**

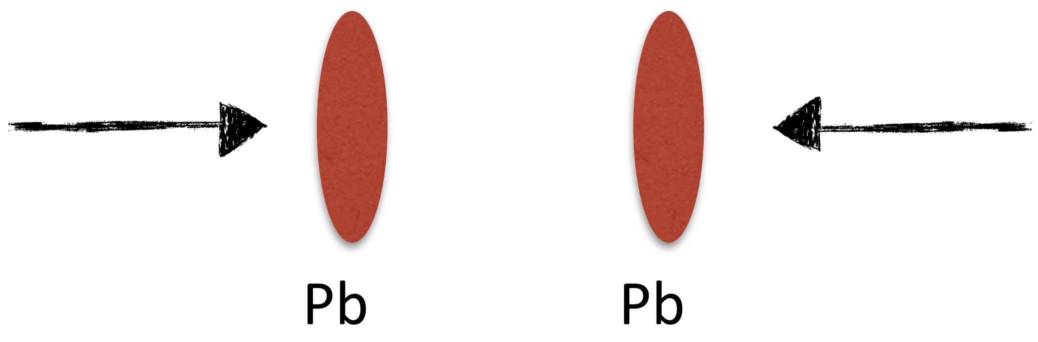
Prompt photons in various collision systems

- **pp collisions**
  - pQCD benchmark
  - reference for larger systems

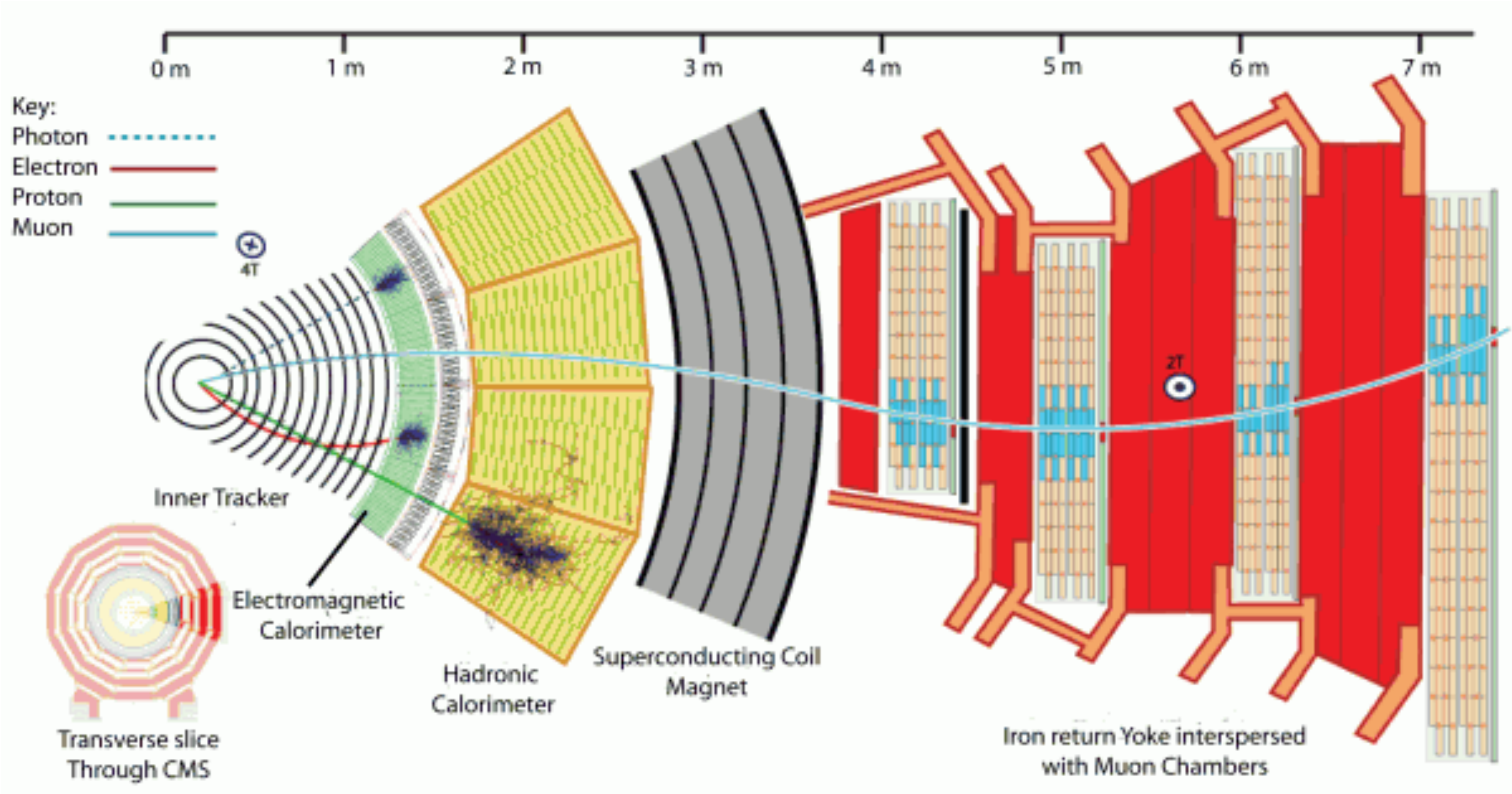
- **pPb collisions**
  - study cold nuclear matter (CNM) effect
  - PDF modification:
    (anti)shadowing, gluon saturation



- **PbPb collisions**
  - study hot nuclear matter effect (QGP)



CMS detector



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

CMS detector

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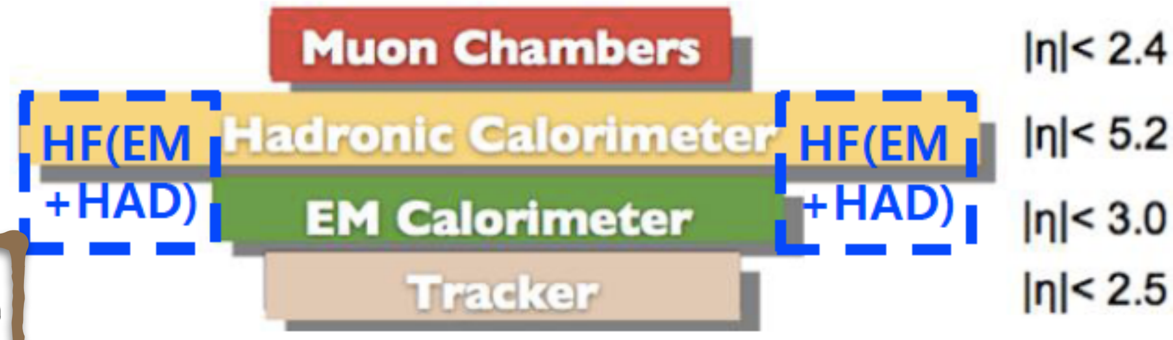
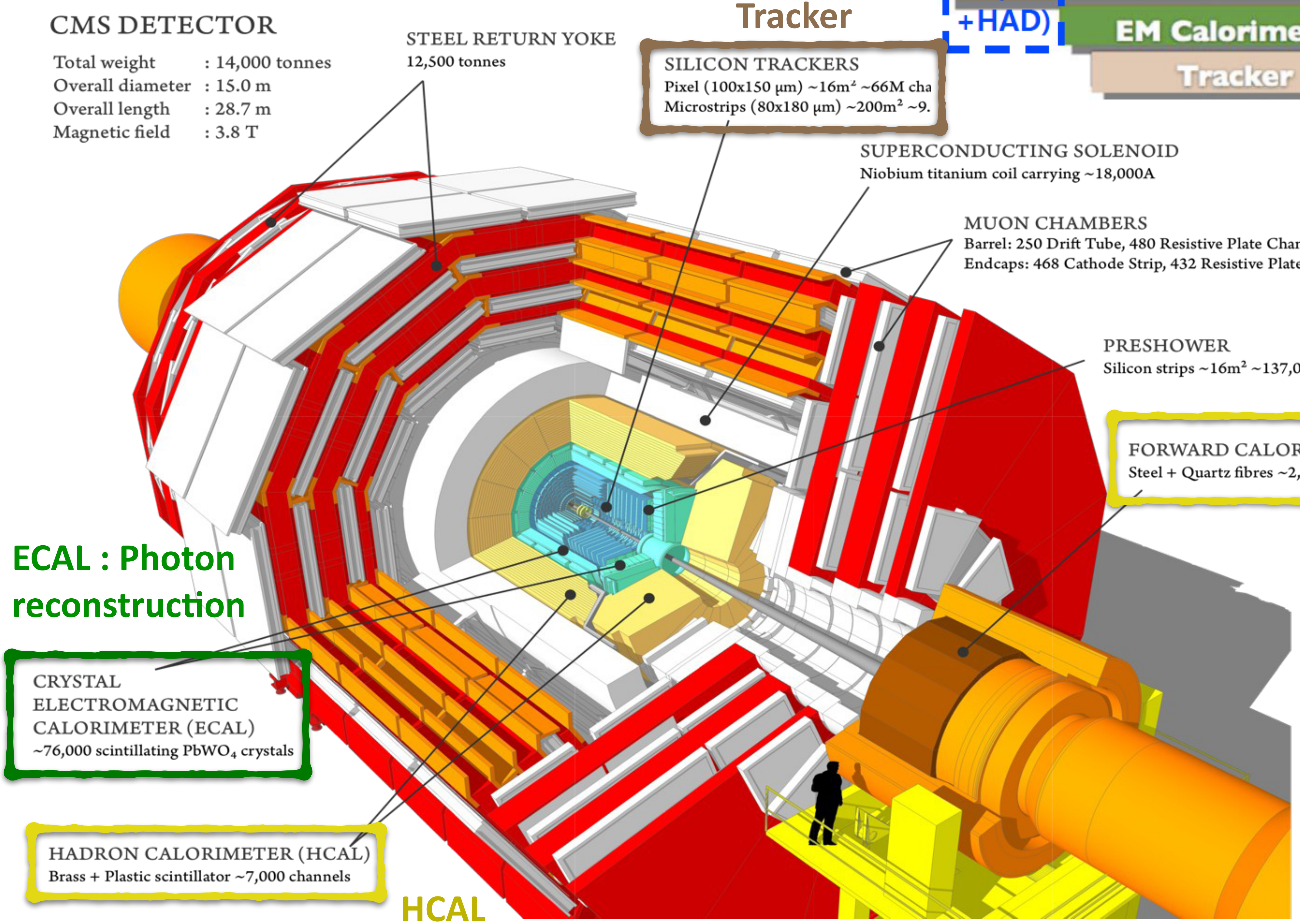
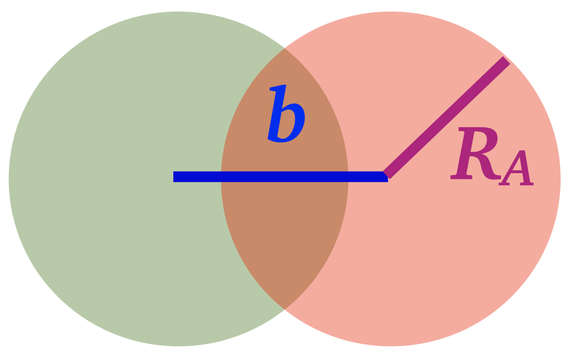




HF : Centrality determination

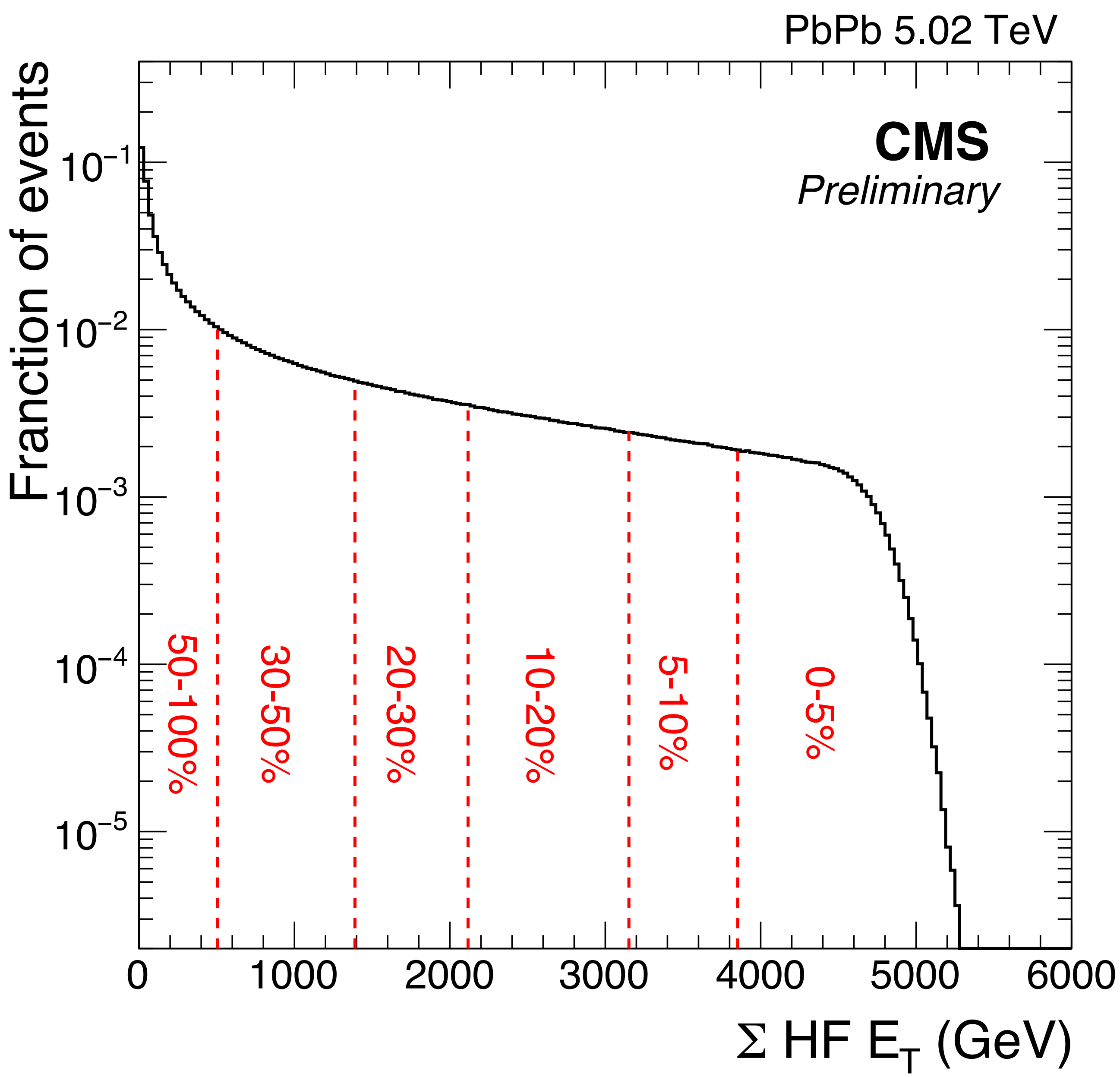
Centrality

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



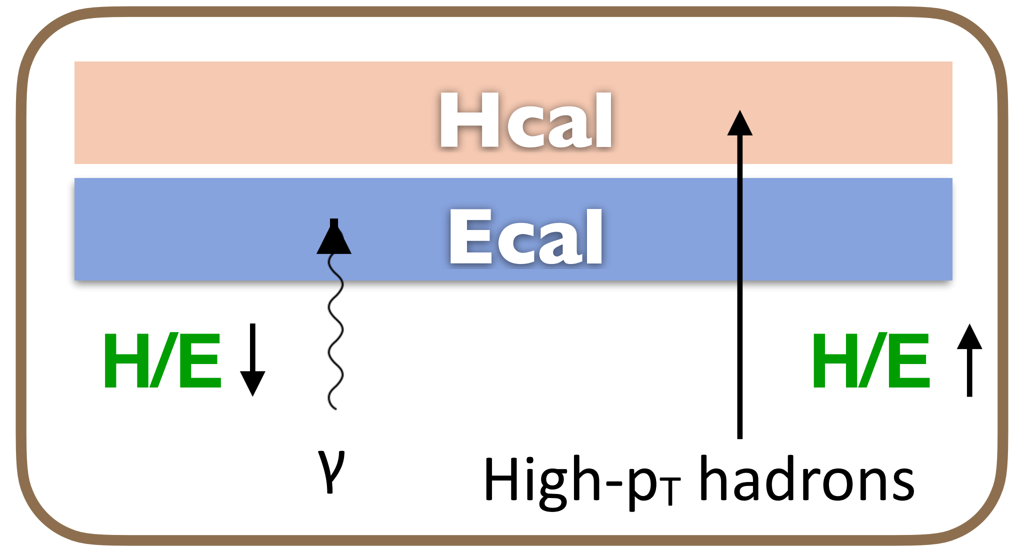
$$centrality = \frac{\pi b^2}{\pi (2R_A)^2}$$

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



Photon identification and isolation requirement

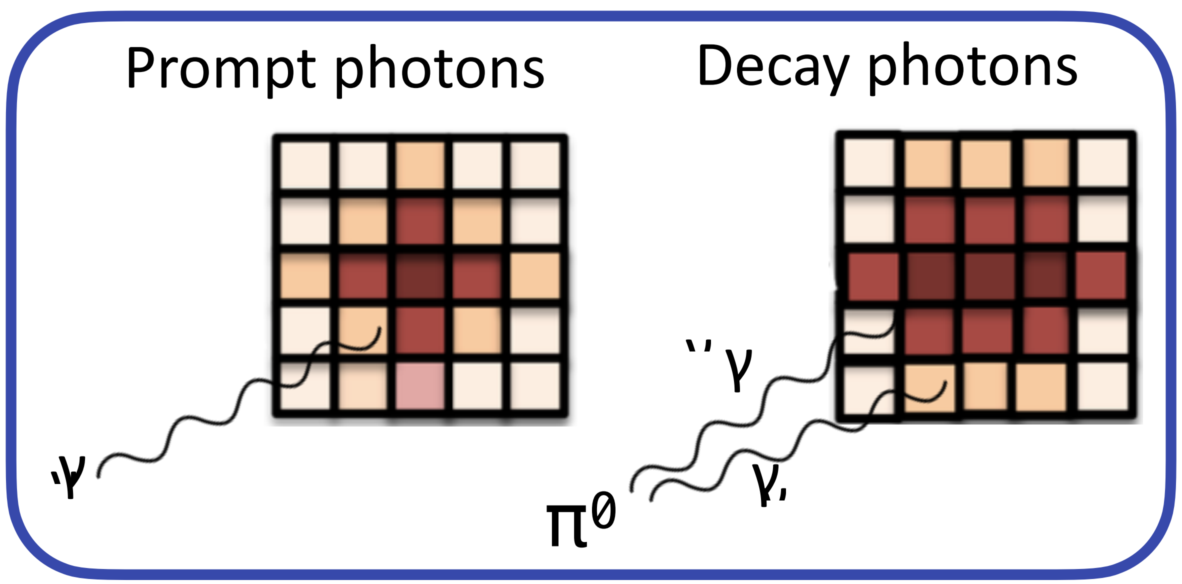
- **1) H(Hcal)/E(Ecal) < 0.1**
  - removes high-p_T hadrons



- **2) $\sigma_{\eta\eta}$ (shower shape variable) < 0.01**
  - removes decay photons using energy deposit shape

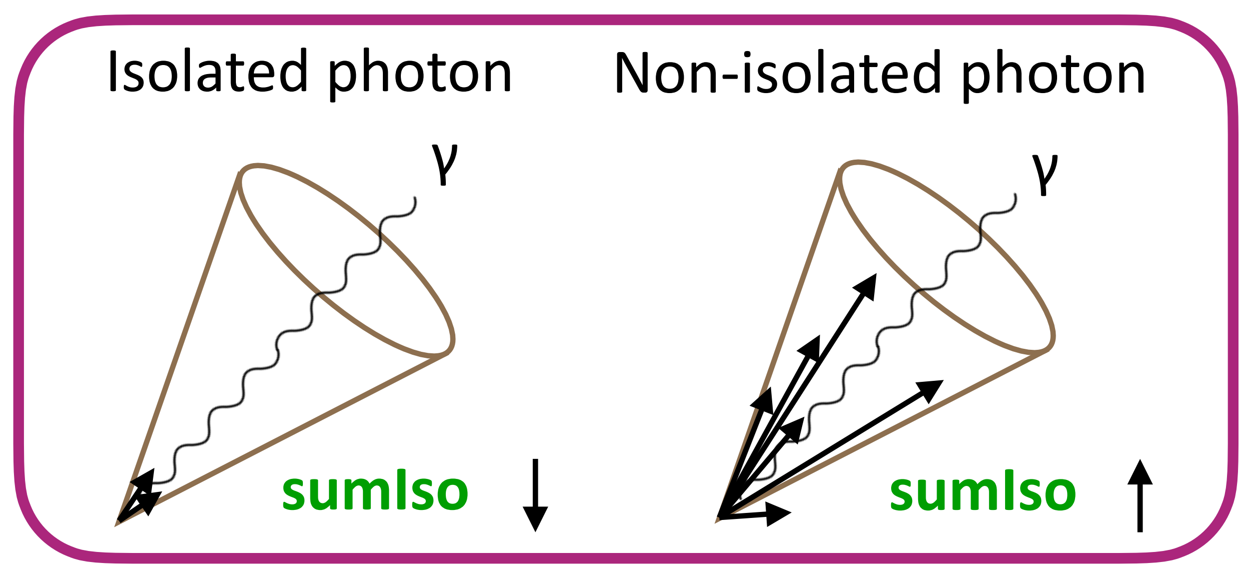
$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i},$$

$$w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}\right)$$



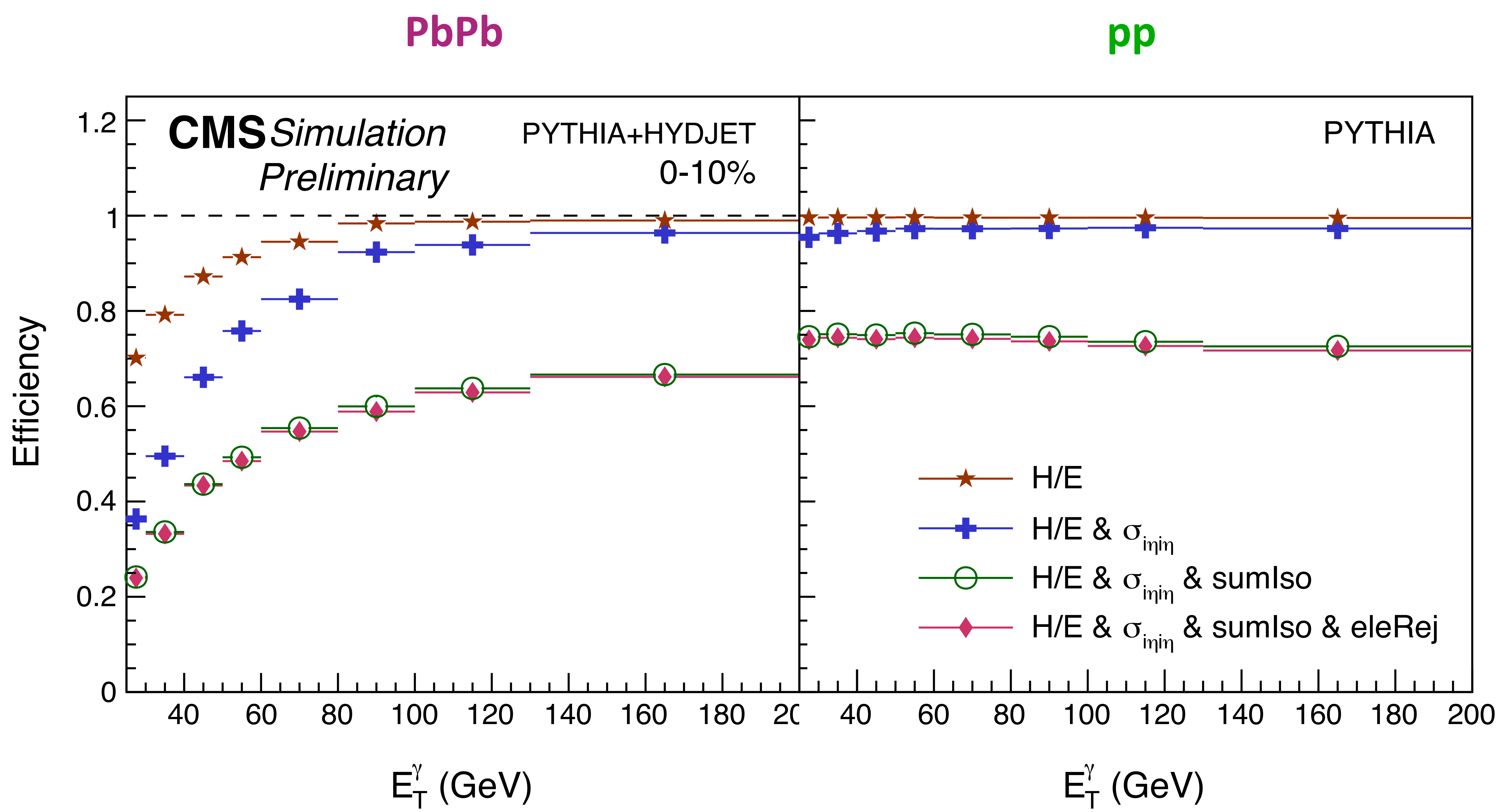
$\sigma_{\eta\eta}$ ↓ $\sigma_{\eta\eta}$ ↑

- **3) sumIso < 1 GeV**
  - sumIso: energy sum around photon candidates
    - sumIso = tracker iso + Ecal iso + 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**

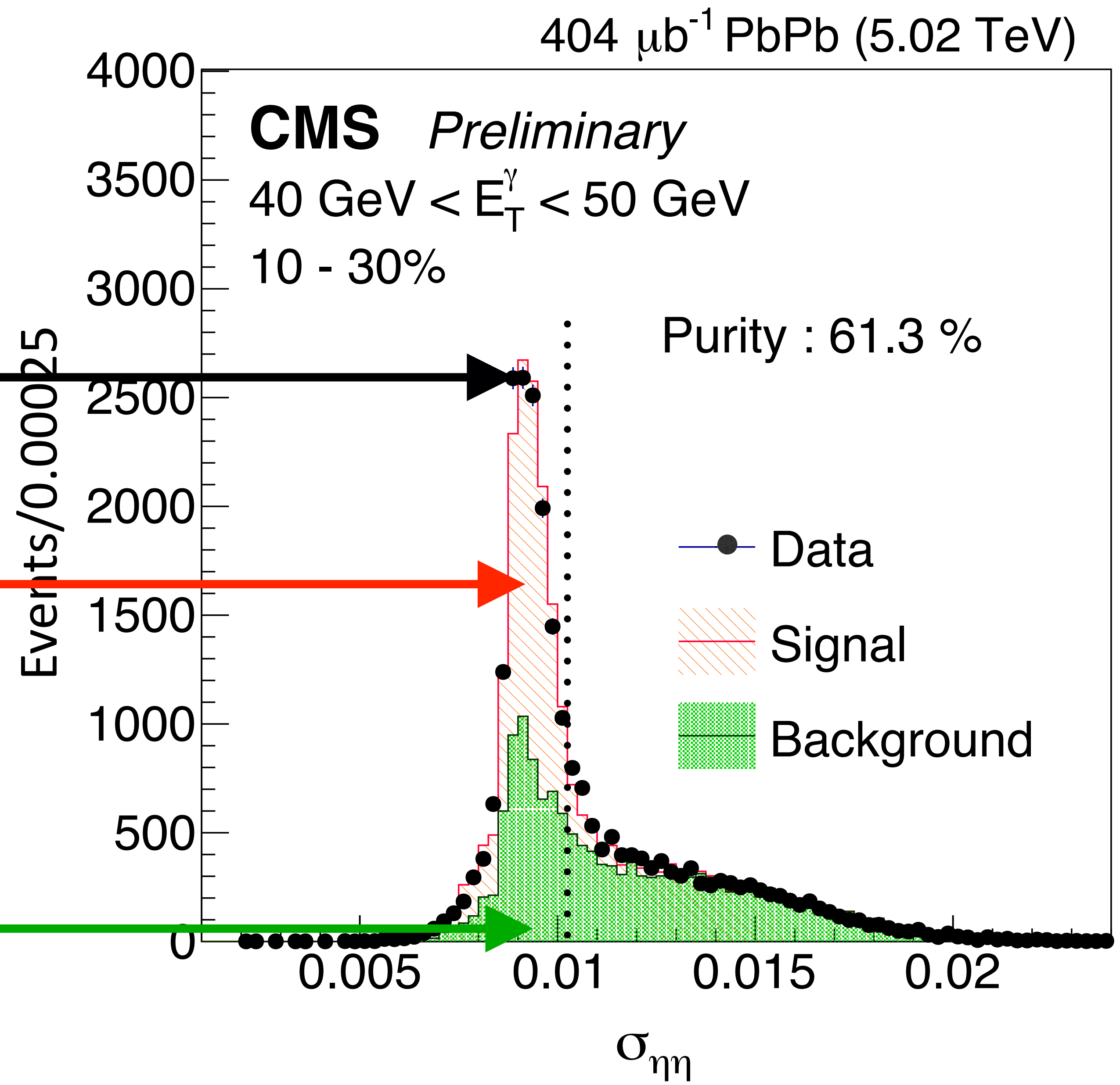


Purity : template fit method

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

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

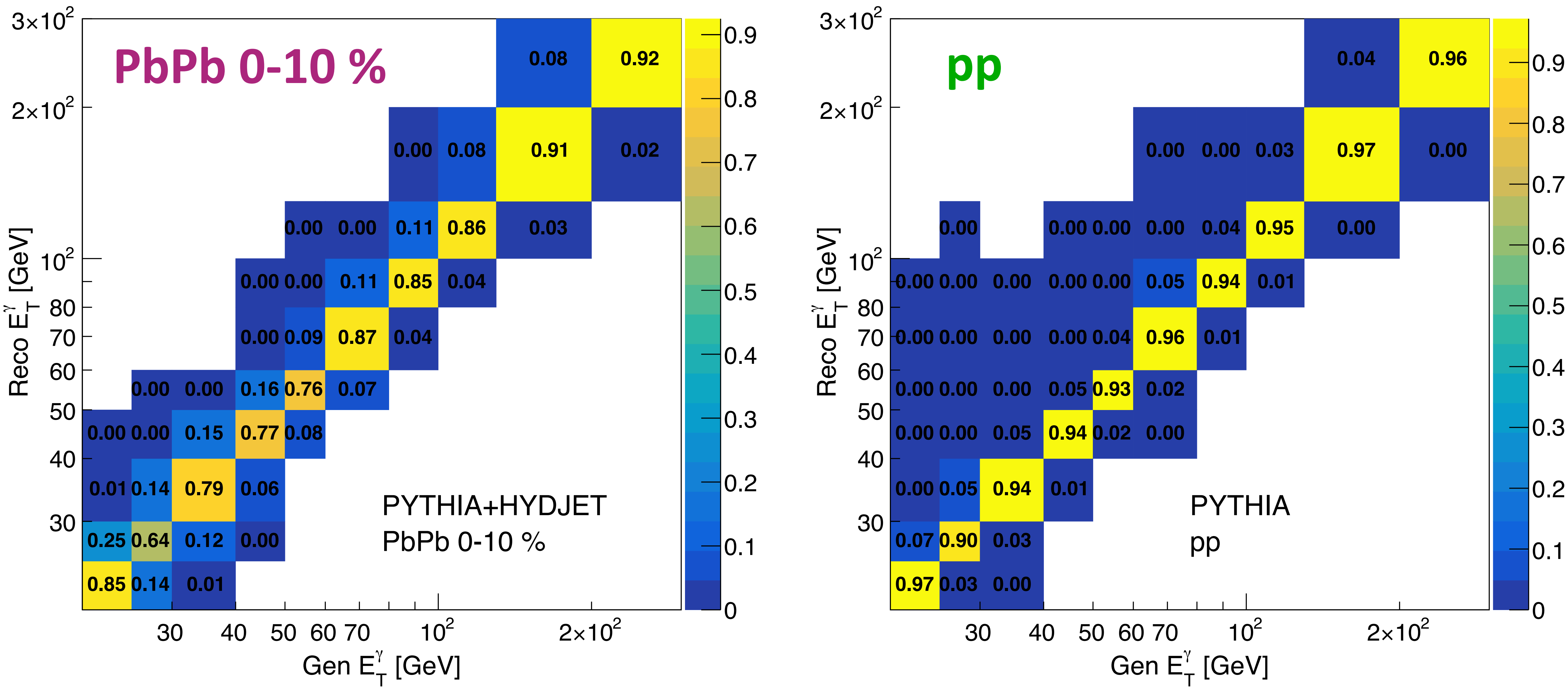
- **DATA**
  - H/E < 0.1
  - sumIso < 1 GeV
- **Signal template (from MC)**
  - Gen-level prompt isolated photons
  - H/E < 0.1
  - sumIso < 1 GeV
- **Background template (from DATA in sideband)**
  - H/E < 0.1
  - sideband cut : 1 < sumIso < 5 GeV



$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i}, \qquad w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}\right)$$

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%

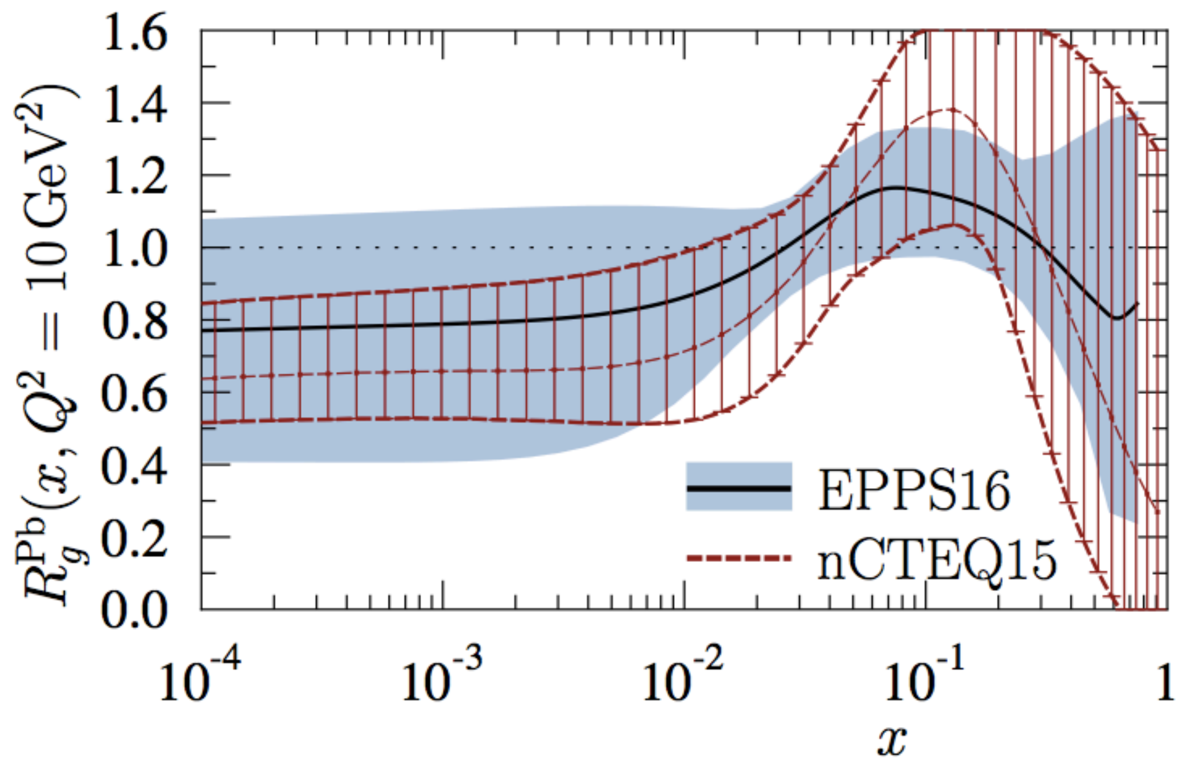
Systematic uncertainty: R_{AA}

- 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}

	PbPb centrality				
Source	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, $E_T^{had} < 5$ GeV**
- PDF of free proton : **CT14** (56 PDF error sets)
- Nuclear PDF : **EPPS16** (97 nPDF error sets), **nCTEQ15** (33 nPDF error sets)



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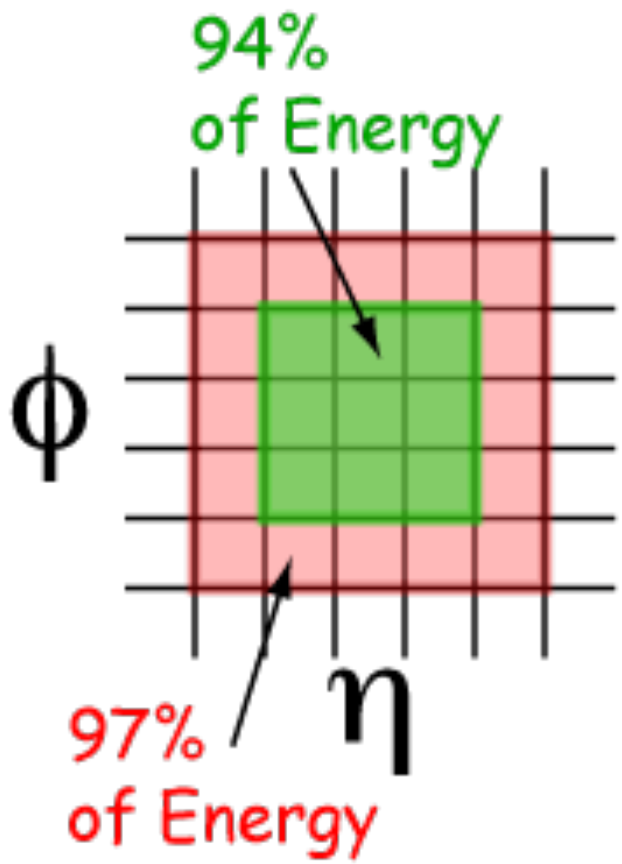
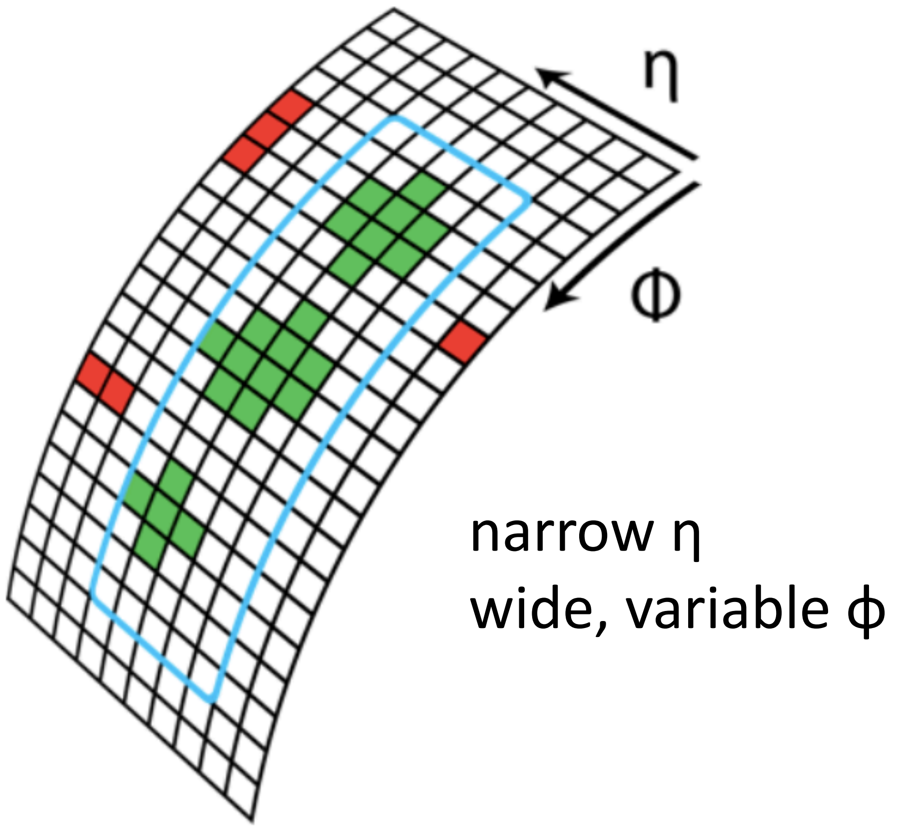
Photon reconstruction

- 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

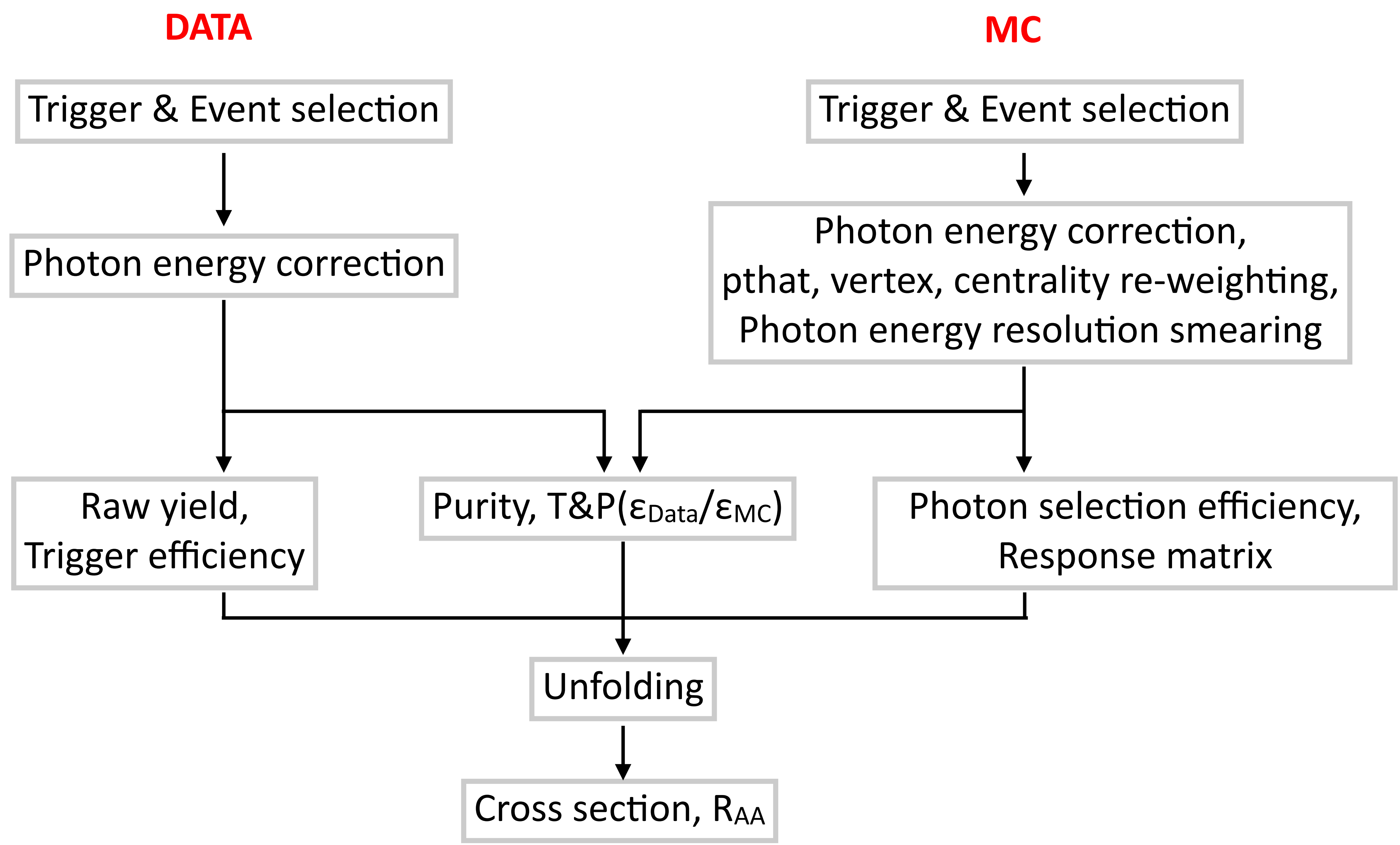
Un-converted photons



Converted photons



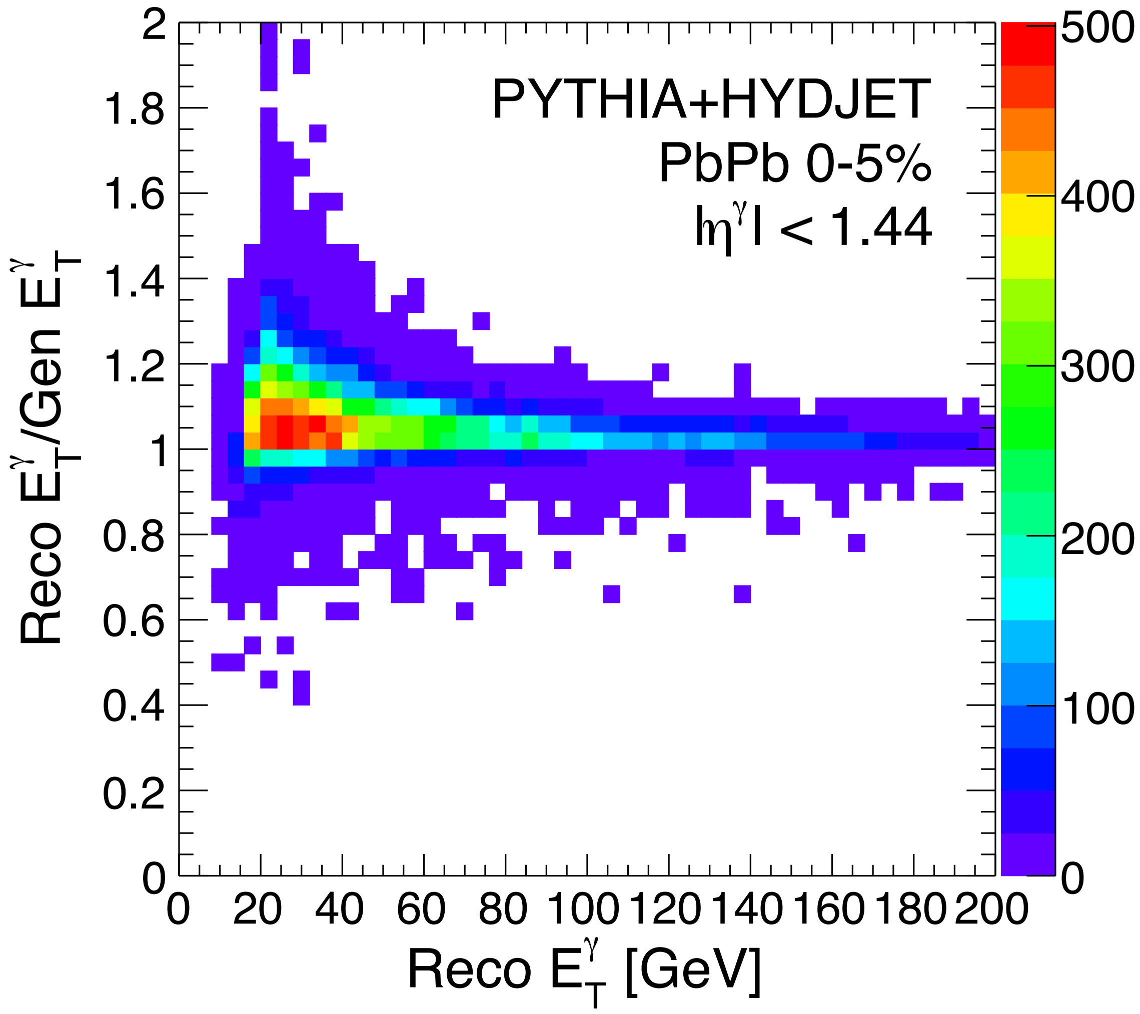
Analysis flow chart

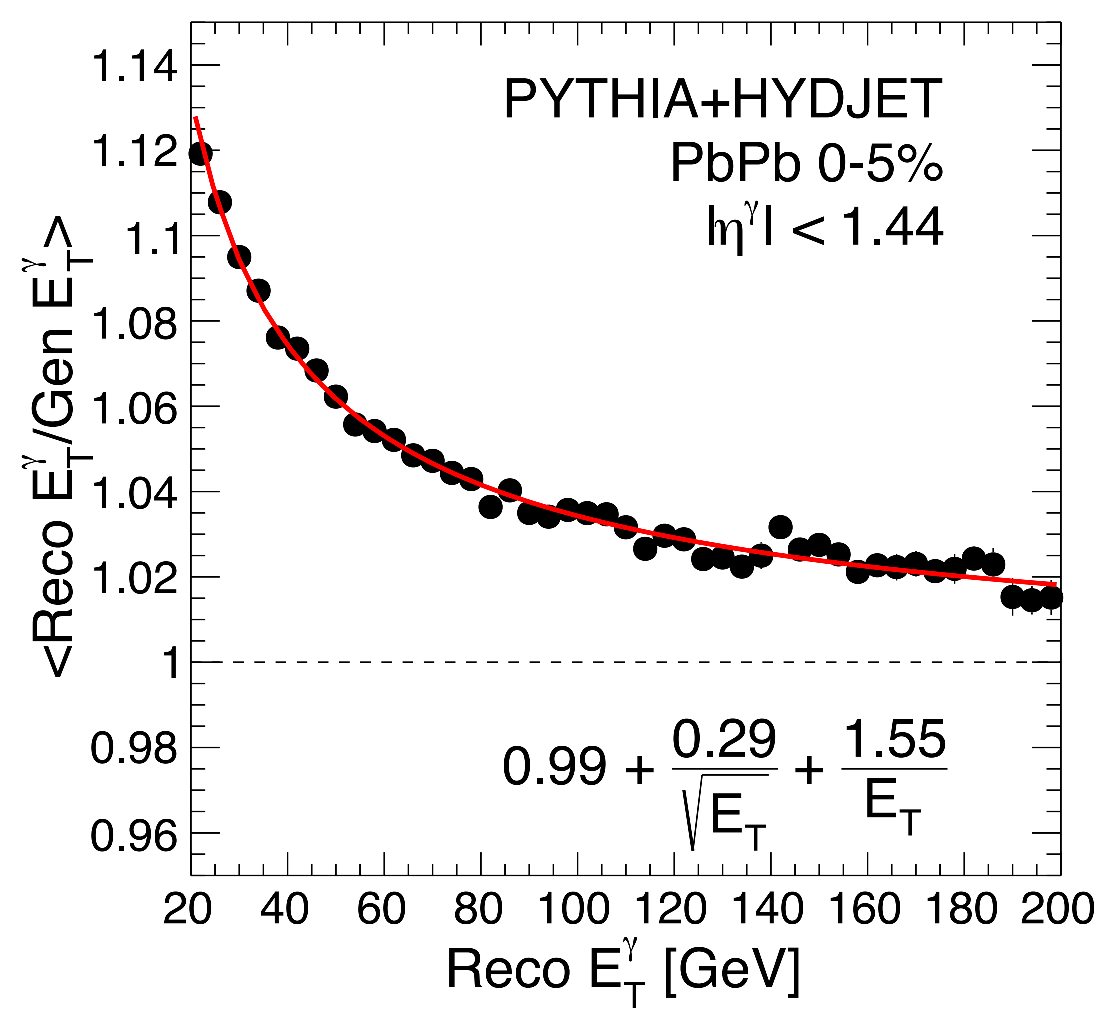


* Below conditions are applied on Efficiency, Purity and Yield calculation

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

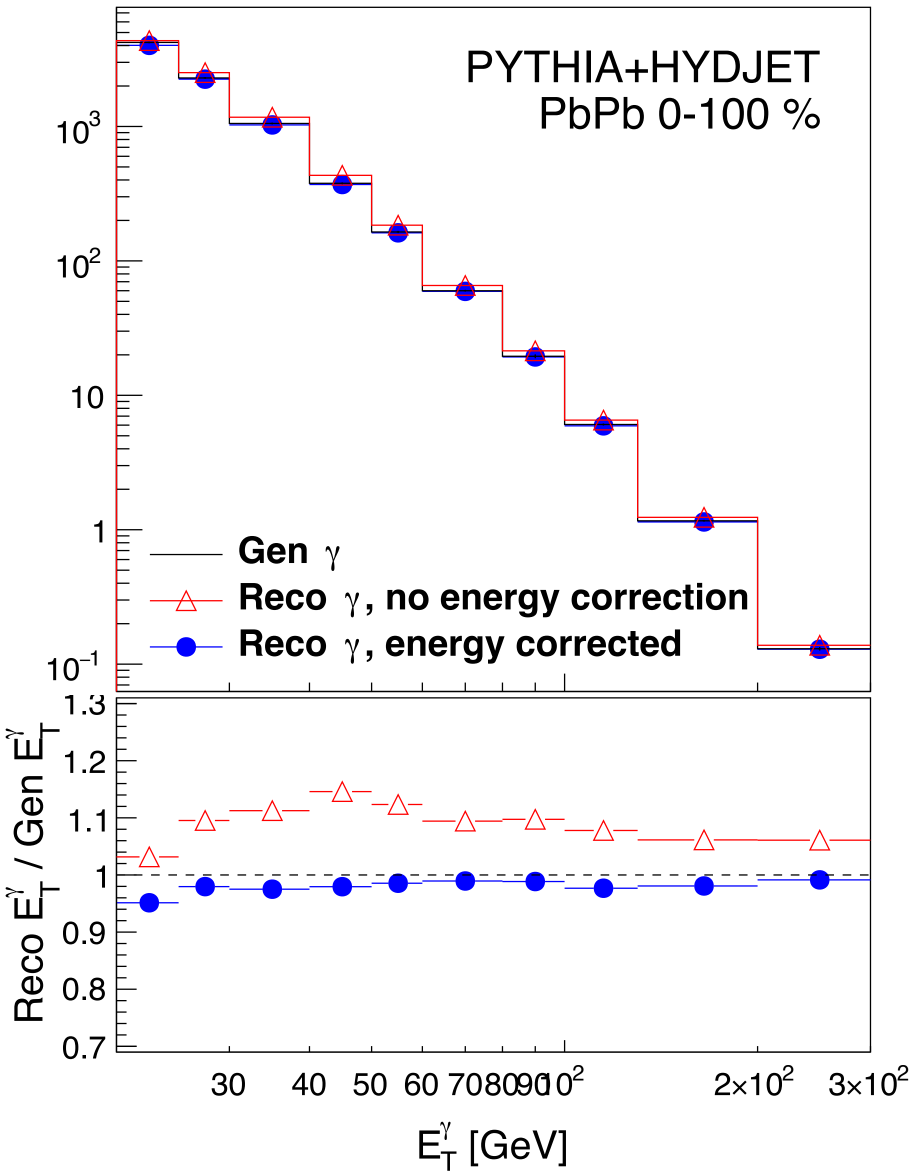
Photon energy correction



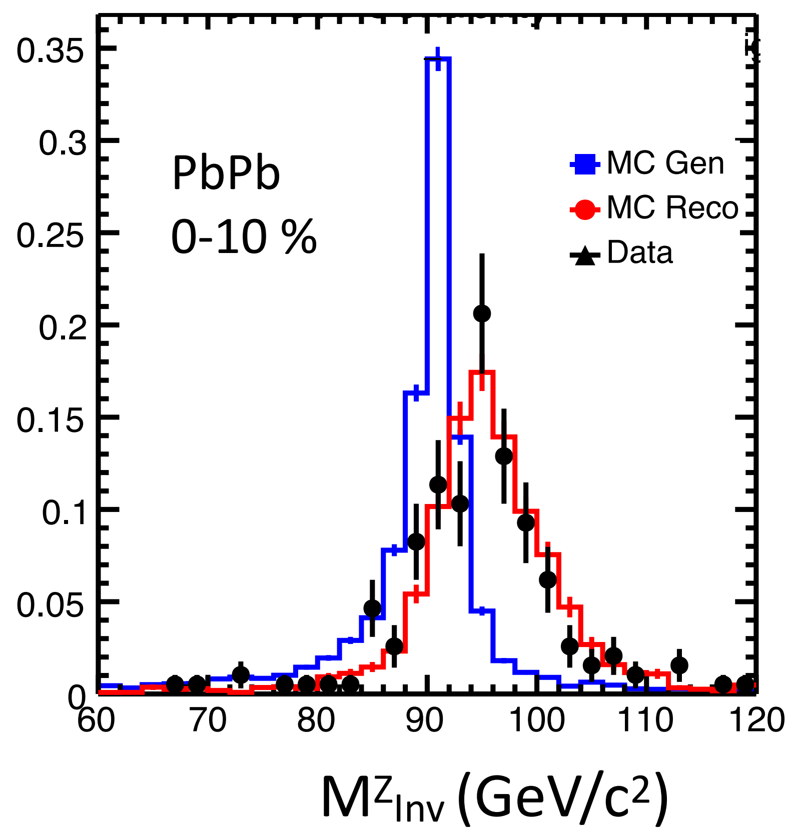


- **Energy of the reconstructed photons is corrected**
  - photon energy scales as a function of E_T are determined by simulation in 7 different centrality intervals

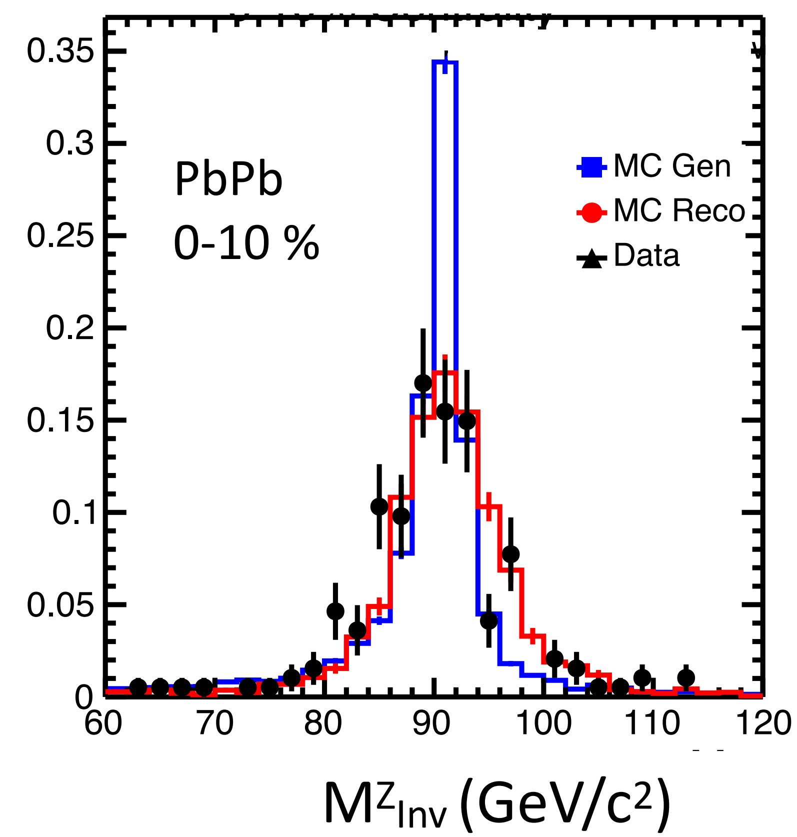
Validation: photon energy correction



Before energy correction



After energy correction

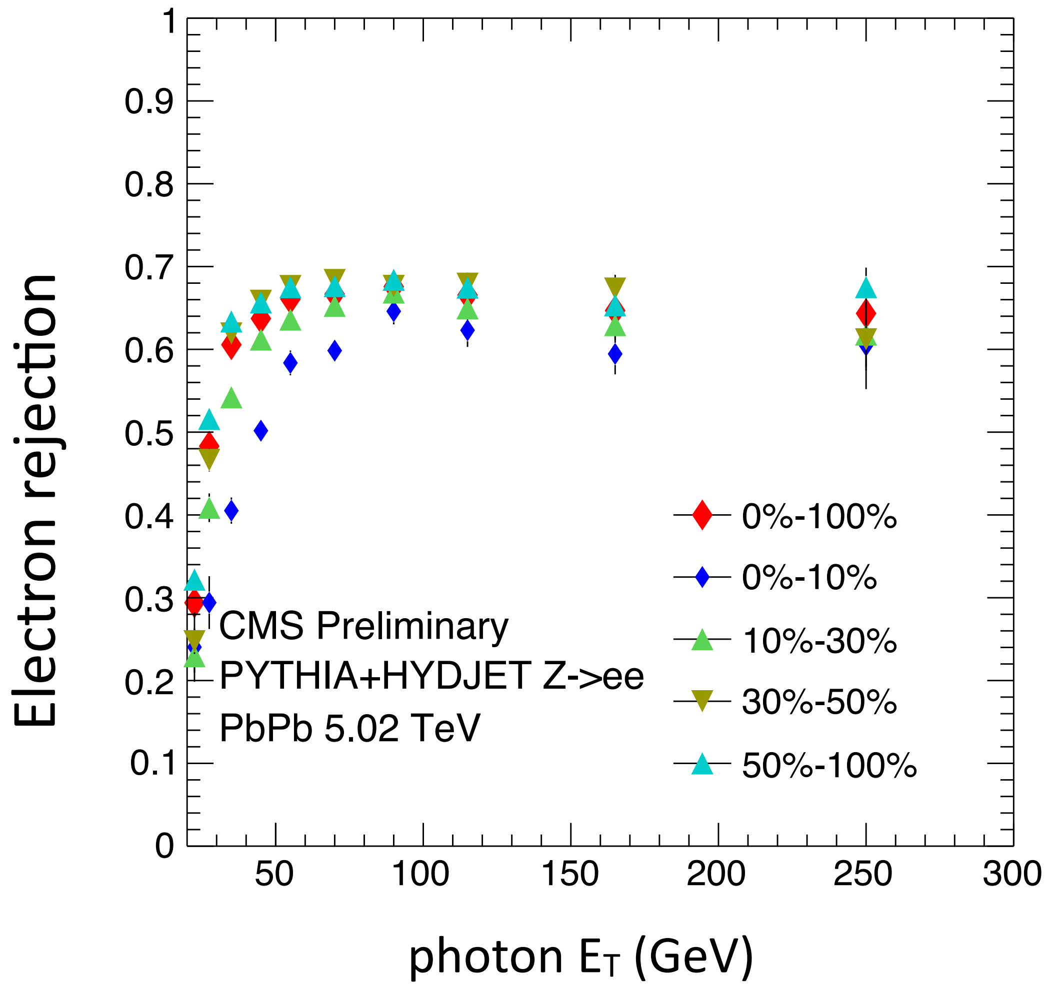


- **Validation:** Z mass is reconstructed well after the energy correction
- Systematic uncertainty: **residual difference** btw data and MC

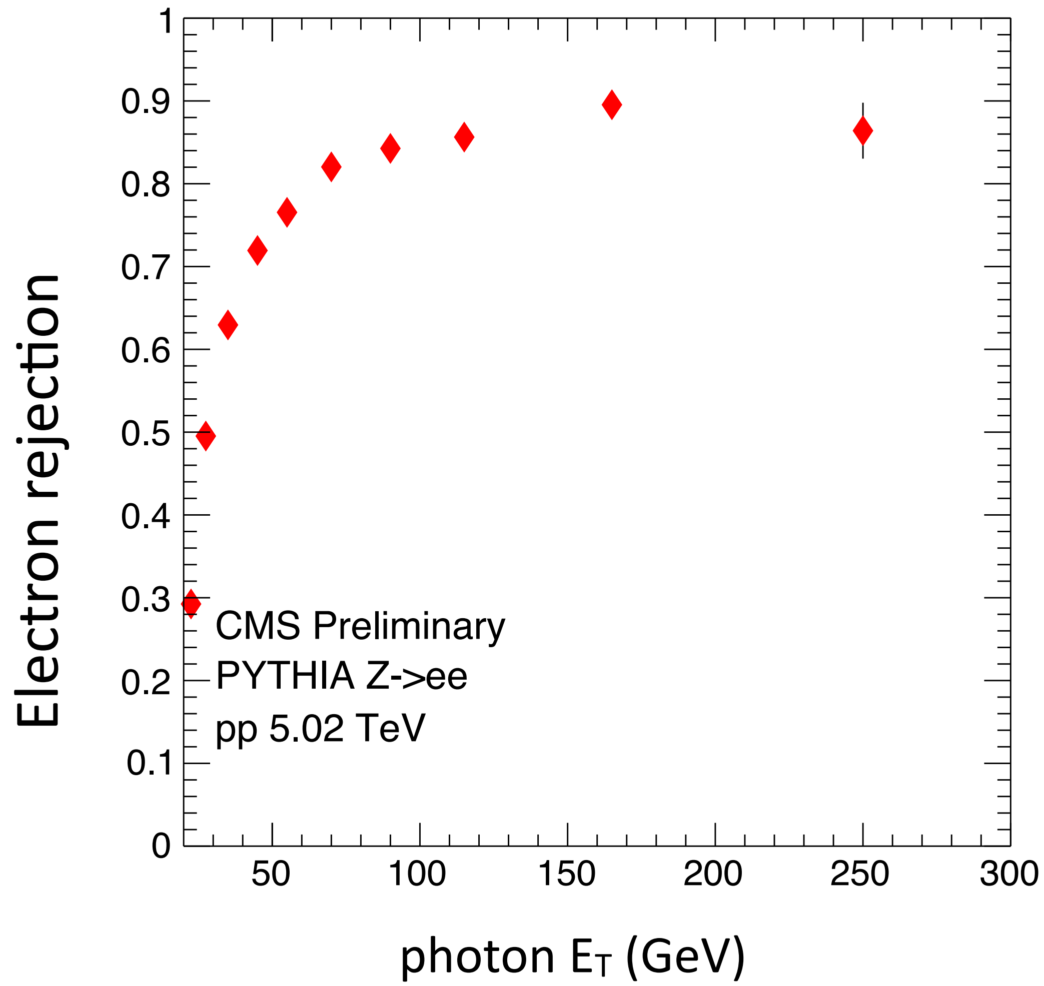
Electron rejection

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

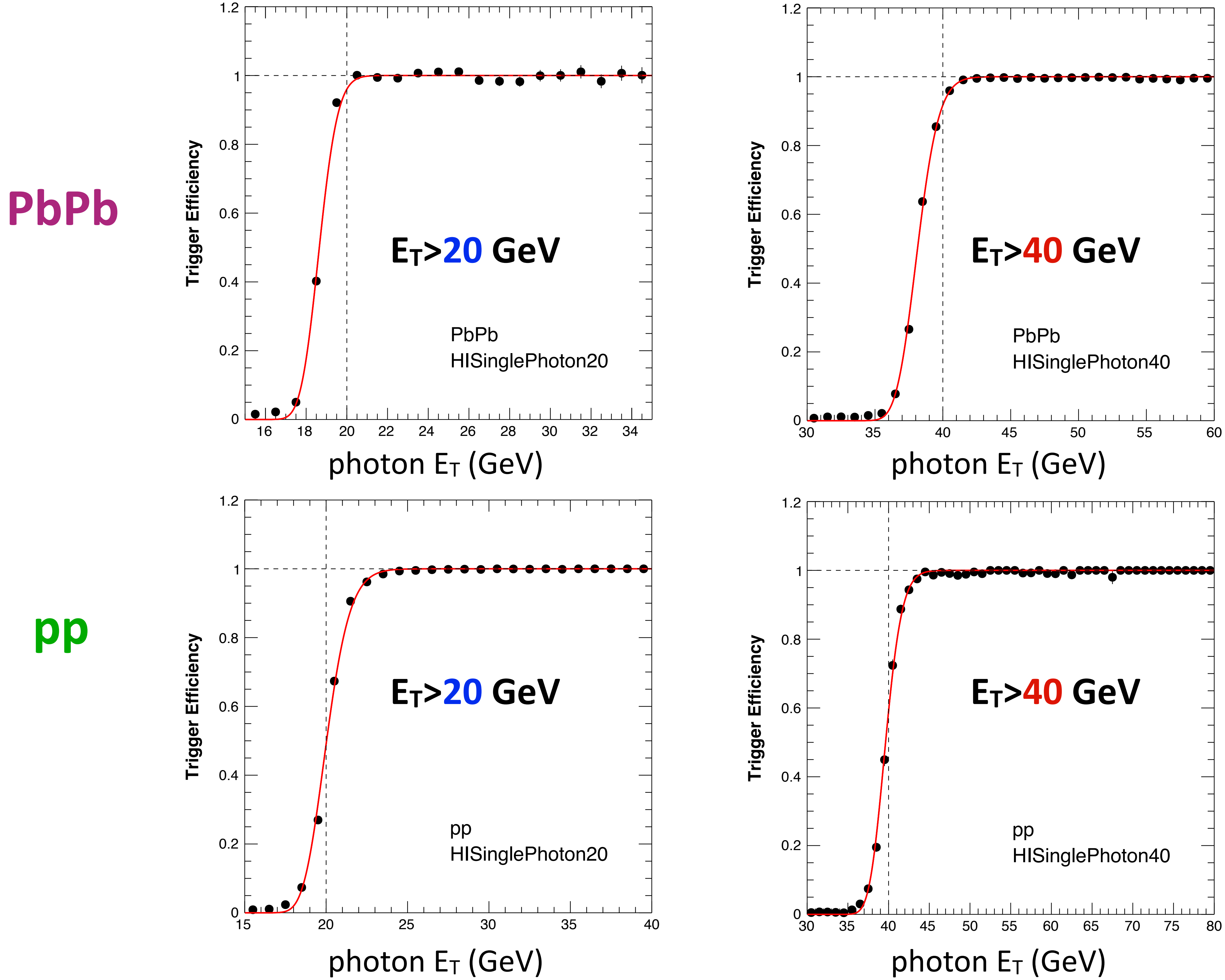
PbPb



pp

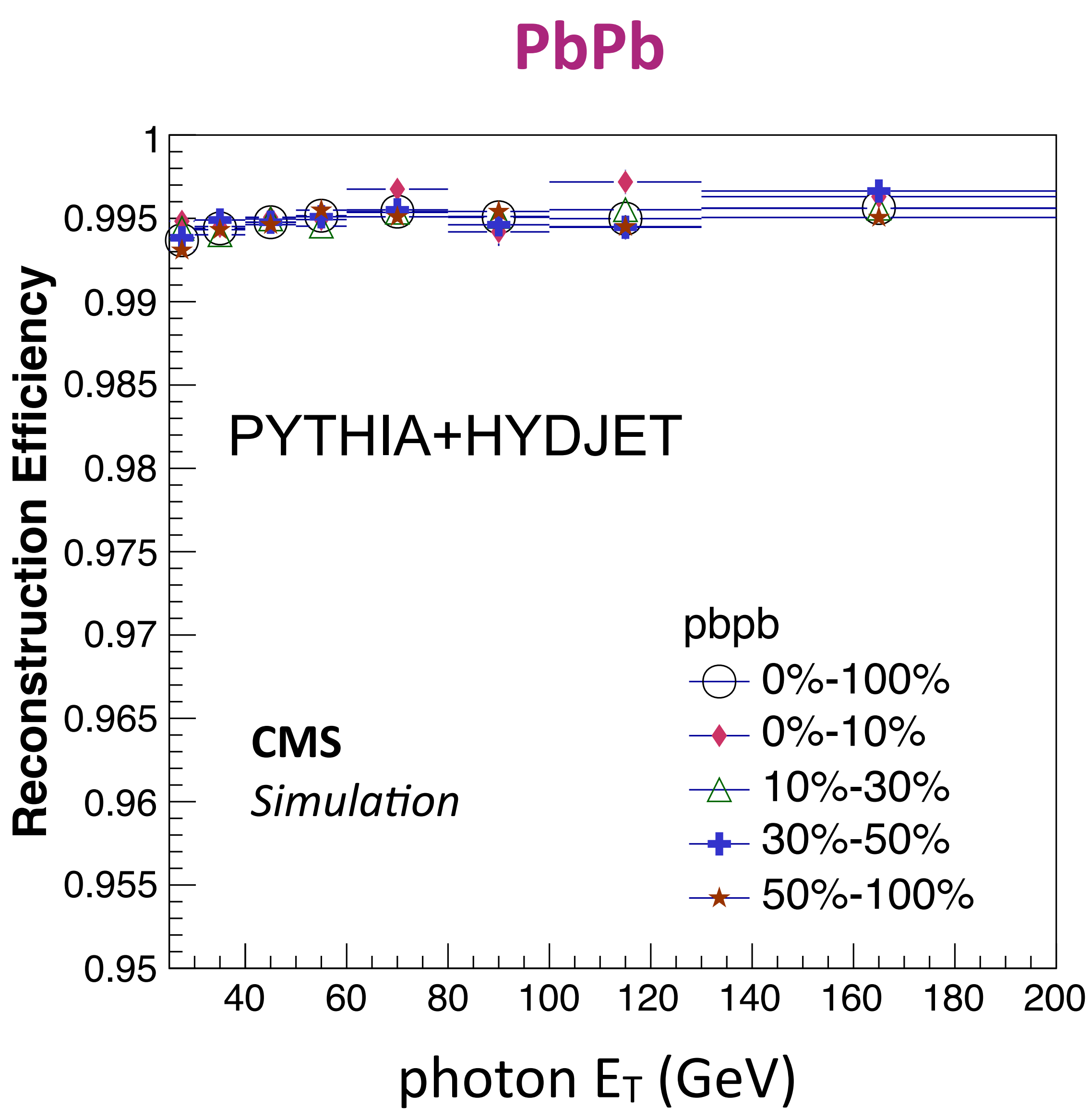


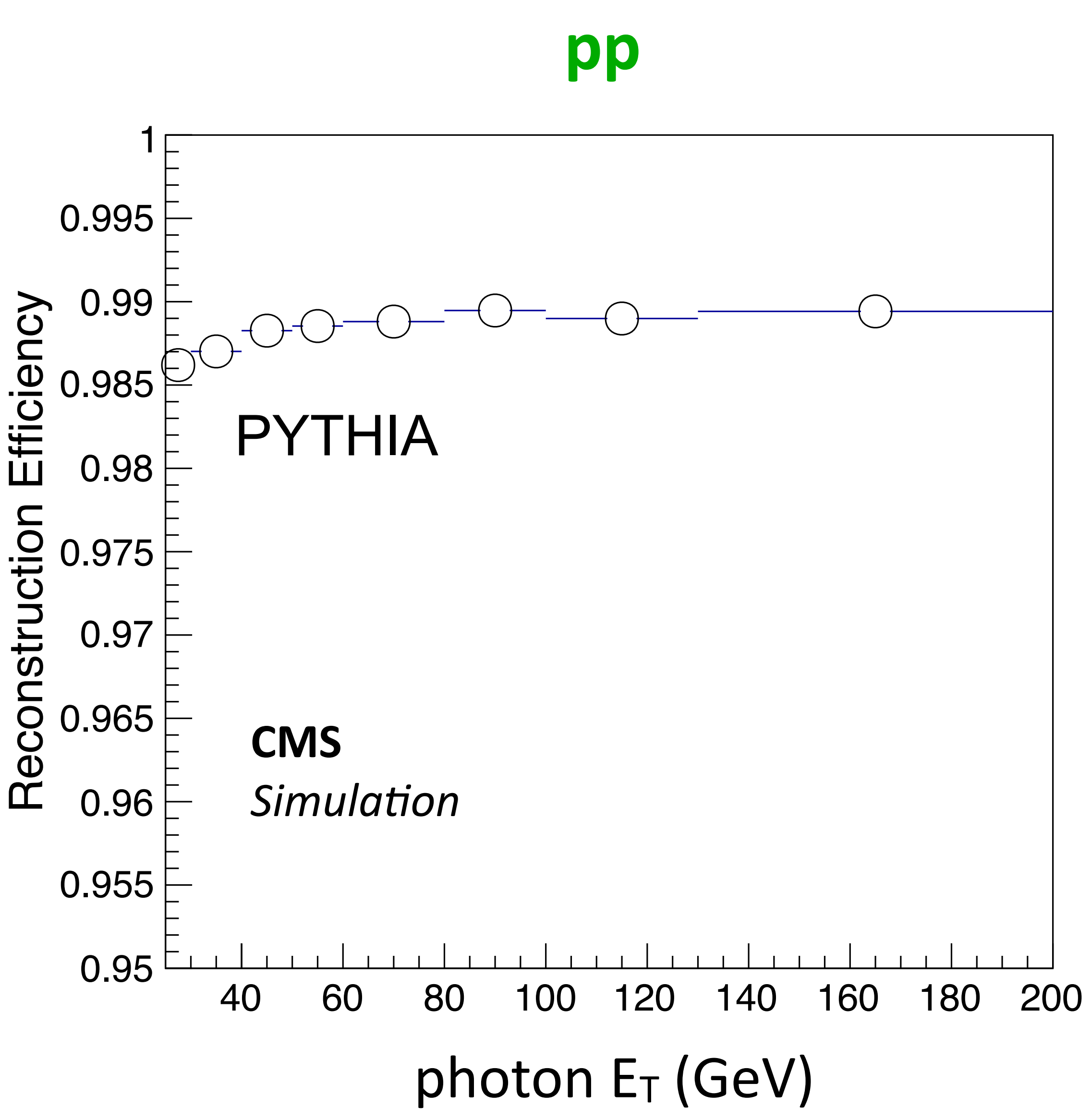
Trigger efficiency



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

Reconstruction efficiency



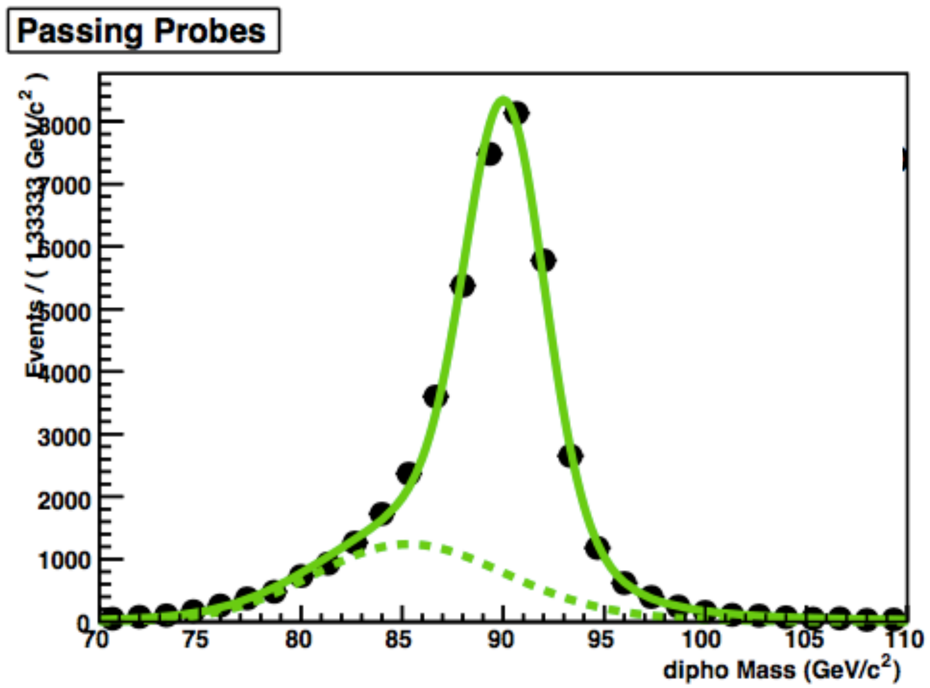


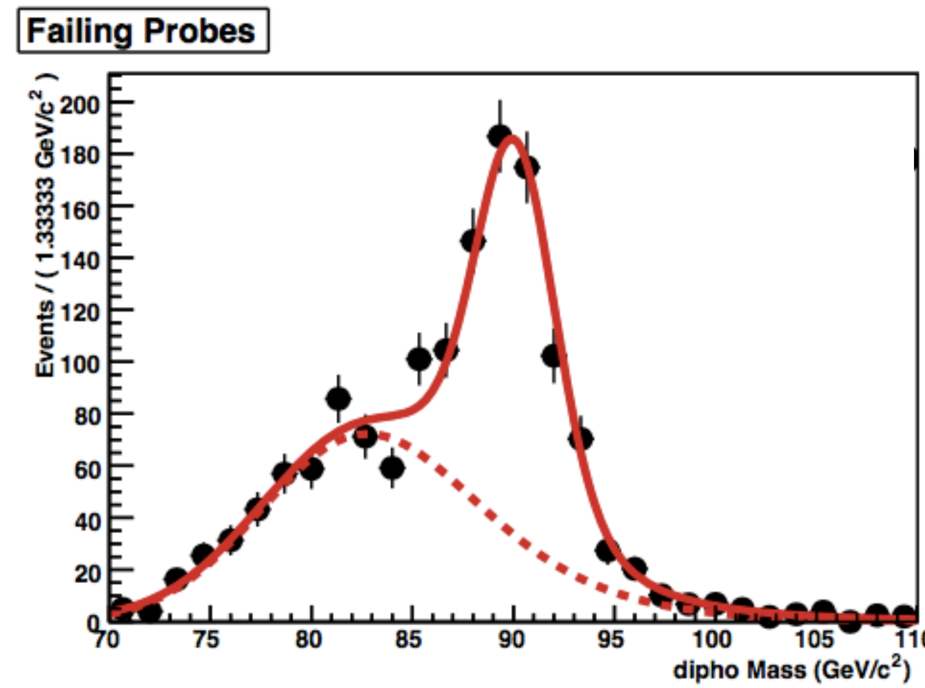
- **Reconstruction efficiency** = $N_{\text{generated and reconstructed photons}}$ / $N_{\text{generated photons}}$
  - generator-level isolation energy < 5 GeV inside a cone of dR = 0.4
  - generated and reconstructed photon matching in dR < 0.15

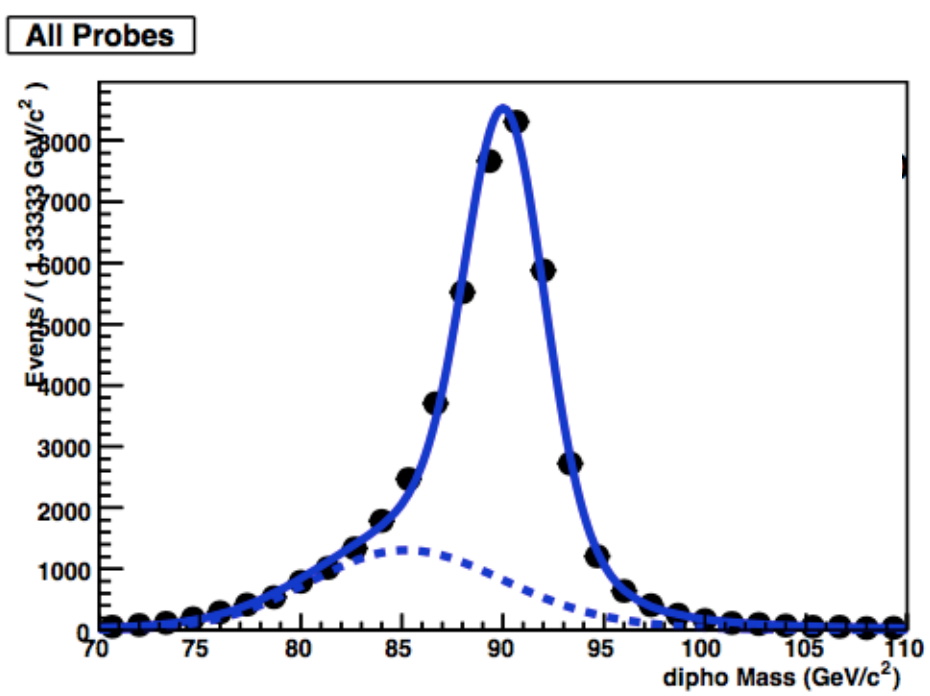
- Reconstruction efficiency is **~99 %** for pp and PbPb in all centrality classes

Tag-and-Probe method

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







alphaFail = 84.8 ± 0.9
alphaPass = 90.0 ± 0.3
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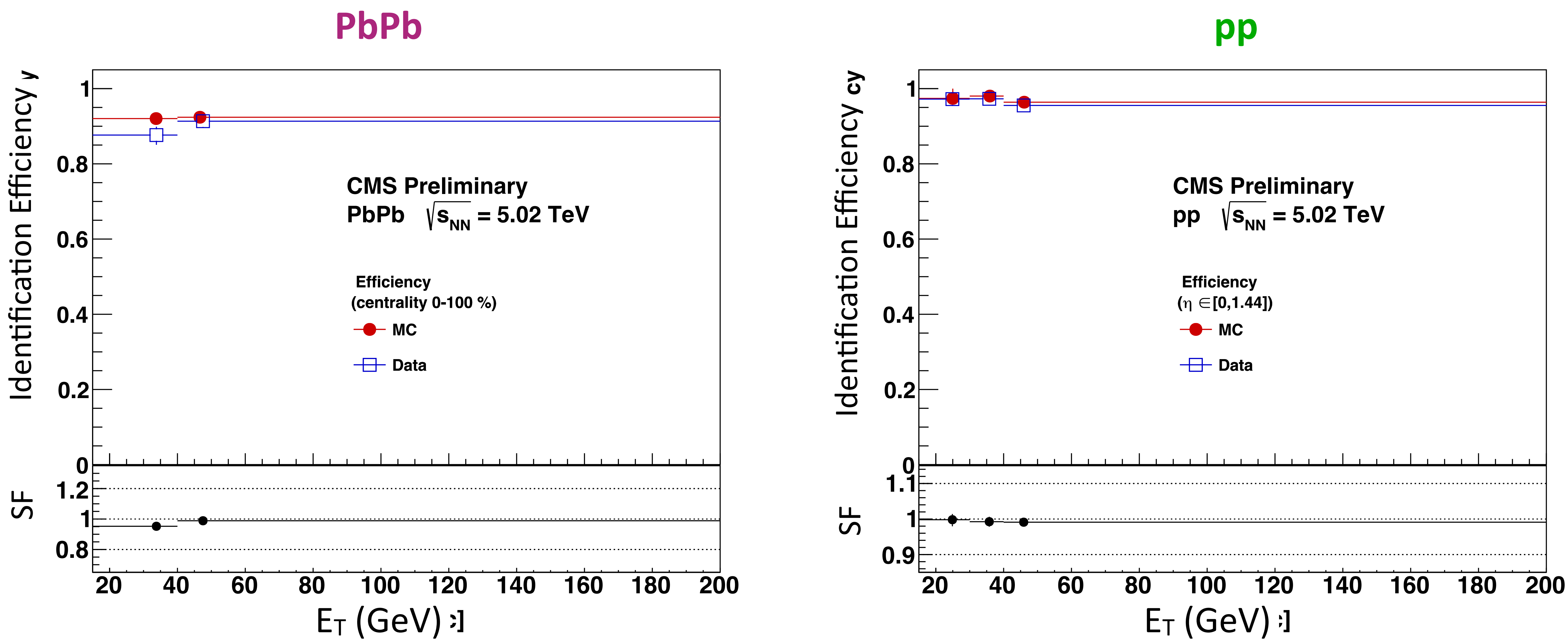
gammaPass = 0.372 ± 0.008
mean = 90.09 ± 0.05
numTot = 46023 ± 210
sigma = 1.69 ± 0.05
width = 1.6 ± 0.1

pp MC
ID efficiency
30 < probe E_T < 40 GeV

Efficiency scale factor (SF)

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



- **Total efficiency**

  = Trigger ε x Reconstruction ε x Identification and Isolation ε x Scale factor (SF)

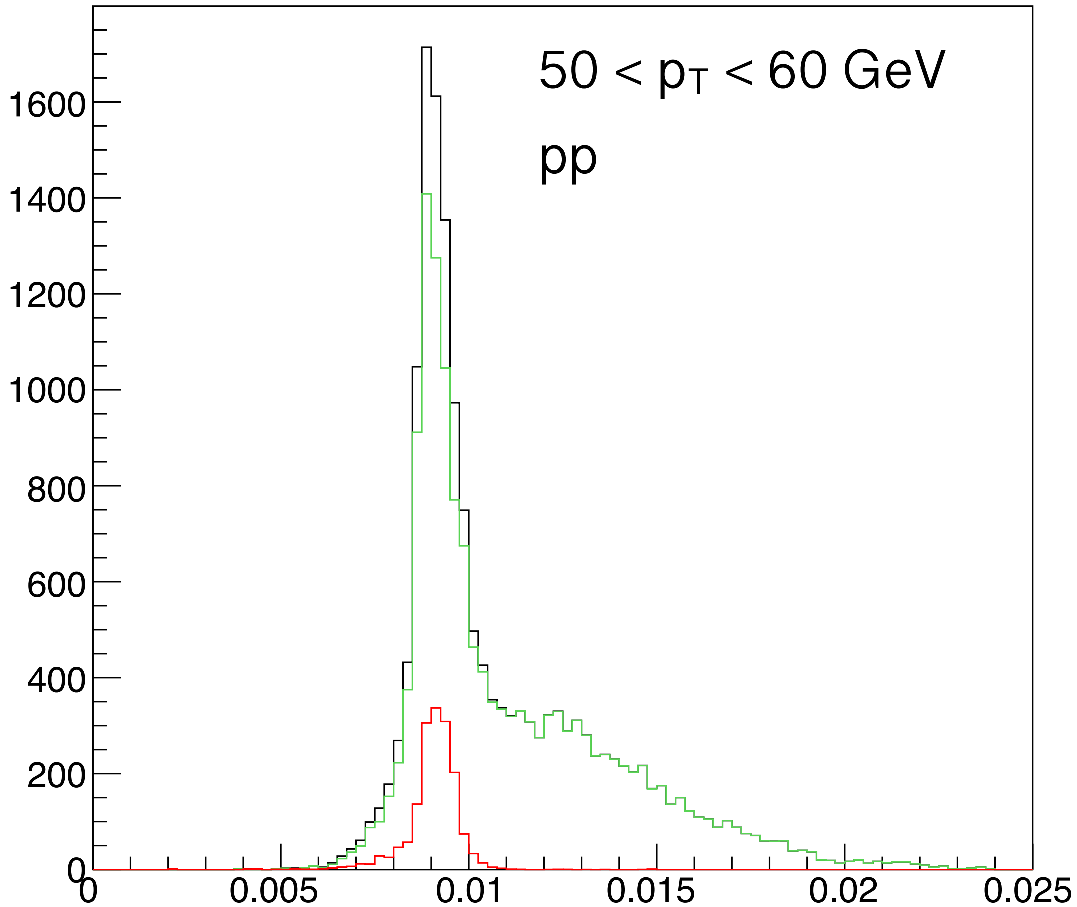
Signal contamination removal in purity background template

- Take signal contamination shape from signal MC in sideband region.

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

- 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
    - **$p*N_{data,sb}$**: # 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

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

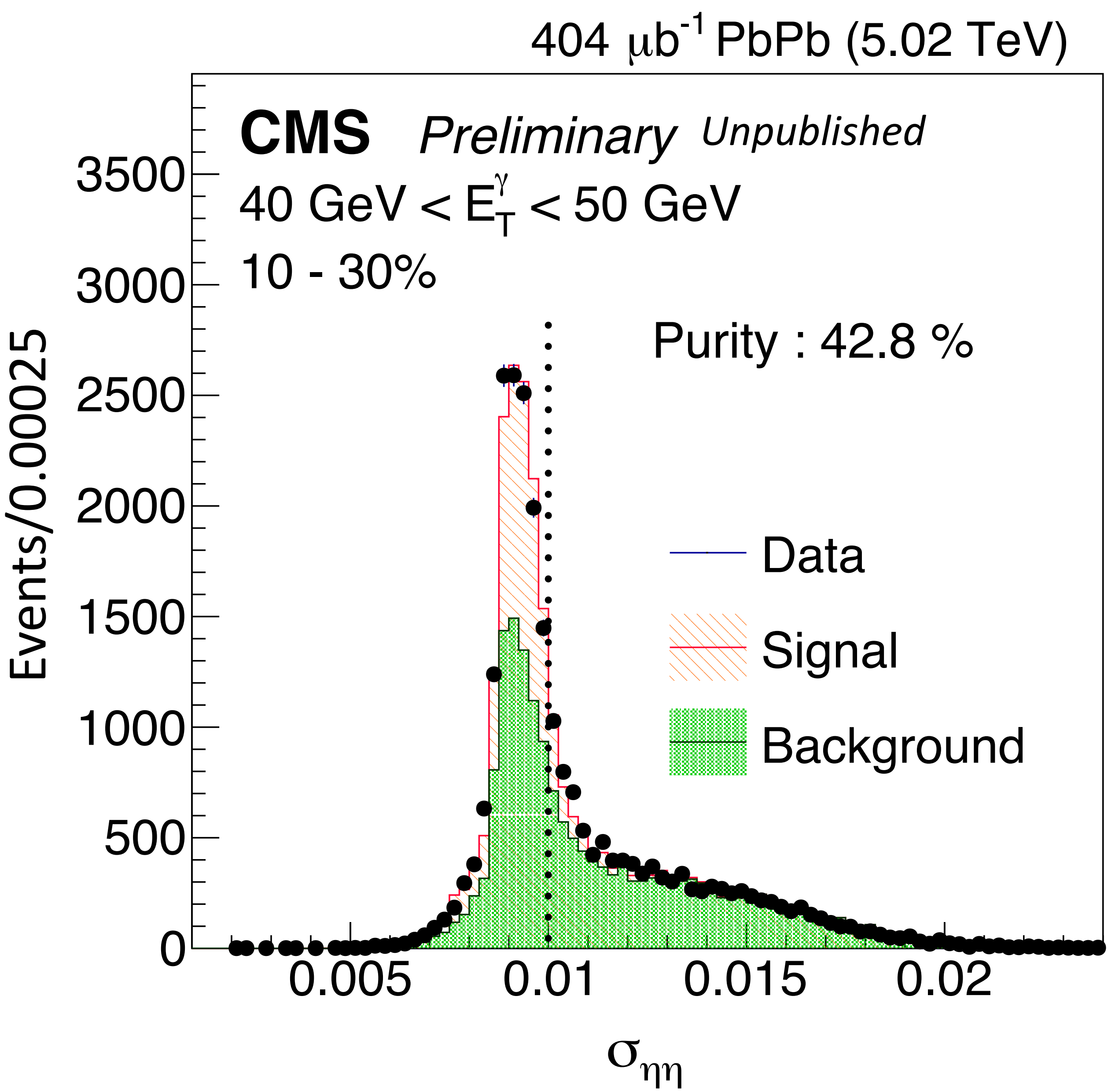


- Subtract signal photon shape in sideband region with norm $N_{true,sb}$ from sideband template

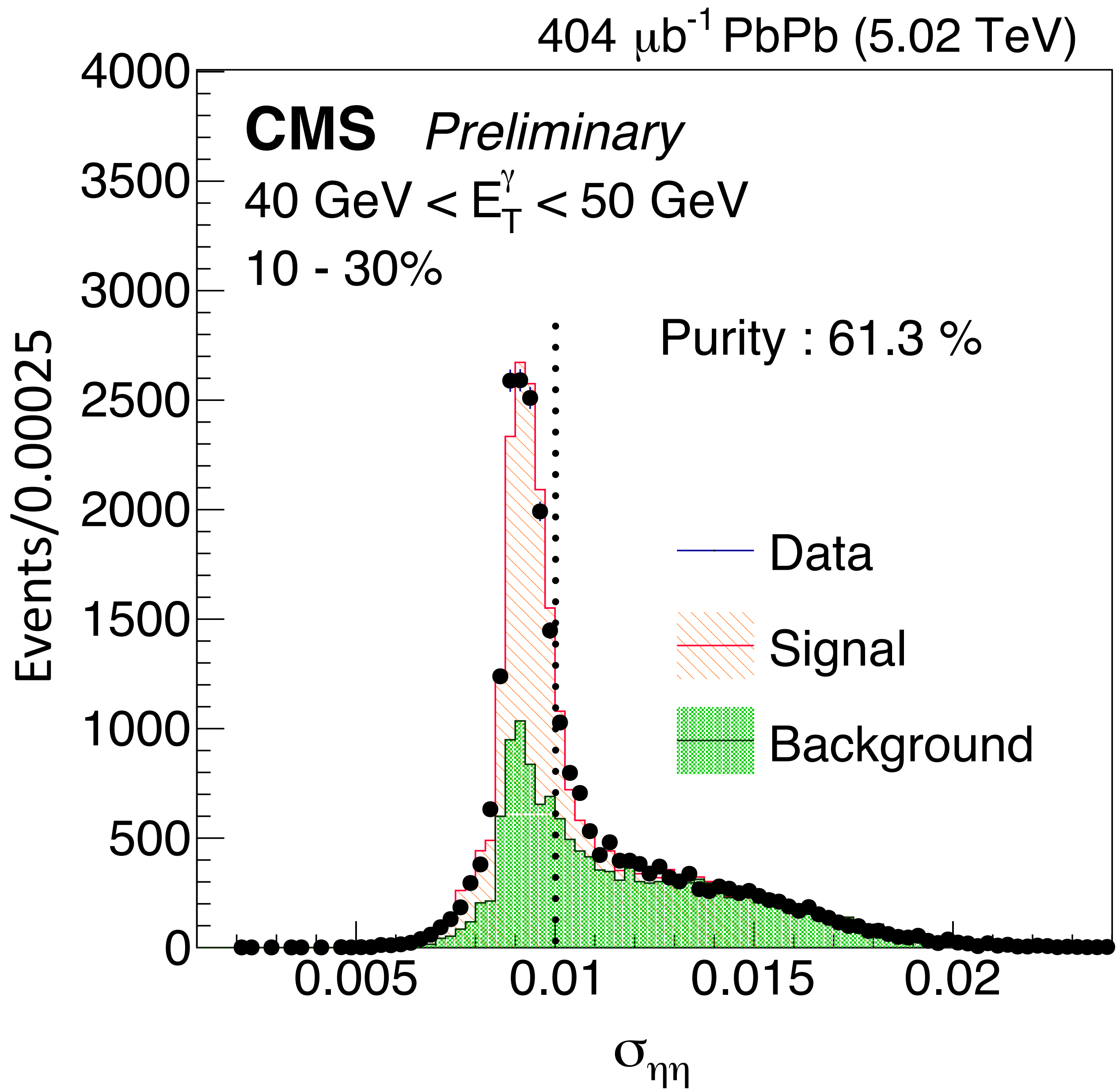
Purity : signal subtraction in bkg template

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

Before signal subtraction in background template



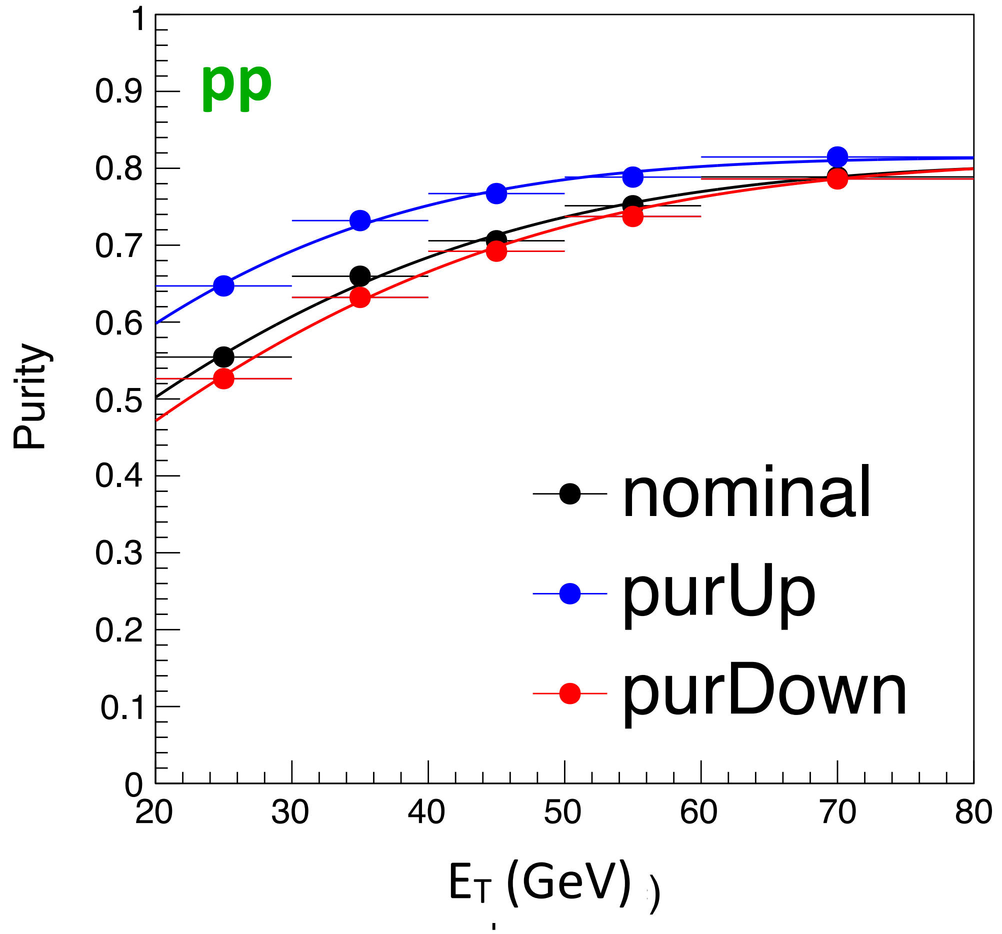
After signal subtraction in background template

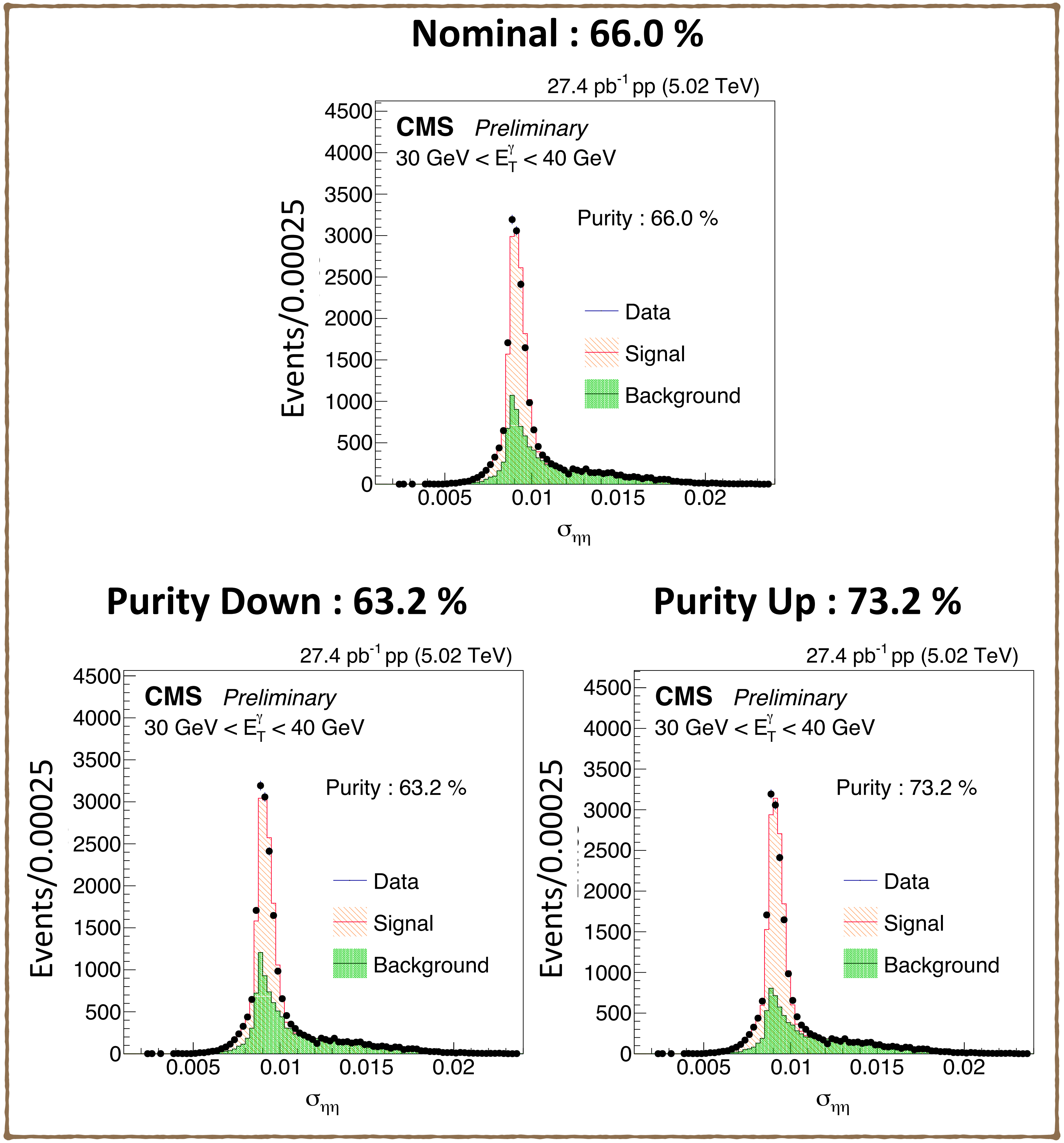


- Peak in the background template decreases in magnitude -> **higher purity**

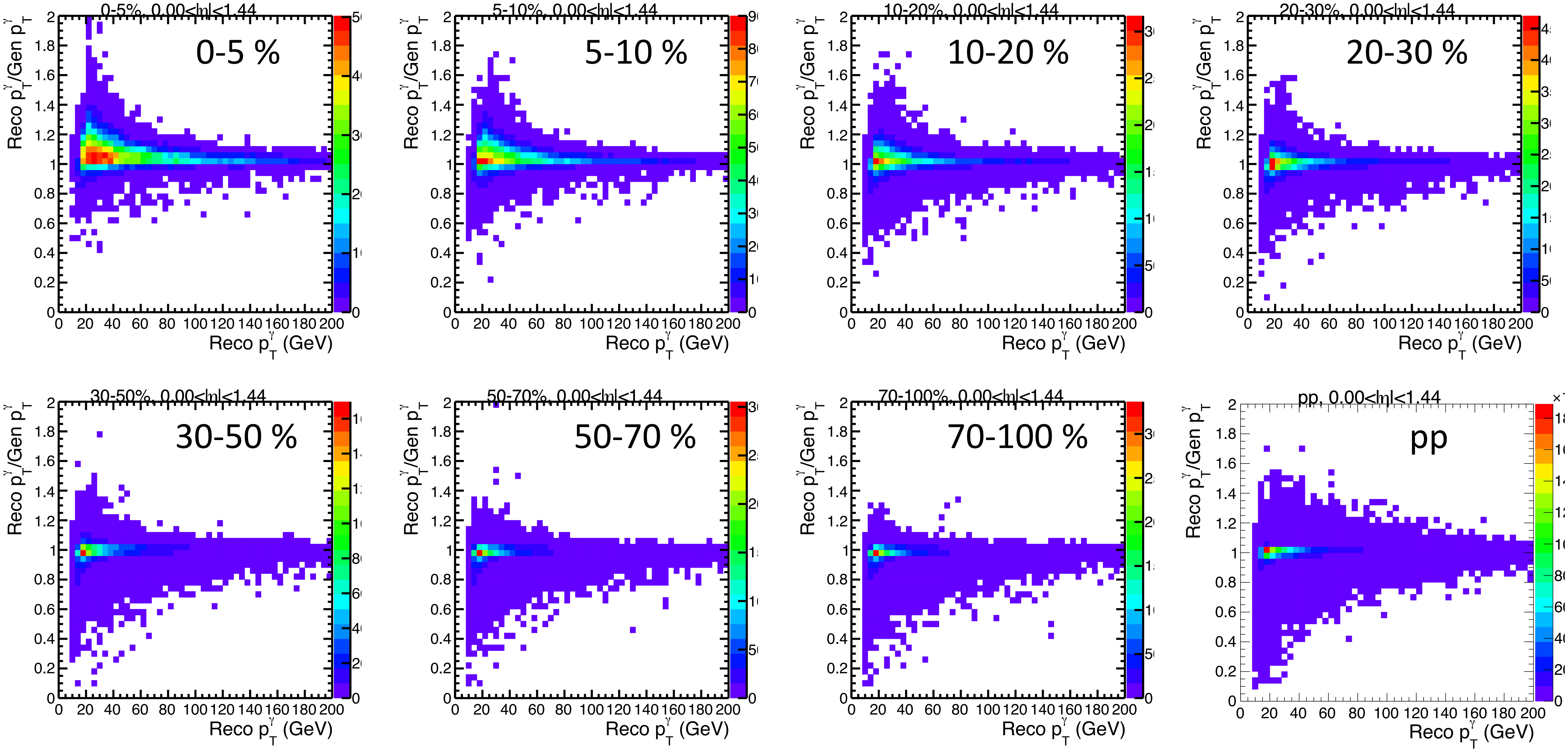
Purity : systematic

- **Purity systematics**
  - sideband range change
  - quote maximal deviation between variations



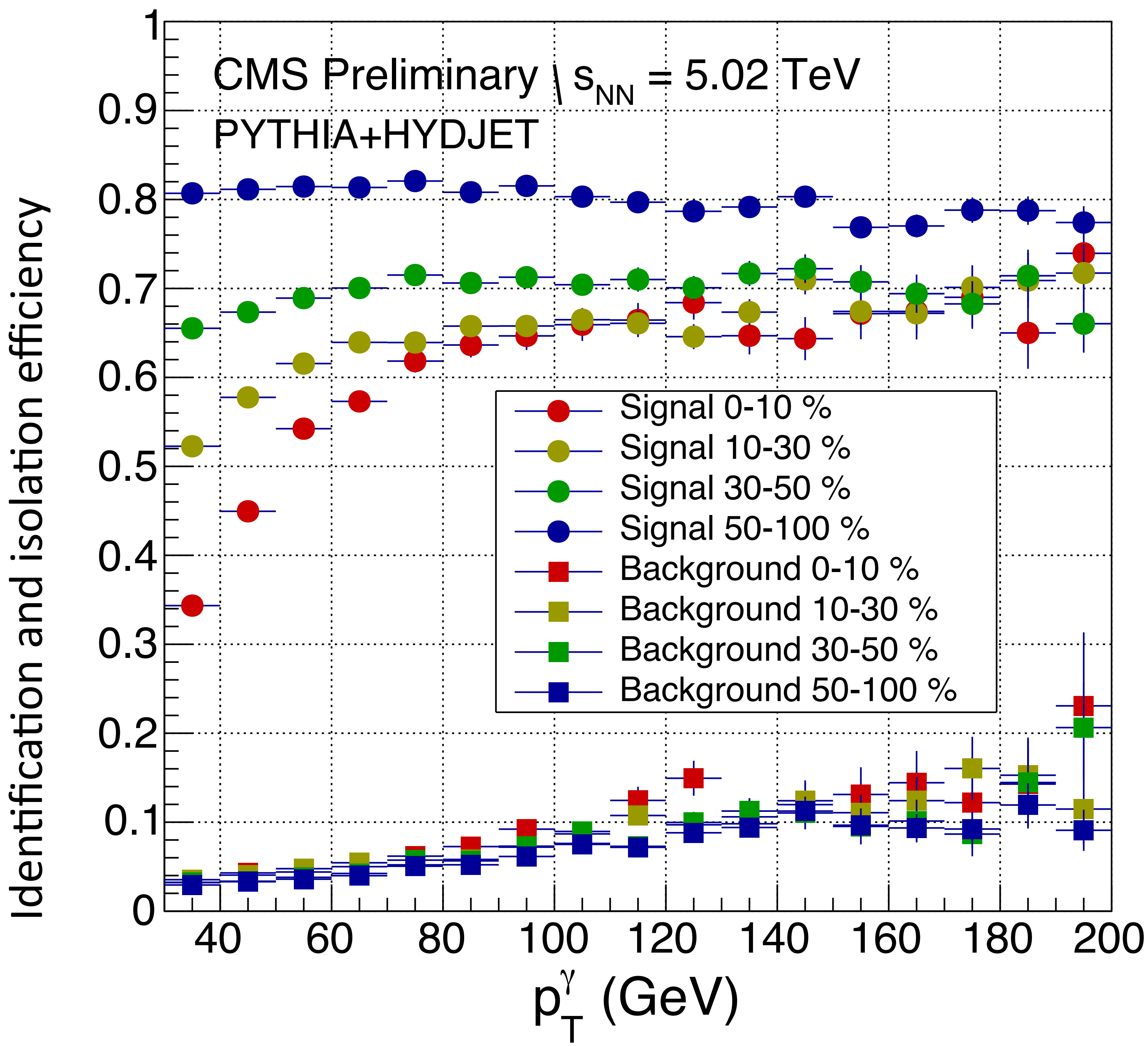


Photon energy correction



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

Background photon rejection



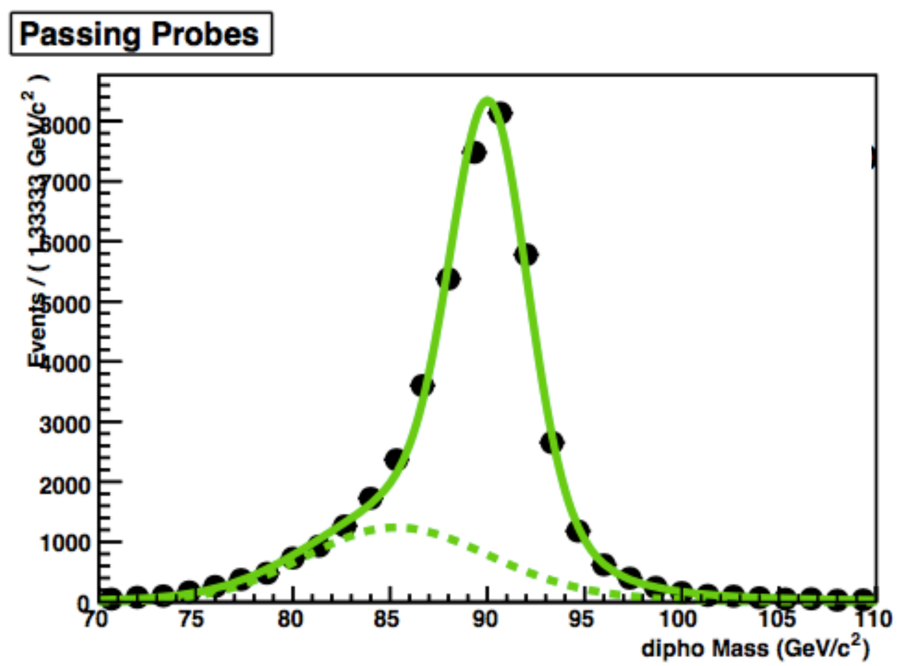
- **Over 80 % of background photons are rejected** by identification and isolation requirements though the whole p_T ranges.

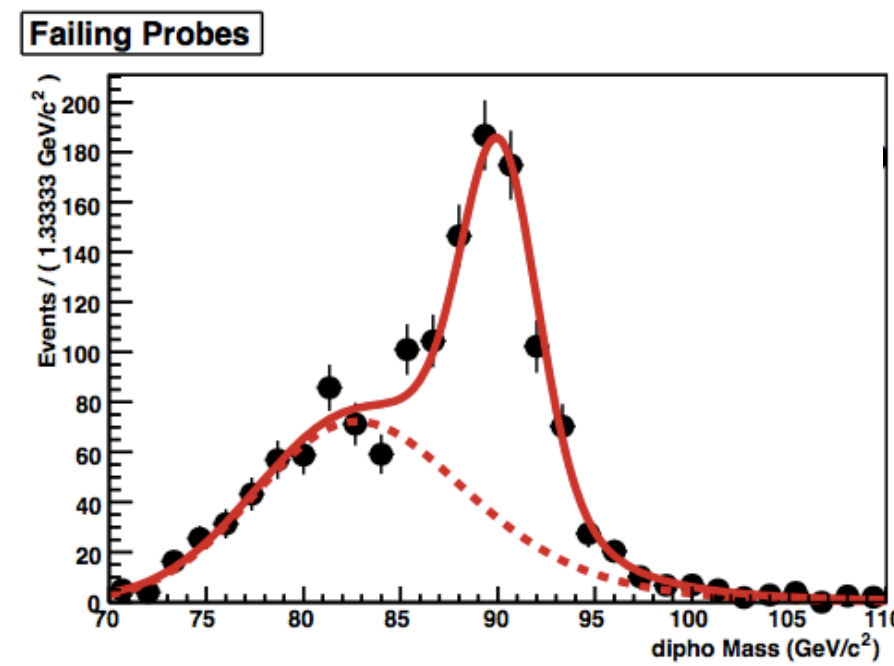
Tag and Probe

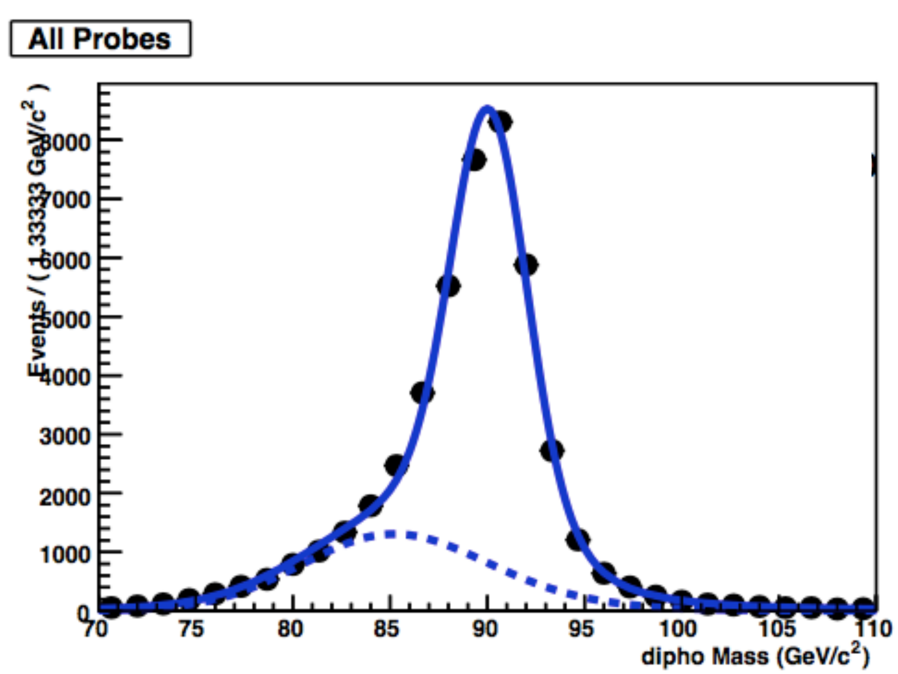
- Signal function : Voigtian
- Background function: 3rd order Chebychev. pol.
- Mass range : [80,100]

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

pp MC
ID efficiency







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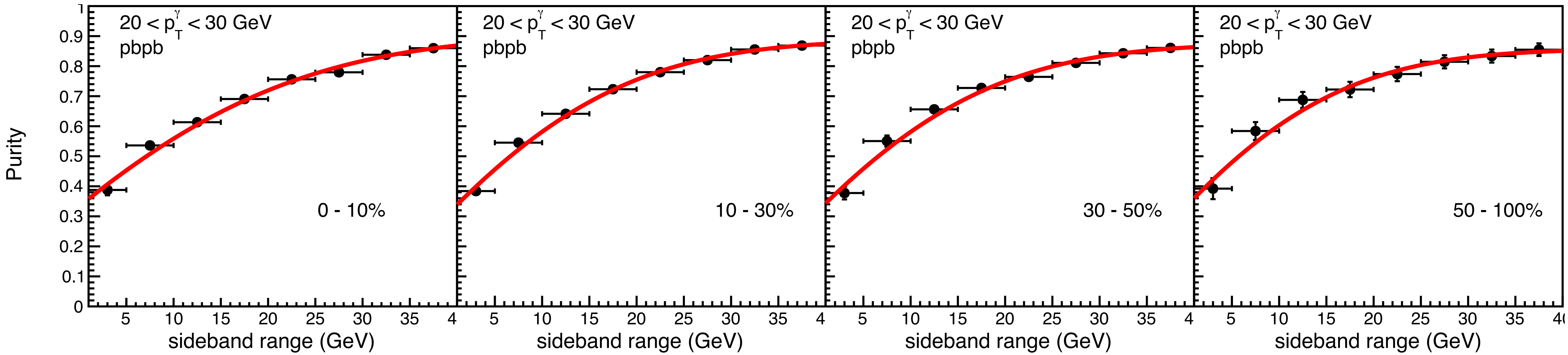
Global numbers

- **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 ± 2)%
- **T_{AA}** from Glauber model simulation
  - uncertainties estimated by varying Glauber model parameters

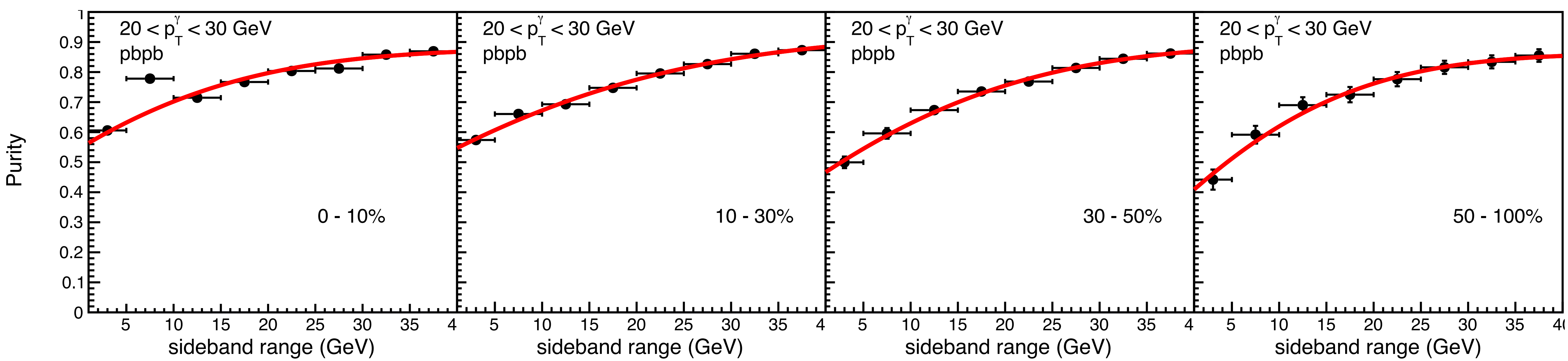
Centrality	T_{AA} [mb^{-1}]
0–10%	$23.22^{+0.43}_{-0.69}$
10–30%	$11.51^{+0.30}_{-0.39}$
30–50%	$3.82^{+0.21}_{-0.21}$
50–100%	$0.44^{+0.05}_{-0.03}$

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

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$\theta = 2\arctan\left(e^{-\eta}\right)$$

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

rapidity

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

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

Order in α_s	EPS09 LO & NLO	DSSZ NLO	nCTEQ15 NLO	EPPS16 NLO
NC DIS lA/ld	✓	✓	✓	✓
DY pA/pd	✓	✓	✓	✓
RHIC pions dAu/pp	✓	✓	✓	✓
νA DIS		✓		✓
πA DY				✓
LHC pPb W, Z				✓
LHC pPb jets				✓

DATA as input

LHC DATA as input

- **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