Measurement of the differential isolated diphoton production cross section at CMS

and other research activities during my PhD studies

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Overview

- **Main goal of my PhD thesis: measurement of diphoton differential cross sections with the CMS detector**
  - challenging from the experimental point of view
  - stringent test of QCD higher-order calculations
  - tight connection between analysis performance and understanding of detector and reconstruction algorithm details

- Several other activities in the context of the **electromagnetic calorimeter (ECAL) group**:
  - **pileup effect studies** on ECAL reconstruction
  - improved **energy corrections** scheme providing better resolution
  - **sampling calorimeter prototype** construction and first test-beam measurements

Diphoton production

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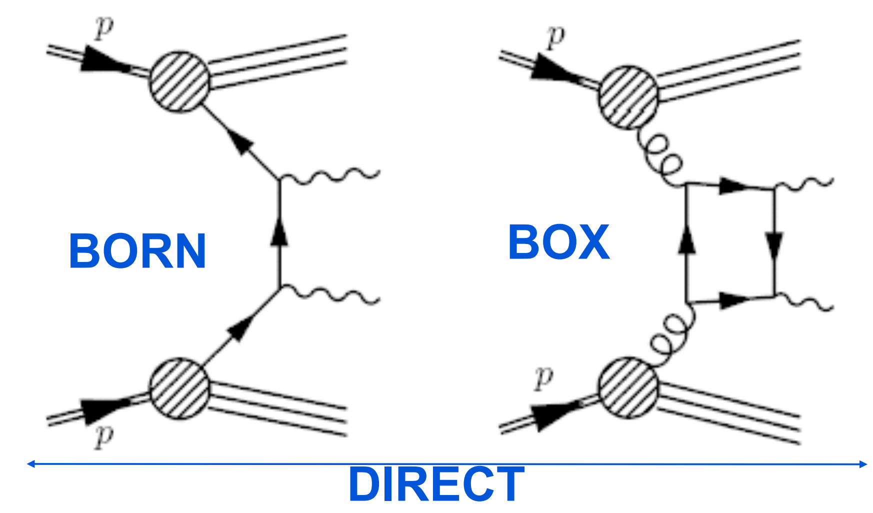
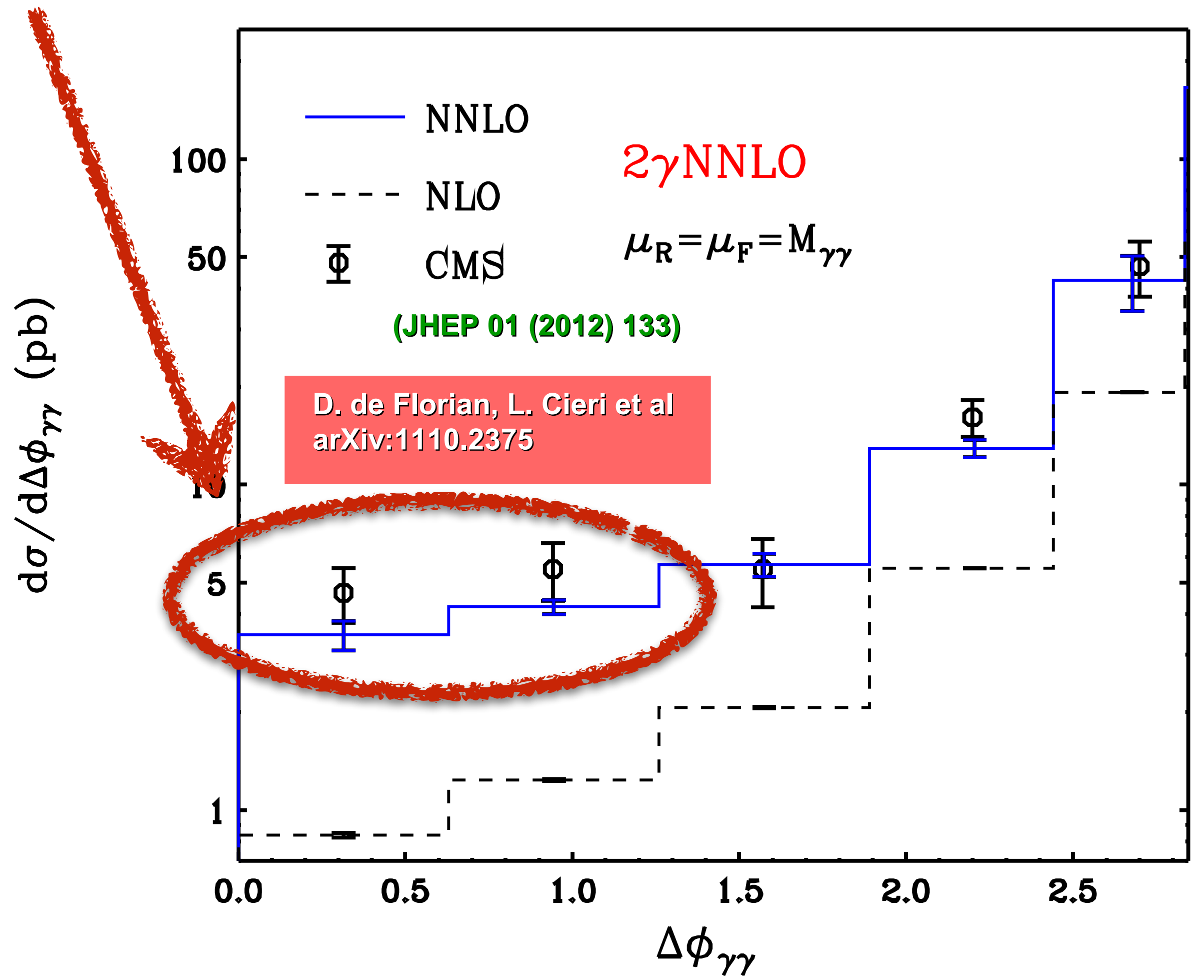
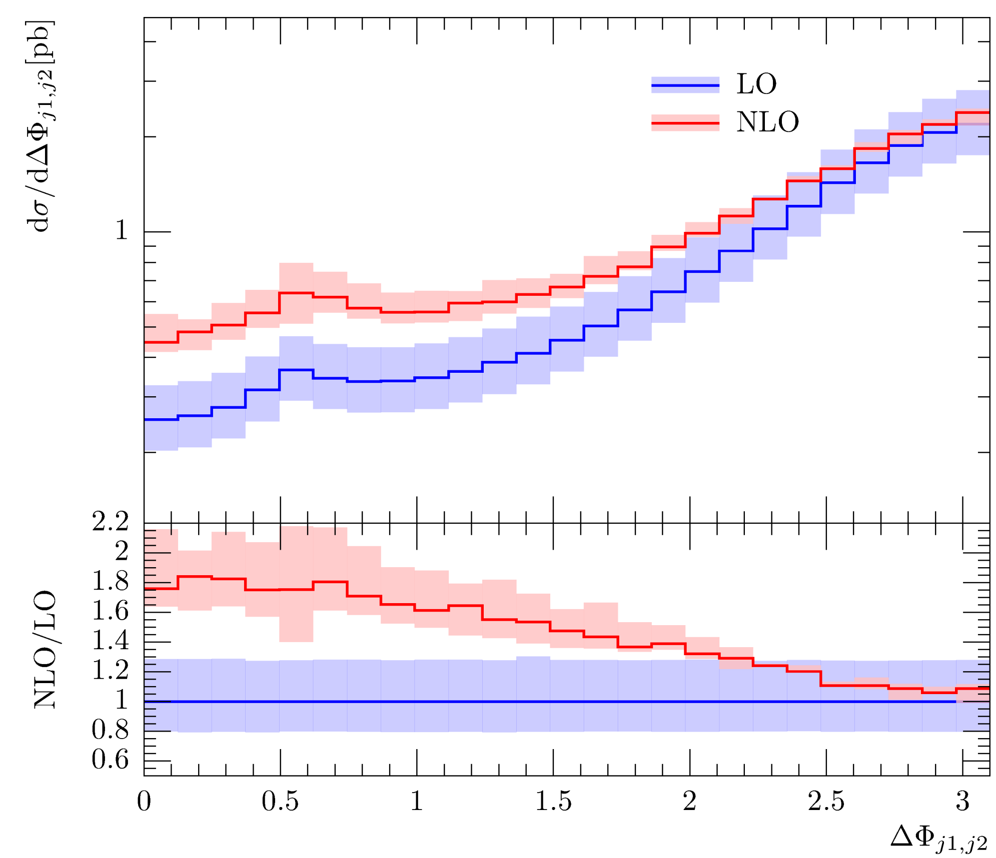
- Diphoton production **probes perturbative QCD @ NNLO**
  - · theoretical calculation arXiv:1110.2375 (Catani, Cieri, De Florian, Ferrera, Grazzini)



At LO (photons back to back), this region is not populated: we can probe NNLO with excellent sensitivity

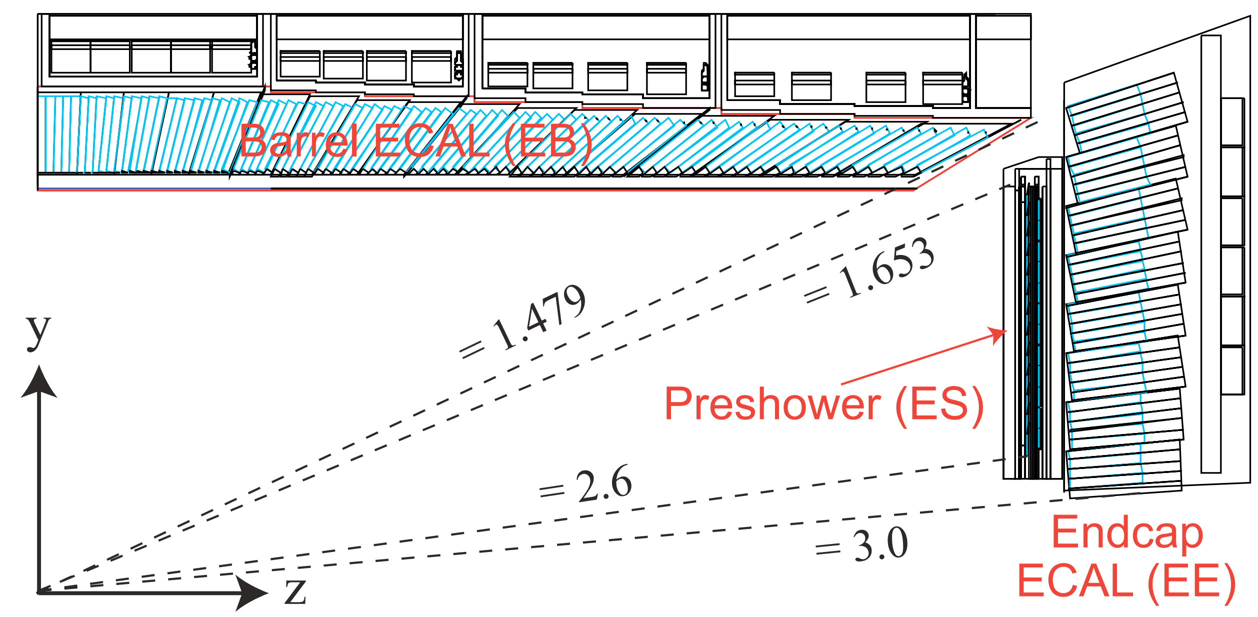




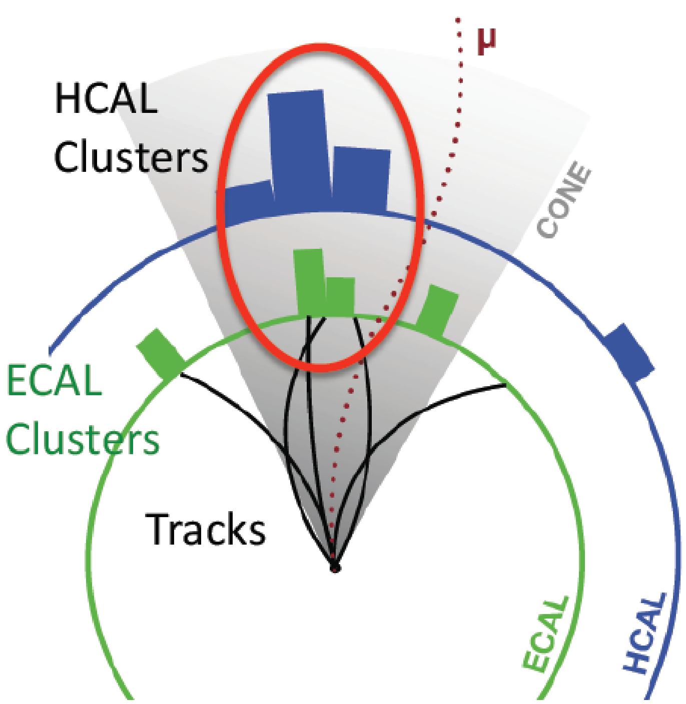
· Developments on γγ + 2 **jets** at NLO
arXiv:1308.3660 (Gehrmann, Greiner, Heinrich)

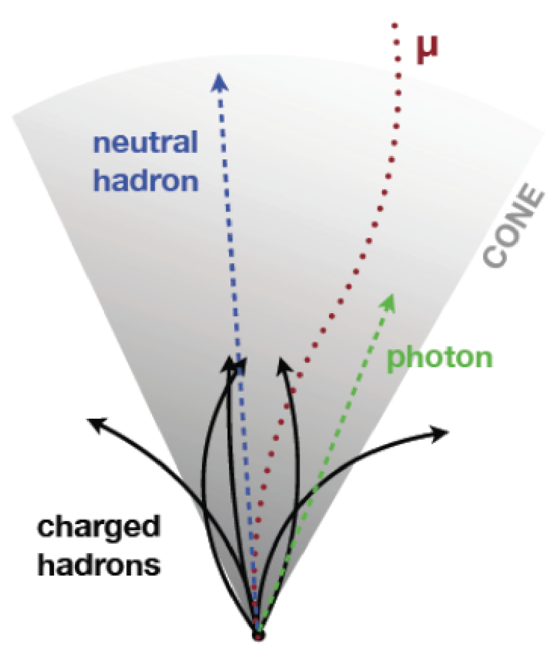
Photon reconstruction

- **$PbWO_4$ crystal electromagnetic calorimeter**
- **Excellent energy resolution and granularity**



Clusters and tracks <-> Particles

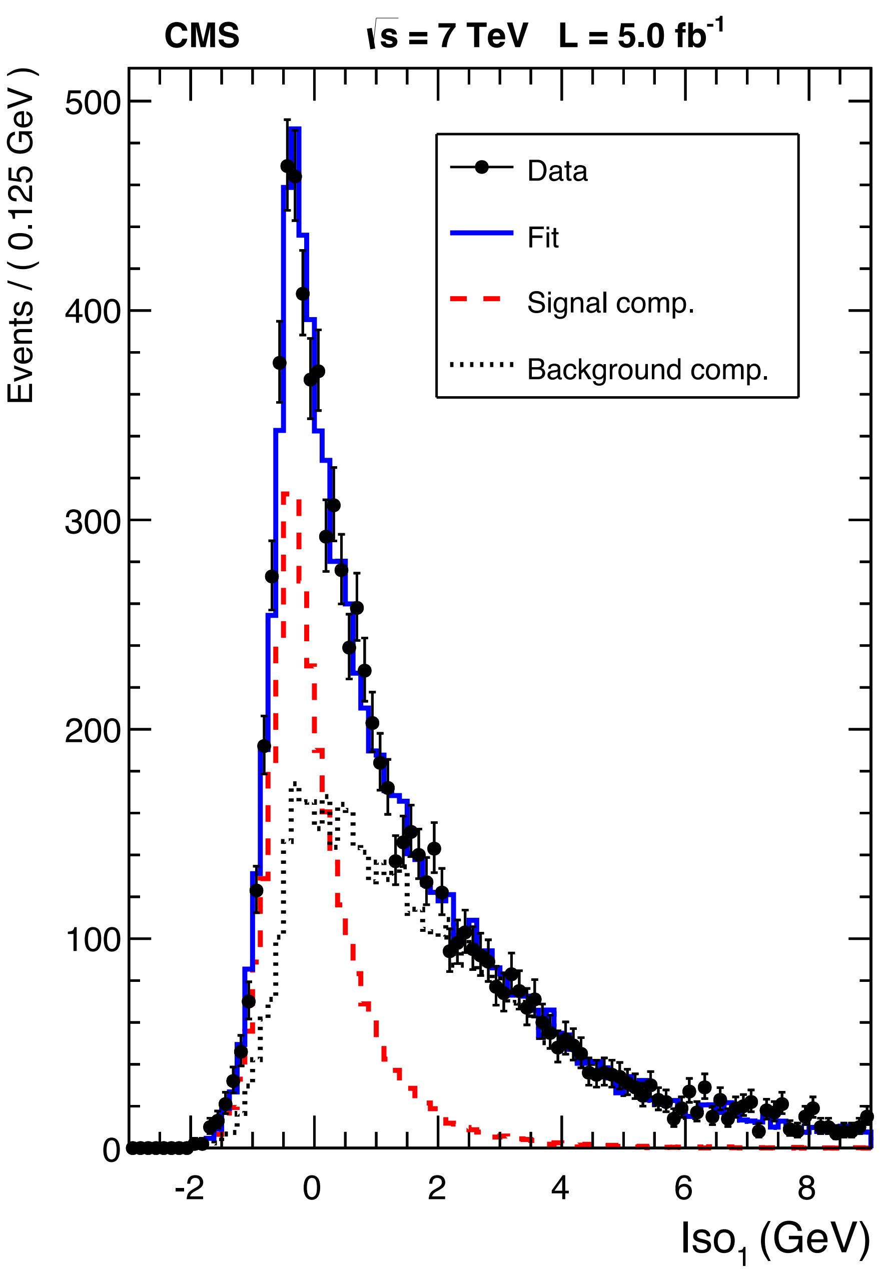


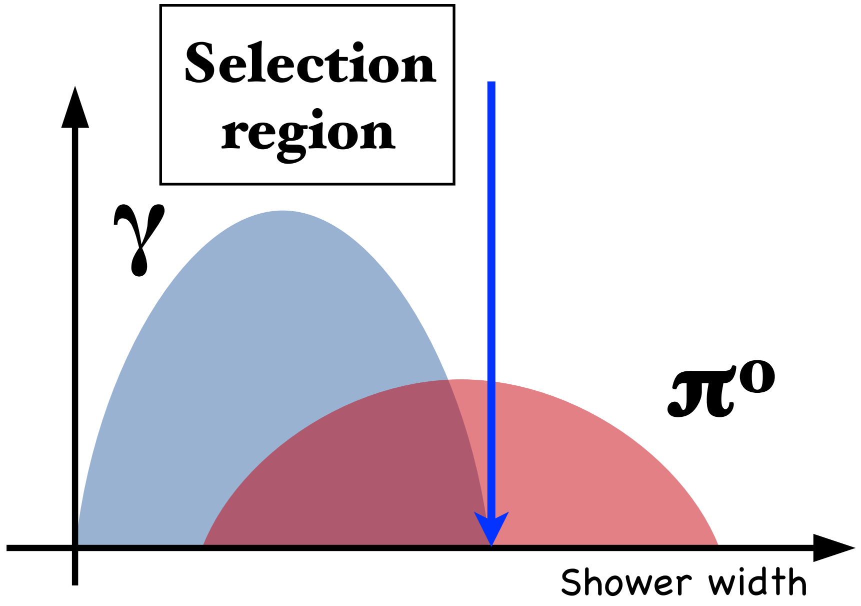


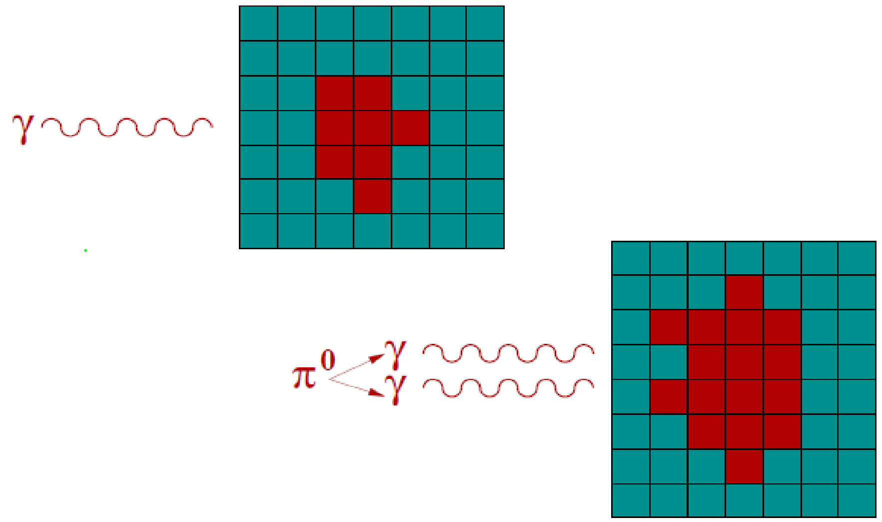
- Calorimeter cells clustered to reconstruct energy deposit
- **Particle-Flow** reconstruction algorithm combines information from all sub-detectors

Background subtraction

- Background from boosted neutral mesons collimated diphoton decays, reconstructed as single photons

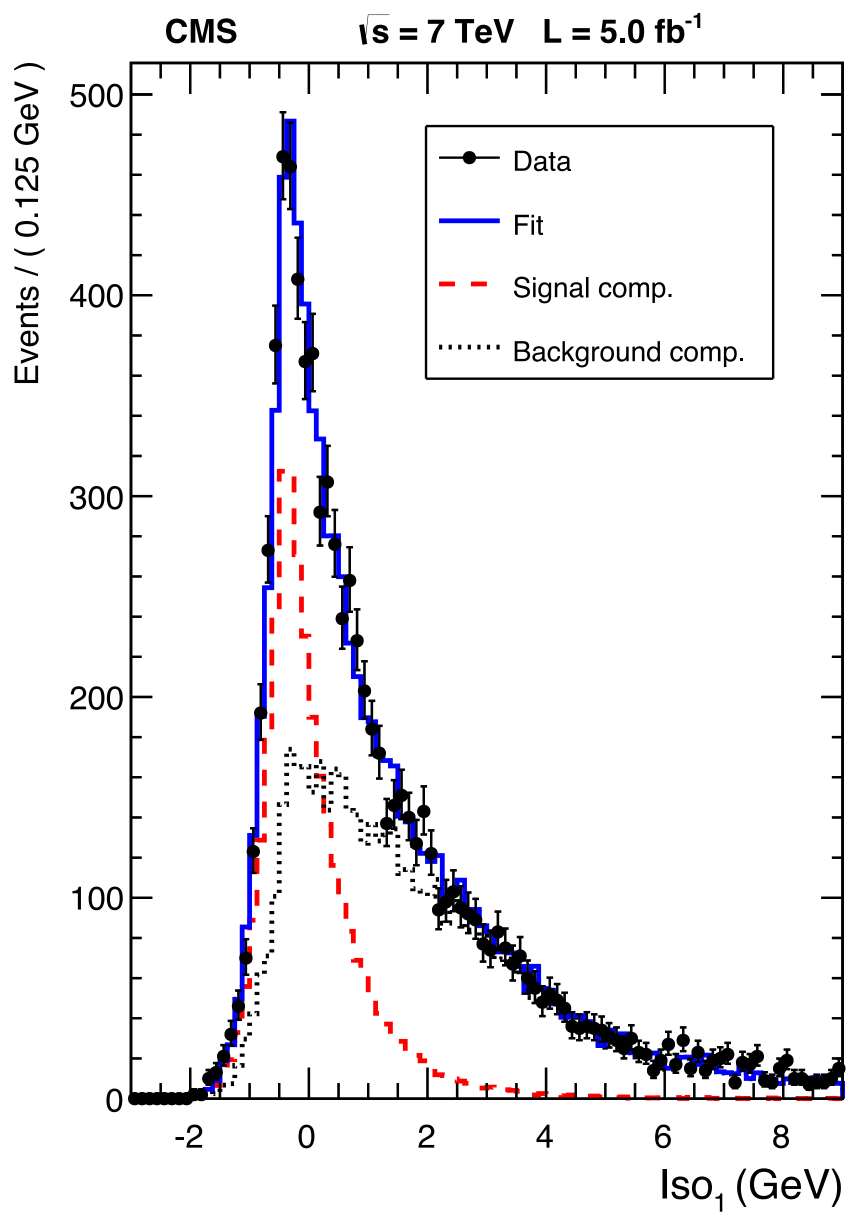






- **Key concepts**:
  - **shape of em shower**
  - **isolation energy**
- Variables de-correlated
  ➠ **sideband method**
- Background fraction from a template fit

Analysis strategy



➢ **Discriminating variable: photon component of particle-flow (PF) isolation**
(reconstructed energy deposits in the ECAL)

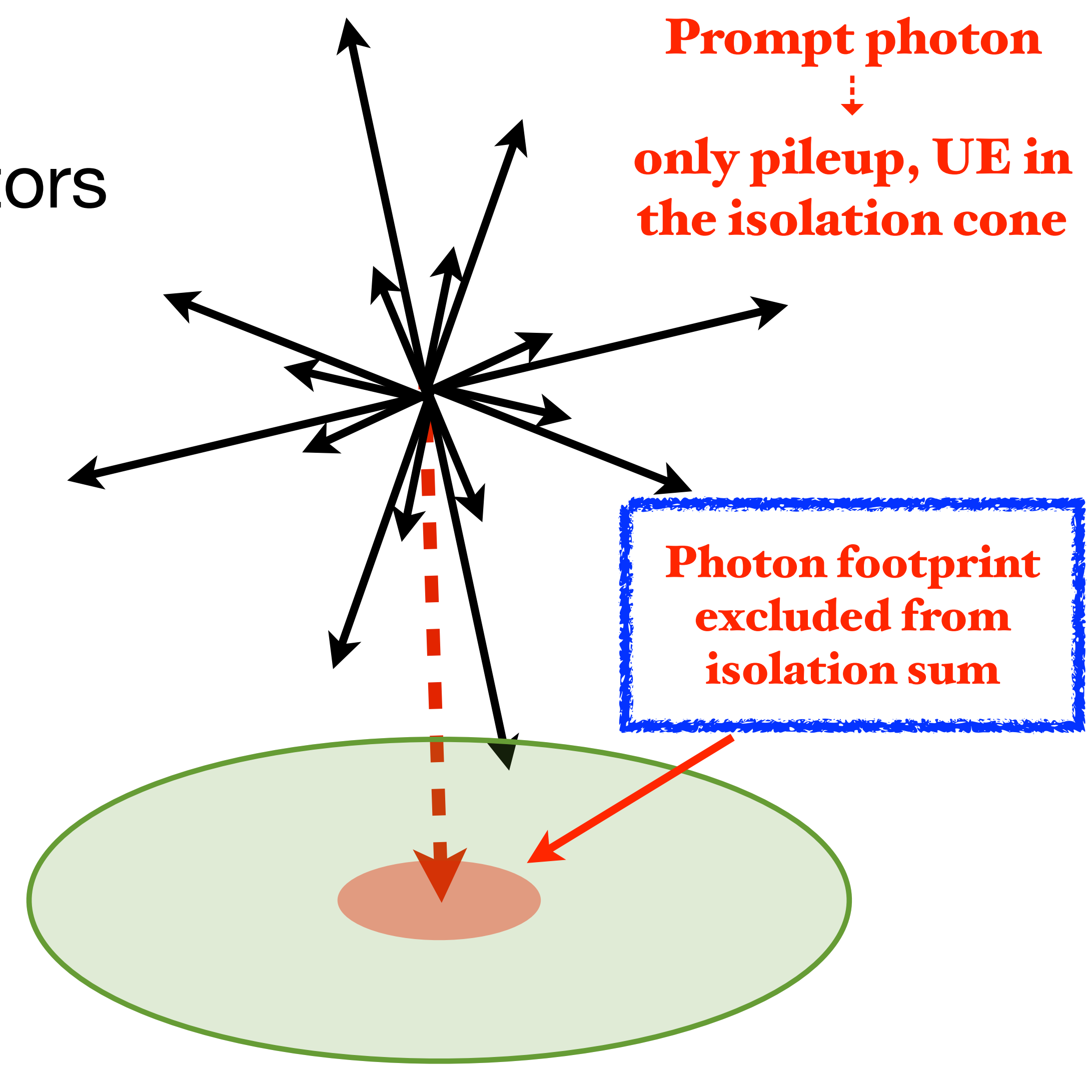
➢ **Goal: extract the fraction of prompt diphoton events**

$$\frac{d\sigma}{dX} = \frac{N^U_{\gamma\gamma}}{\varepsilon \cdot \mathcal{L} \cdot \Delta X}$$

- Asymmetric selection on photon p_T (40/25 GeV) enhancing contribution from higher-order corrections
- **Fully data-driven templates** for prompt photons and background
- Fit the PF isolation distribution in data, extracting purity of prompt diphotons
- Unfold to generator-level quantities, correct for selection efficiency
- Compare the results to theory

Particle-Flow photon isolation

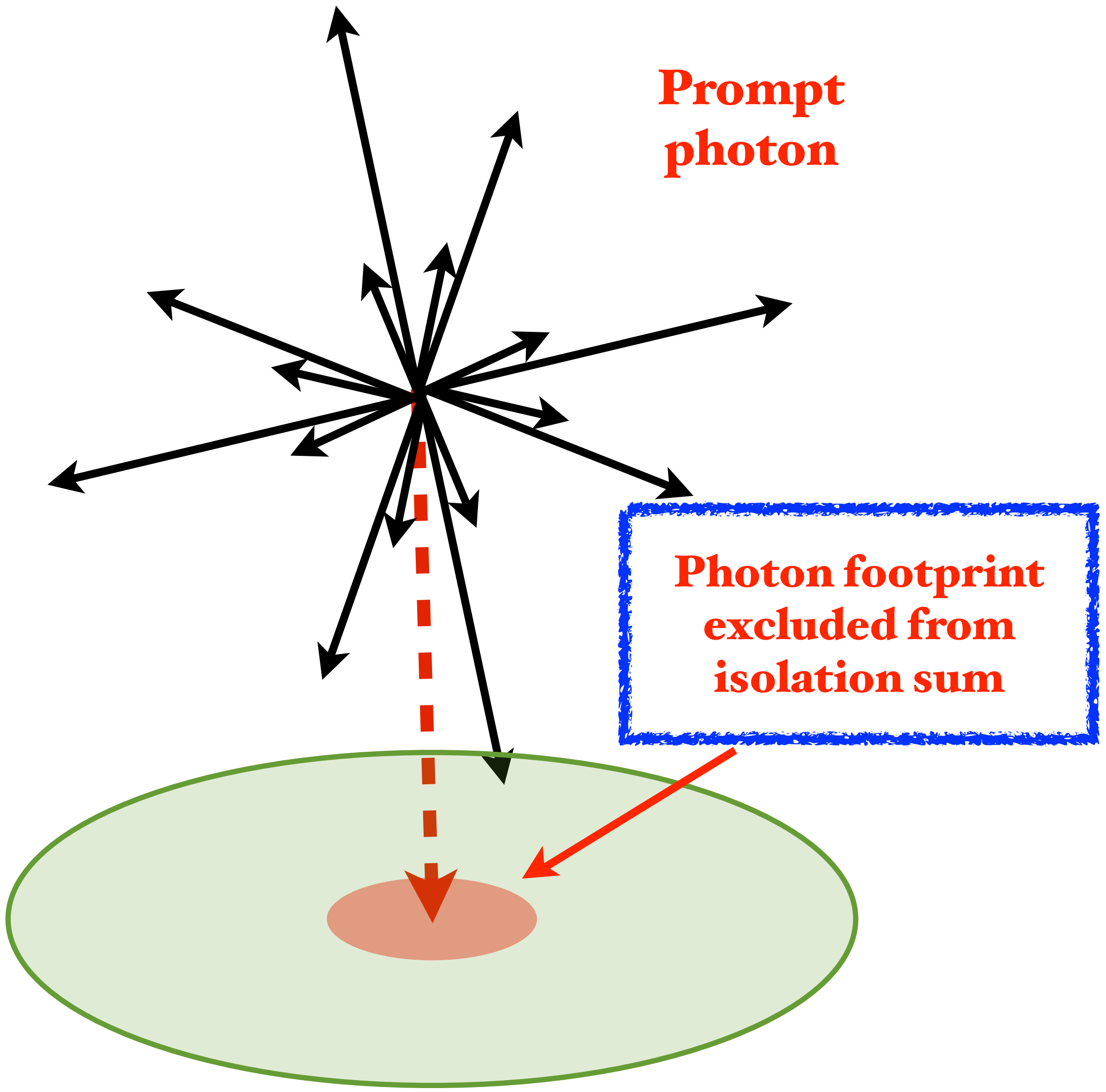
- **Particle-Flow (PF) event reconstruction**
  - combines information from all subdetectors
  - exploits full detector granularity
  - unambiguous event interpretation in terms of particle candidates



- **Novel algorithm developed to use PF isolation in photon measurements**
- Paves the way for using PF in all CMS precision measurements with photons

- Has become the **reference variable for photon purity estimation in CMS**
- Improvements propagated to global reconstruction code, being commissioned for LHC Run 2 data taking

Signal template: random cone

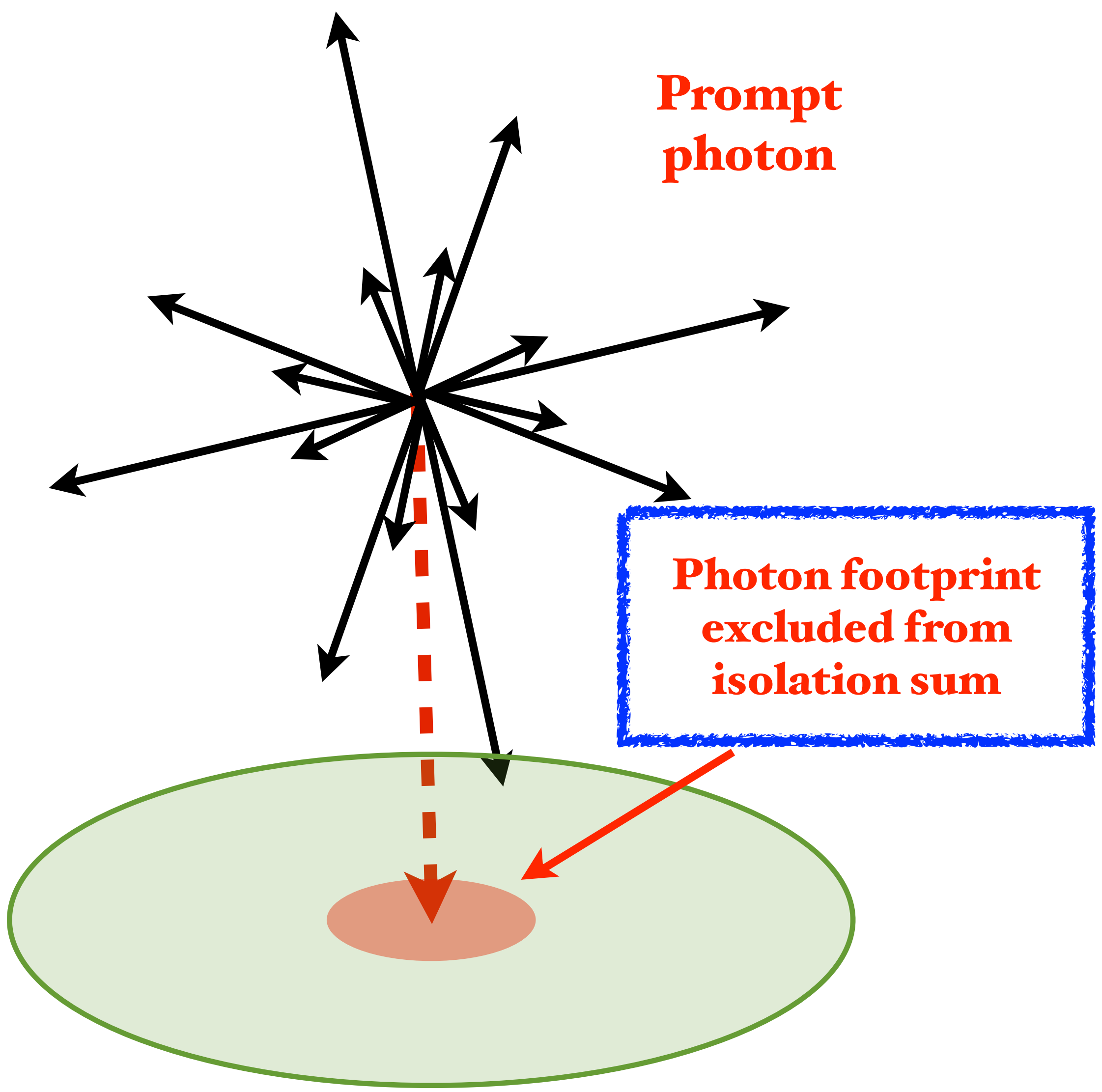


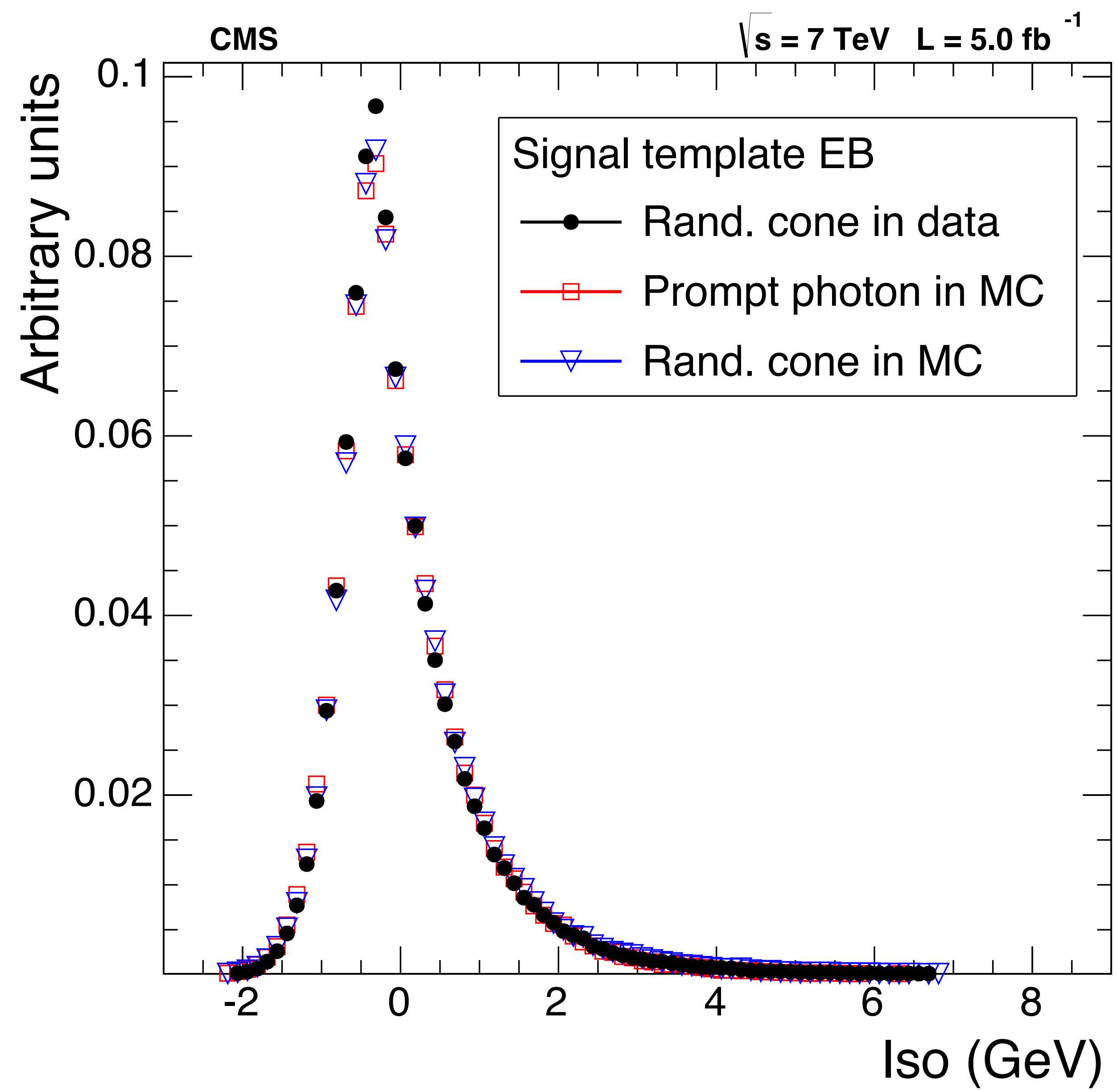
➢ Prompt photon template
built in data with **random cone**:
gauge pileup in an "empty" region
of the detector

❖ Procedure (event-by-event):

- rotate the isolation cone in φ by a random angle
- check that no other photon or jet is nearby
- underlying activity does not change (same η)
- build the template from this isolation sum away from the photon candidate

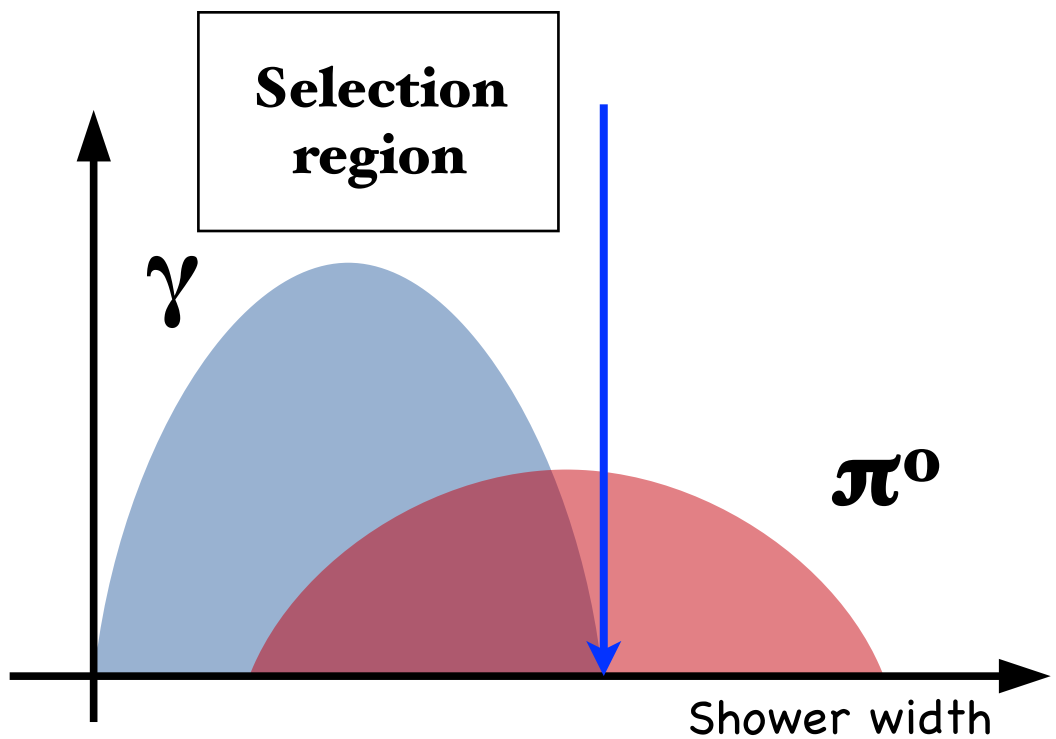
Signal template: random cone

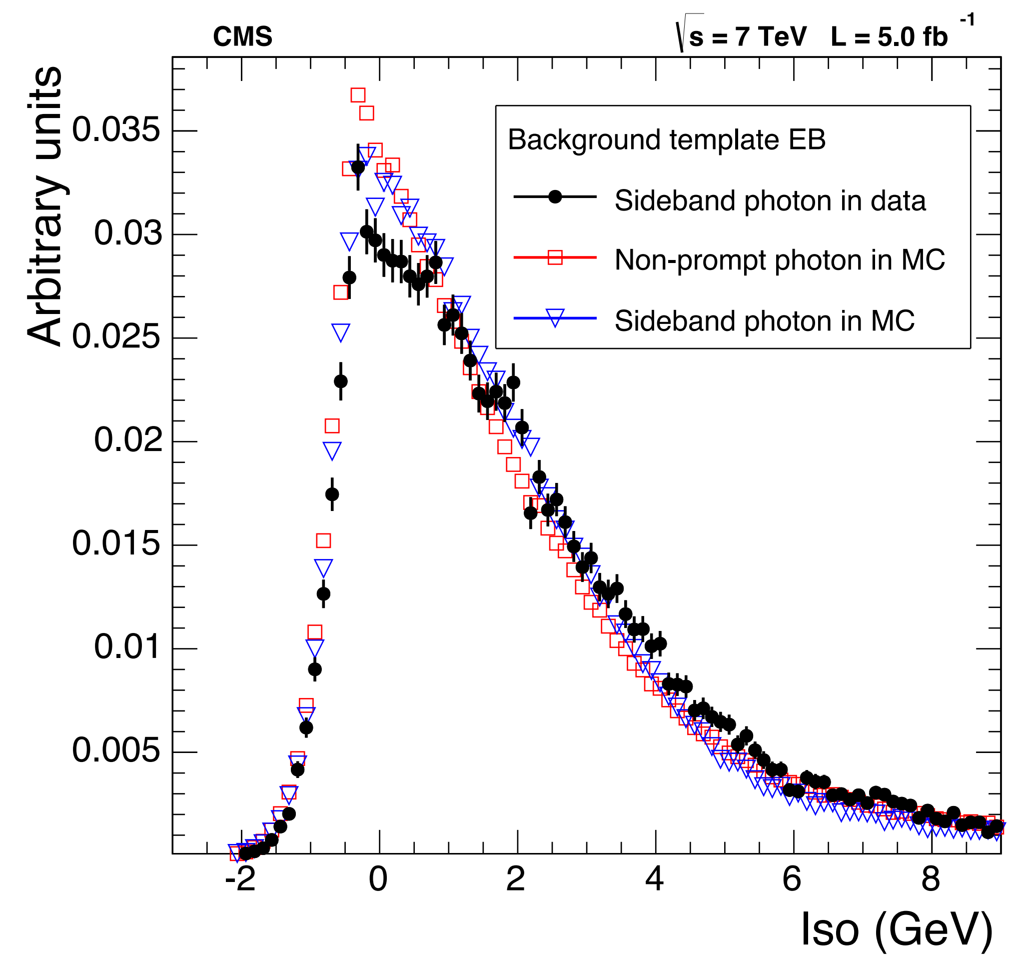




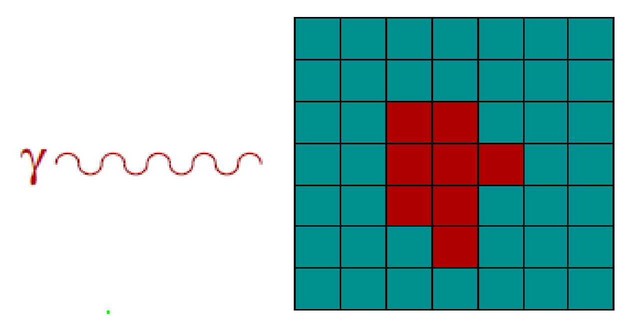
- **Excellent performance thanks to the new technique**
- Removing photon footprint from the isolation cone very effectively

Background template: sideband

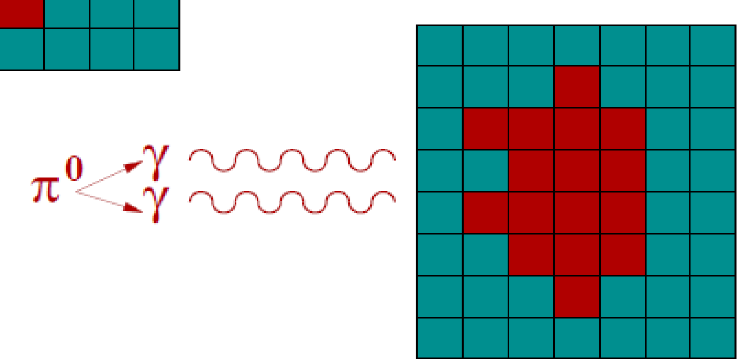




- Fake photon template built in data with **sideband technique**: exploit small correlation between shower width and isolation sum



➢ **Very good performance** after effective photon footprint removal



Event mixing at particle level

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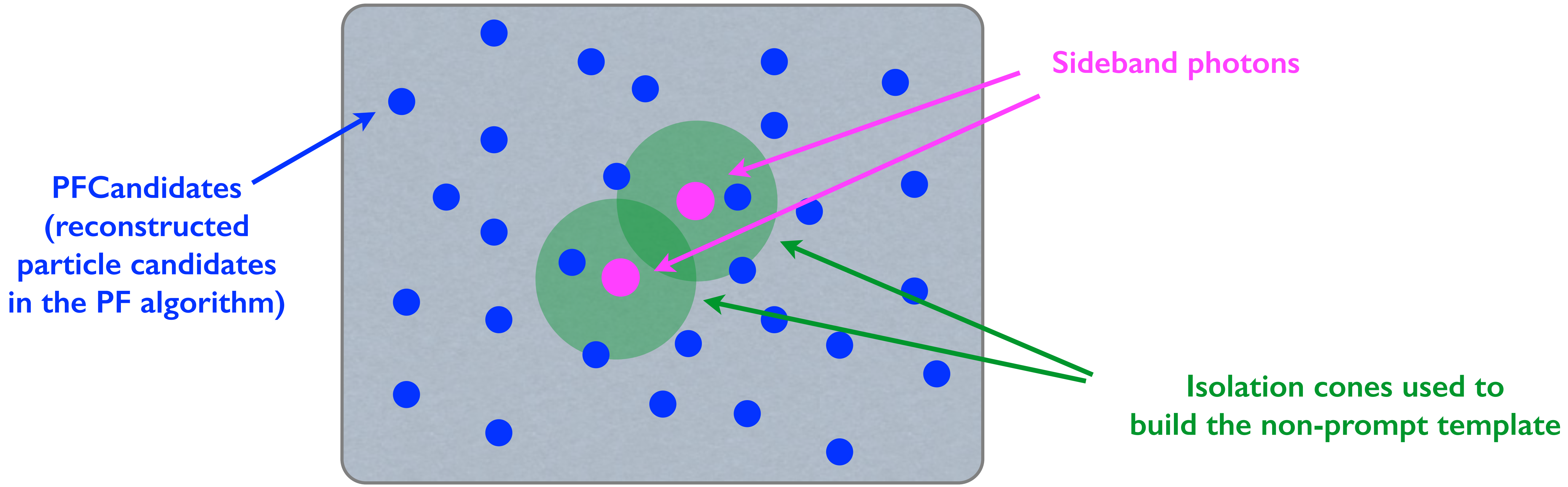
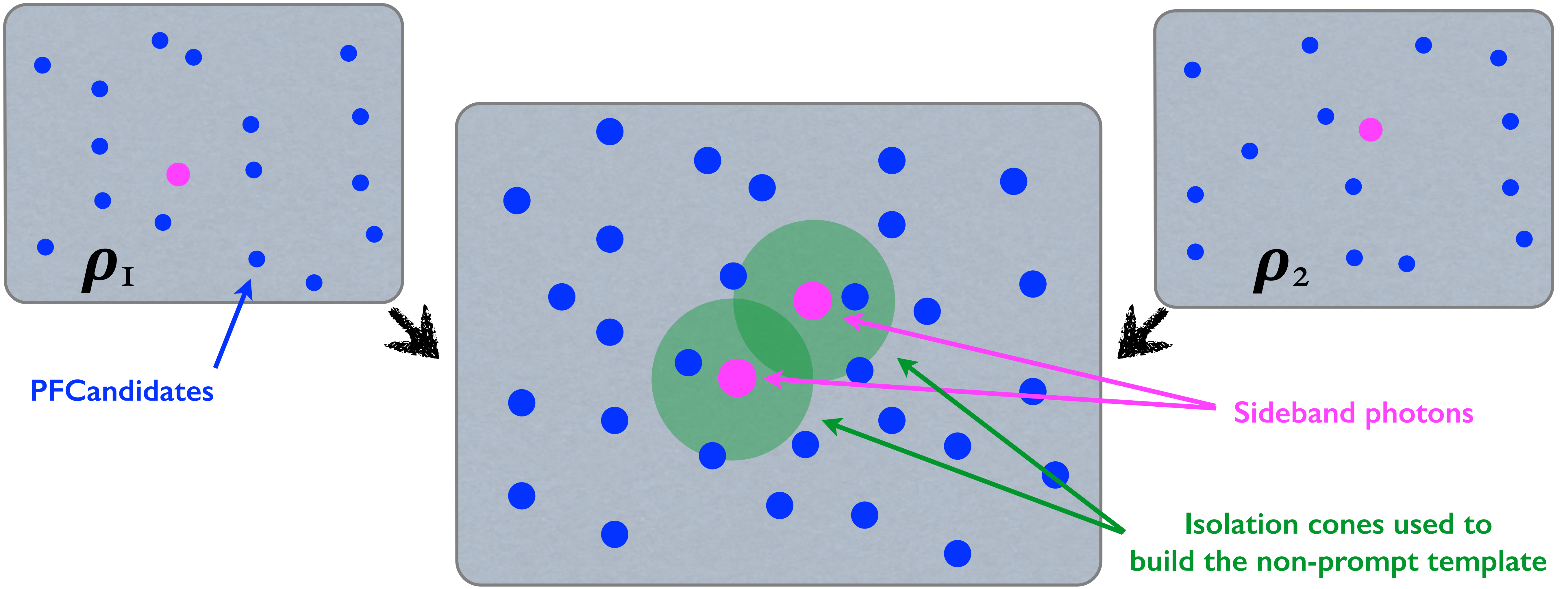


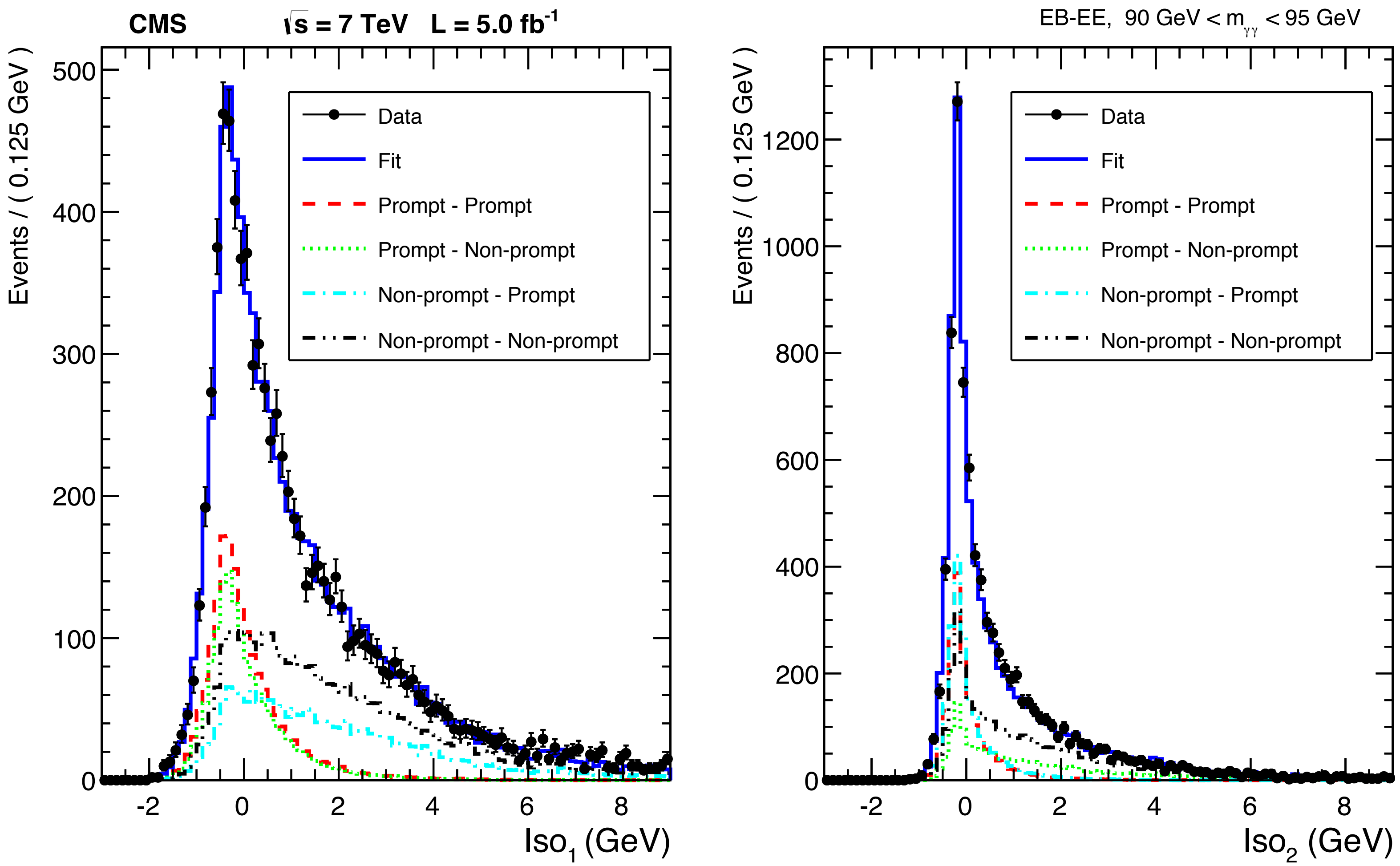
- Low statistics for building two-dimensional background template: would need two sideband photons in the same event
- Product of one-dimensional templates would not describe the **correlation between isolation sums**
- Solution is to use an **event mixing strategy**

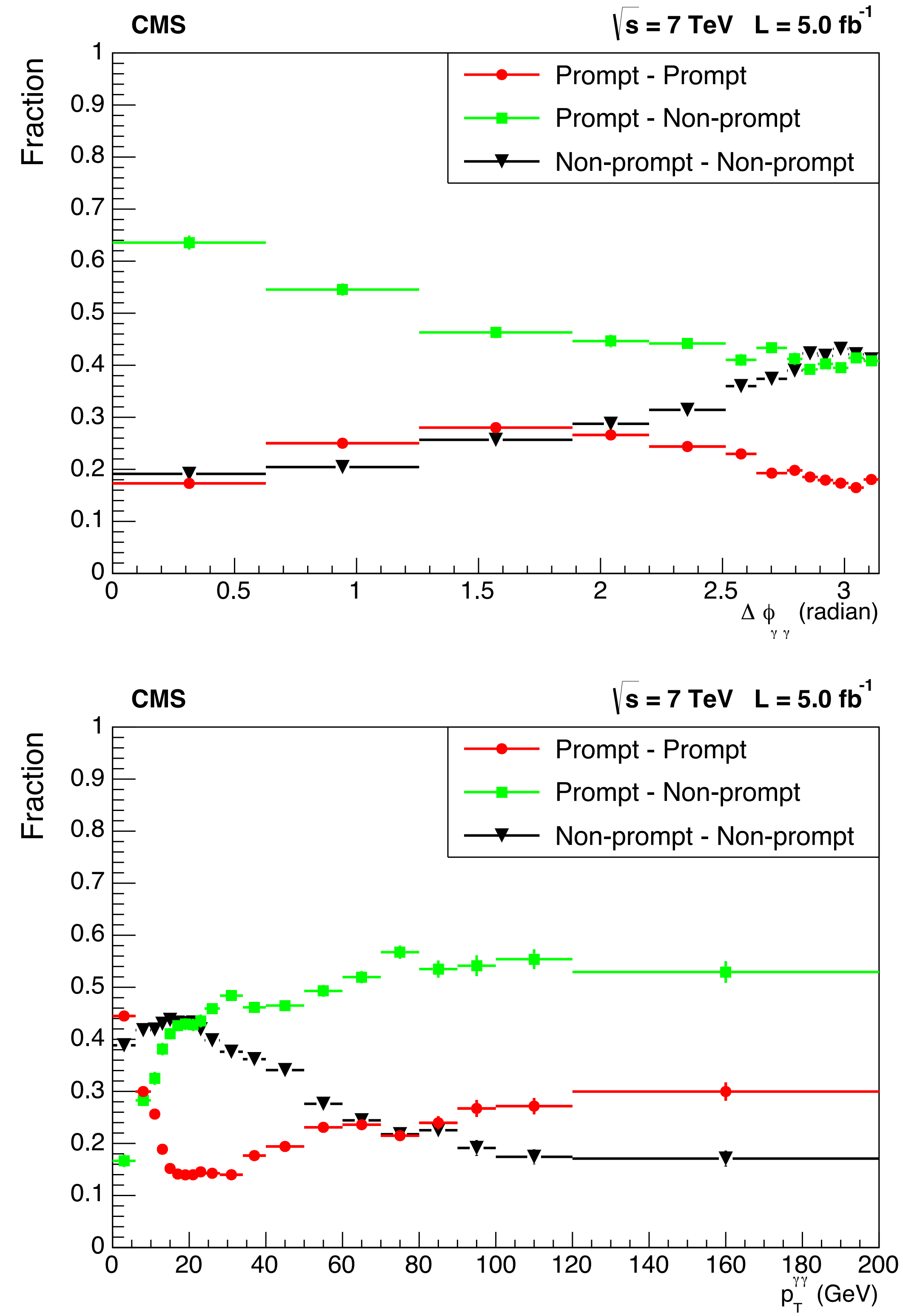
Event mixing at particle level



- Template events chosen with $\rho_1 + \rho_2 = \rho$ measured in the event to be fitted
- Fully exploiting the **rationale of the Particle-Flow** reconstruction approach
- A **leap forward** in the use of Particle-Flow:
  Mixing had never been used before in this way for SM precision measurements
- **Dramatic increase in template statistics in the most interesting region of the phase space**

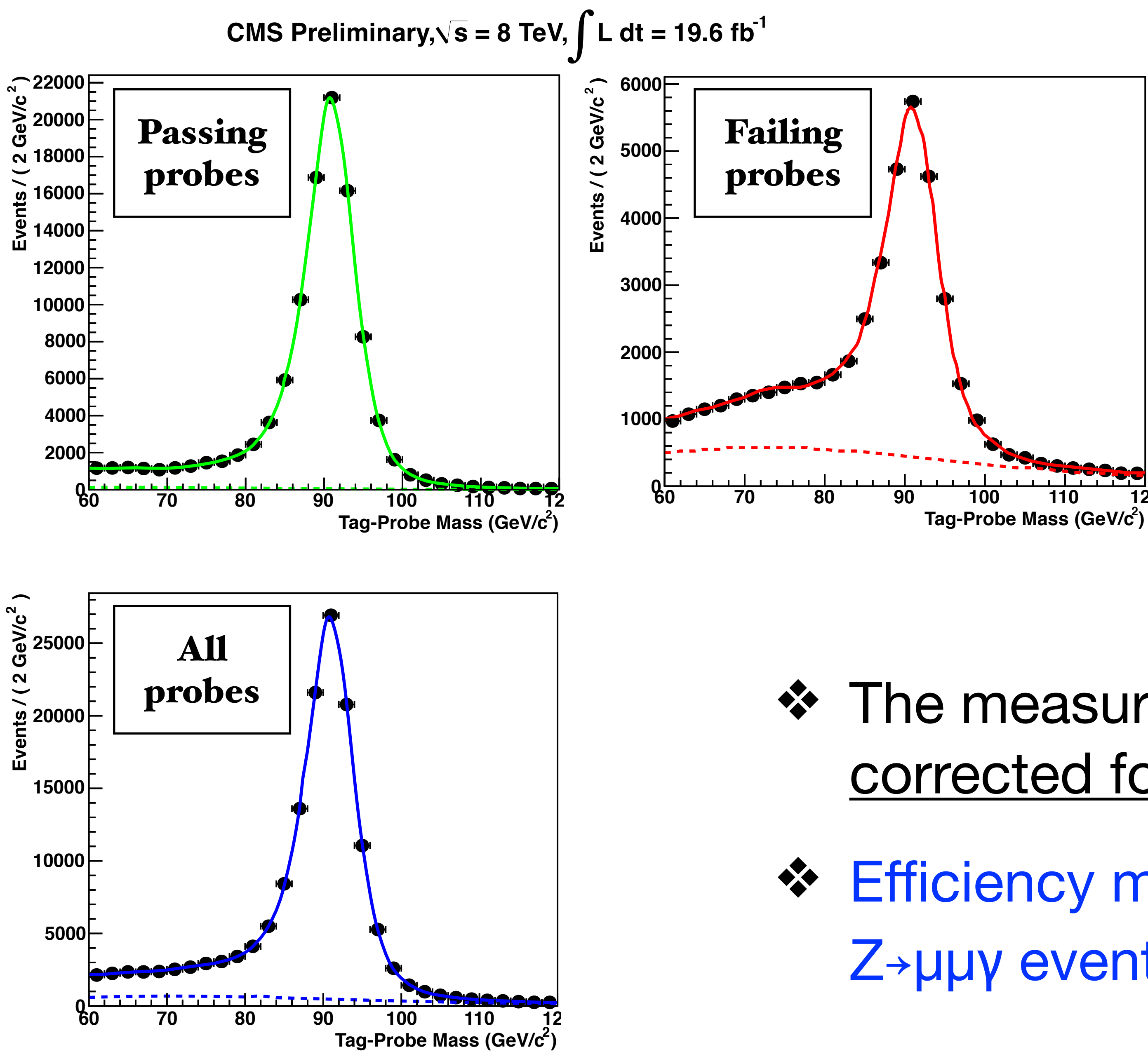
Purity extraction





- Prompt diphoton fraction extracted through **two-dimensional template fit**, measuring <u>γγ, γ+jet, di-jet components</u>
- Differential measurement as a function of $m_{\gamma\gamma}$, $p_T^{\gamma\gamma}$, $\cos\theta^*$, $\Delta\varphi_{\gamma\gamma}$

Efficiency correction



$$\frac{d\sigma}{dX} = \frac{N^U_{\gamma\gamma}}{\varepsilon \cdot \mathcal{L} \cdot \Delta X}$$

- The measured diphoton yield is corrected for selection efficiency
- Efficiency measured in data from $Z \to ee$ and $Z \to \mu\mu\gamma$ events, with tag-and-probe methods:

$$\epsilon_{\gamma\gamma} = \epsilon_{trigger} \times \epsilon_{reco\&sel} \times C^{Z\to e^+e^-}_{\gamma 1} \times C^{Z\to e^+e^-}_{\gamma 2} \times C^{Z\to \mu^+\mu^-\gamma}_{\gamma 1} \times C^{Z\to \mu^+\mu^-\gamma}_{\gamma 2}$$

Theoretical predictions

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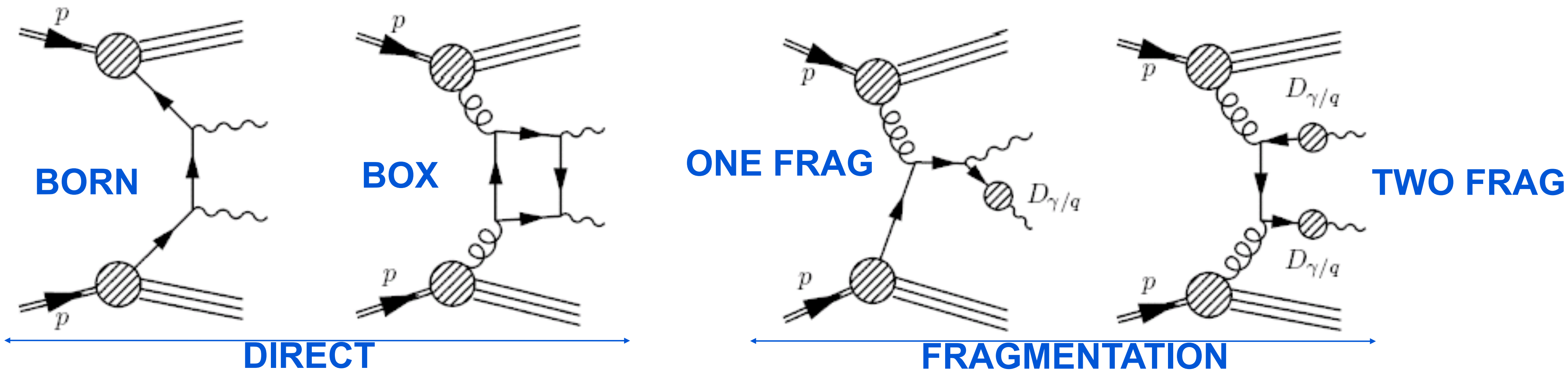
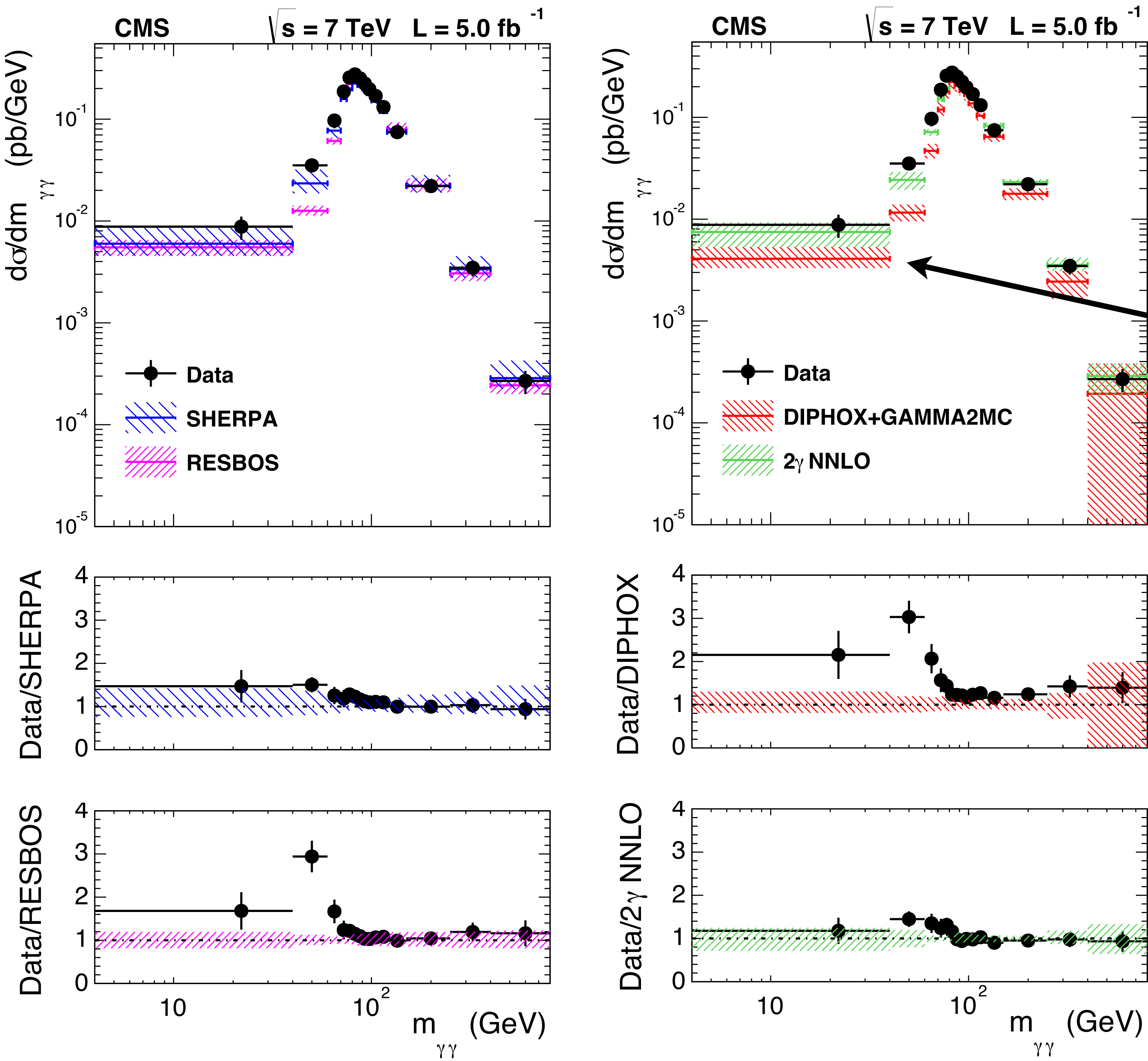
❖ Diphoton production diagrams:



❖ Properties of the theoretical calculations:

Generator	ME/PS	Resumation	Born	1-frag	2-frag	Box
$2\gamma NNLO$	ME	-	NNLO	-	-	LO
DIPHOX	ME	-	NLO	NLO	NLO	(LO)
+ GAMMA2MC	ME	-	-	-	-	NLO
RESBOS	ME	NNLL	NLO	LO	-	NLO
Sherpa	ME+PS	LL	LO + up to 3 jets	-	-	LO

Cross section results



arXiv:1405.7225, submitted to EPJC

NNLO-enhanced region

- **NNLO prediction improves the data/theory agreement** in the low mass region
- **SHERPA** also shows good agreement

➢ **Very low systematic uncertainties** ~ 10%, **despite challenging conditions** (pileup)

Cross section results

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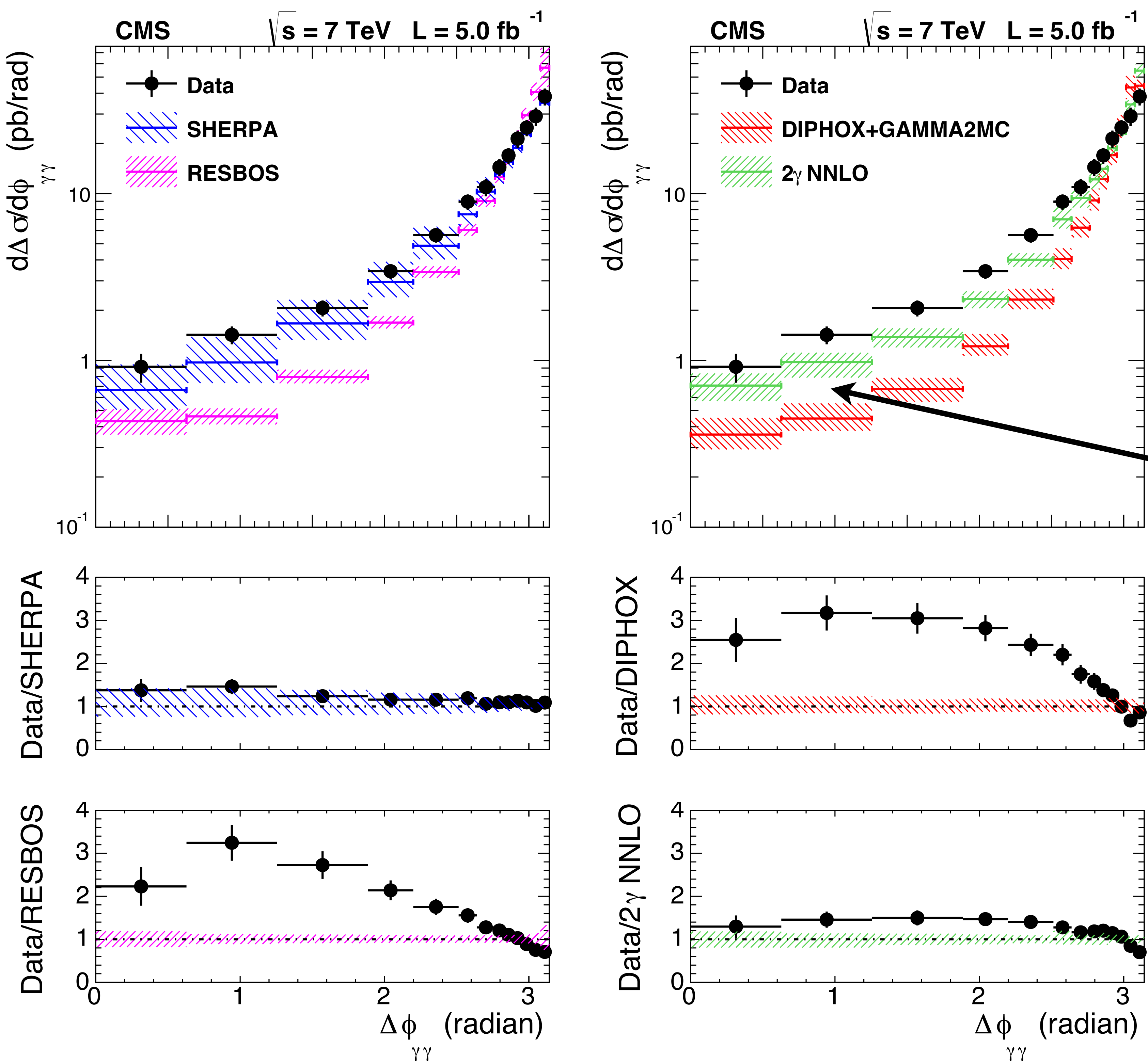

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NNLO-enhanced region

➢ **Low $\Delta\varphi_{\gamma\gamma}$ region** corresponds to low mass, after the kinematic selection

Cross section results

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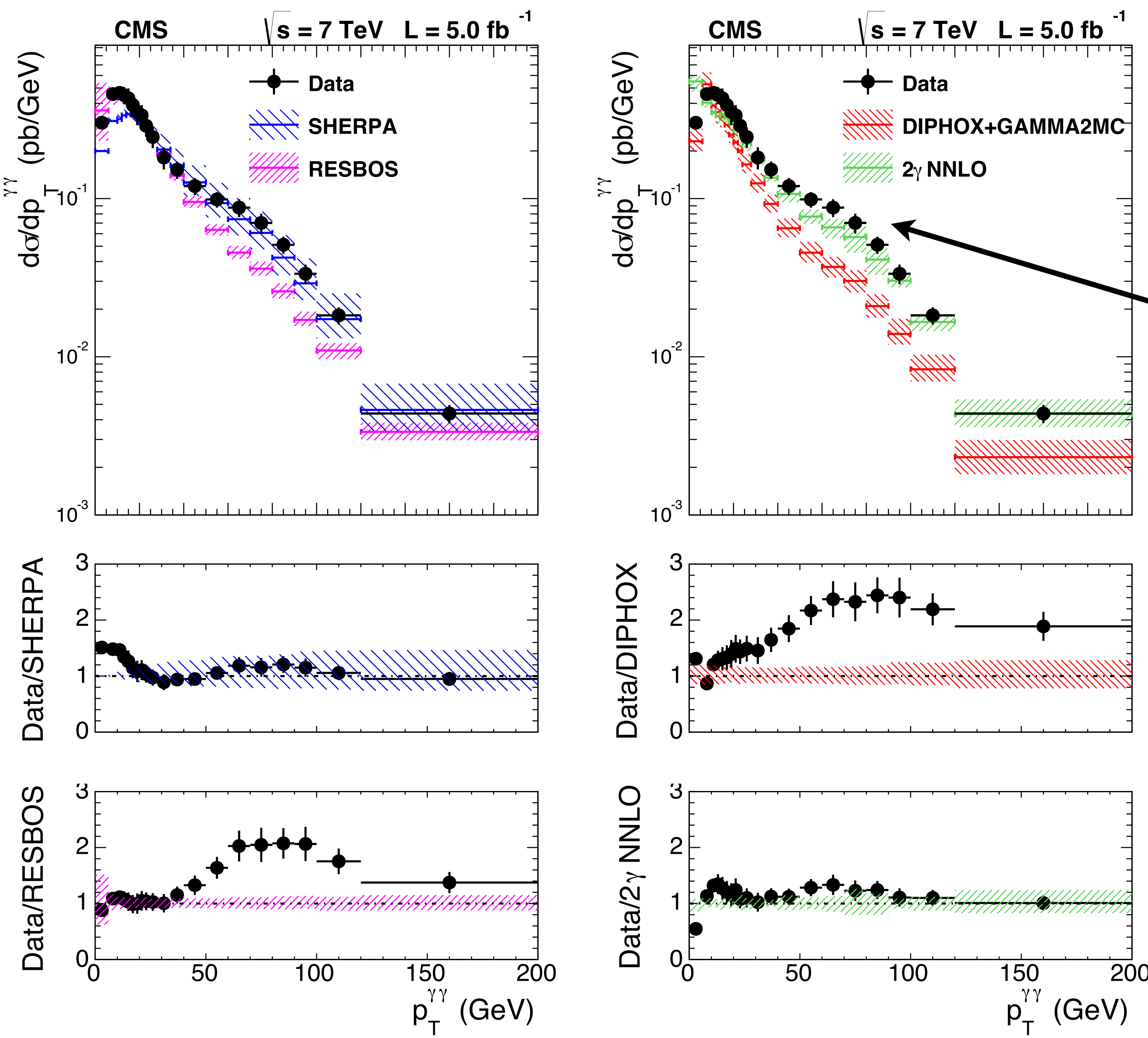

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NNLO-enhanced region

➢ "**Shoulder**" around **$p_{T1}+p_{T2}$** described by SHERPA and NNLO predictions

Integrated cross section

- The measured integrated diphoton cross section is:

$$\sigma = 17.2 \pm 0.2\,(\text{stat.}) \pm 1.9\,(\text{syst.}) \pm 0.4\,(\text{lum.})\,\text{pb},$$

to be compared to:

$$\begin{aligned}
\sigma_{\text{NNLO}}(2\gamma\text{NNLO}) &= 16.2^{+1.5}_{-1.3}\,(\text{scale})\,\text{pb},\\
\sigma_{\text{NLO}}(\text{DIPHOX} + \text{GAMMA2MC}) &= 12.8^{+1.6}_{-1.5}\,(\text{scale})^{+0.6}_{-0.8}\,(\text{pdf}+\alpha_S)\,\text{pb},\\
\sigma_{\text{NLO}}(\text{RESBOS}) &= 14.9^{+2.2}_{-1.7}\,(\text{scale}) \pm 0.6\,(\text{pdf}+\alpha_S)\,\text{pb},\\
\sigma_{\text{LO}}(\text{SHERPA}) &= 15.2^{+3.2}_{-1.9}\,(\text{scale})\,\text{pb}.
\end{aligned}$$

- **Best agreement with the NNLO calculation**
- ~10% final uncertainty is the result of a **strong effort** towards detailed **detector understanding and algorithm optimization**

Out-of-time pileup in ECAL

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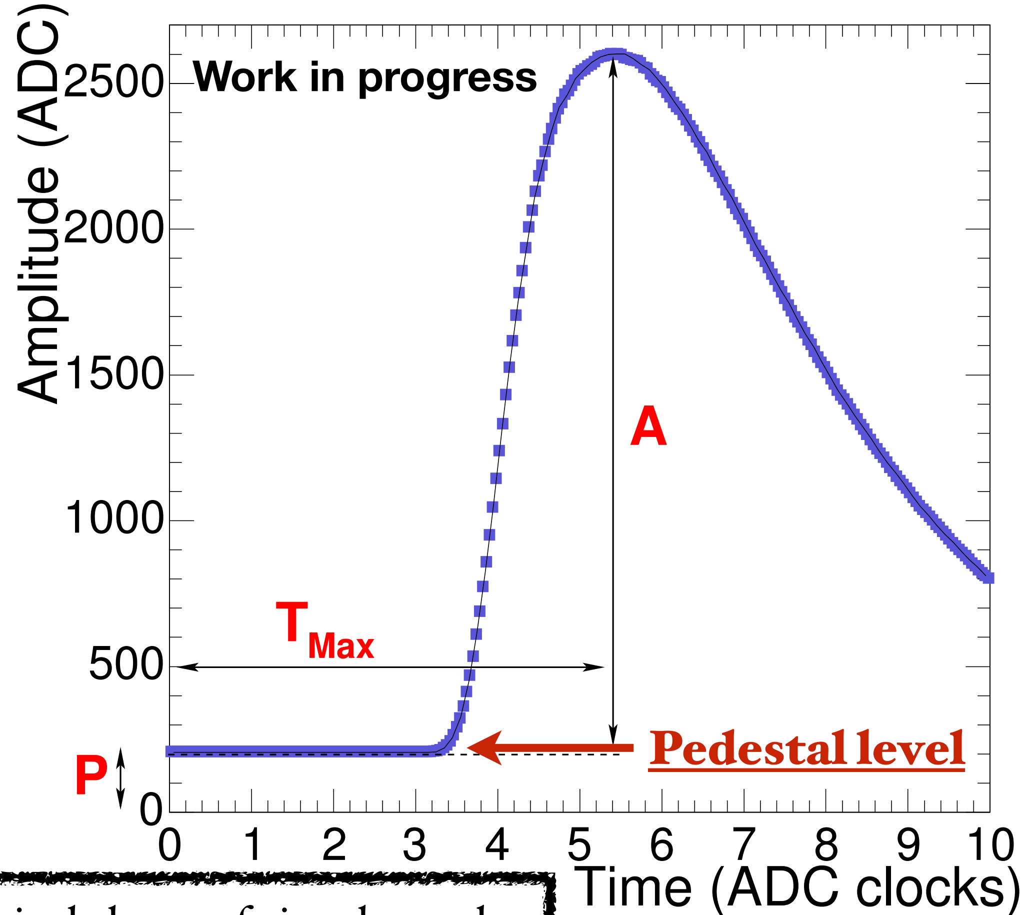
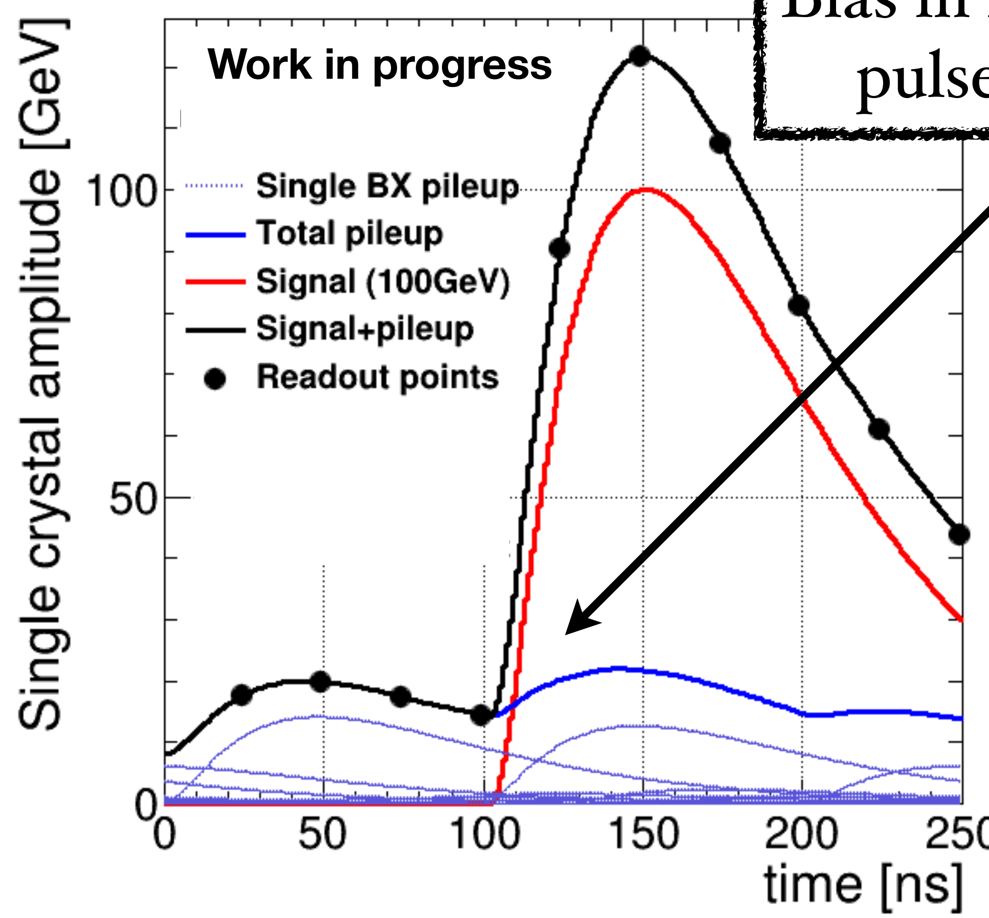


Typical shape of signal seen by ECAL readout electronics



Bias in reconstructed pulse amplitude

- Energy deposition in ECAL crystals measured with a **pulse shape fit**
- Dynamic pedestal subtraction used to subtract the noise
- Level of pedestal influenced by previous energy depositions:
  - pulse shape much longer than spacing between LHC bunches
  - effect scales with pileup (detector occupancy increases)

ECAL simulation improvement

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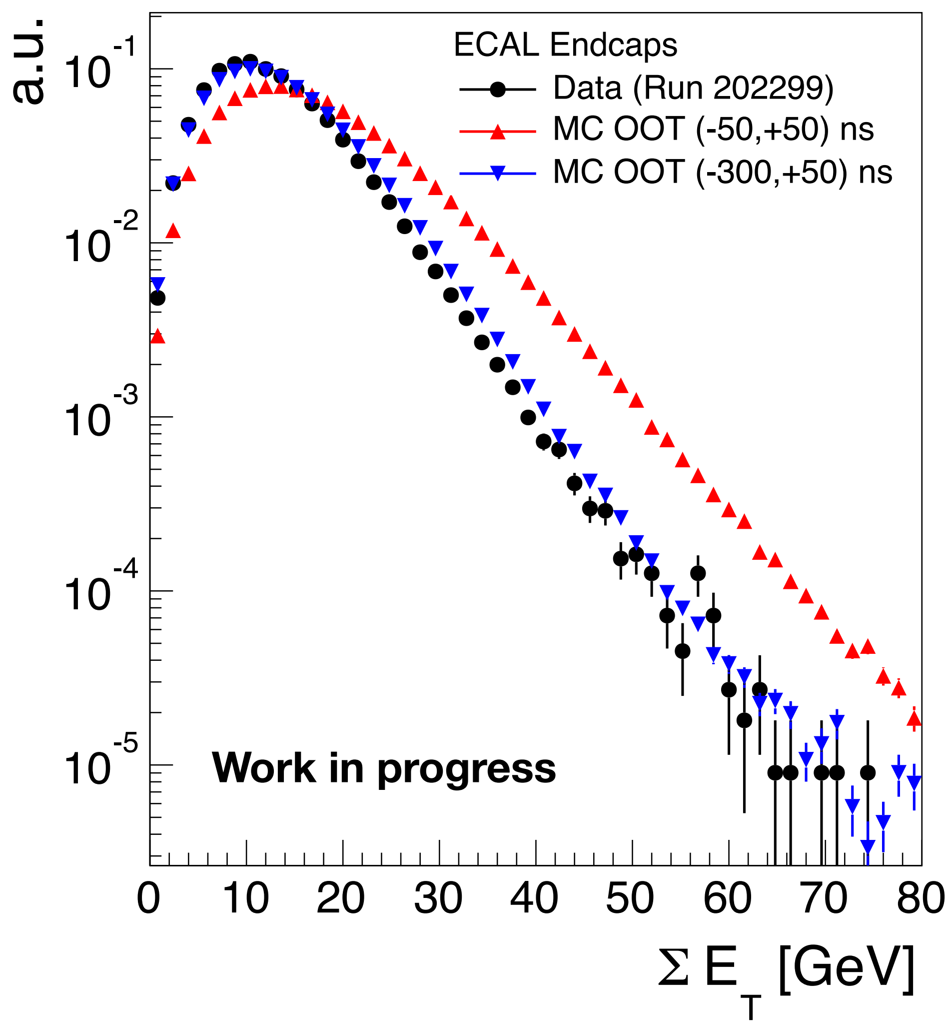
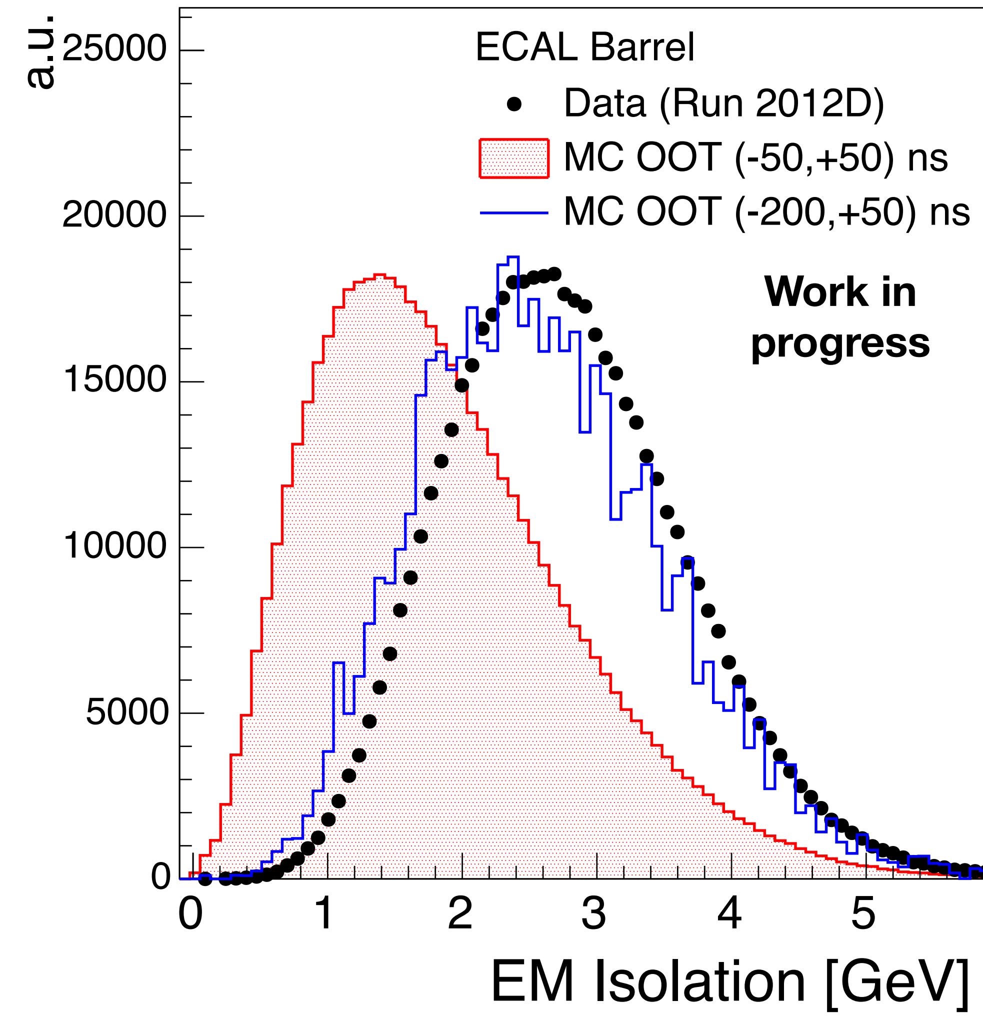
- **Discrepancies between data and simulation** observed in ECAL quantities:





- **The main reason was the OOT pileup**
- **Simulation improved**:
  - **benefit to all analyses using photons**
  - crucial to understand this effect in view of the next data taking (high pileup)

Photon energy corrections

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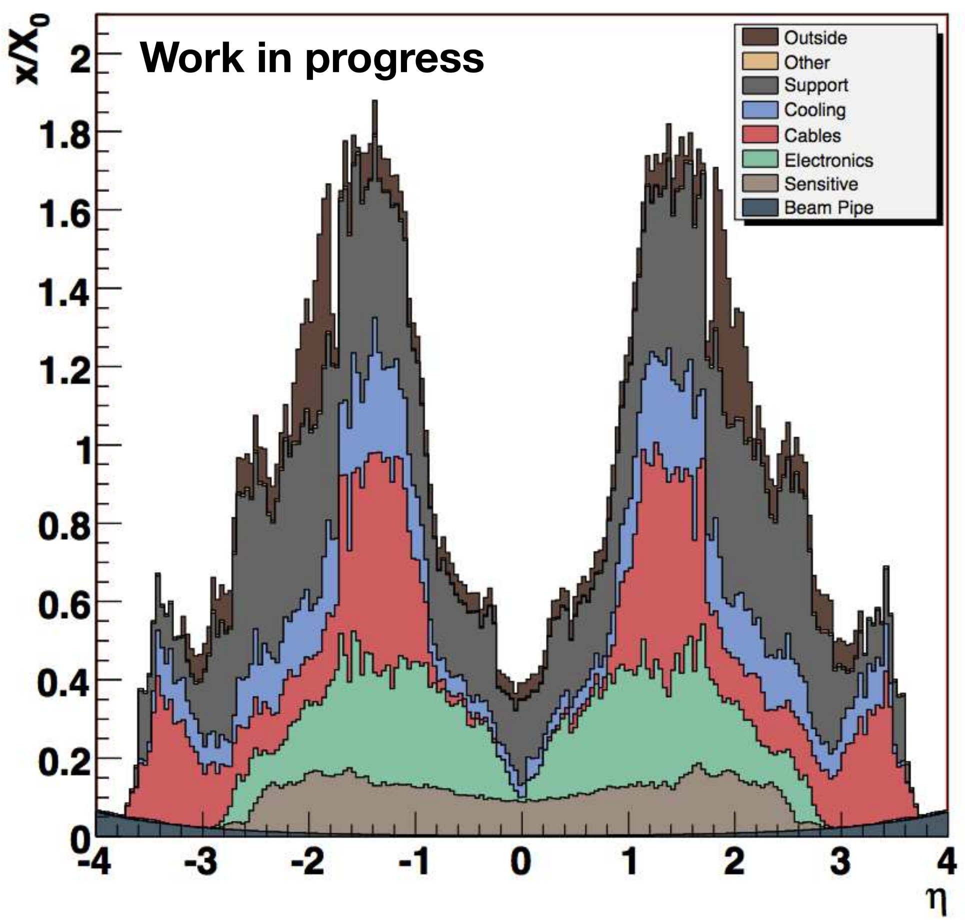

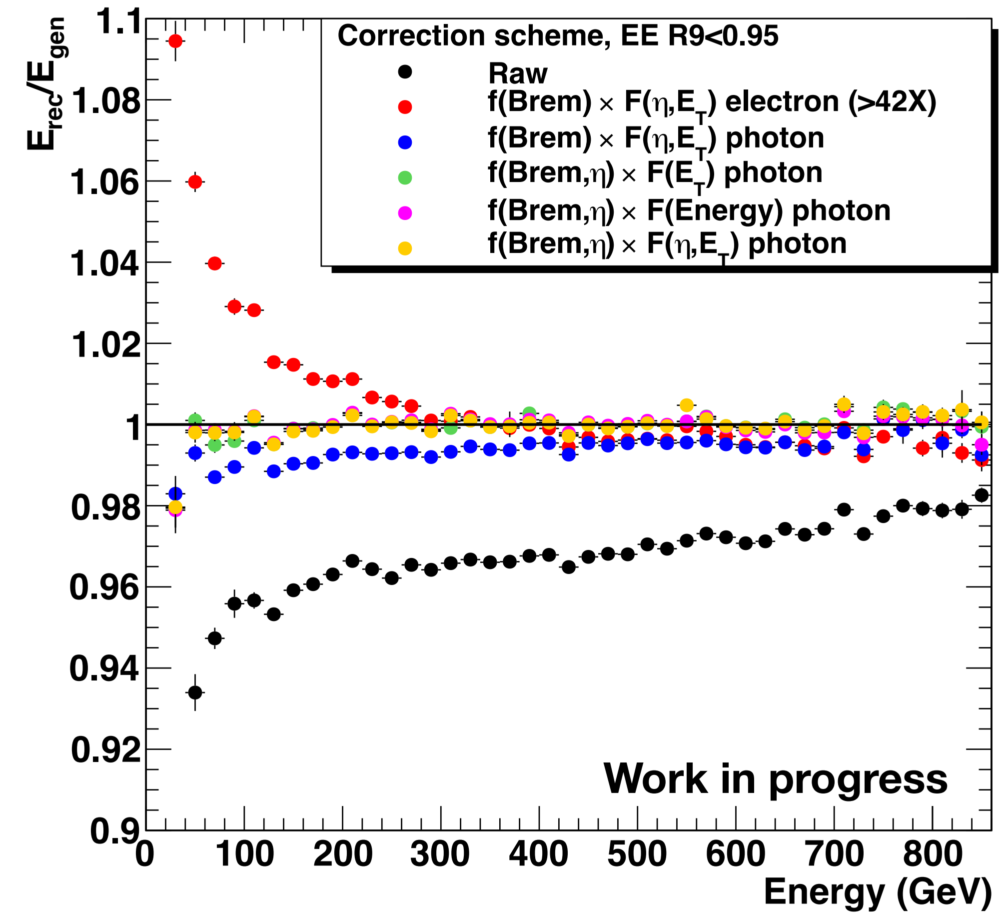

- Photon energy corrections development:
  - Photons can convert in the tracker material in front of ECAL
  - Correlation between azimuthal energy spread and position in the detector
- New factorization of cluster energy corrections : $f(\sigma_\phi/\sigma_\eta, \eta) \times F(ET)$
- **Improvement in resolution, very robust method used as default both in trigger and offline reconstruction**

ECAL upgrade studies

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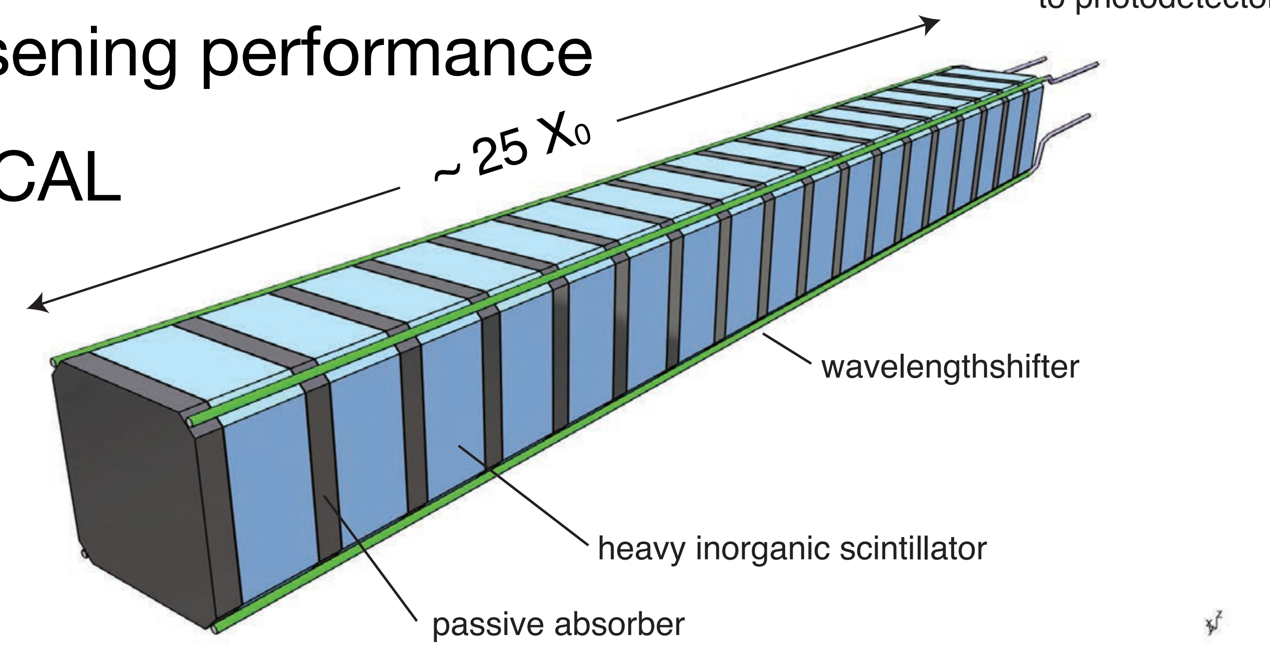
- Studies in the framework of the CMS **ECAL Phase II upgrade project**
  - radiation-induced damage of $PbWO_4$ crystals, leading to loss of transparency and worsening performance
  - need to upgrade the endcap region of ECAL for operation at HL-LHC



- Joint ETHZ / INFN effort to build a **sampling calorimeter prototype channel**:
  - **CeF3 scintillating crystals**, tungsten absorber plates
  - **wavelength-shifting fibers** on channel corners to extract light to PMT readout
  - BGO crystals for lateral shower energy containment

Test-beam activity

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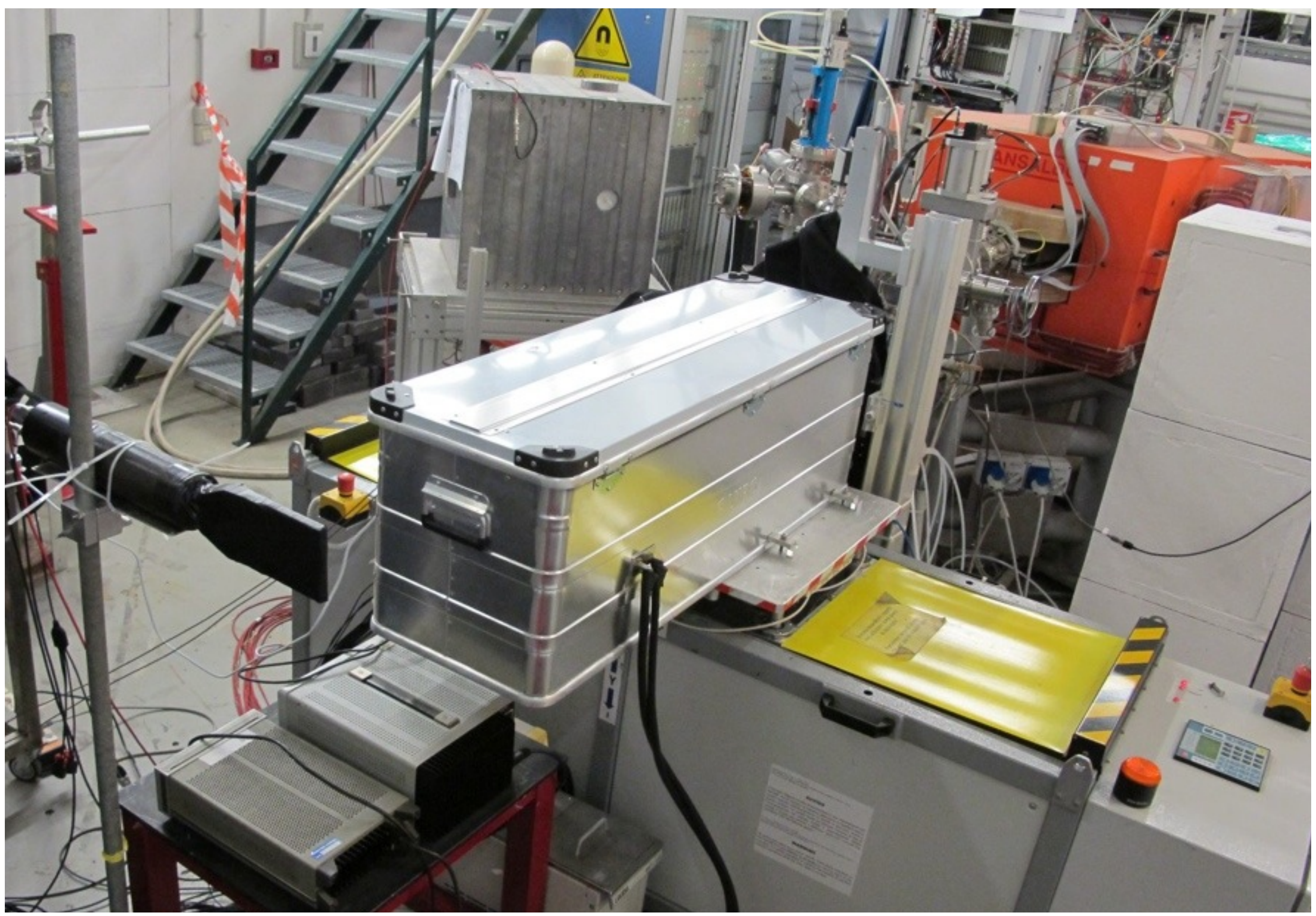
- **Involvement throughout design, construction and commissioning** phases
- **Very successful (and exciting) test-beam!**
  Excellent experience gathered in Frascati
- First look at data looks really promising



Conclusions and outlook

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- **Diphoton cross sections measurements probe QCD at NNLO**
- **Data-driven techniques** specially developed to make the analysis robust and **reduce the systematic uncertainties**
- This work has paved the way for using PF isolation in precision SM measurements involving photons at CMS
- More to come: inclusion of jet information in the analysis, expected to be finalized in summer

- Contributions in understanding ECAL reconstruction behaviour in high-pileup conditions
- Involvement in **R&D studies for CMS ECAL upgrade**, from design of a sampling calorimeter prototype channel to successful tests in an e^- beam