Central Exclusive Production at CMS

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Outline

- **Introduction to Exclusive processes**

- **Light-by-Light scattering in Pb-Pb at 5 TeV**
  (arXiv:1810.04602, submitted to PLB)

- **Photoproduction of ρ^0 in p-Pb at 5 TeV**
  (arXiv:1902.01339, submitted to EPJC)

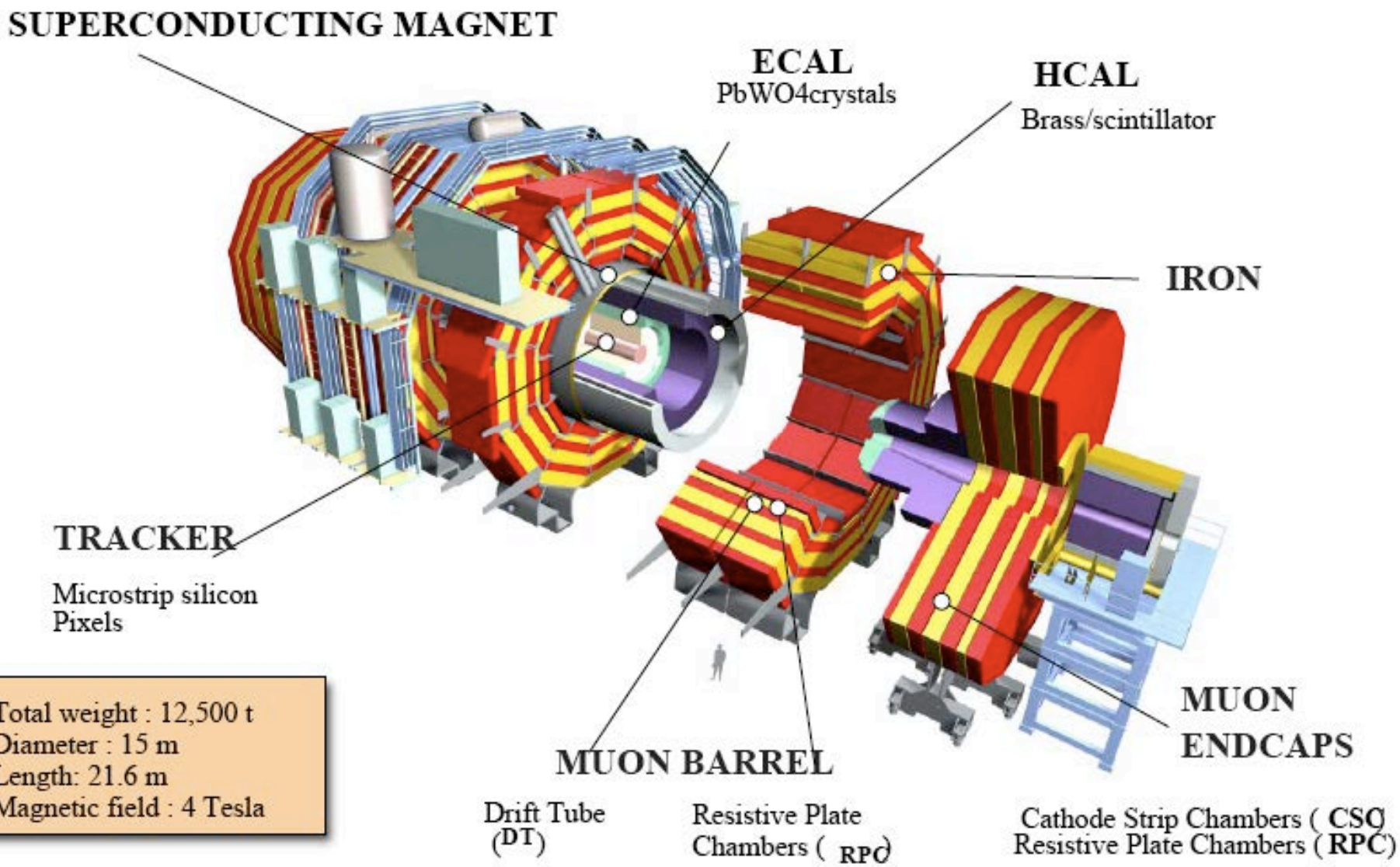
- **Photoproduction of Υ in p-Pb at 5 TeV**
  (arXiv:1809.11080, submitted to EPJC)

- **Measurement of Exclusive $\pi^+\pi^-$ production in p-p collisions**
  (arXiv:1706.08310, submitted to PRD)

Documentation: All Forward physics results at CMS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

CMS detector

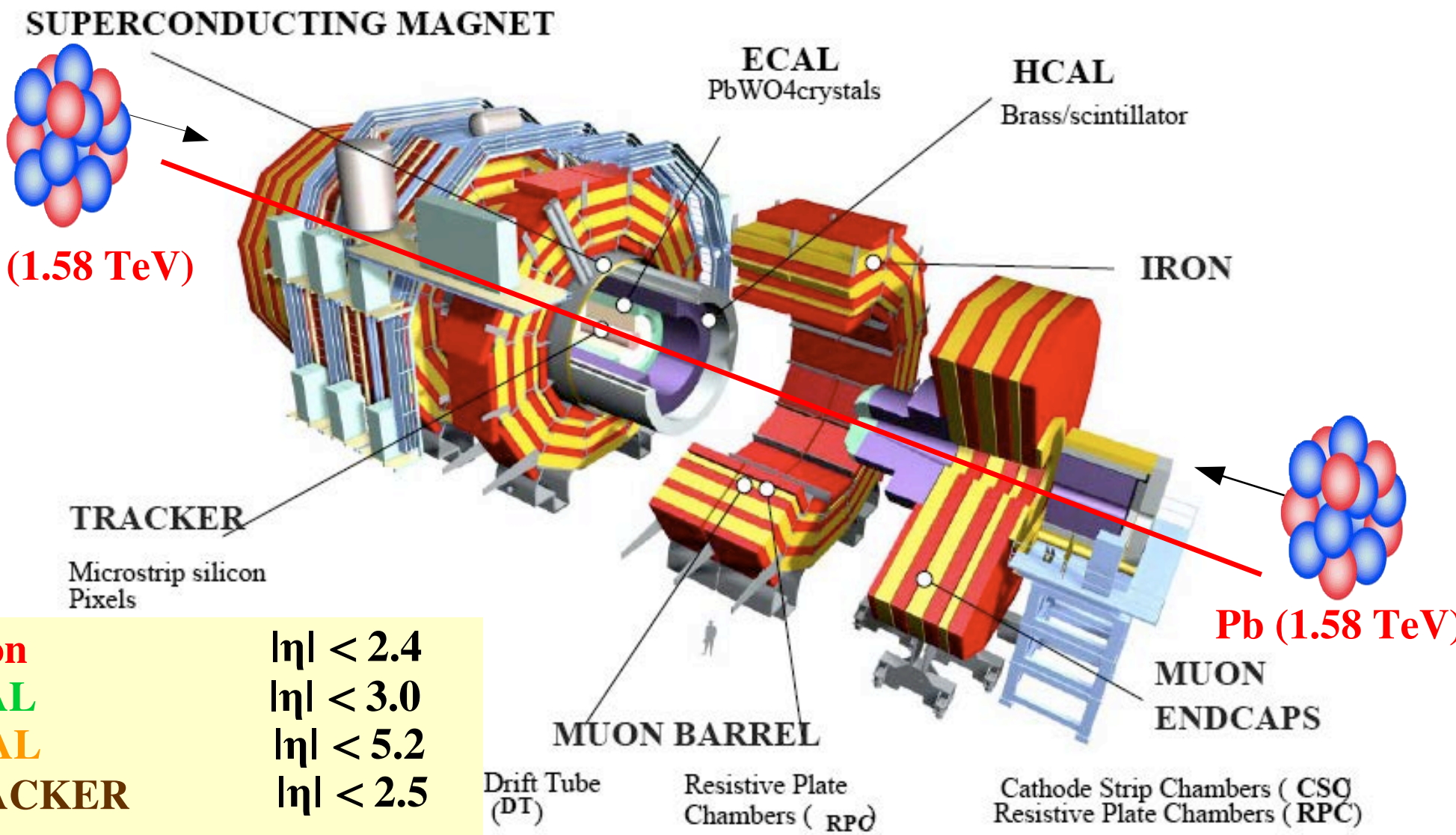
CMS (Compact Muon Solenoid)



Total weight : 12,500 t
Diameter : 15 m
Length: 21.6 m
Magnetic field : 4 Tesla

Pseudorapidity: $\eta = -\ln(\tan(\theta/2))$

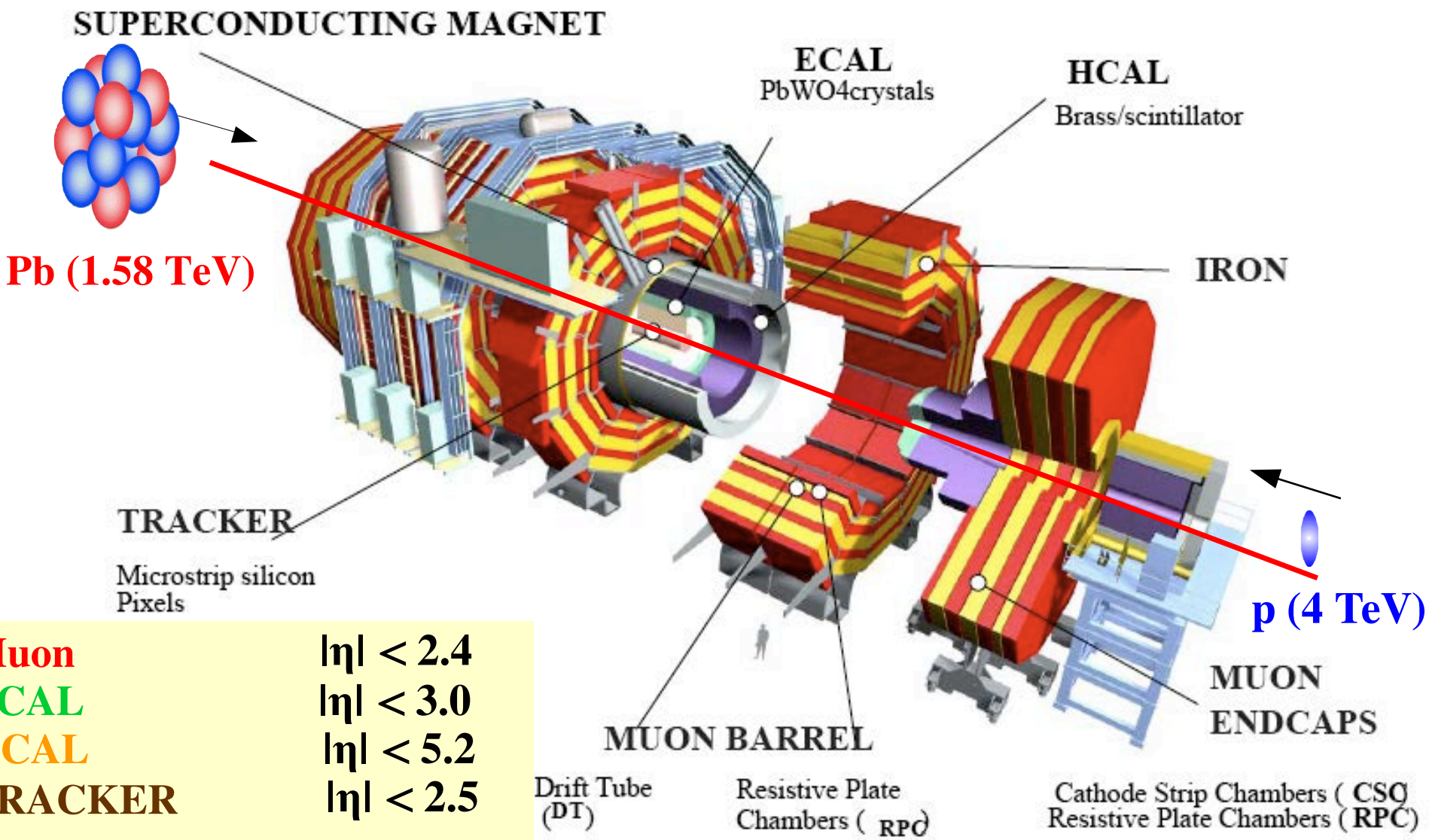
CMS (Compact Muon Solenoid)



Muon	$\lvert\eta\rvert < 2.4$
ECAL	$\lvert\eta\rvert < 3.0$
HCAL	$\lvert\eta\rvert < 5.2$
TRACKER	$\lvert\eta\rvert < 2.5$

Pseudorapidity: $\eta = -\ln(\tan(\theta/2))$

CMS (Compact Muon Solenoid)



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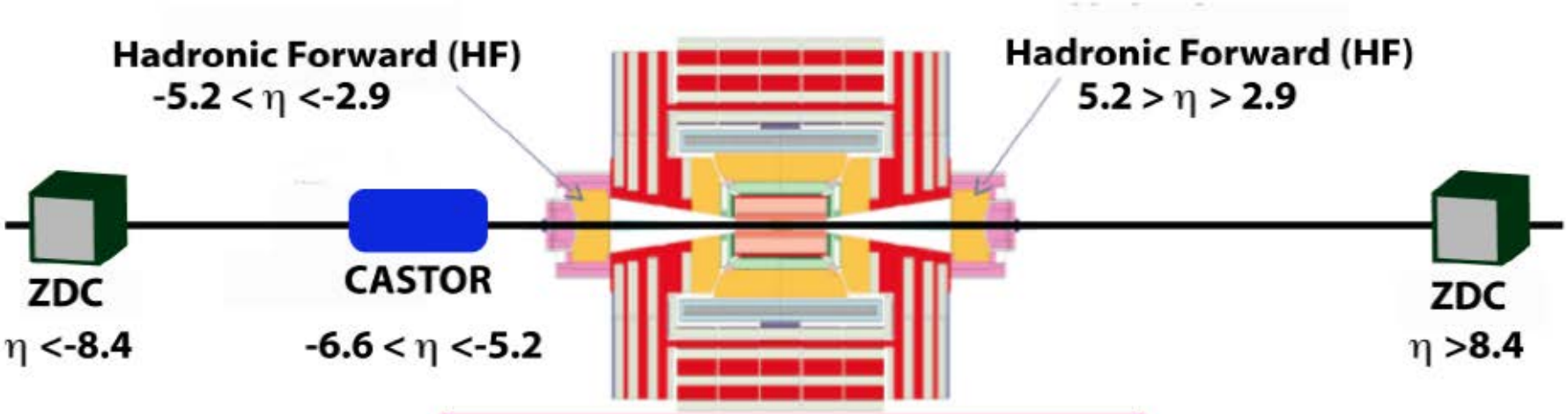
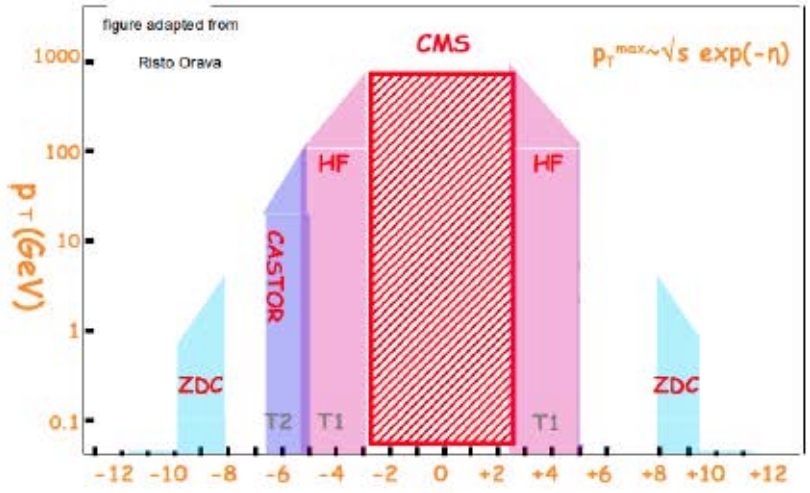
Forward detectors at CMS

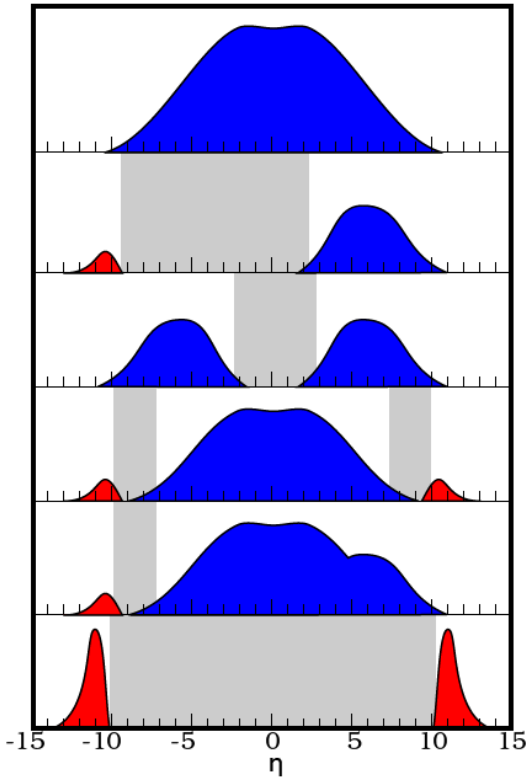


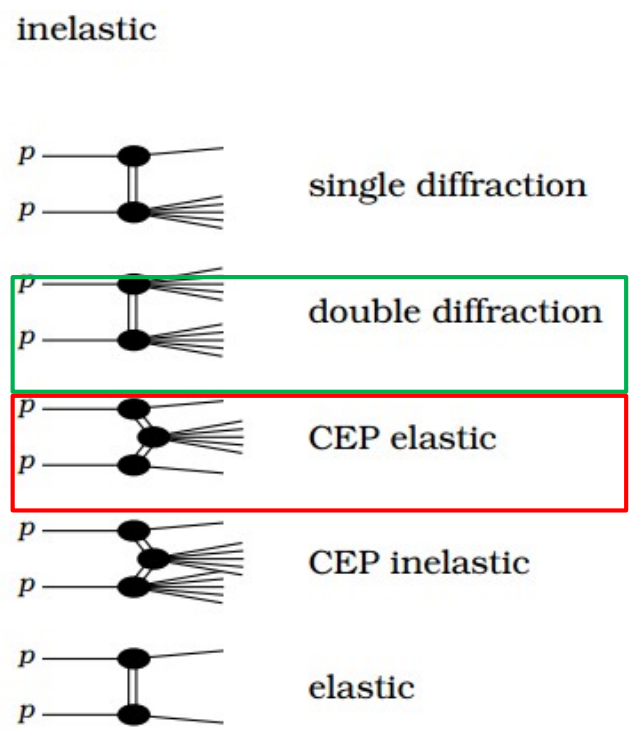
Three cherenkov calorimeters:

- **HF**
  - rapidity coverage: $2.9 < |\eta| < 5.2$
  - at 11.2 m from IP
- **CASTOR**
  - rapidity coverage: $-6.6 < \eta < -5.2$
  - at 14.3 m from IP
- **ZDC**
  - rapidity coverage: $|\eta| > 8.4$
  - at 140 m from IP



Introduction





Motivations:

- To test the QCD and the pomeron in a clean enviroment;
- To be sensitive to the diffractive PDF at very low (to 5×10^{-6});
- Tested and Measured at HERA/Tevatron but different γp energy and central mass energy

Central Exclusive Production

➢➢**Central exclusive production:**

$$\mathbf{p}(\mathrm{Pb})\ \mathbf{p}(\mathrm{Pb}) \rightarrow \mathbf{p}(\mathrm{Pb}) + X + \mathbf{p}(\mathrm{Pb})$$

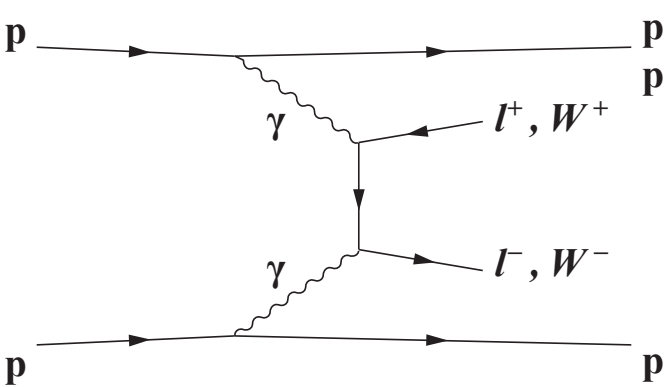
➢➢Both protons (Pb) emerge intact from the interaction

➢➢X: a simple fully measured system

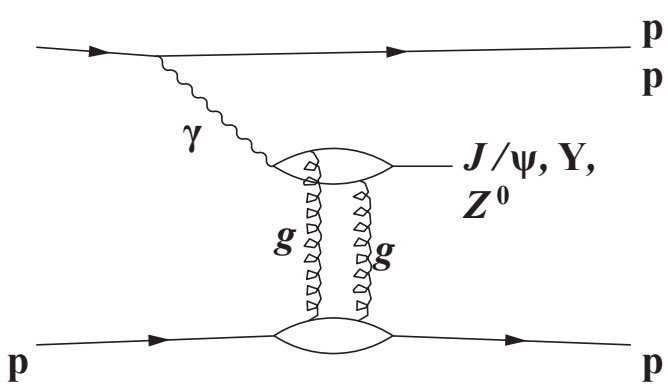
➢➢Exclusive: no other particles produced & large rapidity gaps

➢➢Cleanest and simplest inelastic pp collision

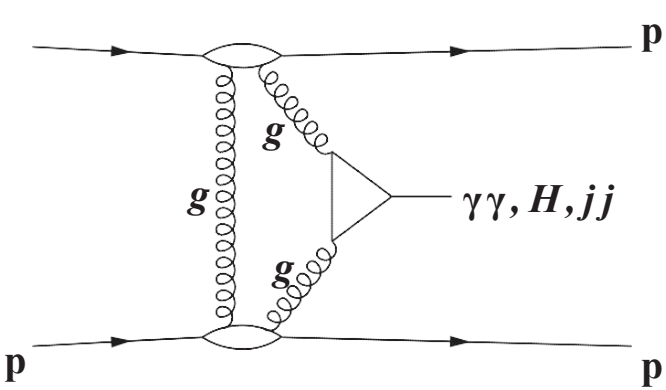
➢➢Physics processes involved: γγ interactions, γIP fusion, and IPIP exchange



γγ interactions



γIP fusion



IPIP exchange

Light-by-Light scattering in Pb-Pb at 5 TeV

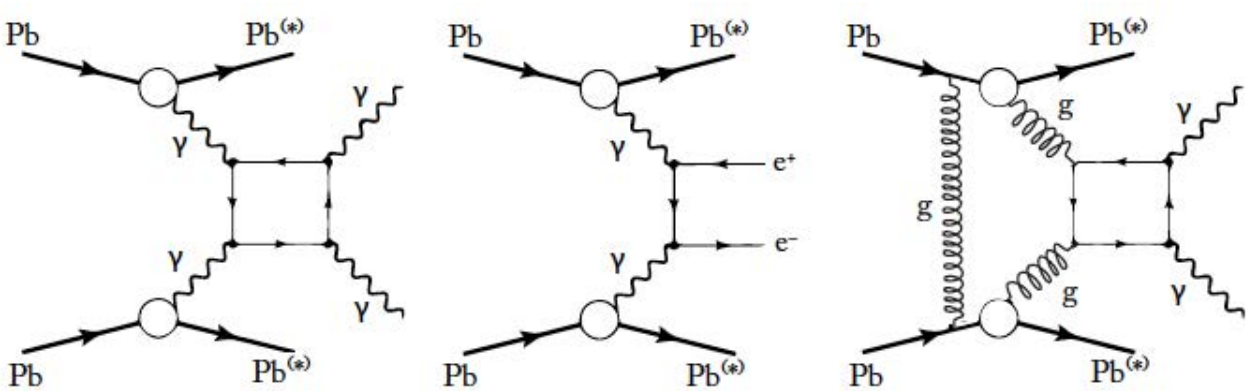
(arXiv:1810.04602, submitted to PLB)

Search for LbL in Pb-Pb UPC at 5.02 TeV

- **Elastic light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering**
  - ✓ Fundamental QED process
  - ✓ Difficult to observe: very supressed production cross section to ~ O ($\alpha^4 \approx 3 \times 10^{-9}$)
  - ✓ Sensitive to physics signals beyond the SM

The intensity of the photon beam is proportional to Z^2.
Heavy nuclei are intense sources of quasi-real photons!

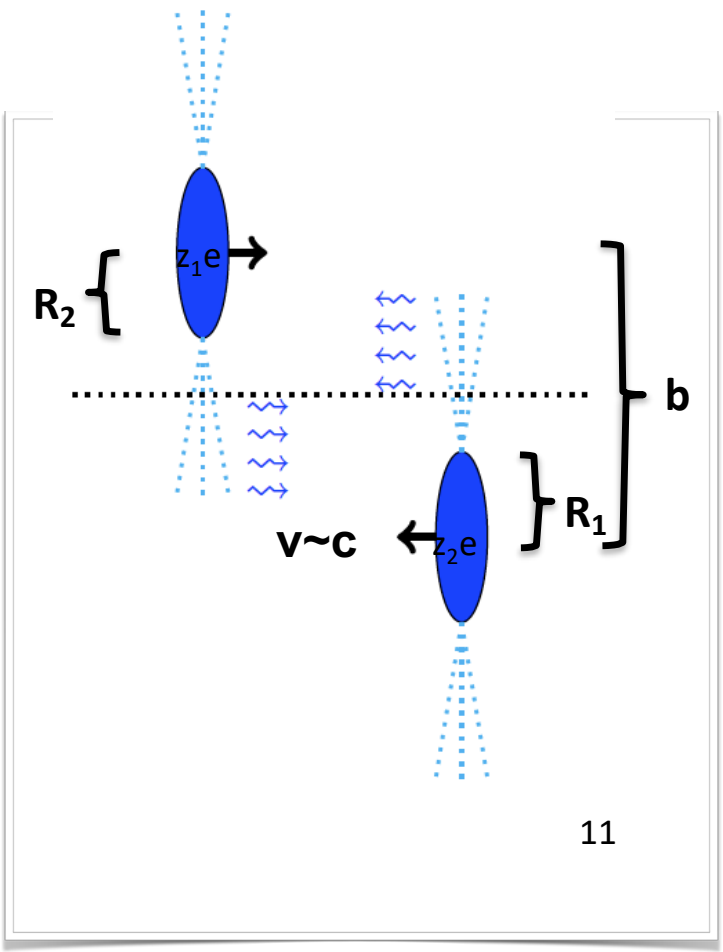
- **Ultraperipheral collisions (UPCs) : $b_{min} > R_1+R_2$**
  Only electromagnetic interaction, no hadronic overlap



LbyL scattering (Signal)

QED dielectron (Background)

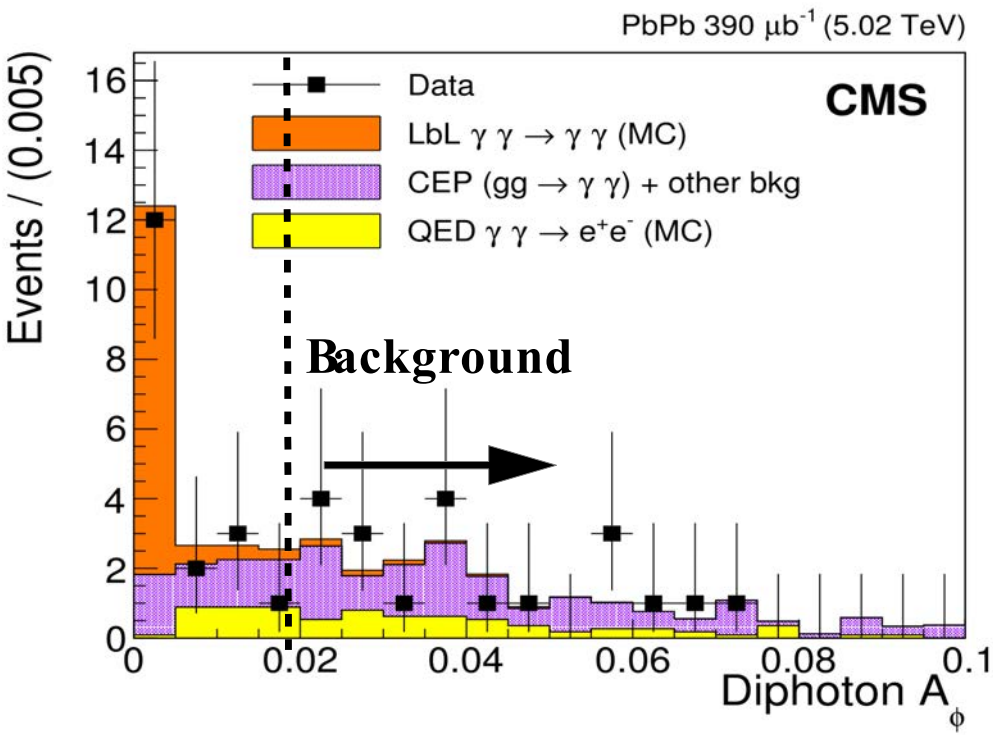
Central exclusive diphoton (Background)

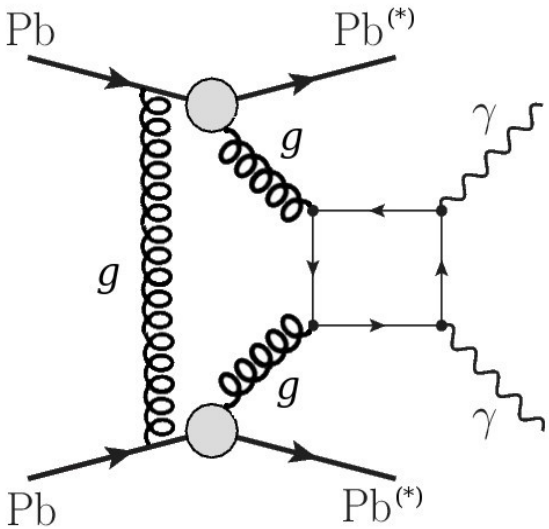


Search for LbL in Pb-Pb UPC at 5.02 TeV …

arXiv: 1810.04602

- **Central exclusive production (CEP) + residual background**
- Two back to back photons:
  - $E_T > 2$ GeV, $|\eta| < 2.4$, $P_T^{\gamma\gamma} < 1$ GeV, $m^{\gamma\gamma} > 5$ GeV
- Exclusivity: no tracks, no extra neutral activity
- Larger theoretical uncertainty for CEP in Pb-Pb collisions





Search for LbL in Pb-Pb UPC at 5.02 TeV …

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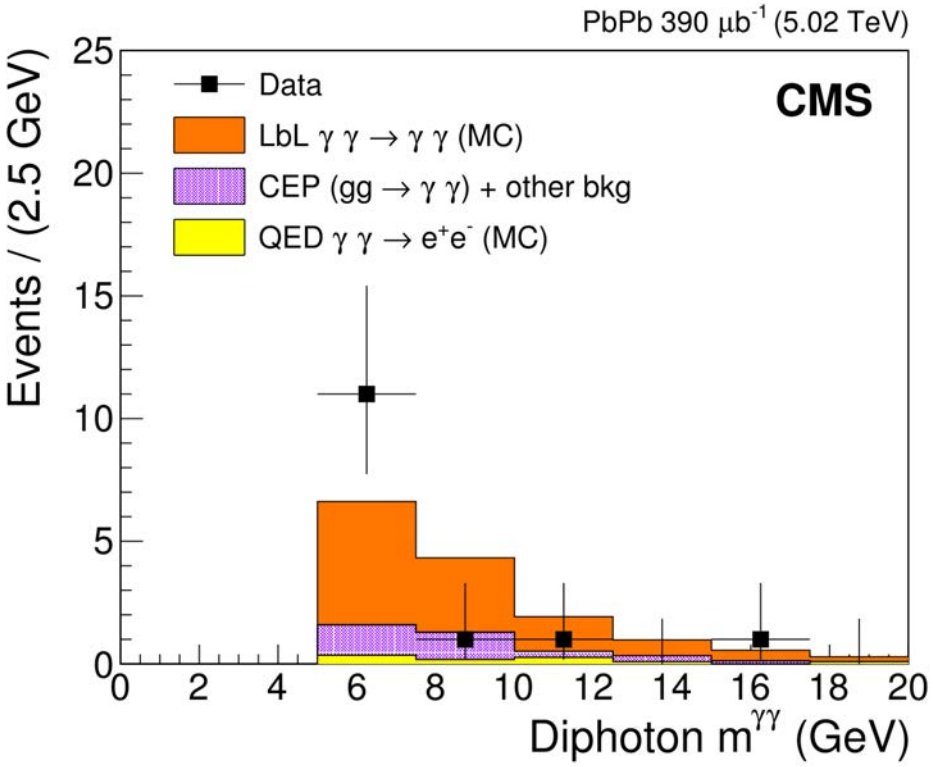
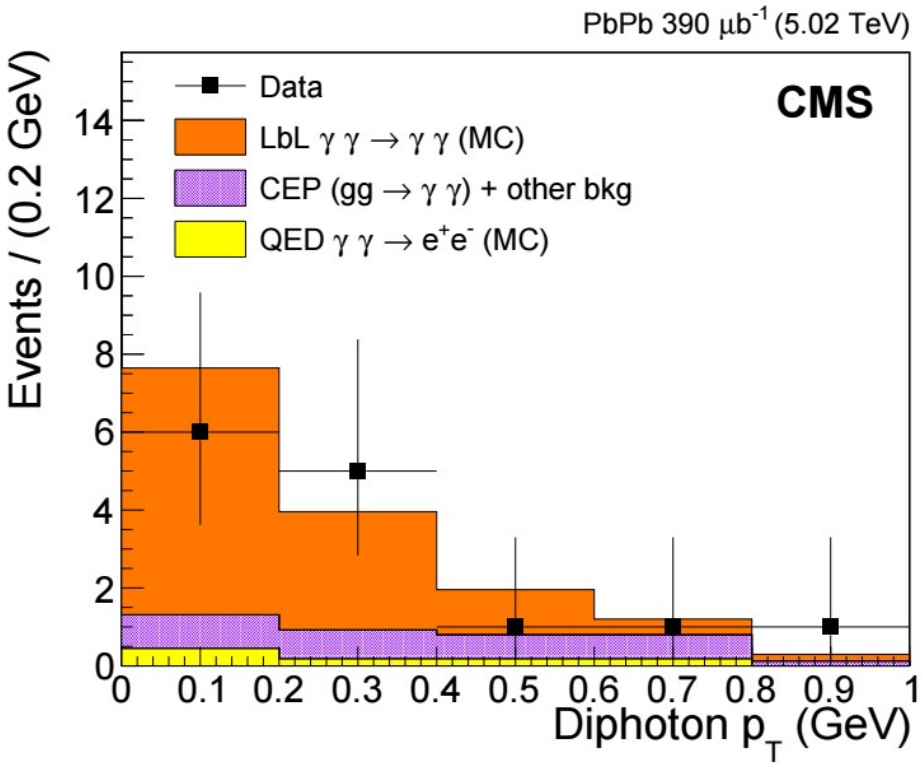




For $A_\Phi < 0.01$

Observed: 14 events

Expected: 11.1 ± 1.1 (th) signal,

N_{bkg}: 4.0 ± 1.2 (stat) background events

Significance: 4.1σ (expected 4.4 σ)

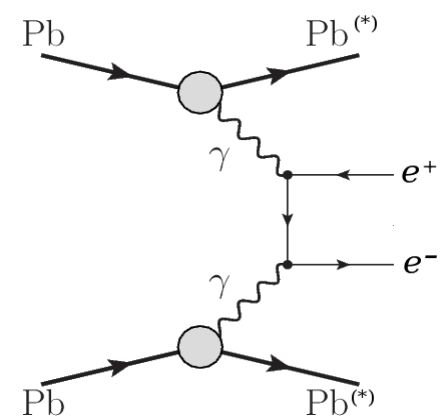
The measured yields and kinematic distributions are in good agreement with the MC expectations (LbL+QED+CEP+other)

LbL cross section

arXiv: 1810.04602

Measured the ratio of LbL to QED e^+e^- cross section

- Reduces uncertainties related to luminosity
- The main sources of uncertainties: trigger, single $\gamma/e^{\pm}$ efficiencies



- $\mathbf{R = \sigma_{fid}\,(\gamma\gamma\rightarrow\gamma\gamma) \,/\, \sigma(\gamma\gamma\rightarrow e^+e^-)}$

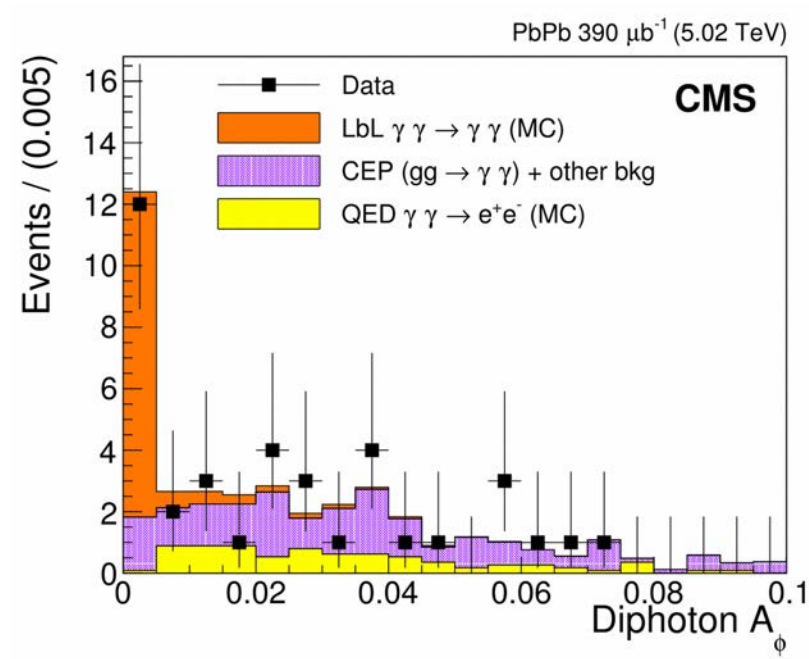
  $= [25.0 \pm 9.6\ (\text{stat}) \pm (\text{syst})\ ] \times 10^{-6}$

- Fiducial LbL cross section derived from R and QED e^+e^- cross section using STARLIGHT = 4.82 ± 015 (th.) mb

$\sigma_{fid}\,(\gamma\gamma \rightarrow \gamma\gamma) = 120 \pm 46\ (\text{stat}) \pm 28\ (\text{syst}) \pm 4\ (\text{th})$ nb,

consistent with SM prediction: $\sigma_{fid}(\gamma\gamma\rightarrow\gamma\gamma) = 134 \pm 14$ nb.

Compatibility of the data with background-only hypothesis, via profile-likelihood ratio of acoplanarity distribution:
LbL significance: 4.1σ observed (4.4σ expected)



Photoproduction of ρ^0 in p-Pb at 5 TeV

(arXiv:1902.01339, submitted to EPJC)

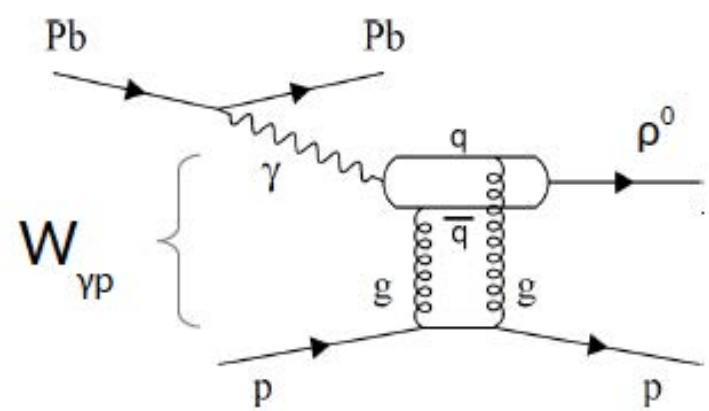
Experimental signature

- **In this case, one of hadron may emits a quasi-real photon that fluctuates into a quark and anti-quark**

- **Exclusive vector meson photoproduction off proton have been also studied by H1 and ZEUS experiments**

- **Advantage of looking at p-Pb collisions**
  - The photon flux grows with the square of the charge
  - Possibility to reproduce HERA and potential to go beyond in W(γ-p)

- **Signal:**
  - Only two tracks, no other track on vertex
  - No additional signals in the calorimeters
  - $p_T(\pi) > 200$ MeV/c
  - $|y(\pi)| < 2.0$



Signal extraction and backgrounds

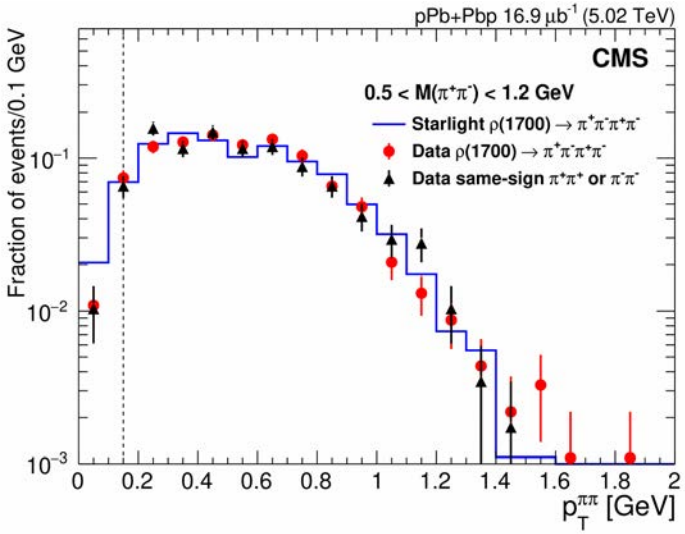
Two main backgrounds to ρ^0 signal known from HERA Experiments:

1. Proton dissociation – high p_T region

- Data driven approach requiring activity in the forward detectors

2. $\rho' \rightarrow {}^{+-+-}$ (a source of same-sign events)

- These mesons decay mostly into a $\rho(770)$ meson and a pion pair, leading to final states with four charged pions or with two charged and two neutral pions.



Validation is performed by comparing the shapes of p_T distributions of 2 track events

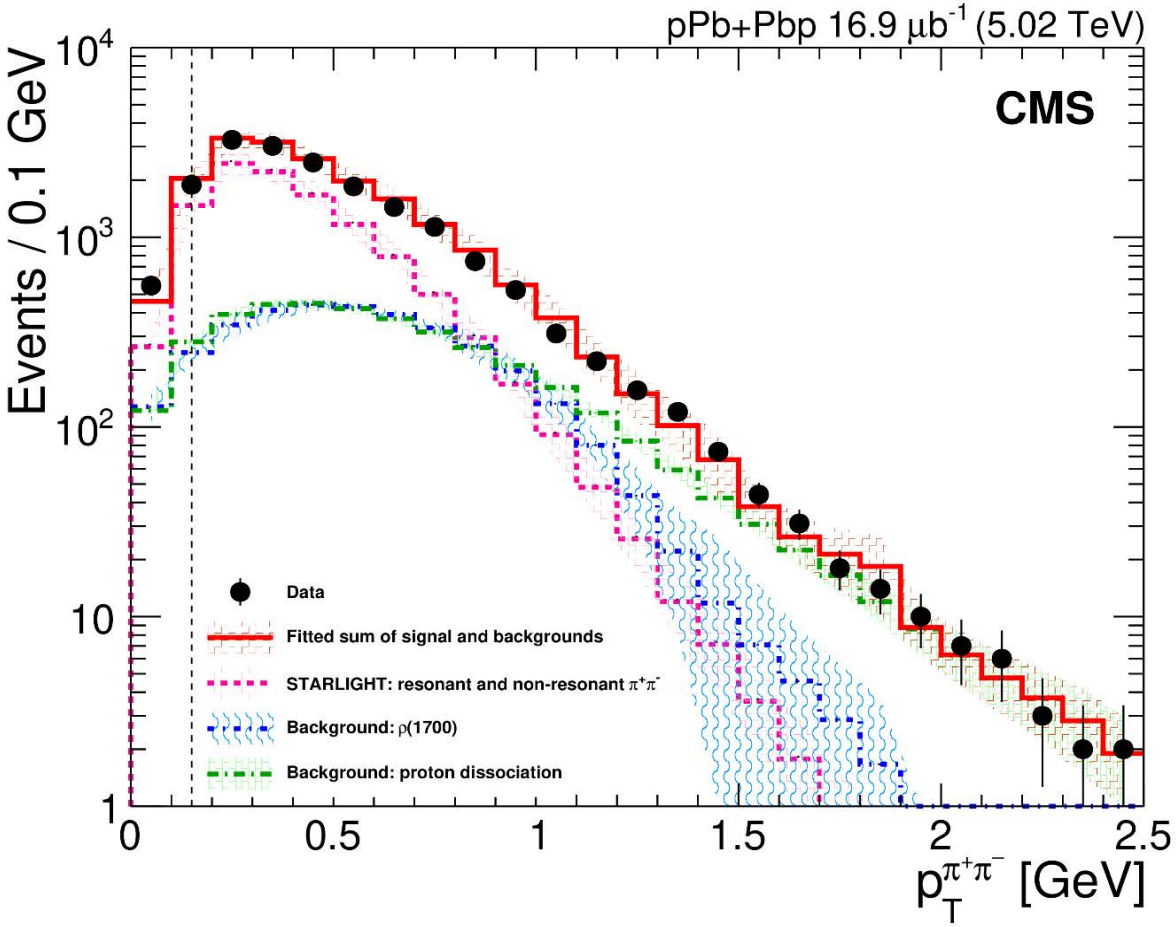
Other background contributions:

3. non-resonant $\pi^+\pi^-$ and ω production accounted in the invariant mass fits

4. Exclusive production of $\phi \rightarrow K^+K^-$: Removed by M_{inv} $(K^+K^-) > 1.04$ GeV

5. DPE and γ-Pb-interactions: Found to be negligible in this analysis

Signal extraction and backgrounds



arXiv:1902.01339

Submitted to EPJC

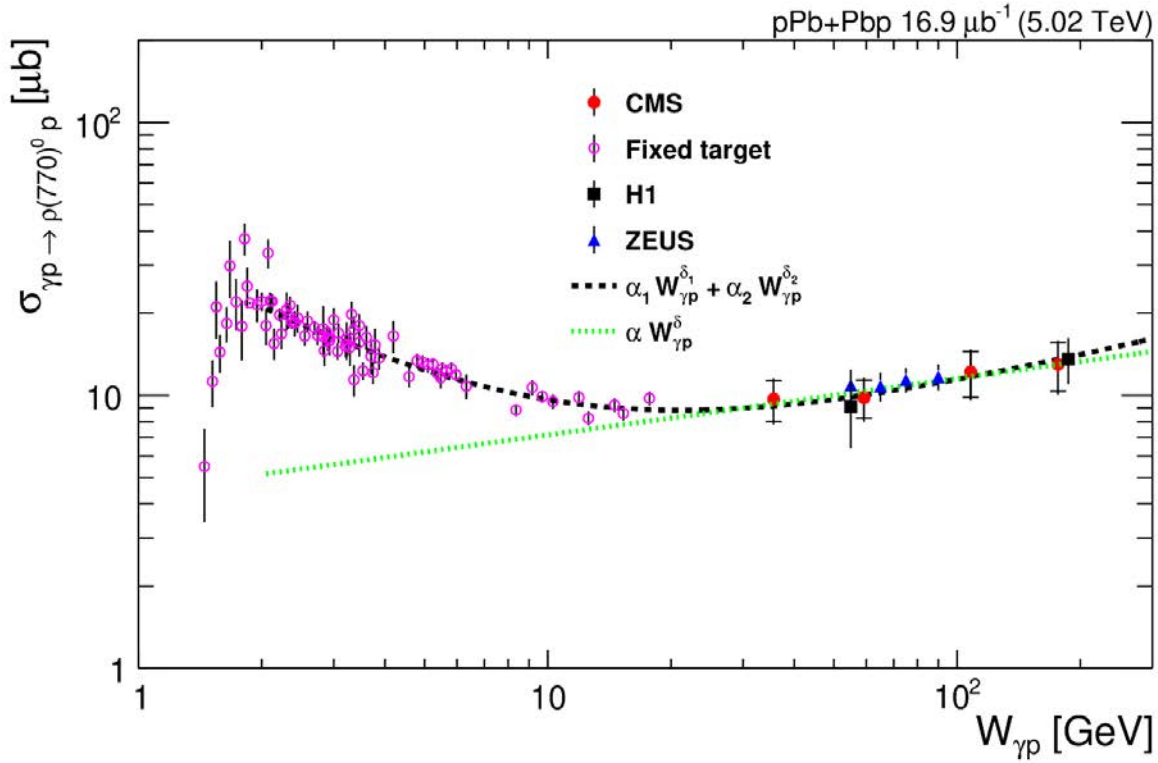
Template fit is performed to extract the residual background contributions

Signal:	$\rho^0 \rightarrow \pi^+\pi$ & $\pi^+\pi$	lowp $_T$	Starlight
Backgrounds:	$\rho(1700)^0 \rightarrow \pi^+\pi\pi^+\pi$	midp $_T$	Starlight &
	pdiss background	highp$_T$	Data Data

Data is well described by the sum of these contributions after the fit

Exclusive ρ^0 meson photoproduction cross section

- The photon-proton cross-section of ρ^0 for all rapidity bins
- The distribution shows the compilation of fixed target and HERA results
- The result is fit to all data



Corrected by the photon flux

The CMS Experiment extends the energy range measured at HERA

$29 < W_{\gamma p} < 213$ GeV

Good agreement with the HERA data and theoretical models, indicating that ion-proton collisions can be used in the same way as electron-proton ones, with ions acting as a source of quasi-real photons.

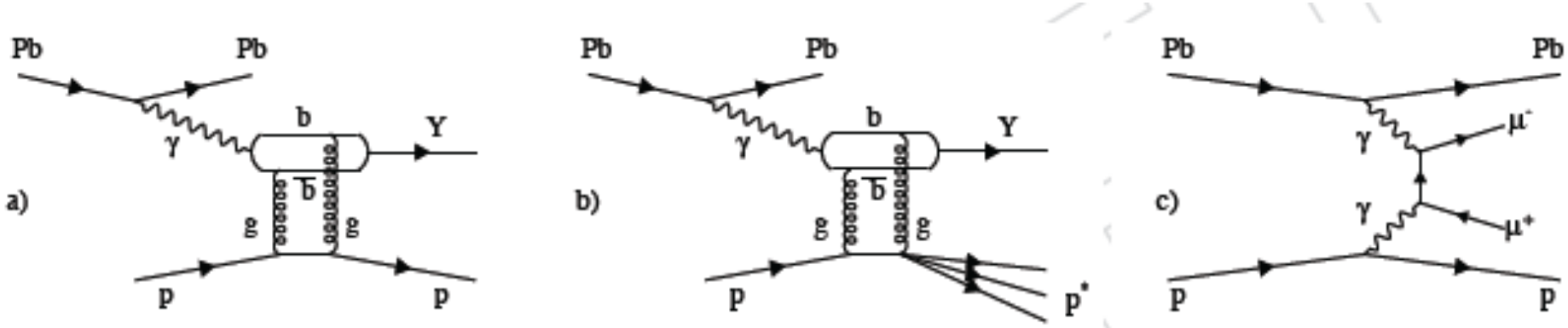
Photoproduction of Υ in p-Pb at 5 TeV

(arXiv:1809.11080, submitted to EPJC)

Aim of exclusive Y photoproduction study in pPb

- Photon emitted by Pb nucleus oscillates to virtual qq(bar) pair
- qq(bar) pair scatters elastically from proton
- Photoproduction cross-section of Y is related to the gluon density square in proton

- **Region of interest in CMS:**
  - Looking for poorly known **gluon distribution in the proton at low-x** (2×10^{-2} to 10^{-4}) and search for **saturation effects**
  - Probe region: photon-proton center of mass energy **$W_{\gamma p}$: 91-826 GeV**

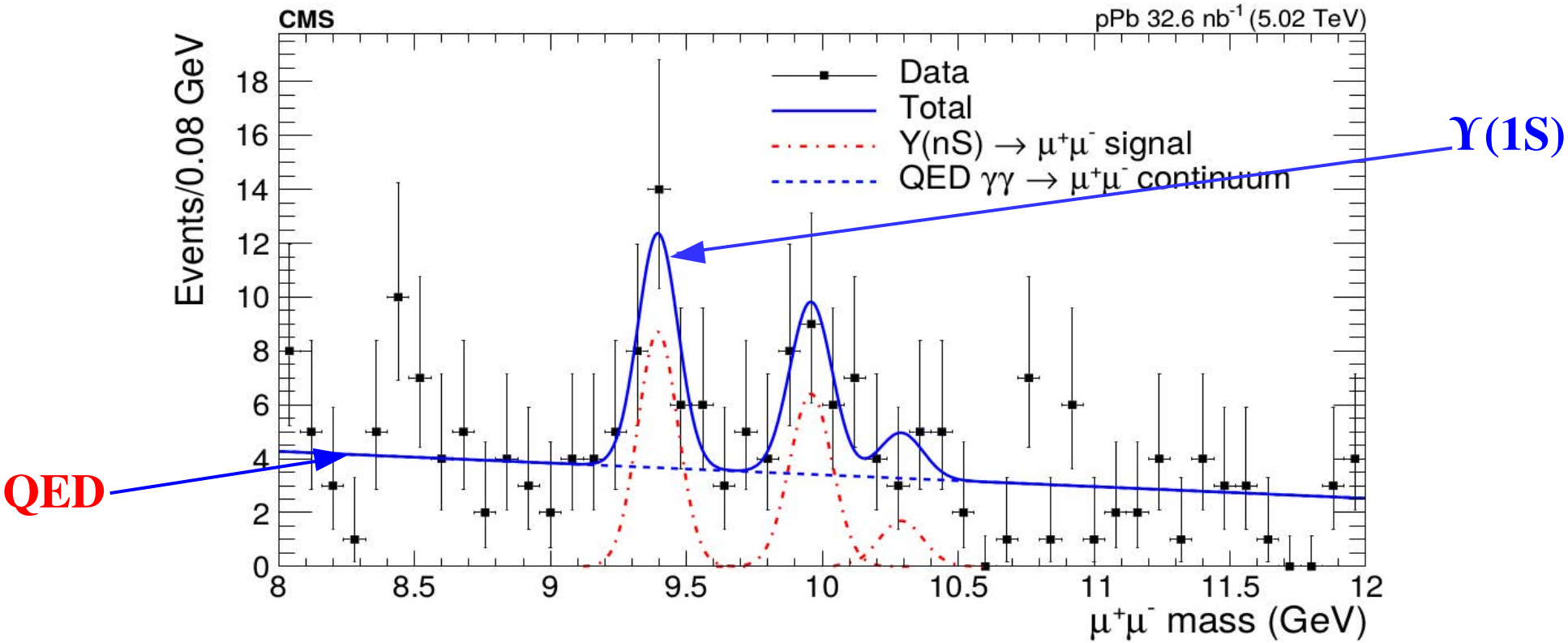


Photon-Nuclear Interaction (Signal)

Proton dissociation (PD background)

Photon-Photon Interaction (QED background)

Invariant Mass Fitting



- Perform Data with an unbinned likelihood fit (using ROOFIT):
  - QED ($\gamma\gamma \rightarrow \mu^+\mu^-$) is fitted with 1st order polynomial (Linear function)
  - Three Gaussian peaks are signal(Y(nS)) (Gaussian function)
    - Mass and width of Y(1S) are free parameters
    - The Y(2S)-Y(1S) and Y(3S)-Y(1S) mass differences are set to the PDG values
    - The widths of the higher states(Y(2S),Y(3S)) are scaled by width of Y(1S) times the ratio of masses(Y(nS)/Y(1S))

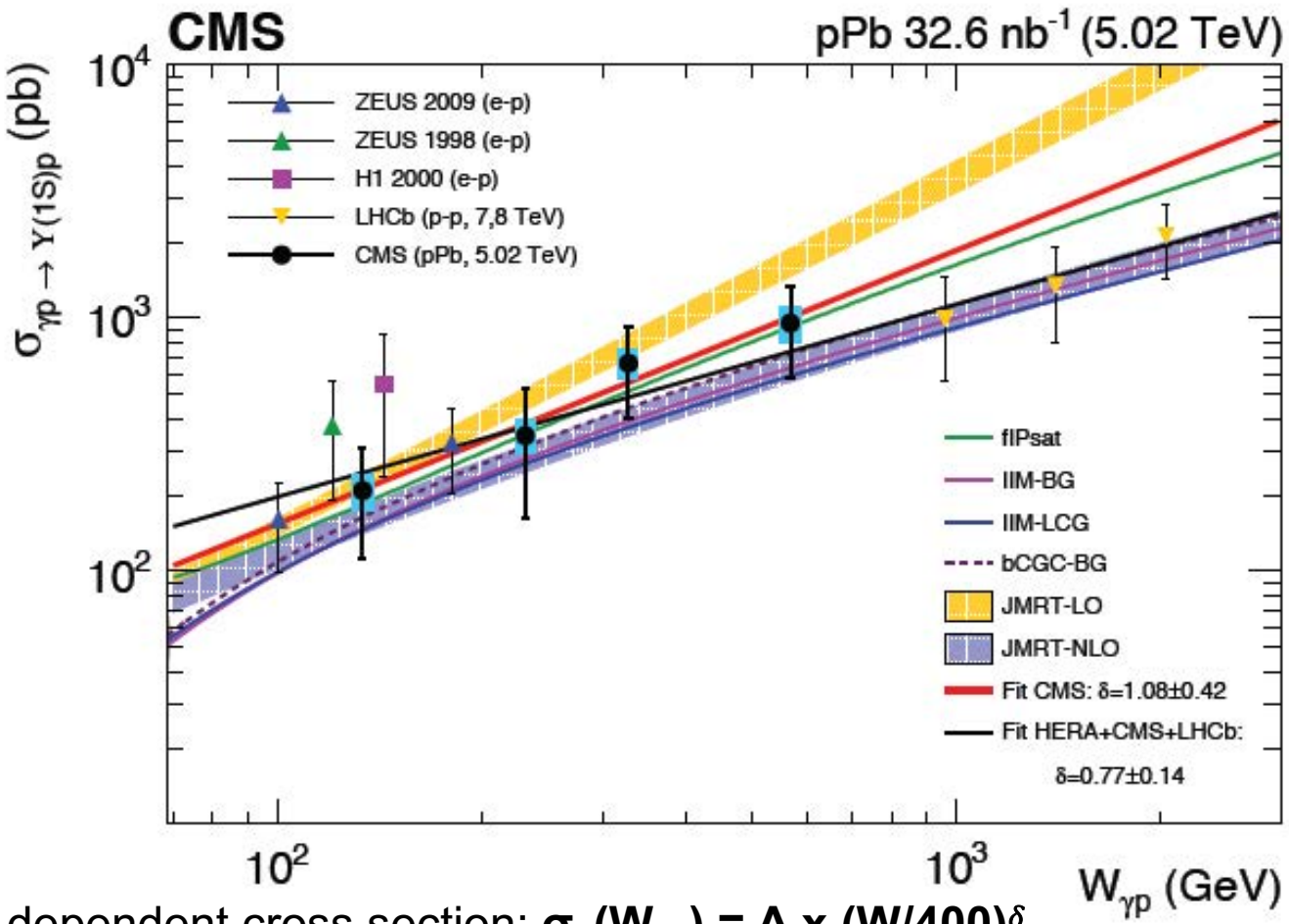
Exclusive Υ photoproduction cross section vs $W_{\gamma p}$

- Cross section of the exclusive **Υ(1S)** photoproduction as a function of **$W_{\gamma p}$** in region of photon-proton center-of-mass energy **($W_{\gamma p}$: 91-826 GeV)**:

$$W_{\gamma p}^2 = 2E_p M_\Upsilon \exp(\pm y)$$

$$\sigma_{\gamma p \to \Upsilon(1S)p}(W_{\gamma p}^2) = \frac{1}{\Phi}\frac{d\sigma_{\Upsilon(1S)}}{dy},$$

Where **Φ** is the photon flux.



- Fit parameters of power law dependent cross section: **$\sigma_\Upsilon(W_{\gamma p}) = A \times (W/400)^\delta$**

CMS result: A = 690 ± 184 pb, δ = 1.08 ± 0.42

ZEUS result: δ = 1.2 ± 0.8

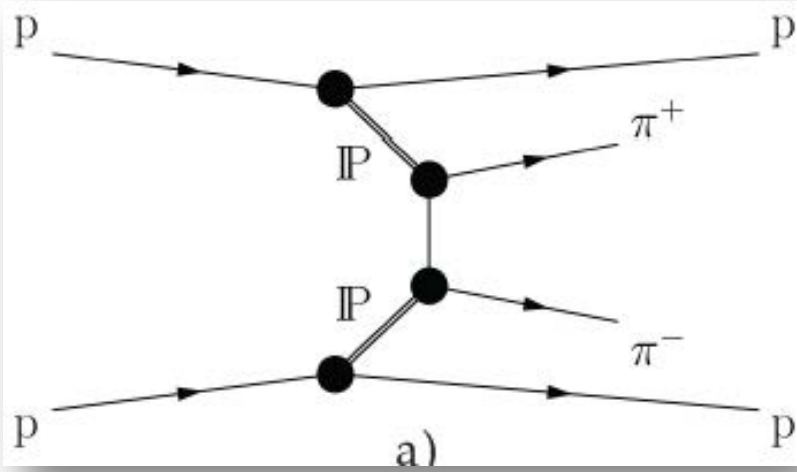
Together with the previous measurements from H1, ZEUS, and LHCb, and the five model predictions. The CMS results cover the range of energies between the HERA and LHCb data.

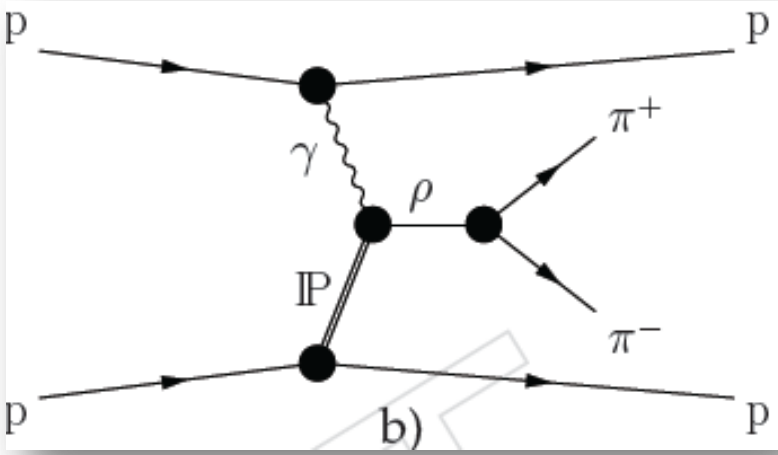
Measurement of Exclusive $\pi^+\pi^-$ production in p-p collisions (arXiv:1706.08310, submitted to PRD)

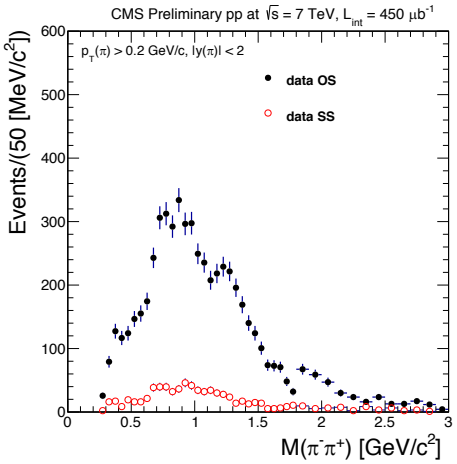
Experimental signature

- **Signal:**
  - Only two tracks, no other track on vertex
  - No additional signals in the calorimeters
  - $p_T(\pi) > 200$ MeV/c
  - $|y(\pi)| < 2.0$

- **Exclusive production of hadrons at central rapidities phenomenologically described in terms of "DPE" Double Pomeron Exchange when the mass of central system is low, or perturbatively in "CEP"**

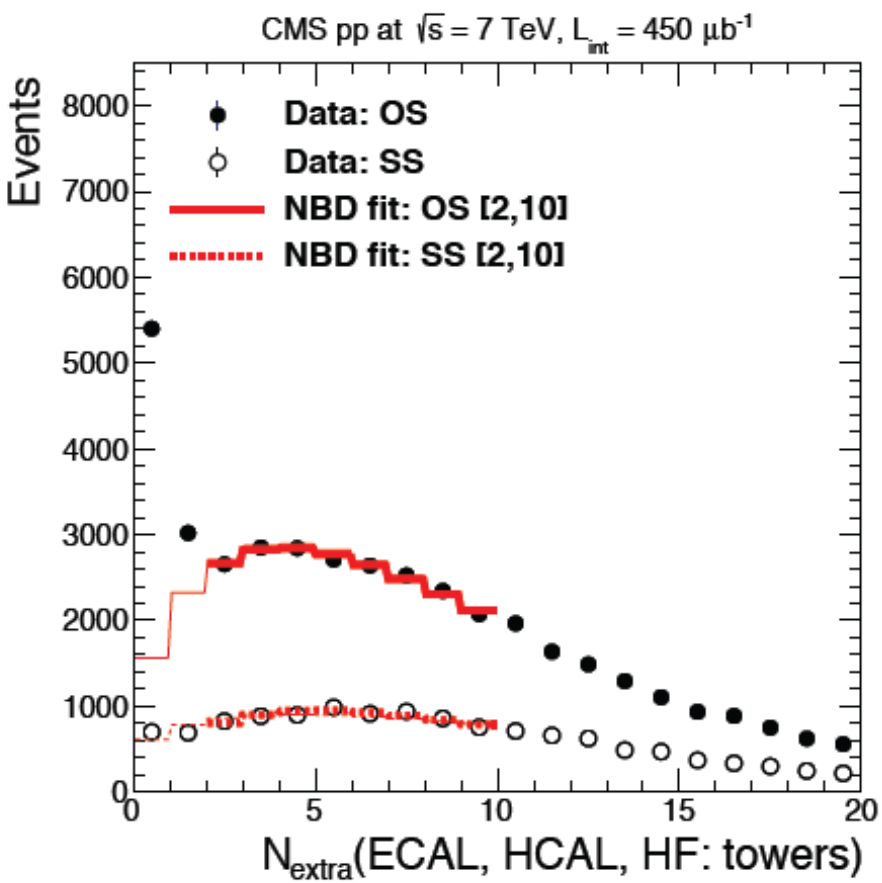






Data-driven estimate of background

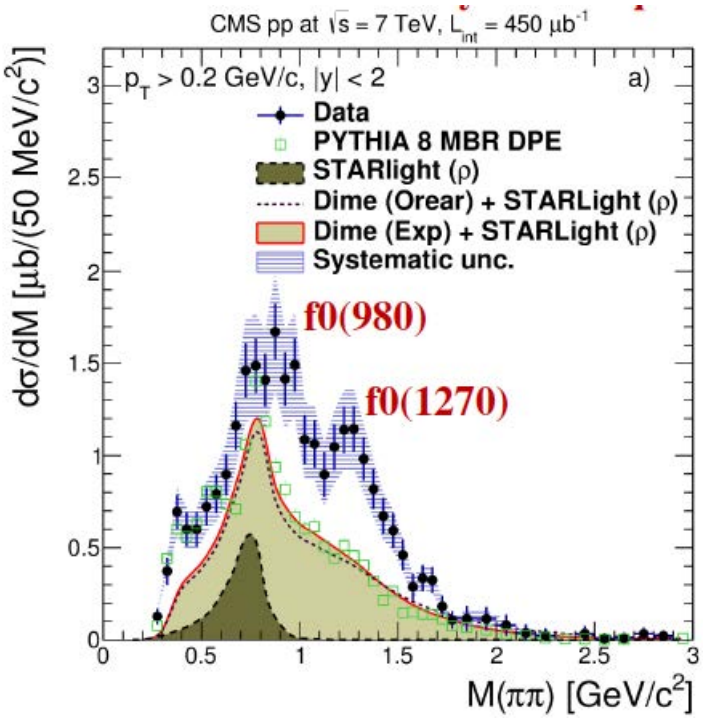
Background control region

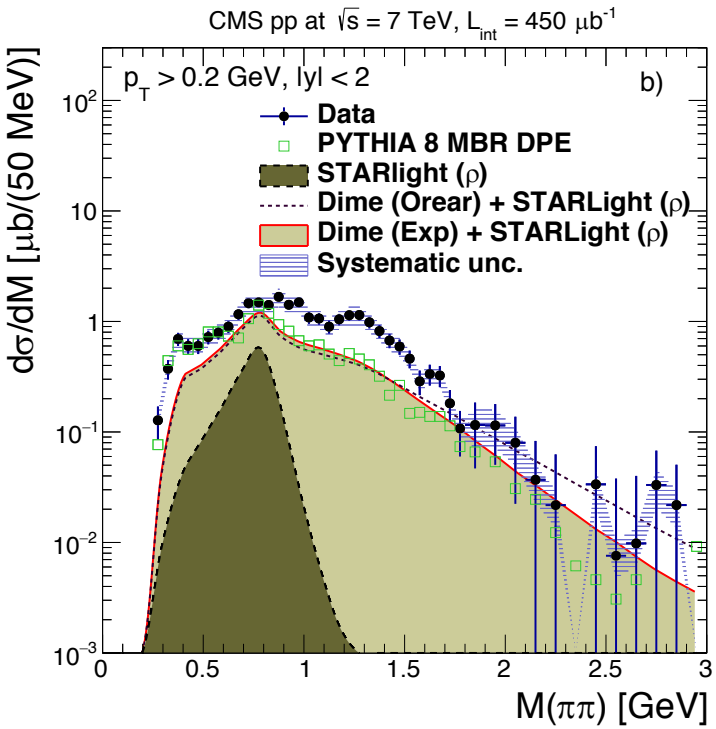


- **Signal**: (Zero-bin with opposite-sign (OS) events)

- **Background**:
  - ✓ Make "data-driven"
  - ✓ Correct for residual backgrounds at $N_{extra} = 0$, and to account for signal migration to the $N_{extra} = 1$ bin.
  - ✓ Two-track events (OS, SS) is fitted in the range $2 < N_{extra} < 10$ by a negative binomial distribution (**NBD**), and extrapolated down to $N_{extra} = 0$.
  - ✓ The NBD is used to estimate the background in the OS events including contributions from diffractive dissociation when any dissociation products have $|\eta| < 4.9$.
  - ✓ The SS control sample has contributions of (semi)exclusive multihadron, nondiffractive, and single and double diffractive events, the NBD extrapolation reproduces well the full N_{extra} distribution.

dσ / dM





- **Differential cross section**:
  - with $p_T(\pi) > 0.2$ GeV/c and $|y(\pi)| < 2$
  - compared to the predictions of DPE productions from the Dime MC (red/green-curves), and STARLIGHT (dash). (Here: Dime MC & Starlight are stacked)
  - The shaded blue band shows the overall systematic uncertainty, and the thin error bar indicates the statistical uncertainty
  - The results are plotted on a linear scale (left) and a logarithmic scale (right)

$$\sigma_{vis} = 26.5 \pm 0.3\ (stat) \pm 5.0\ (syst) \pm 1.1\ (lumi)\ \mu b$$

Summary

- Exclusive production in pp collisions
- Search for LbL in PbPb
- Exclusive photoproduction of VM in pPb collisions
  - CMS is the perfect facility to study photoproduction in UPC
  - CMS extends HERA results on photoproduction of Y and ρ^0 mesons
- The CMS Experiment has good capabilities to study exclusive production.

Thank you for your attention!