Exclusive processes from CMS

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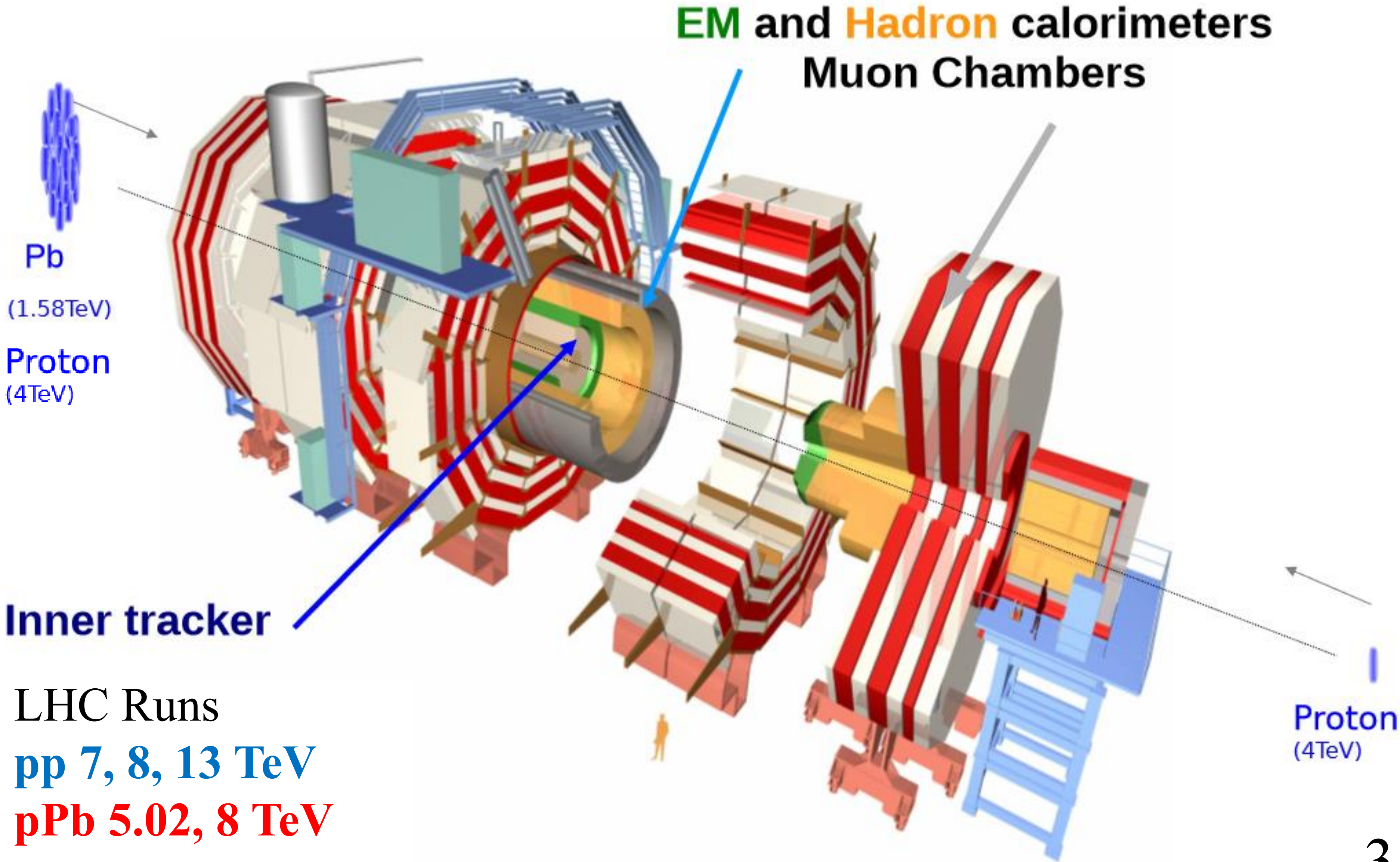
On behalf of the CMS Collaboration

25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April, Birmingham, United Kingdom

Outline

- Introduction
- Proton-proton collisions
  - Exclusive $\gamma\gamma \rightarrow W^{+}W^{-}$ production
    - Limits on anomalous quartic gauge couplings
  - Exclusive $\pi^{+}\pi^{-}$production
    - Differential and integrated cross-sections
- Proton-lead collisions
  - Exclusive photoproduction of Upsilon in pPb collisions at $\sqrt{s} = 5.02$ TeV
    - estimate the |t| dependence of the cross-section
    - photonuclear cross-section
- Ongoing analyses and future prospects
  - Using CMS-TOTEM data to extend studies of central exclusive production
  - Vector meson production in pPb

The CMS Experiment



LHC Runs

pp 7, 8, 13 TeV

pPb 5.02, 8 TeV

Exclusive electroweak boson pairs

Motivation: Exclusive electroweak boson pairs

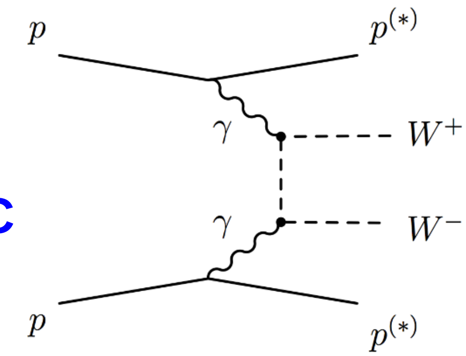
- The exclusive production of W pairs is sensitive to anomalous quartic gauge couplings (aQGC)
- **The electroweak sector of Standard Model predicts QGC**
- **Any deviation from SM expectations can reveal a sign of new physics**
- Objective: Measure SM cross section and look for aQGC.
- aQGC are introduced via effective Lagrangian

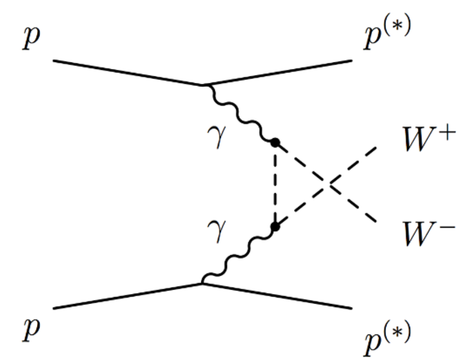
$$\mathcal{L}_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha$$

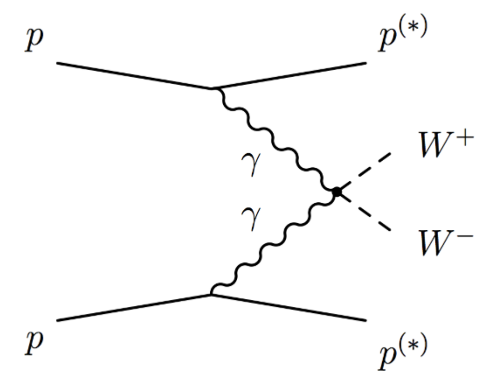
$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta - W^{-\alpha}W^+_\beta)\,.$$

Anomalous coupling constant for quartic vertex

Λ : Scale for New Physics







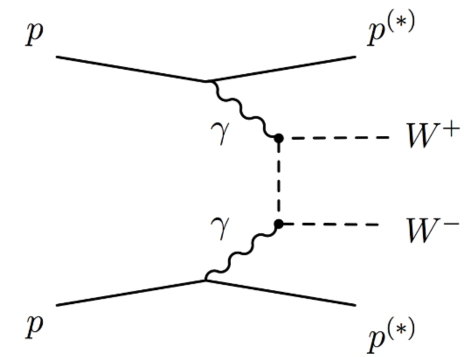
Exclusive $\gamma\gamma \rightarrow W^+W^-$: event selection

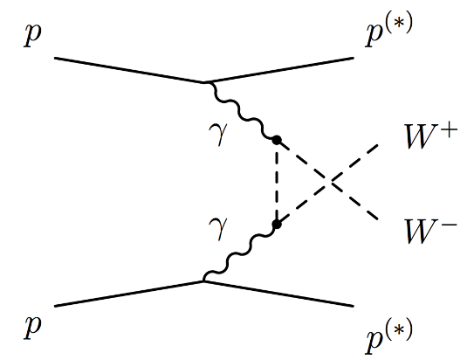
- Exclusive production of W pairs

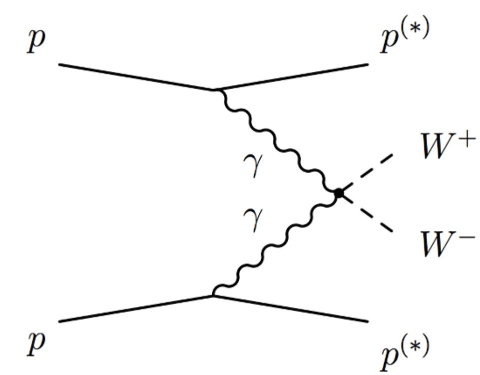
  $$pp \rightarrow p^{(*)}W^+W^-p^{(*)}$$

  $p^{(*)}$: Elastic + Inelastic contributions

- 2011 pp collision data at 7 TeV with 5.05 fb^{-1}
- 2012 pp collision data at 8 TeV with 19.7 fb^{-1}
- Offline exclusive $\gamma\gamma \rightarrow W^+ W^-$ signal selection
  - Opposite-sign eμ pair (final state) originating from commom primary vertex
  - No extra tracks at eμ vertex
    to remove inclusive background
  - Invariant mass (eμ) > 20 GeV
    to get rid of any low mass resonances
  - p_T (eμ) > 30 GeV
    to suppress DY and $\gamma\gamma \rightarrow \tau^+\tau^-$
- Proton dissociation factor from μμ sample

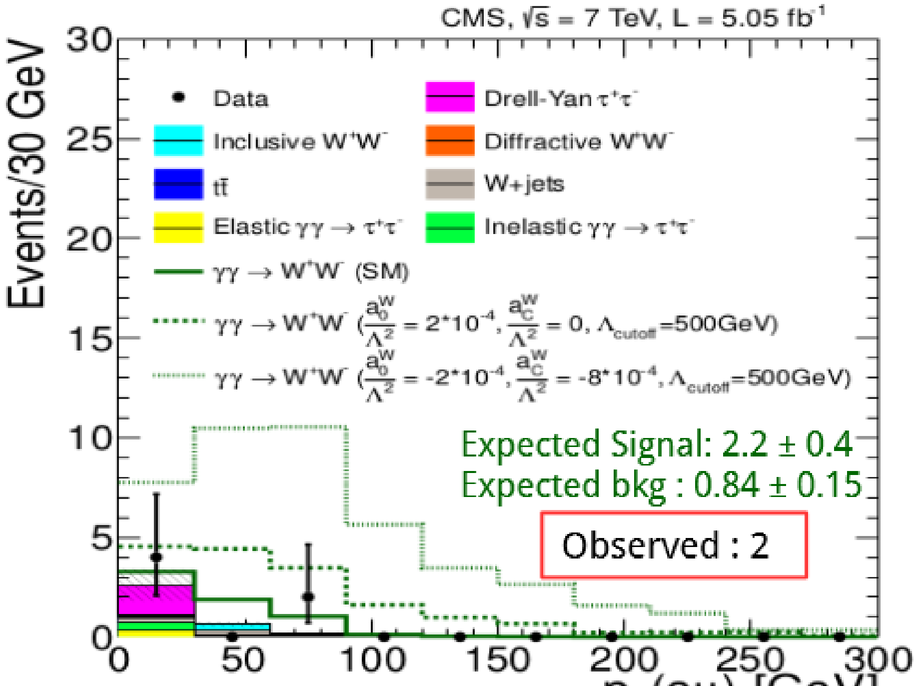




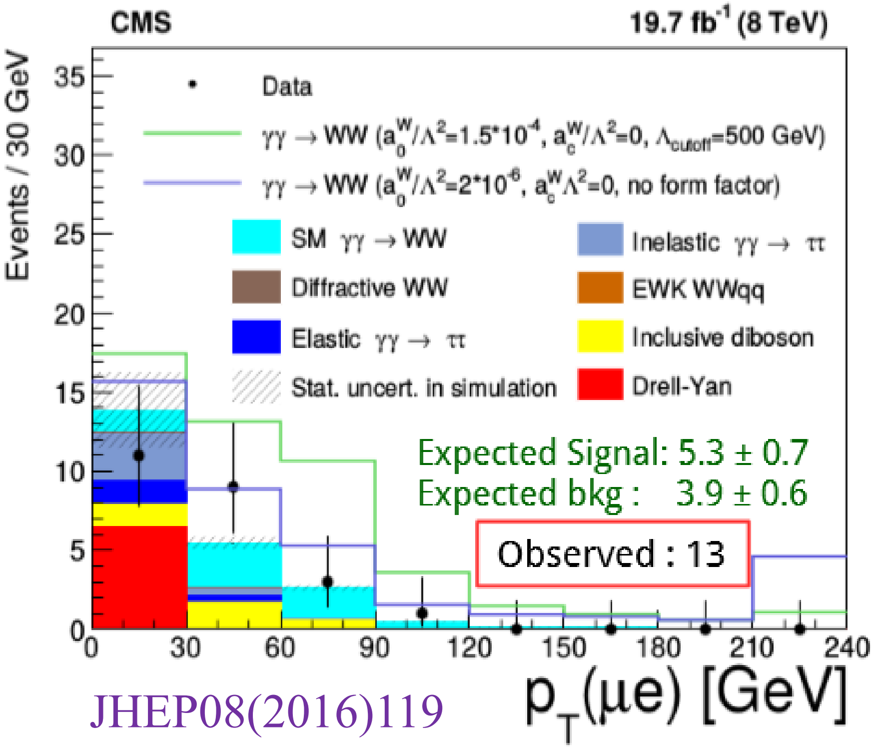


Exclusive $\gamma\gamma \to W^+W^-$ production at 7 and 8 TeV

SM signal region : N extra tracks =0 , p_T (eμ) > 30 GeV



JHEP07(2013)116



JHEP08(2016)119

Cross section times branching fraction

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\,\text{fb}$$

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 10.8^{+5.1}_{-4.1}\,\text{fb}$$

SM Prediction : 4.0 ± 0.7 fb

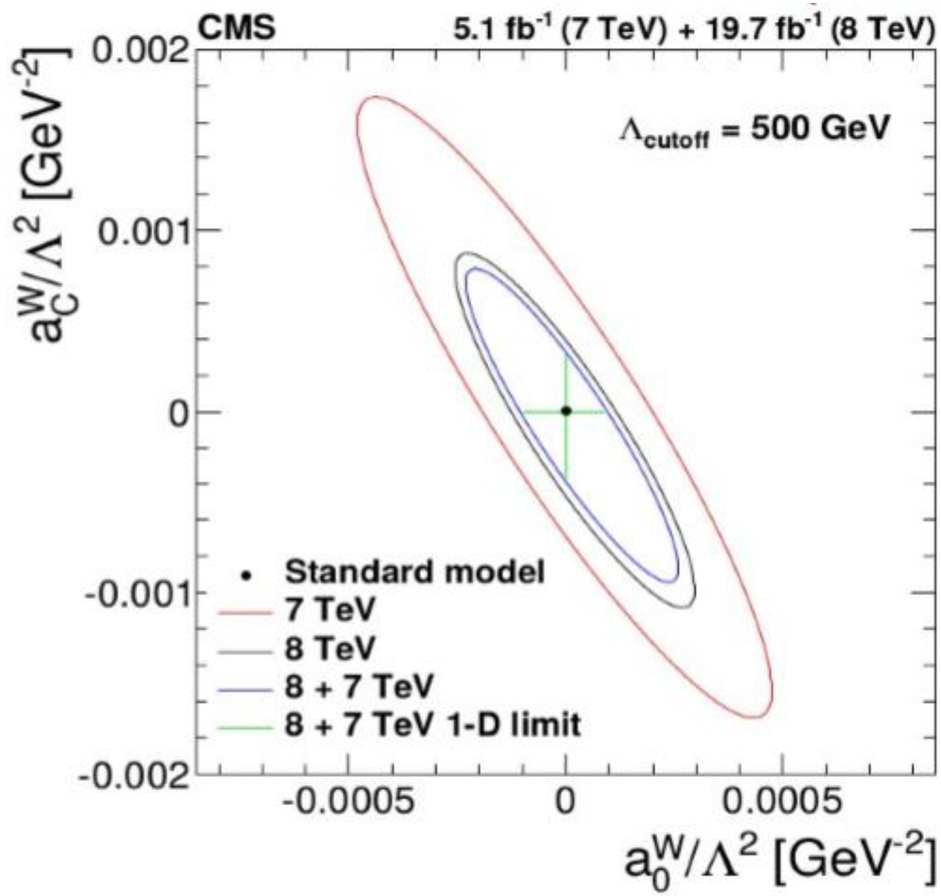
SM Prediction : 6.9 ± 0.6 fb

The observed significance for 7 and 8 TeV combination is 3.4σ

Exclusive $\gamma\gamma \rightarrow W^+W^-$: aQGC limit

JHEP08(2016)119

- Used shape of p_T ($e\mu$) distribution to search for sign of anomalous quartic gauge couplings
- p_T ($e\mu$) > 100 GeV used at 7 TeV
- Two bins at 8 TeV $30 < p_T(e\mu) < 130$ GeV and $p_T(e\mu) > 130$ GeV
- Region outside solid line is excluded at 95% CL
- **The most stringent limit so far, two orders of magnitude more stringent than LEP**



Dimension-6 AQGC parameter	7 TeV ($\times 10^{-4}$ GeV^{-2})	8 TeV ($\times 10^{-4}$ GeV^{-2})	7+8 TeV ($\times 10^{-4}$ GeV^{-2})
$a_0^W/\Lambda^2(\Lambda_{cutoff} = 500\,\text{GeV})$	$-1.5 < a_0^W/\Lambda^2 < 1.5$	$-1.1 < a_0^W/\Lambda^2 < 1.0$	$-0.9 < a_0^W/\Lambda^2 < 0.9$
$a_C^W/\Lambda^2(\Lambda_{cutoff} = 500\,\text{GeV})$	$-5 < a_C^W/\Lambda^2 < 5$	$-4.2 < a_C^W/\Lambda^2 < 3.4$	$-3.6 < a_C^W/\Lambda^2 < 3.0$

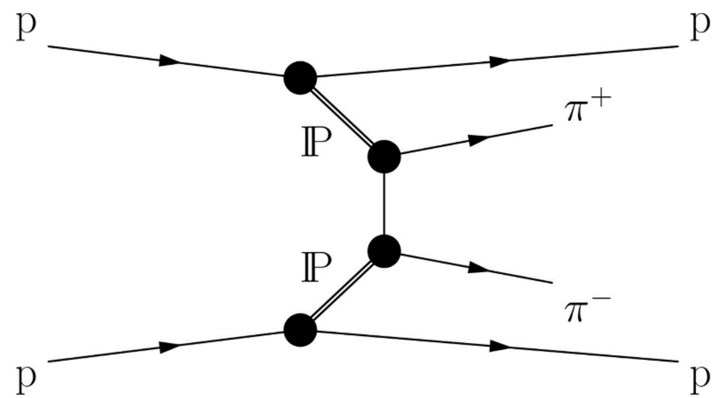
Exclusive $\pi^+\pi^-$production

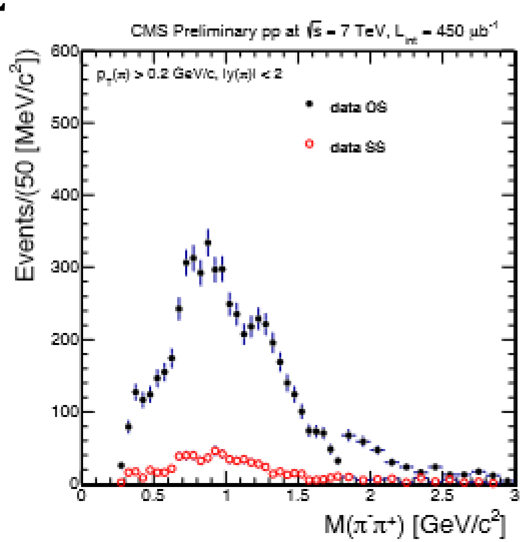
Exclusive $\pi^+\pi^-$ production: Experimental signature

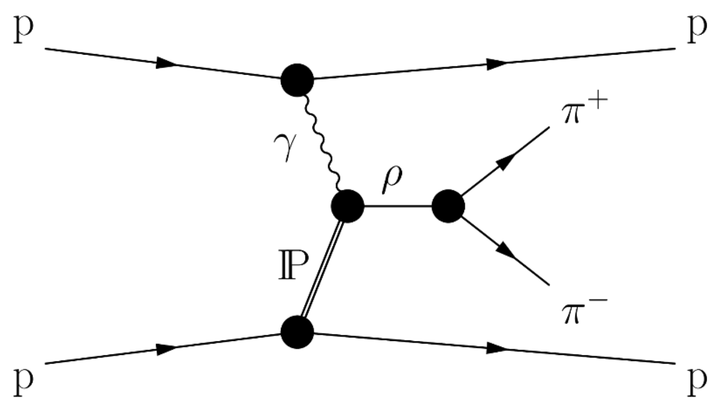
CMS-FSQ-12-004

- 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 pertubatively in "CEP"

- **Experimental signature:**
  - Only two opposite sign tracks ($\pi^\pm$) from the same primary vertex
  - No additional signal in calorimeters
  - $p_T(\pi) > 0.2$ GeV
  - $|y(\pi)| < 2$



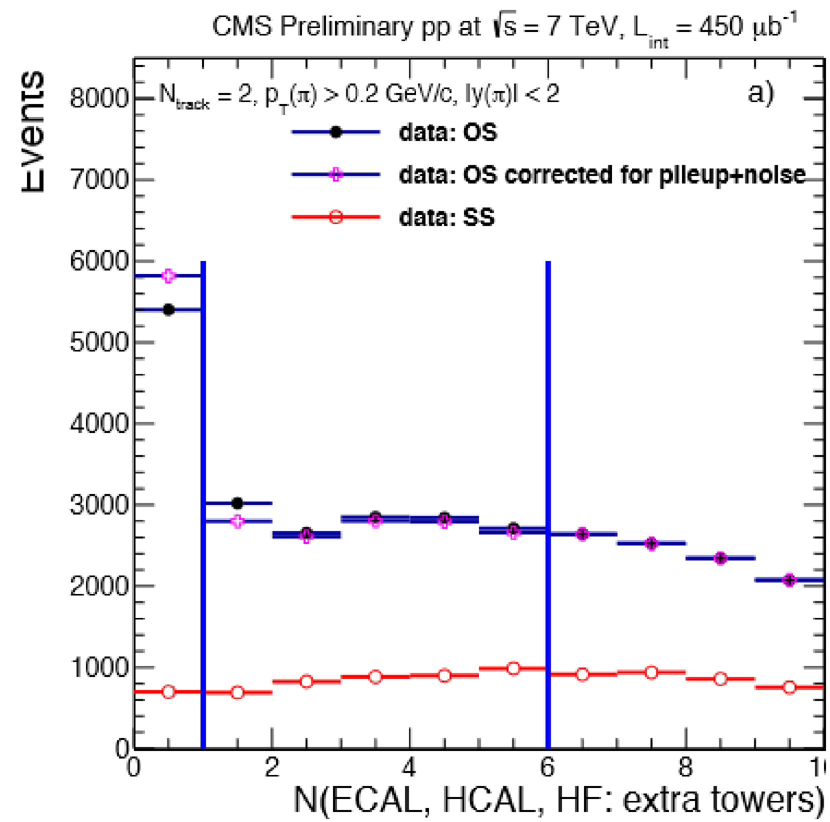




Exclusive $\pi^+\pi^-$ production: Background estimation

CMS-FSQ-12-004

- **Signal**: (Zero-bin with opposite-sign (OS) events)
- **Background**:
  - Make "data-driven"
  - Both normalization and shape for different distributions
  - Use the sample with all cuts applied, but require 1-5 towers above threshold
  - Take the background normalization from the average of these 5 bins
  - Take the shapes from events in these 5 bins
- Use the same procedure on same-sign (SS) events (purely background)

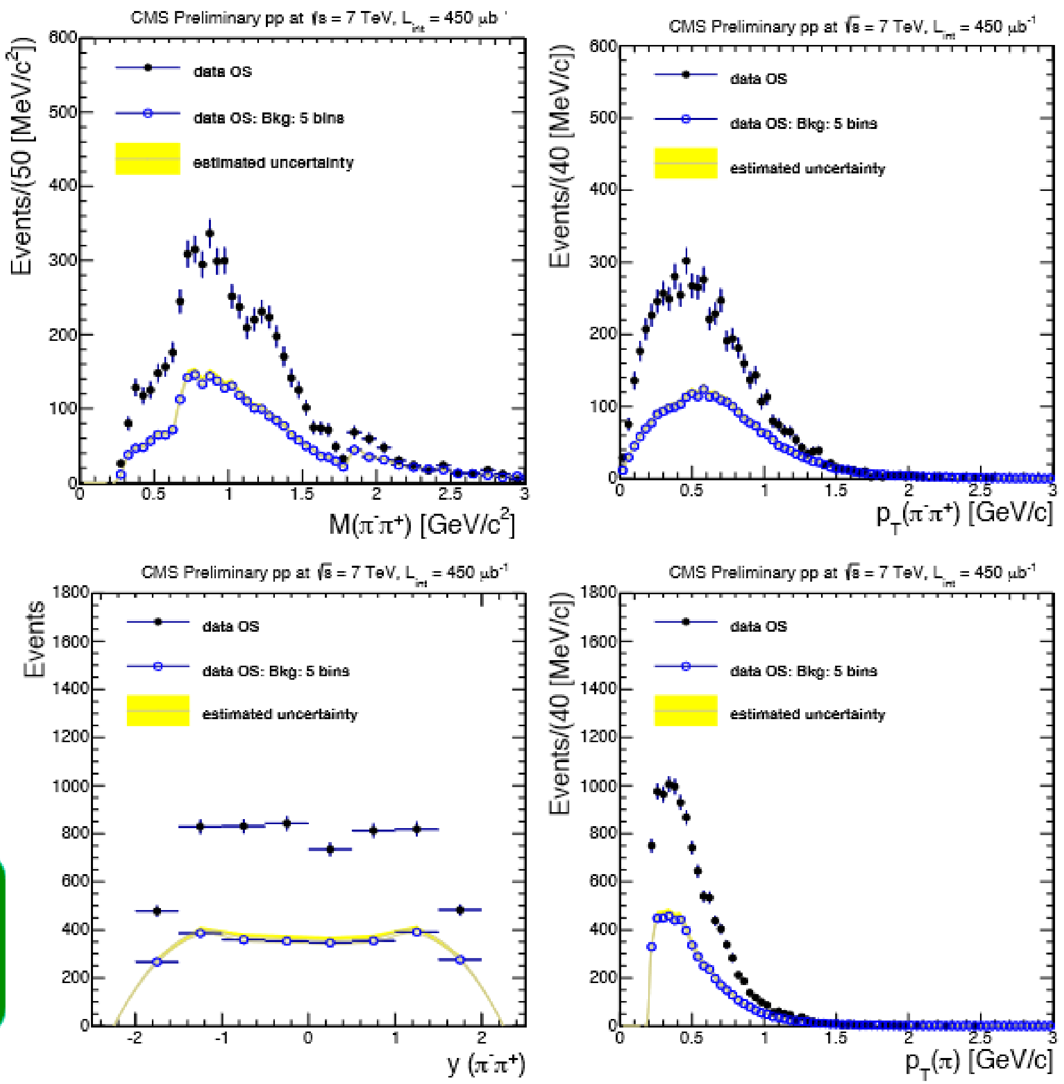


Exclusive $\pi^+\pi^-$ production: Signal distribution

CMS-FSQ-12-004

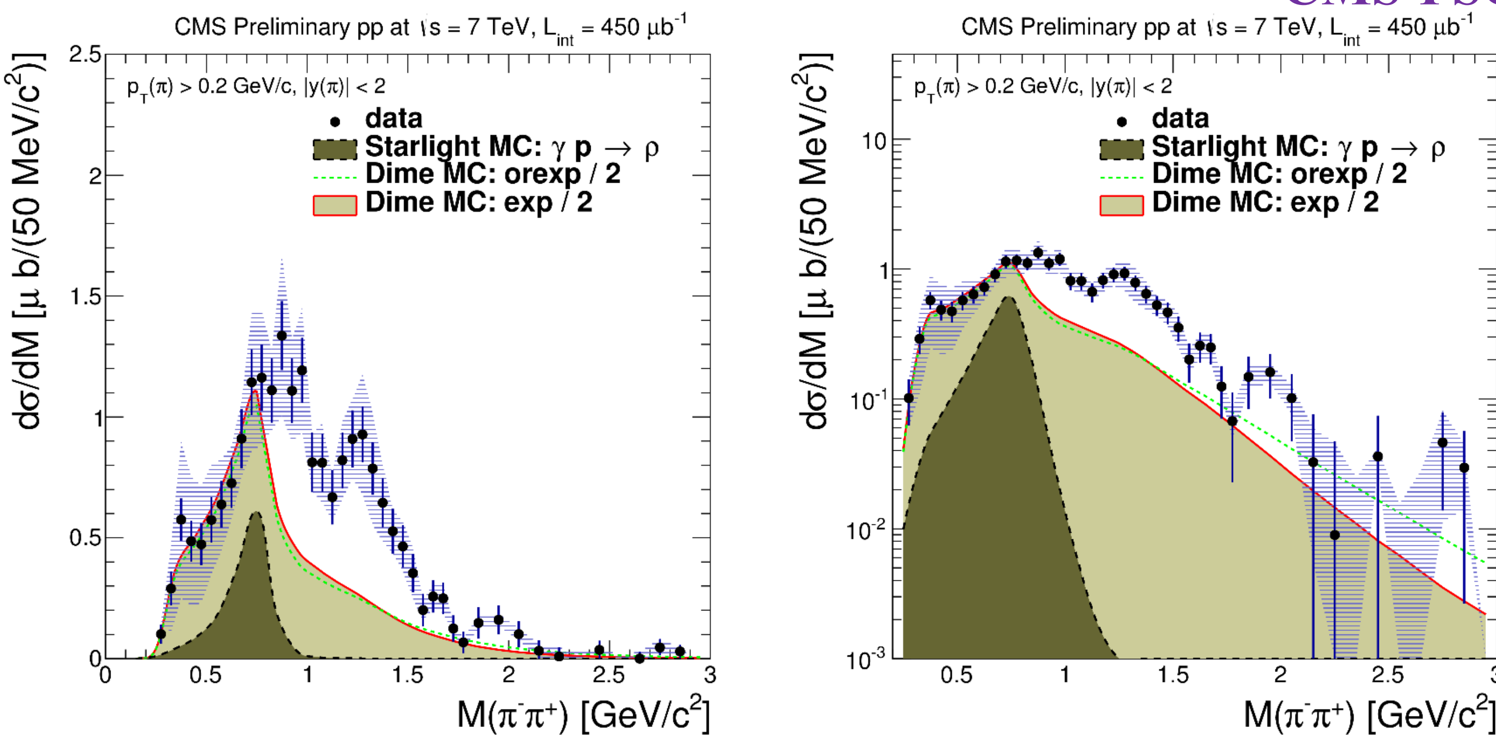
- Using the sideband region in the tower multiplicity distribution
- For the nominal background estimate, use the control sample with 1-5 extra calorimeter towers above threshold, and all other selection criteria applied
- The non-exclusive background shapes obtained from this method are shown, with a normalization given by the average number of events per bin of tower multiplicity

Background is $\pi^+\pi^-$ events but with additional activity



Exclusive $\pi^+\pi^-$production: Results $d\sigma/dM$

CMS-FSQ-12-004

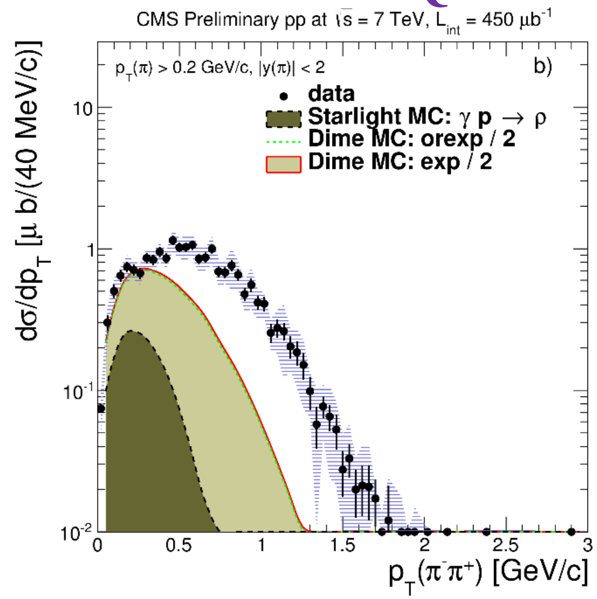


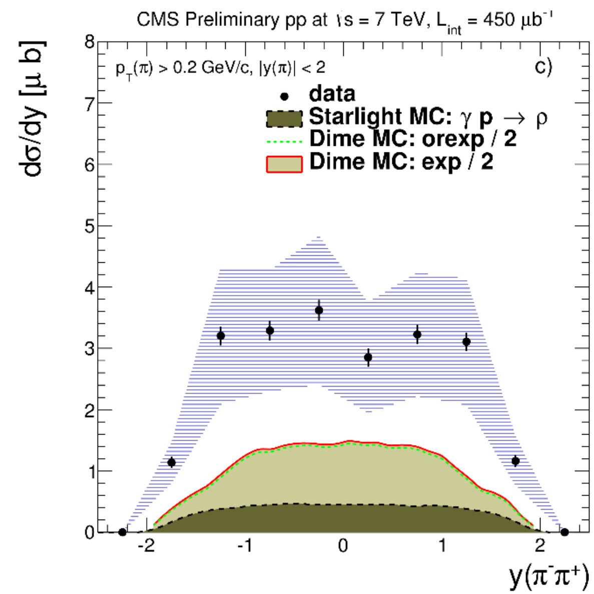
- **Differential cross section:**
  - with $p_T(\pi) > 0.2$ GeV and $|y(\pi)| < 2$
  - Compared to the predictions of DPE production from the **Dime MC** (red/green curves), and **STARLIGHT** (dash). (Here: Dime MC & Starlight are stacked)
  - The shaded blue band shows the overall systematic uncertainty,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

Exclusive $\pi^+\pi^-$production: Results $d\sigma/dp_T$, $d\sigma/dy$

CMS-FSQ-12-004

- **Differential cross sections as a function of p_T and rapidity:**
  - with $p_T(\pi) > 0.2$ GeV and $|y(\pi)| < 2$
  - Compared to the predictions of DPE production 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 logarithmic scale (top) and a linear scale (bottom)



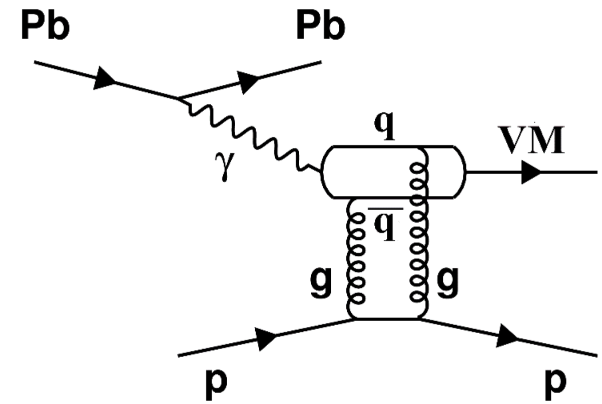


$$\sigma_{vis} = 20.5 \pm 0.3(stat.) \pm 3.1(sys.) \pm 0.8(lumi)\mu b$$

Exclusive vector meson production in pPb

Motivation: Exclusive vector meson production in pPb

- The exclusive production is studied in ultraperipheral pPb collisions
- Ions interact via photons
- The photon flux grows with the square of the charge, Z^2



Motivation: Exclusive vector meson production in pPb

- The exclusive production is studied in ultraperipheral pPb collisions
- Ions interact via photons
- The photon flux grows with the square of the charge, Z^2
- Photoproduction process is sensitive to the gluon density squared in the nucleon (nucleus)

$$\frac{d\sigma_{\gamma p,A\to Vp,A}}{dt}\Big|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xG(x,Q^2)]^2$$

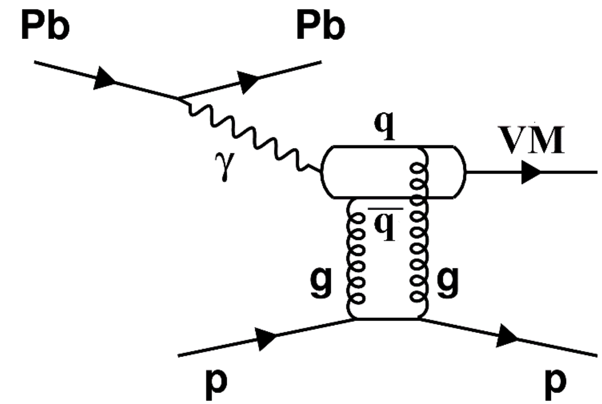
$$\sigma_{\gamma p\to \Upsilon p} = \frac{1}{b} \frac{d\sigma_{\gamma p,A\to Vp,A}}{dt}\Big|_{t=0}$$

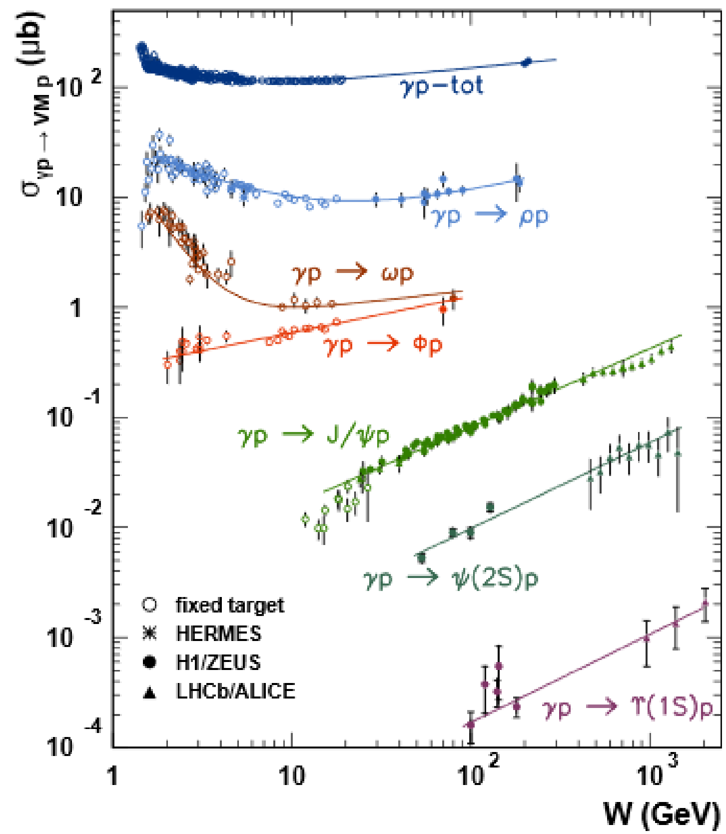
- Probe gluon distributions in the proton at low x (10^{-4} to $2\cdot 10^{-2}$)

$$x = (M_\Upsilon / W_{\gamma p})^2$$

- Photonuclear cross-section shows power law dependence with $W_{\gamma p}$

$$\sigma \propto W_{\gamma p}^{\delta}$$





Motivation: Exclusive Υ production

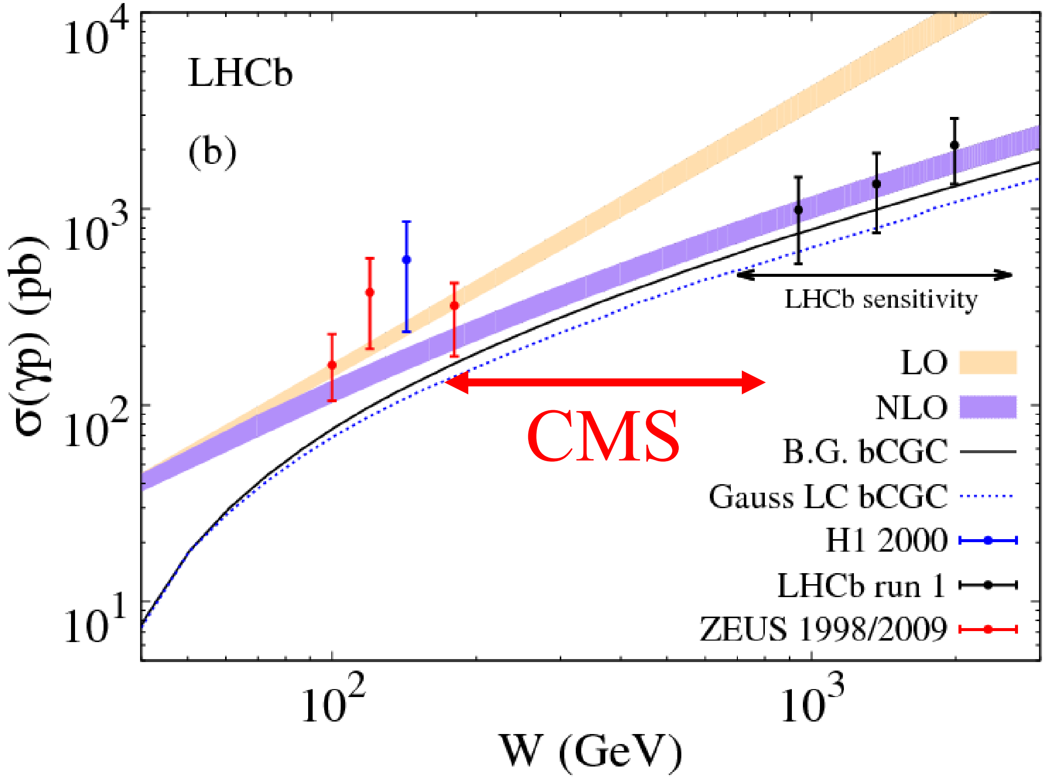
- Energy of the photon-proton collision

$$W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y)$$

E_p - proton beam energy

M_{VM} - Mass of the Vector meson

y – Rapidity of the vector meson

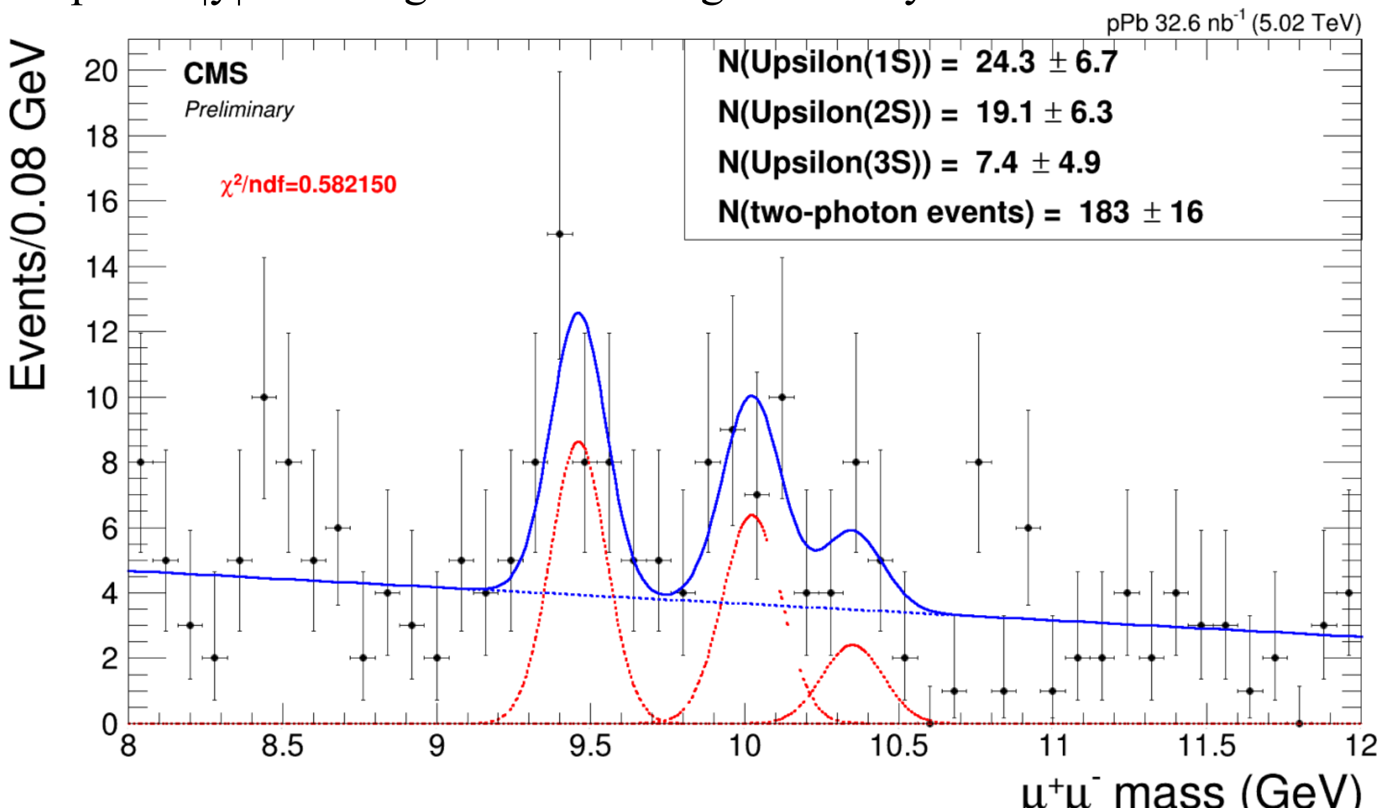


	CMS	HERA	LHCb
E_p [GeV]	4000	820	3000, 4000
y-range	(-2.2;2.2)	(-1.5;1.5)	(2;4.5)
$W_{\gamma p}$ [GeV]	**91-826**	**60-220**	**900-2000**

Exclusive upsilon production

CMS-FSQ-13-009

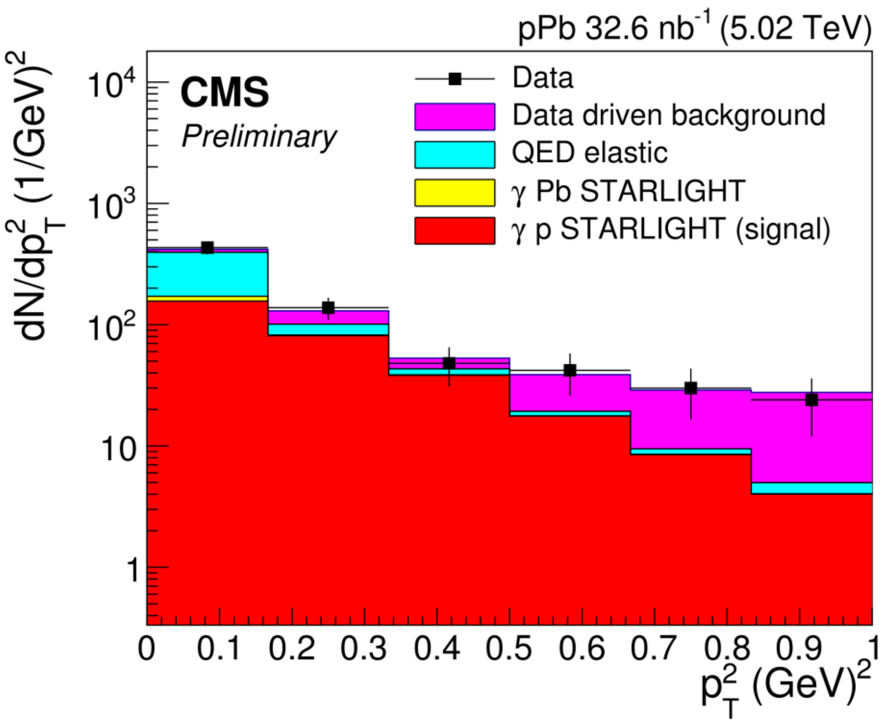
- 2013 pPb data at 5.02 TeV with 32.6 nb^{-1}
- Offline exclusive $pPb \rightarrow \Upsilon(\gamma p) \rightarrow \mu^{+}\mu^{-}$ signal selection
  - Invariant mass (μμ): 9.12 – 10.64 GeV
  - Opposite-sign μμ pair (final state) originating from common primary vertex
  - No extra tracks at primary vertex to remove non-exclusive background
  - Upsilon p_T: 0.1-1 GeV to suppress QED and proton dissociation
  - Upsilon |y| < 2.2 high muon finding efficiency

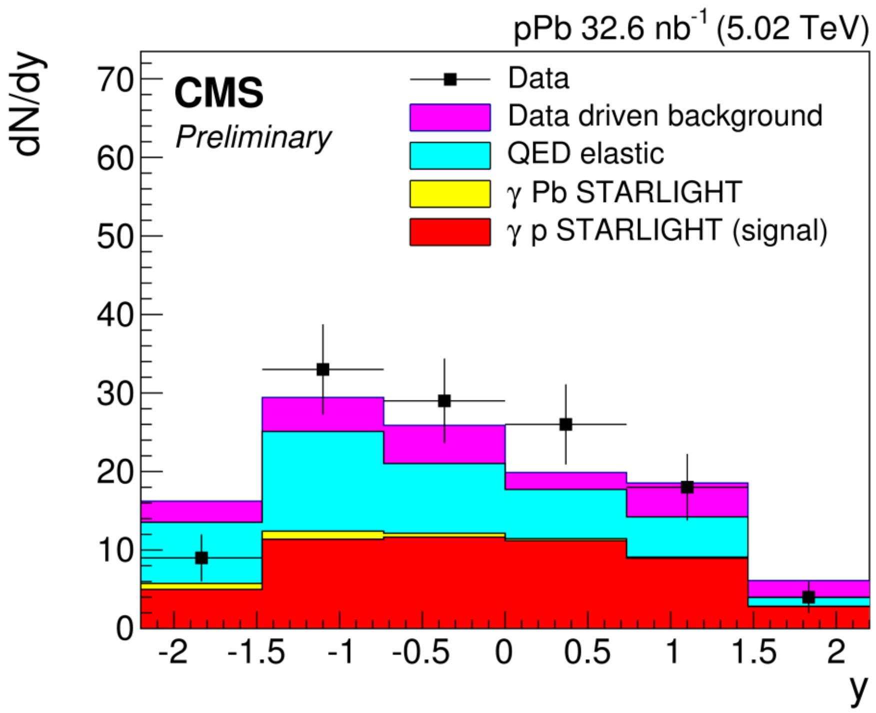


Exclusive upsilon production

CMS-FSQ-13-009

- Data compared to simulation (contains different contributions)
- Low p_T: QED elastic background, estimated by STARLIGHT
- High p_T: Non-exclusive background estimated from data
- Starlight MC: γPb(small contribution) and reweighted γp contribution





Good agreement between data and MC

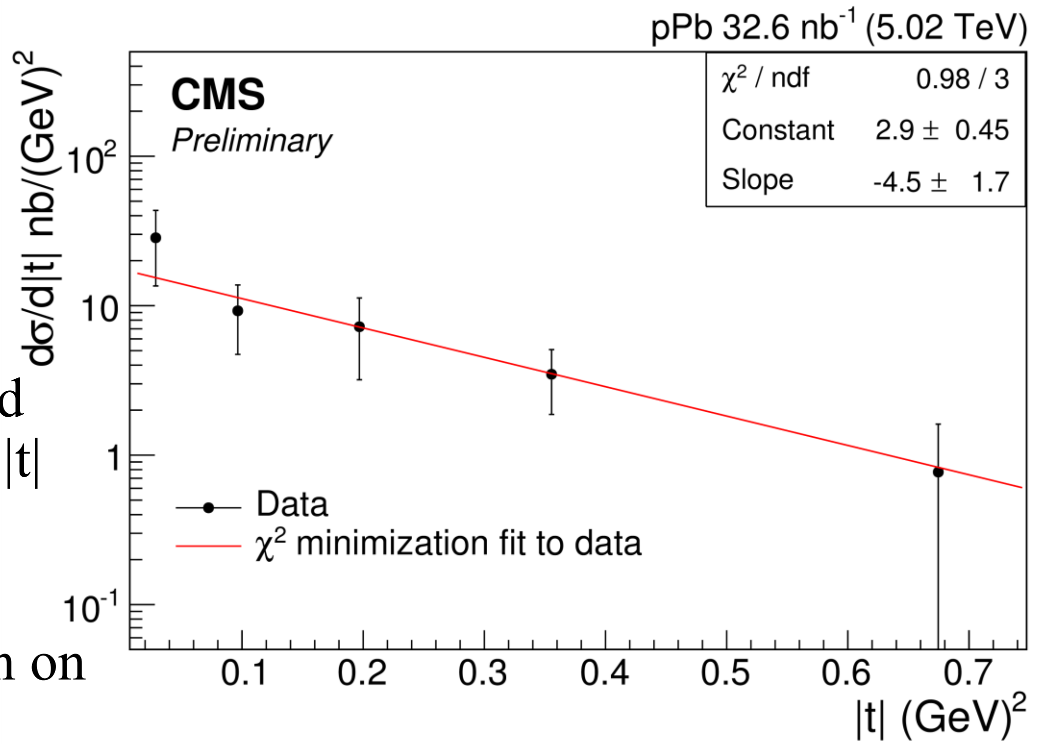
Photoproduction cross-section as a function of |t|

CMS-FSQ-13-009

- The differential cross section is calculated according to

$$\frac{d\sigma_{\Upsilon}}{dt} = \frac{N_{sig}^{Unfolded}}{L \cdot \Delta t}$$

- N_{sig}, the background subtracted, unfolded and acceptance corrected number of upsilon events in each |t| bin.
- $d\sigma/dt$ fitted with an exponential function, provides the information on the transverse profile of the interaction region.



CMS Results
b= 4.5 ± 1.7 (stat.) ± 0.6 (syst.) GeV^{-2}
Data is in agreement with ZEUS measurements and consistent with predictions based on pQCD models

ZEUS for Υ(1S)
b = 4.3$^{+2.0}_{-1.3}$ (stat)
Phys.Lett.B 708 (2012) 14

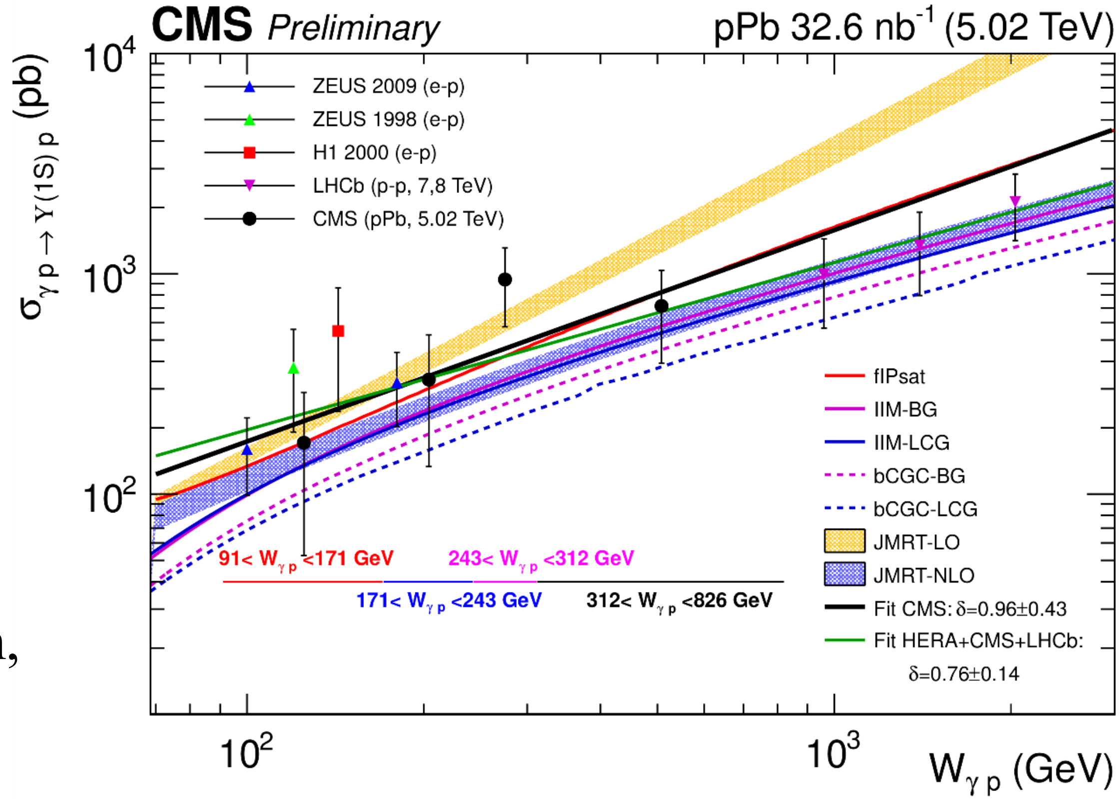
Cross-section as a function of $W_{\gamma p}$

CMS-FSQ-13-009

- The cross section is estimated by

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

- Rapidity distribution of Υ(1S+2S+3S) used to estimate $\sigma_{\Upsilon(1S)}$ vs $W_{\gamma p}$
- The cross-section is corrected for muonic branching ratio, feed-down, upsilon (1S) fraction

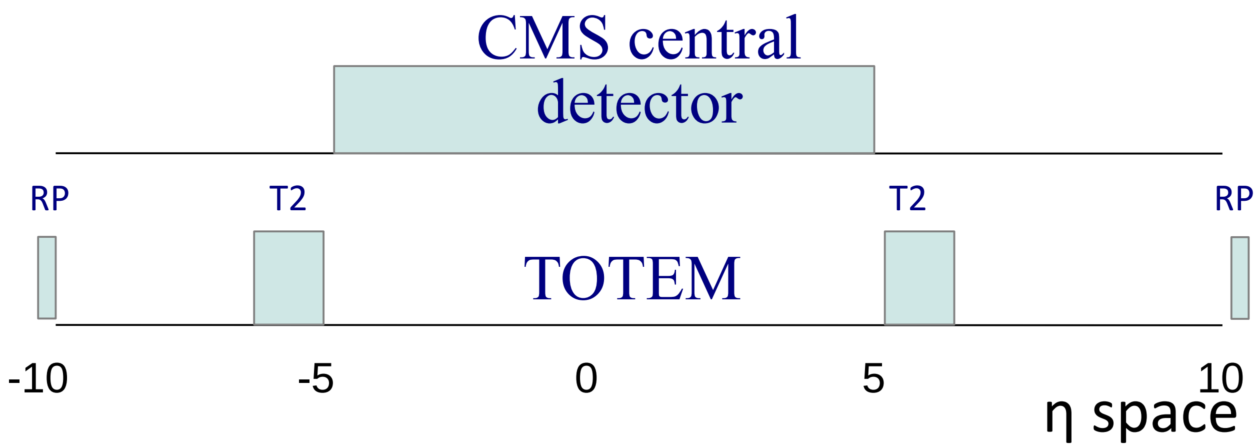


A fit with power-law **A X (W/400)$^{\delta}$** to the CMS data
δ = (0.96 ± 0.43) , A = 655 ± 196
Data compatible with power-law dependence of $\sigma(W_{\gamma p})$, disfavours LO pQCD predictions

ZEUS
δ = 1.2 ± 0.8
PLB 680(2009) 4-12

Future prospects

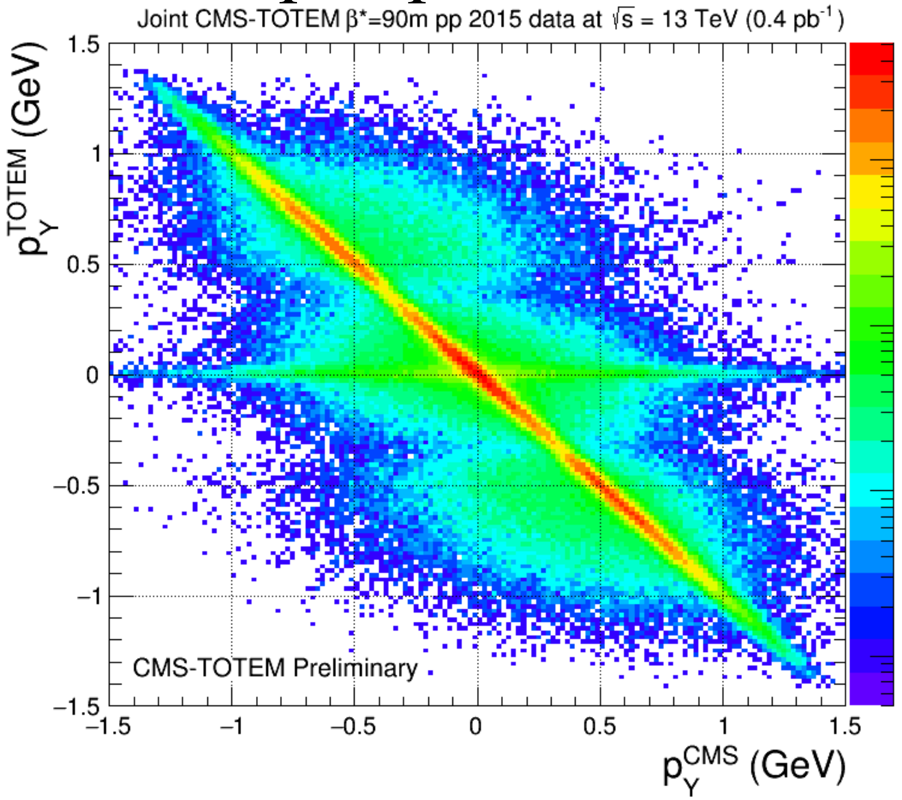
Future prospects: Joint CMS-TOTEM run @13 TeV

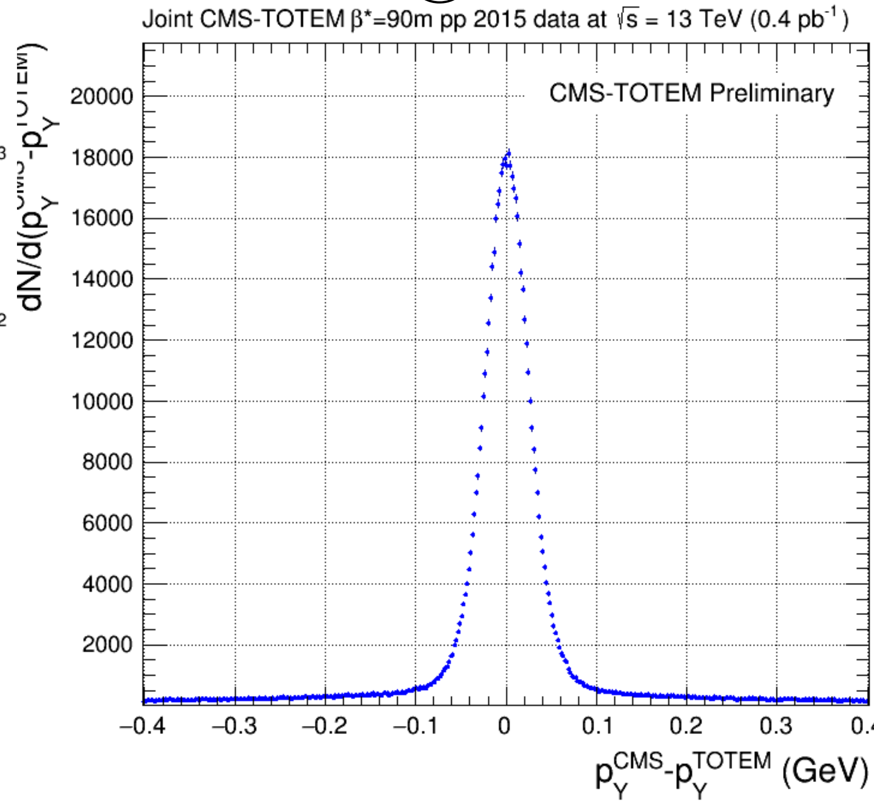


- Joint CMS-TOTEM **β*=90m** runs in October 2015
- About 0.4/pb of **low-pileup** (μ = 0.06-0.15) data at 13 TeV
- Events with central system in CMS and diffractive protons in TOTEM Roman Pots
- Separate DAQ systems with trigger exchange
- CMS and TOTEM **data reconstructed separately**, then merged offline (event by event based on the same orbit and bunch crossing)
- Dedicated CMS track reconstruction tune, to assure high track-finding efficiency for low-p_T tracks and high vertex-finding efficiency for 2-track events

Trigger: Two scattered protons in the TOTEM Roman Pots (RP), no activity in the TOTEM T2 telescopes, at least 5 clusters in the CMS pixel detector

Future prospects: Joint CMS-TOTEM run @13 TeV

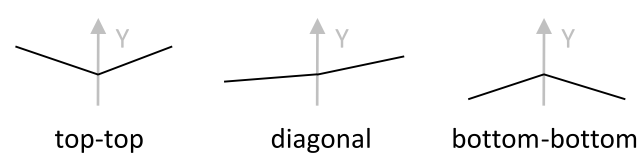




Transverse momenta p_Y of the scattered protons detected in Roman Pots (TOTEM) vs transverse momenta of two pion tracks measured in the central tracking system (CMS) for the pp → pp$\pi^+\pi^-$ production. Events on the diagonal correspond to the exclusive $\pi^+\pi^-$ production

Adding tagged protons from TOTEM greatly helps to select exclusive pp → pp$\pi^+\pi^-$ process with no proton-dissociation

The three distinct regions along the p_Y^{TOTEM} axis correspond to the top-top, diagonal and bottom-bottom proton configurations



Future prospects: cross-section as a function of $W_{\gamma p}$

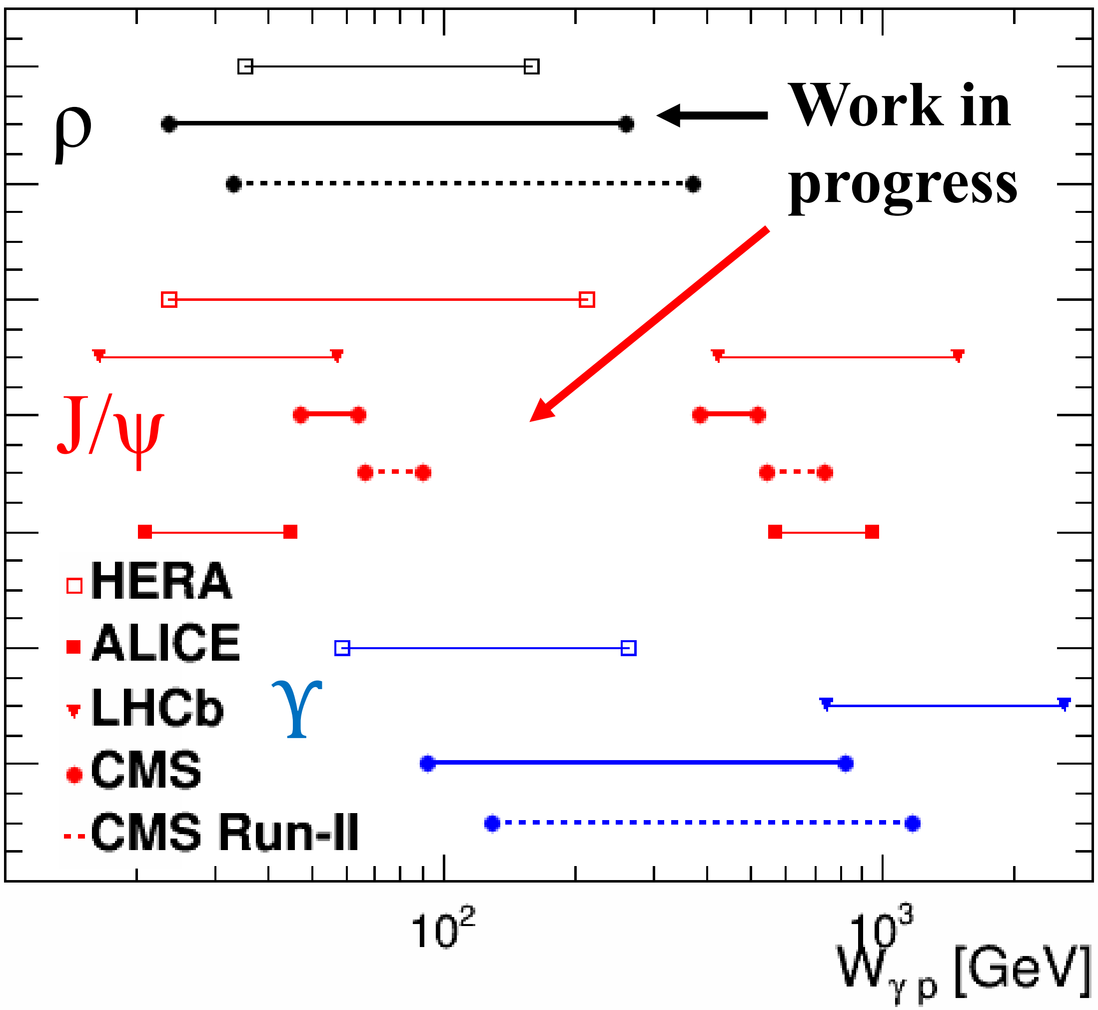
- Energy of the photon-proton collision

$$W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot exp(-y)$$

E_p - proton beam energy

M_{VM} - Mass of the Vector meson

y – Rapidity of the vector meson



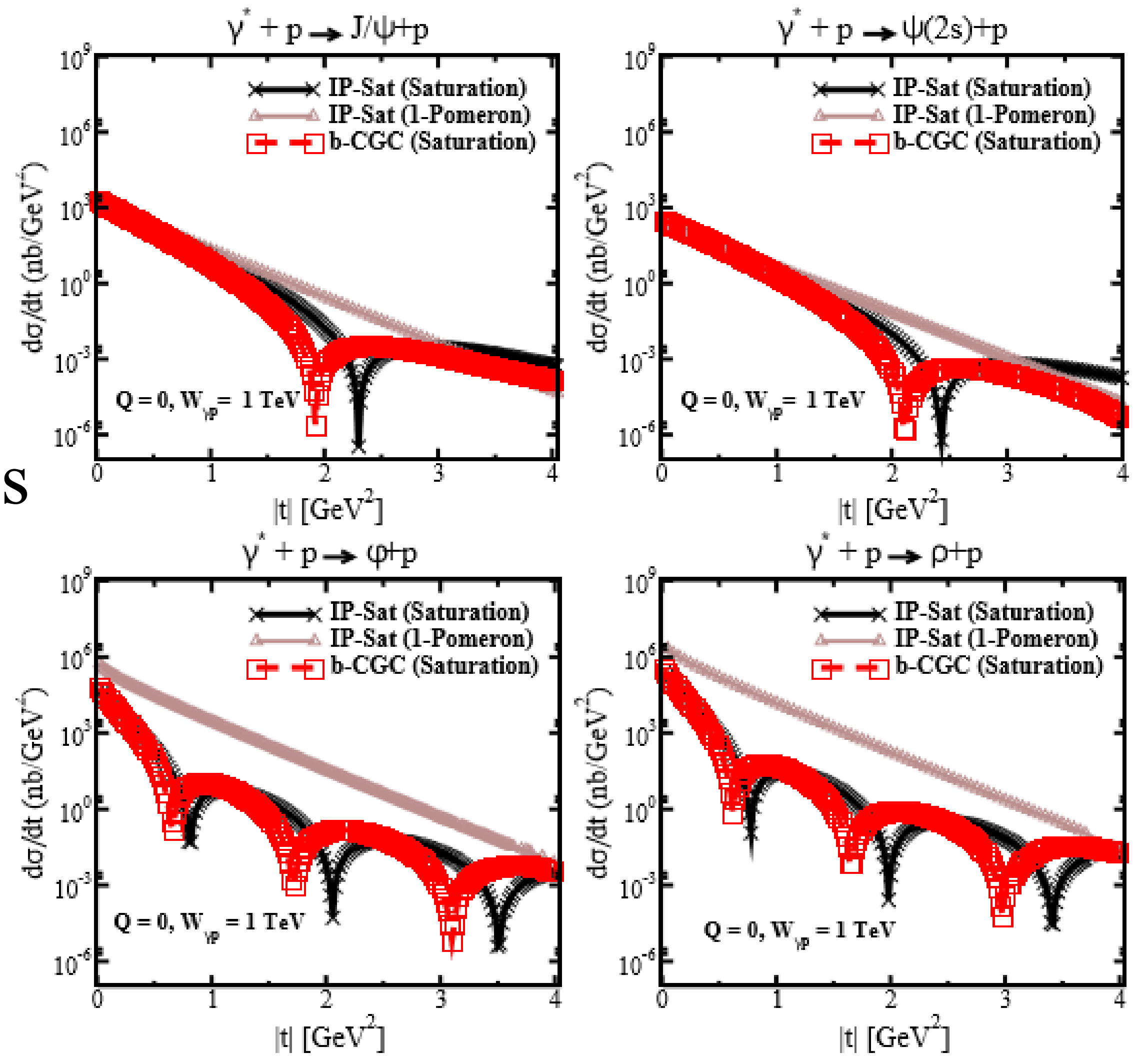
- The proton beam energy at LHC is much higher compared to HERA
  CMS Run-I and Run-II data extend measurements performed at HERA
- CMS covers both forward and backward rapidity regions
  It is a unique possibility to cover the energy region between HERA experiments and LHCb data

Future prospects: |t|-distributions

Appearance of diffractive dips are signature of gluon saturation according to b-CGC and IP-Sat models

Both H1 and ZEUS measured only low |t| region

It is necessary to extend the measurement to higher t-values



Nestor Armesto and Amir H. Rezaeian,
Phys. Rev. D 90, 054003 (2014)

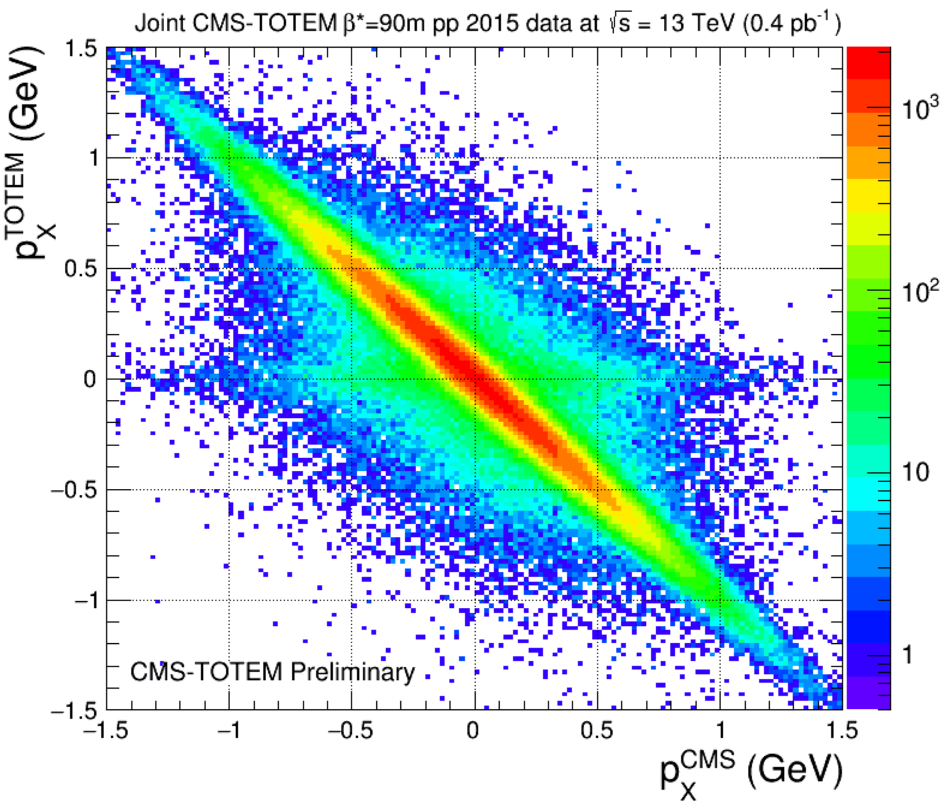
Summary

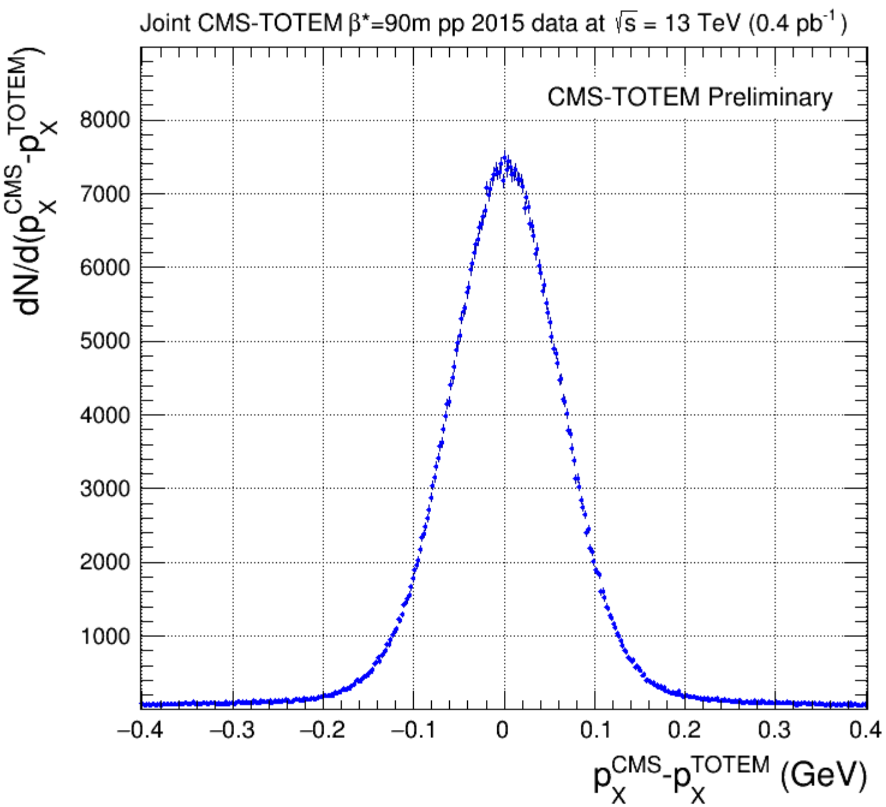
- Exclusive $\gamma\gamma\rightarrow \boldsymbol{W^+W^-}$
  - 2 events observed at 7 Tev, 13 events observed at 8 Tev in SM region
  - No indication of aQGC found
- Exclusive $\boldsymbol{\pi^+\pi^-}$
  - Differential cross-sections above exclusive $\pi^+\pi^-$ + ρ photoproduction predictions for high-pt
  - The invariant mass spectrum shows some features not included in the purely non-resonant predictions
- Exclusive **ϒ** in pPb
  - The first measurement of exclusive ϒ photoproduction in pPb collisions at 5.02 TeV has been presented
  - Data compatible with power-law dependence of $\sigma_{\Upsilon(1S)}(W_{\gamma p})$ and previous measurements by HERA and LHCb
  - The differential cross-section $d\sigma/dt$ in agreement with earlier measurements and consistent with predictions based on pQCD models
- More exciting exclusive results to be presented this year
  - Both in pp and pPb data (and even in PbPb!)

Thank you for your attention!

Additional slides

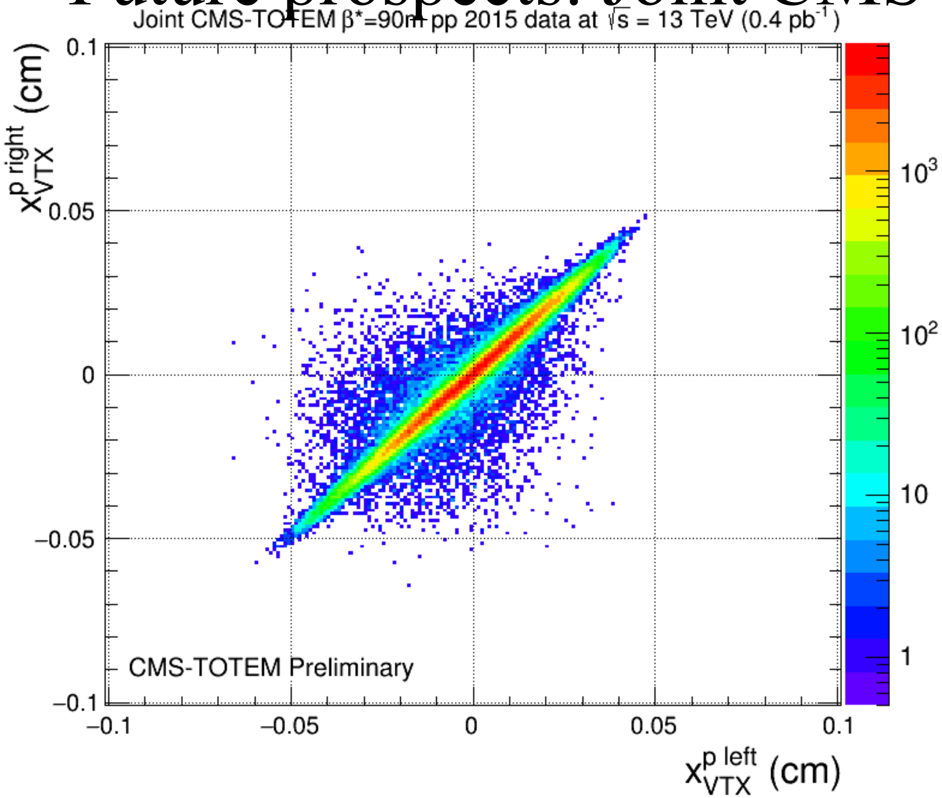
Future prospects: Joint CMS-TOTEM run @13 TeV

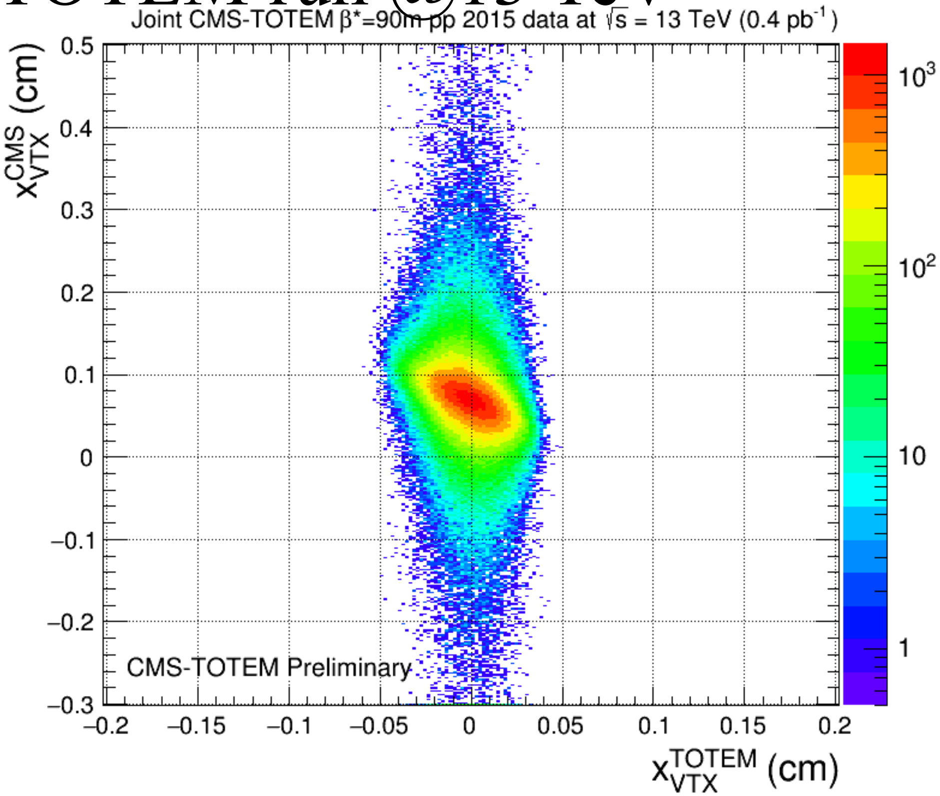




Requirements of the transverse momentum balance $|p_Y^{CMS} + p_Y^{TOTEM}| < 2\sigma_{dpY}$ and $|p_X^{CMS} + p_X^{TOTEM}| < 2\sigma_{dpX}$ are applied to reject background and select events of central exclusive production, $pp \rightarrow ppX$ with $X=\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, … .

Future prospects: Joint CMS-TOTEM run @13 TeV



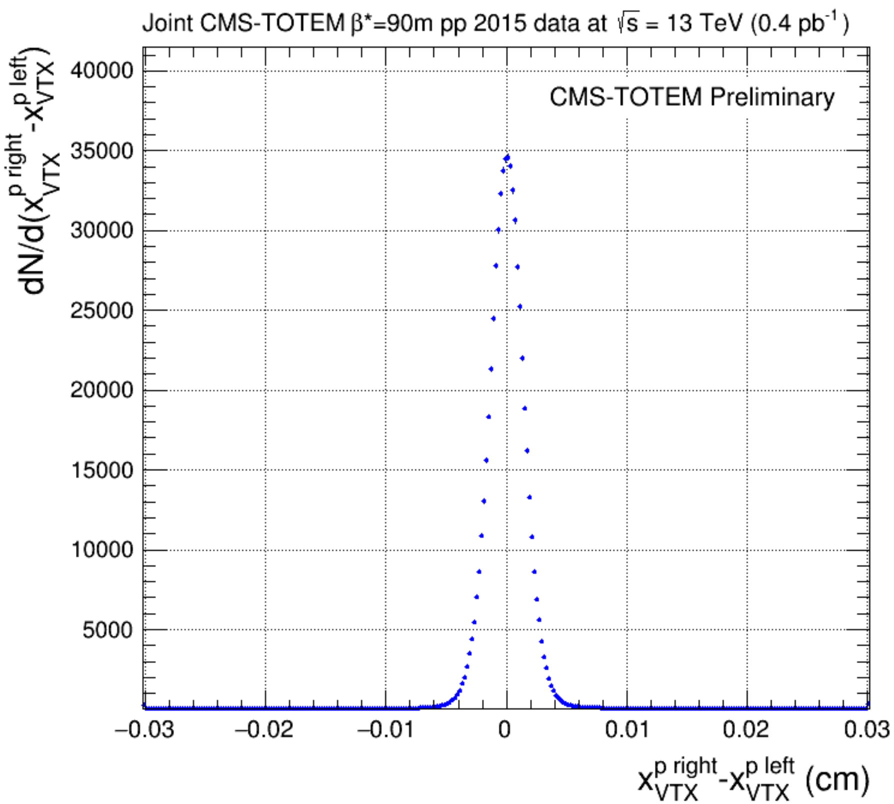


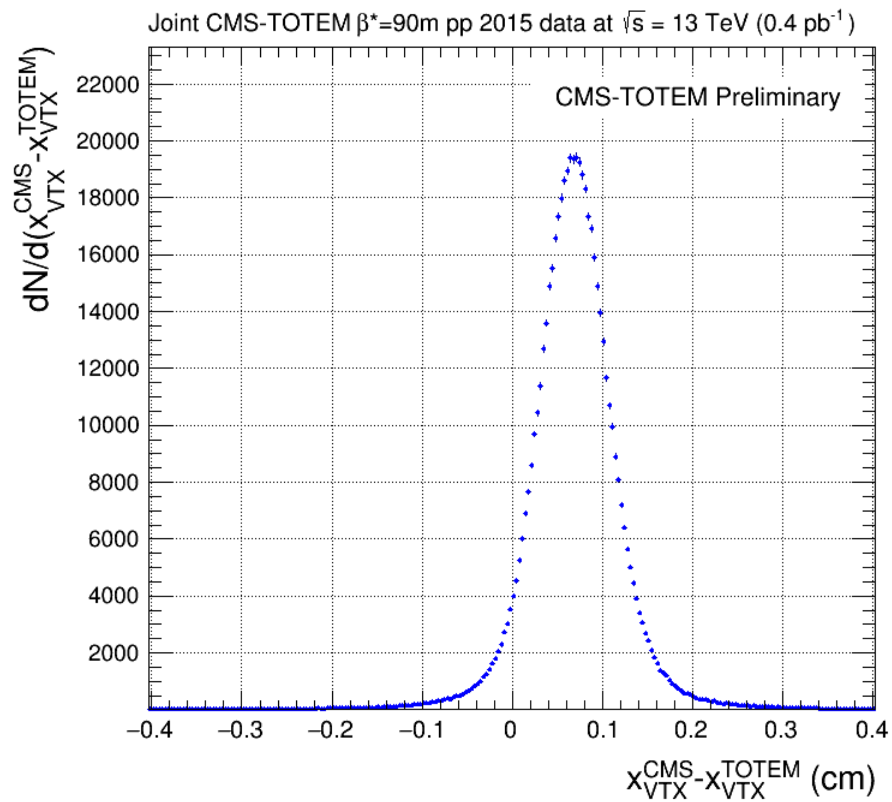
Left: the x position of the event vertex for pp->pp$\pi^+\pi^-$ events reconstructed from an extrapolation of the proton tracks measured in the right (z>0) vs left (z<0) TOTEM Roman Pot.

Right: The CMS vs TOTEM measurement of the x position of the event vertex for pp->pp$\pi^+\pi^-$ events. The CMS value is measured in the CMS reference frame, while the TOTEM value is measured in the LHC reference frame.

The β*=90m optics has parallel-to-point focusing for the y plane – the RP measurement in y has no sensitivity on the vertex (only on the scattering angle).

Future prospects: Joint CMS-TOTEM run @13 TeV





Requirements of the vertex compatibility $|x_{VTX}^{p\ right} - x_{VTX}^{p\ left}| < 2\sigma^{TOTEM}_{dxVTX}$ and $|x_{VTX}^{CMS} - x_{VTX}^{TOTEM} - x_0| < 2\sigma_{dxVTX}$ are applied to reject background and select events of central exclusive production, $pp \rightarrow ppX$ with $X=\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, … .