



Exclusive and Diffractive Physics with CMS

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on behalf of the CMS Collaboration
Universidade do Estado do Rio de Janeiro



LHCP 2013 - First Large Hadron Collider Physics Conference
13-18 May 2013- Barcelona



Outline

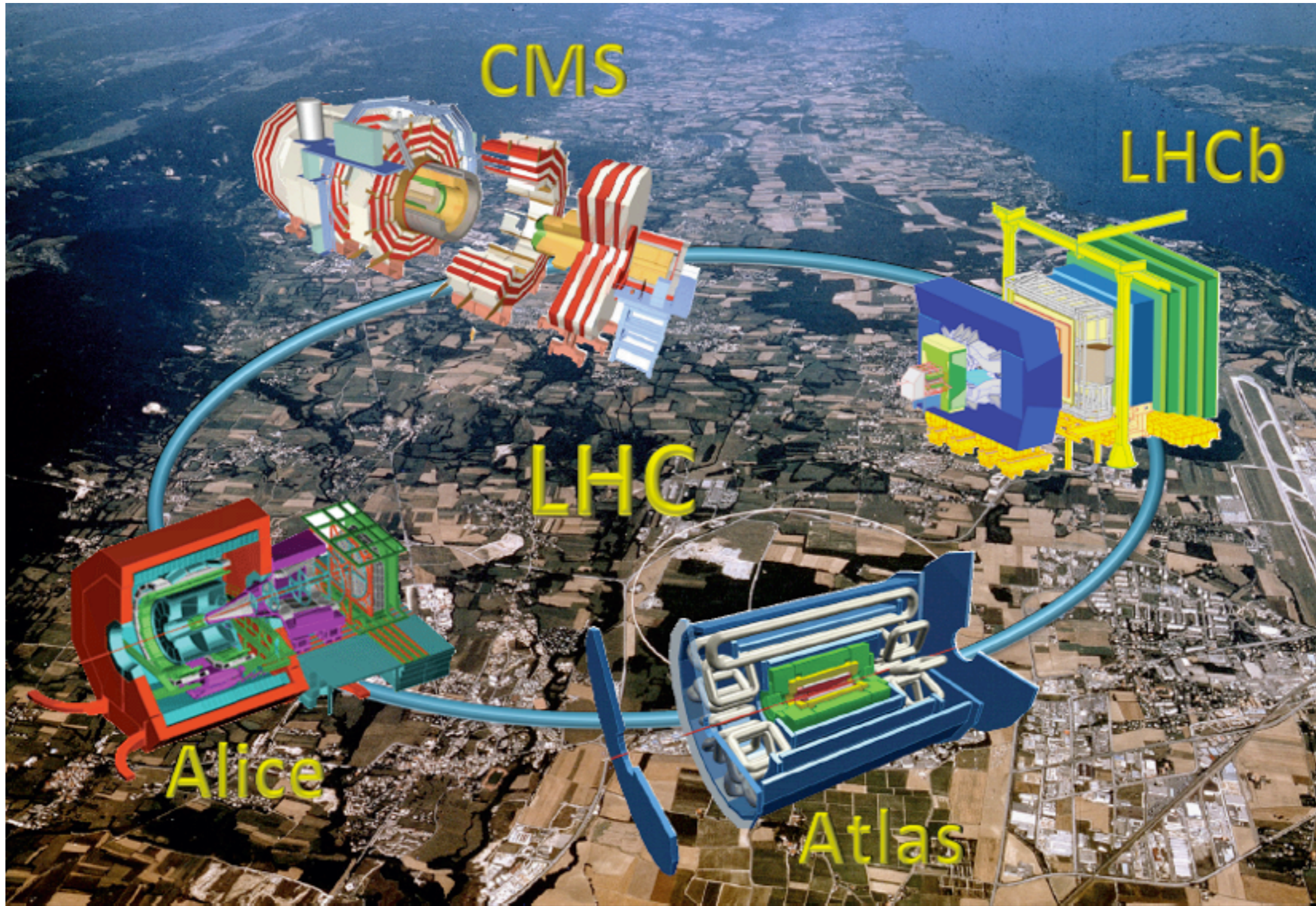


- CMS experiment & Forward detectors
- Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production
- Soft Diffraction Cross Sections
- Diffractive Di-jets
- High-pT Jets with Two Leading Protons @ CMS-TOTEM

All Forward Physics Results at CMS

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ>

LHC Experiment



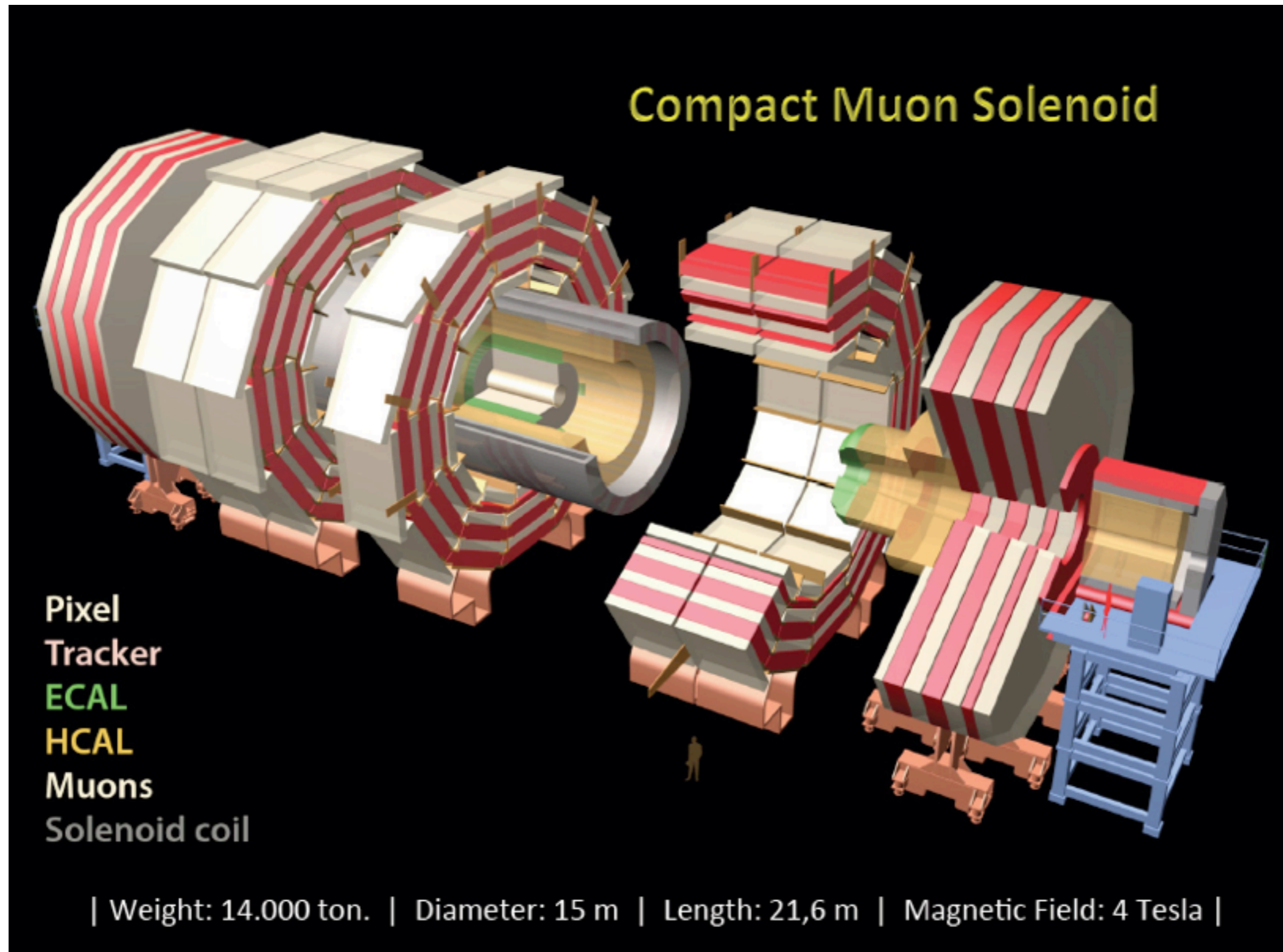


Outline



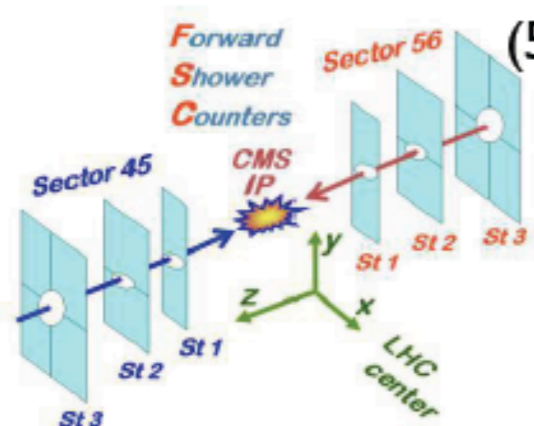
- CMS experiment & Forward detectors
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CMS Detector



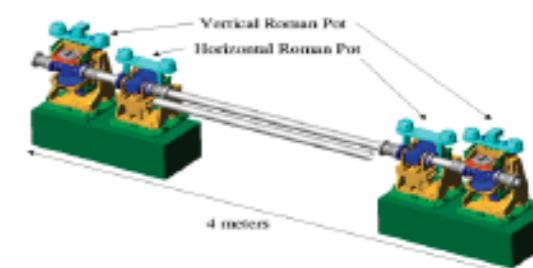
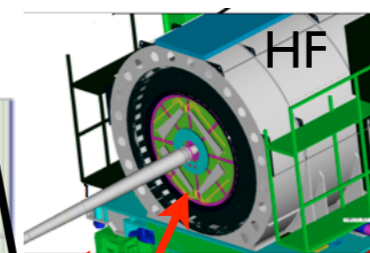
Forward detectors

Forward Shower Counters
(59-114m)



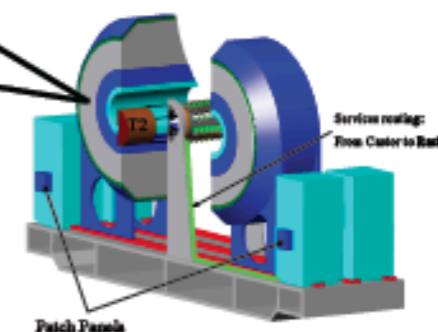
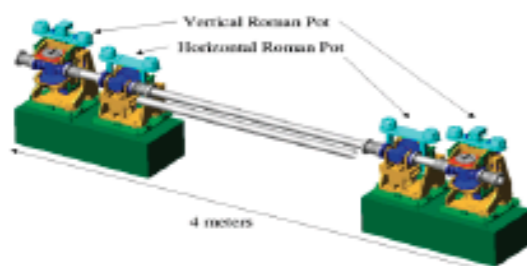
$|\eta| \approx 6 - 8$

HF: $3.0 < |\eta| < 5.0$



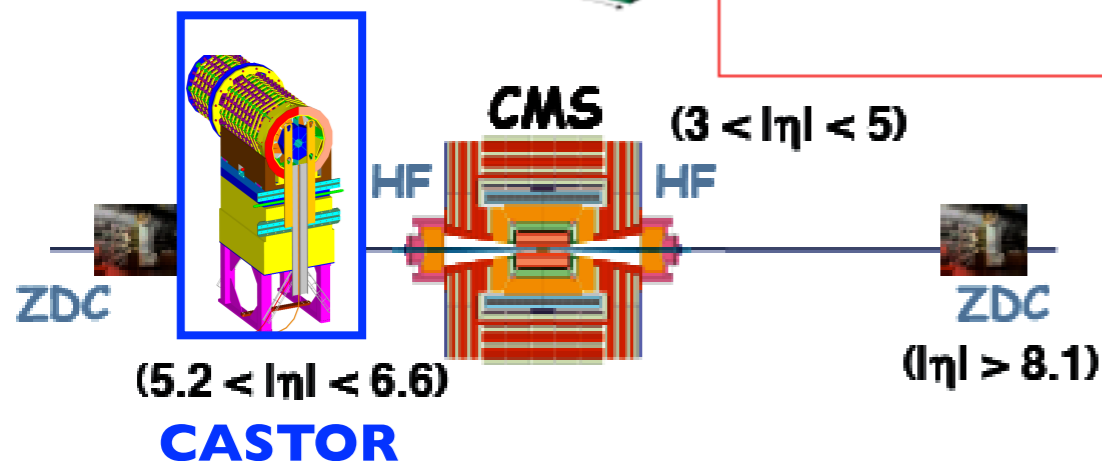
TOTEM RPs
(147, 220m)

TOTEM RPs
(147, 220m)



TOTEM T2
(In front of
CASTOR position)

Common data taking during low-PU
runs in 2012



BSC*: Beam Scintillator Counters
(in front of HF) $3.2 < |\eta| < 4.7$



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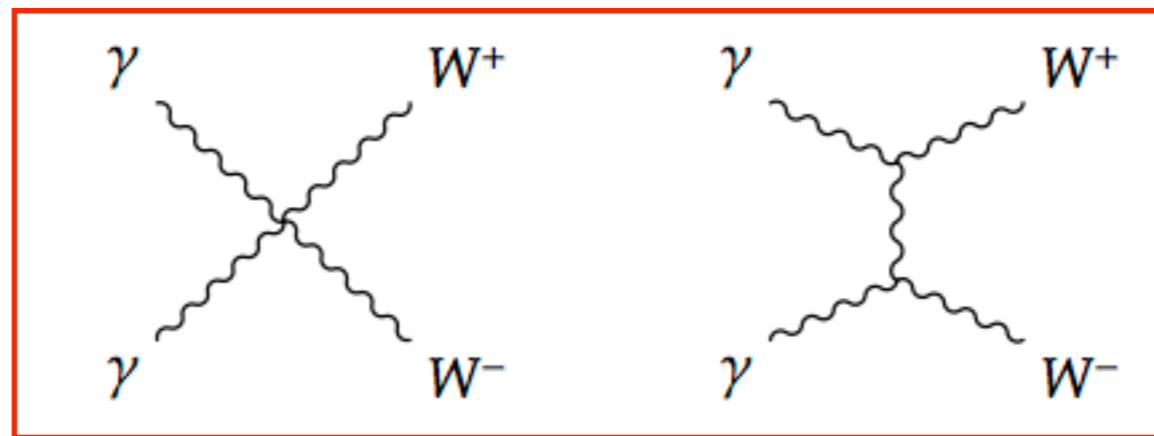


Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production



Motivations [CMS PAS FSQ-12-010](#)

- The measurements of the two-photon production of WW pairs is sensitivity to Anomalous Quartic Gauge Couplings (AQGC).
- Previous exploratory studies (“exclusive” two-photon production of lepton pairs) indicated the potential for extending the experimental research limit beyond of LEP results.
- Existing sensitivity studies performed in the scenario of Forward Detectors upgrade for CMS (**Nucl.Phys.Proc.Suppl. *179-180* (2008) 257-264**) and ATLAS (**Phys. Rev. *D81*(2010) 074003**);



- These processes involve two triple coupling (TGC) vertices involving t-channel W boson exchange.
- Sensibility to a TCG's and QGC limited given the LHC/LEP limits.

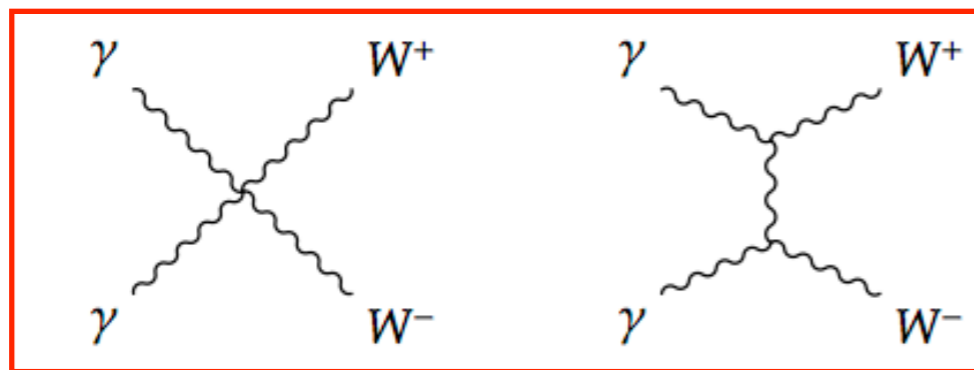


Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production



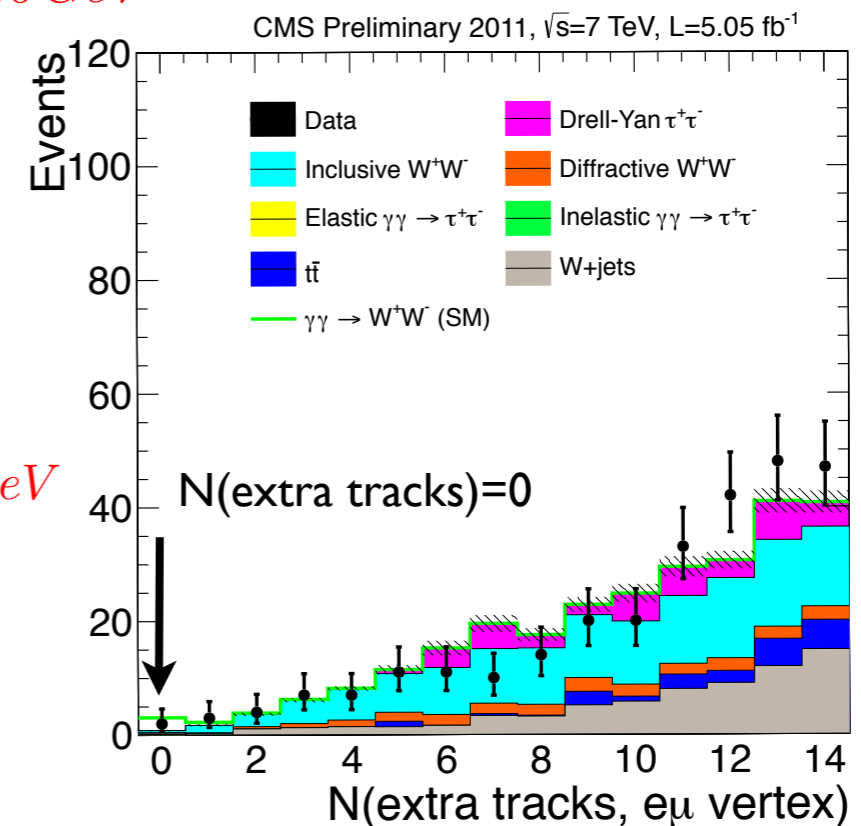
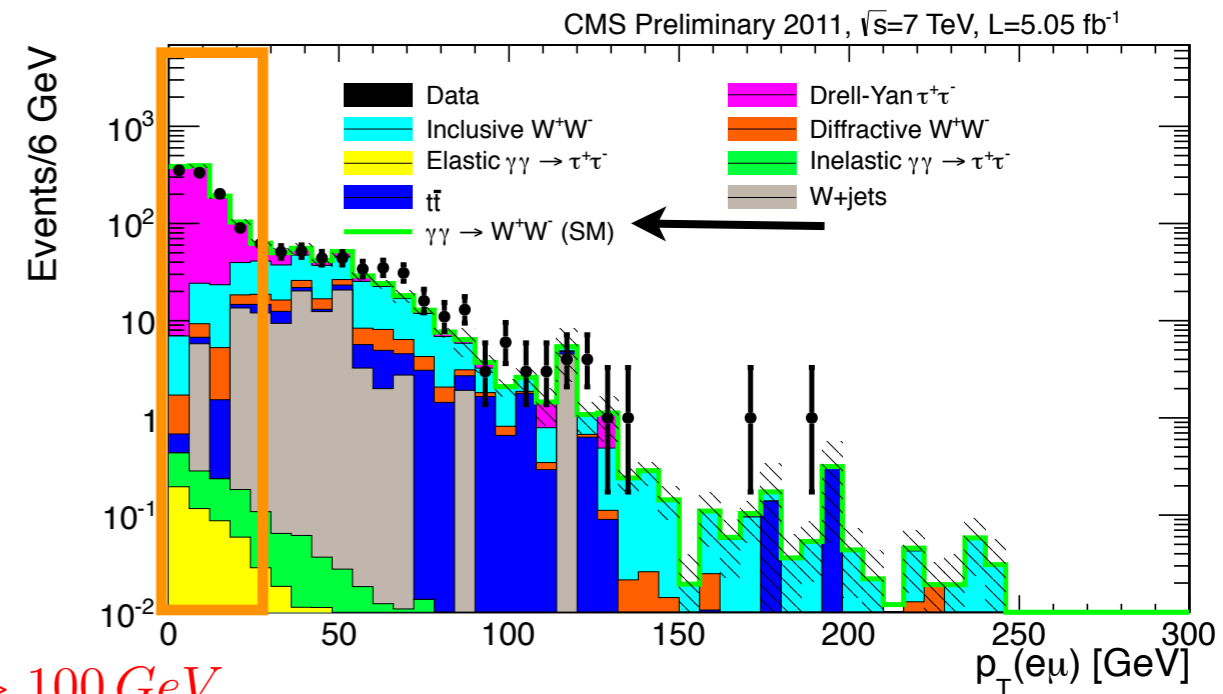
CMS PAS FSQ-12-010

- 2011 data collected corresponding to an integration luminosity of 5.05 fb^{-1} at 7 TeV (moderate: PU~10).
- Criteria of Exclusivity: no extra tracks associated to electron-muon vertex;
- $\gamma\gamma \rightarrow \mu^+\mu^-$ events used as benchmark in efficiencies studies and PU determination.
- SM region selection: $N(\text{extra tracks}) = 0$ and $p_T(\mu e) > 30 \text{ GeV}$
- $\gamma\gamma \rightarrow W^+W^-$ -search region: $N(\text{extra tracks}) = 0$ and $p_T(\mu e) > 100 \text{ GeV}$



Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ Production
[CMS FWD-10-005, J. High Energy Phys.01 \(2012\) 052](#)
 Exclusive $\gamma\gamma \rightarrow e^+e^-$ Production
[CMS FWD-11-004, J. High Energy Phys.11 \(2012\) 080](#)

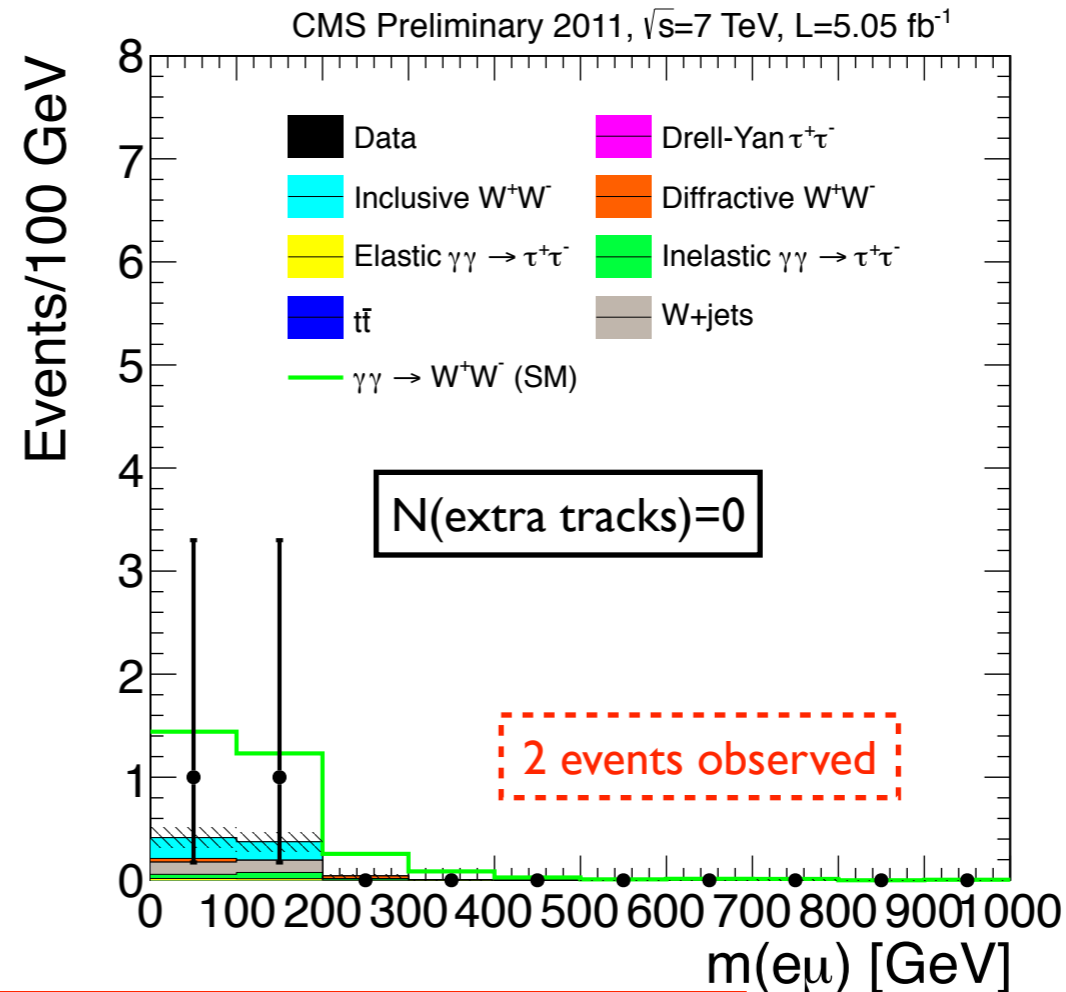
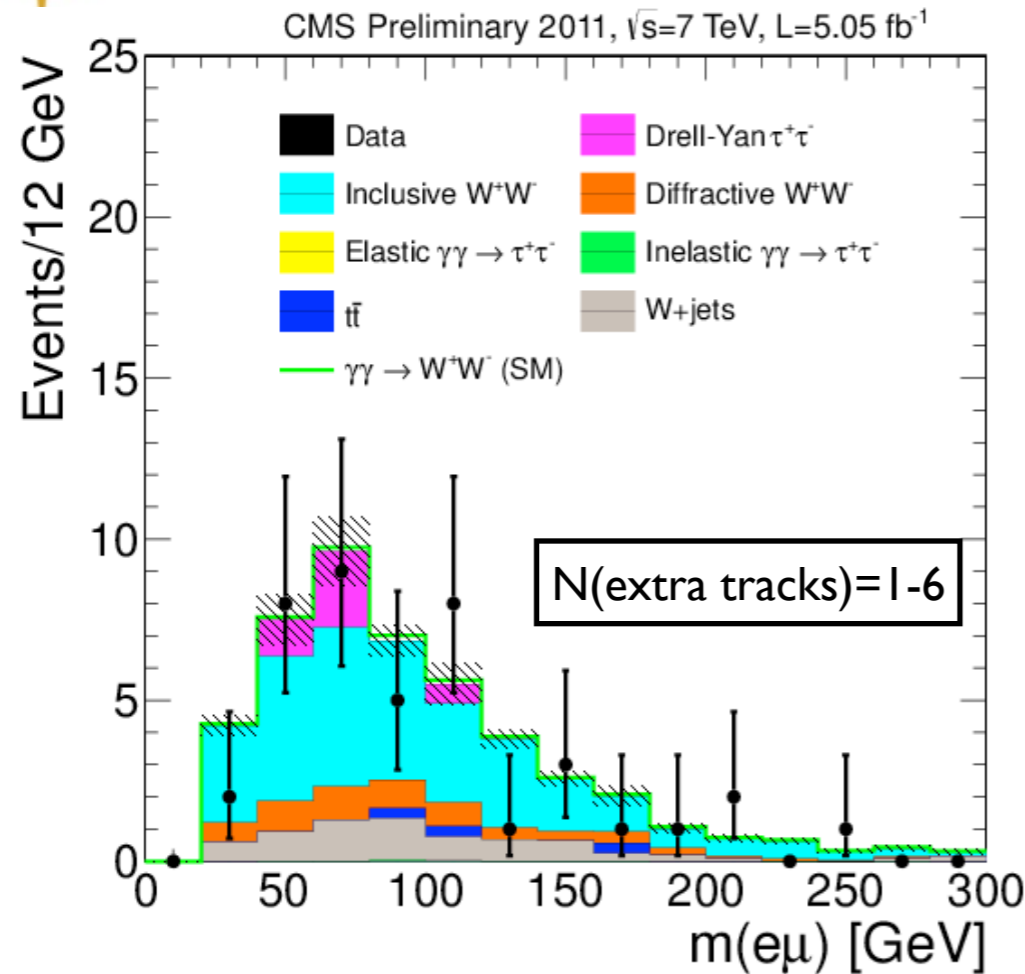
See backup slides!



$p_T(\mu e) > 30 \text{ GeV}$

Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production

CMS PAS FSQ-12-010



Final Signal: 2.2 ± 0.5 ; Background: 0.84 ± 0.13

The observed upper limit is estimated using 95% CL for SM signal region are:

$$\sigma \left(pp \rightarrow p^{(*)} W^+ W^- p^{(*)} \rightarrow p^{(*)} \mu^\pm e^\mp p^{(*)} \right) < 8.4 \text{ fb}$$

$$\sigma \left(pp \rightarrow p^{(*)} W^+ W^- p^{(*)} \rightarrow p^{(*)} \mu^\pm e^\mp p^{(*)} \right) = 2.1_{-1.9}^{+3.1} \text{ fb (CS x BR)}$$

SM prediction $(3.8 \pm 0.9) \text{ fb}$

Significance: 1.1σ

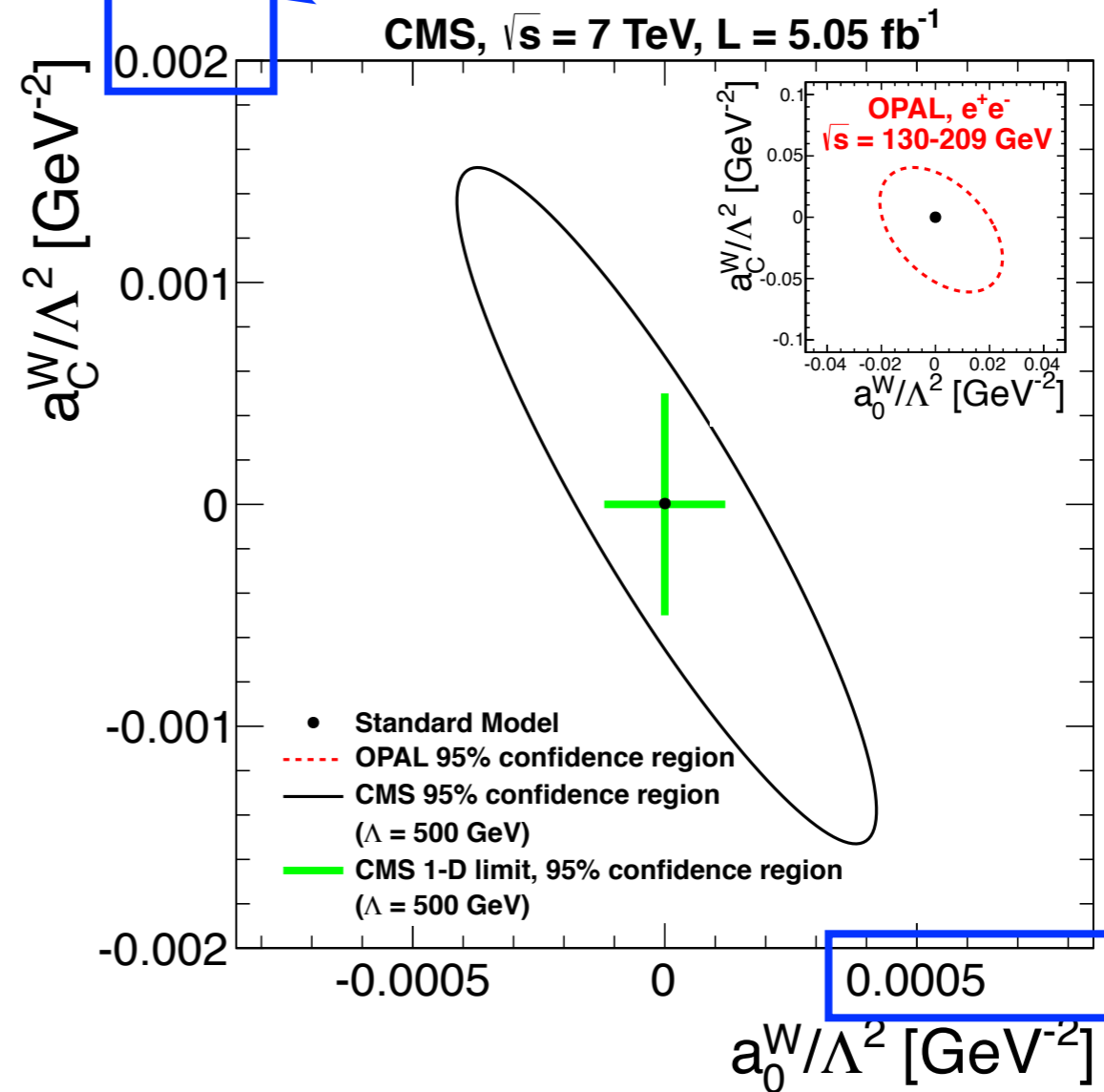
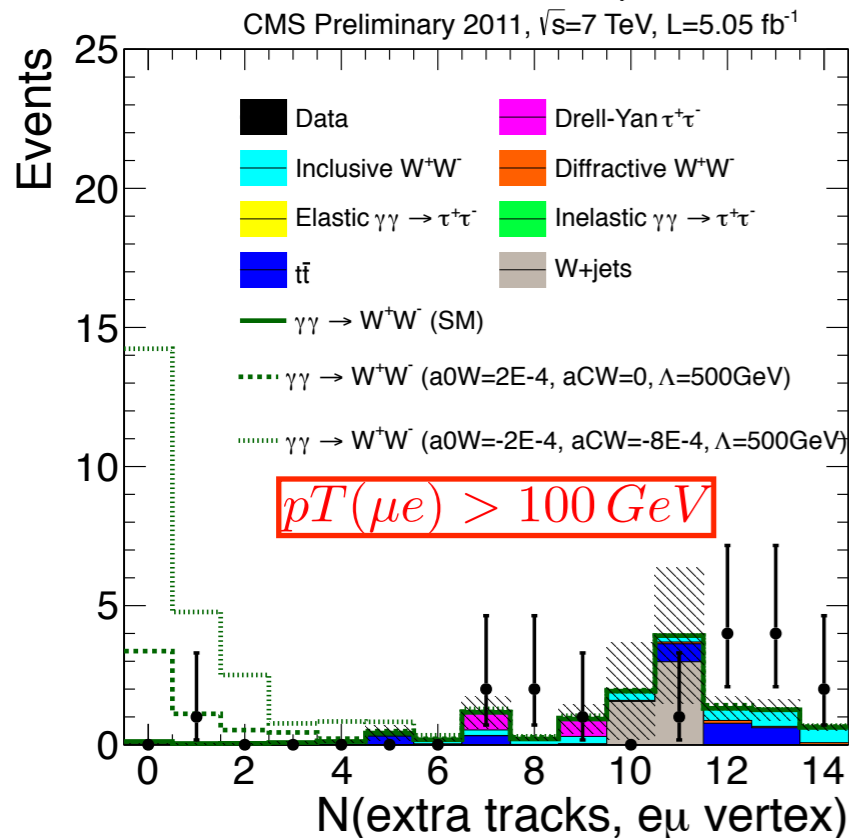
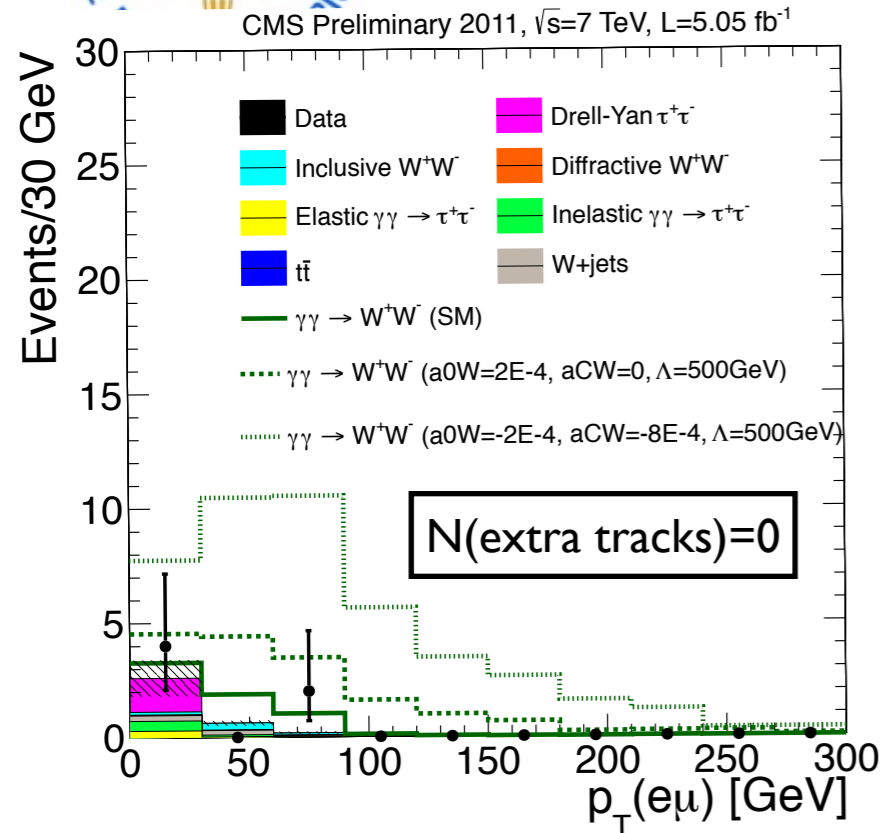
Contribution from proton dissociation (inelastic) in two-photon production are included.

Exclusive $\gamma\gamma \rightarrow W^+W^-$ Production

CMS PAS FSQ-12-010

AQGC would increase yields at high $p_T(\text{pair})$ and No extra event found.

Two orders of magnitude improvements over LEP reach.





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- **Soft Diffraction Cross Sections**
- Diffractive Di-jets
- High- p_T Jets with Two Leading Protons @ CMS-TOTEM



Soft Diffraction Cross Sections

MC simulation:

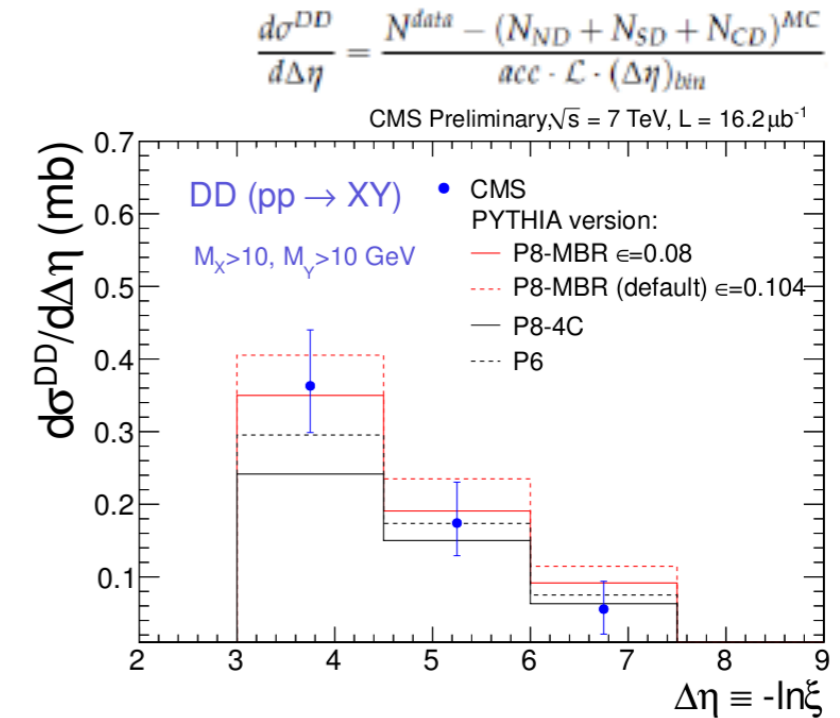
- PYTHIA8-4C: diffraction with Schuler&Sjostrand model from PYTHIA6 (Tune 4C is additional scaling of SD and DD)

-PYTHIA8-MBR: diffraction with Minimum Bias Rockefeller model(<http://indico.cern.ch/conferenceOtherViews.pyview=standard&confid=184925>)

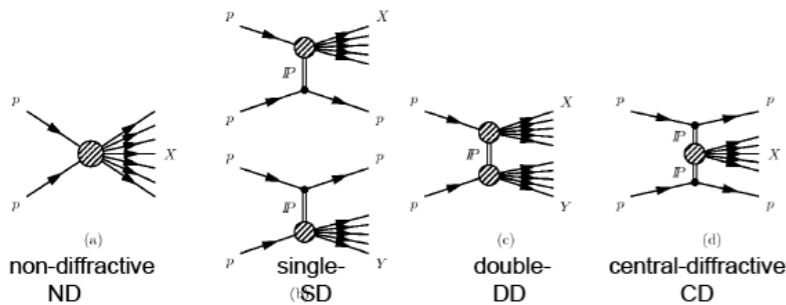
CMS-PAS-FSQ-12-005

- First measurement of the inclusive diffractive cross section
- Using Large Rapidity Gap (LRG) signatures
- SD and DD separated with CASTOR ($-6.6 < |\eta| < -5.2$).

- Analysis based on 2010 data with Low PU.
- Minimum Bias Trigger (hit in either BSCs).
- Based on Particle Flow (PF) objects (tracking + calorimetry).
- At least 2 PF in BSCs acceptance region ($3.2 < |\eta| < 4.7$).
- no vertex requirement (to retain $M_X < 100 \text{ GeV}$).



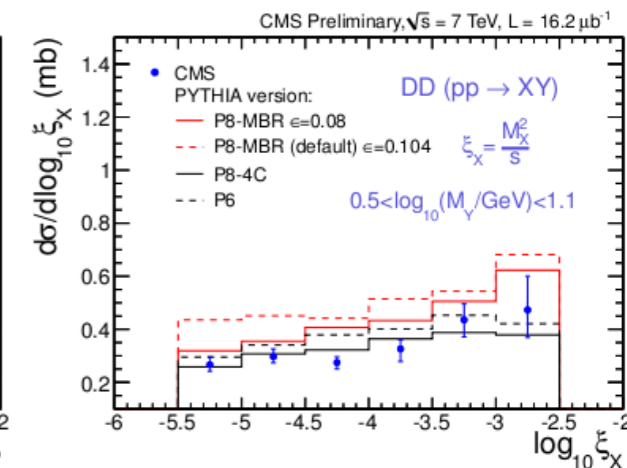
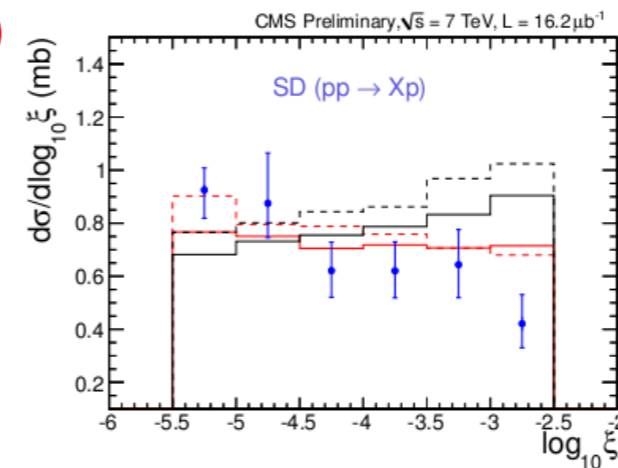
Minimum Bias Samples in central CMS detector ($4.7 < |\eta| < -4.7$)



$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

For single diffractive events!

Proton fraction momentum loss.



$$\sigma_{vis}^{SD} = 4.27 \pm 0.04(stat.)_{-0.58}^{+0.65}(syst.) \quad (12 < M_X < 394 \text{ GeV})$$

$$\sigma_{vis}^{DD} = 0.93 \pm 0.01(stat.)_{-0.22}^{+0.26}(syst.) \quad \Delta\eta > 3, M_X > 10 \text{ GeV}, M_Y > 10 \text{ GeV}$$



Outline

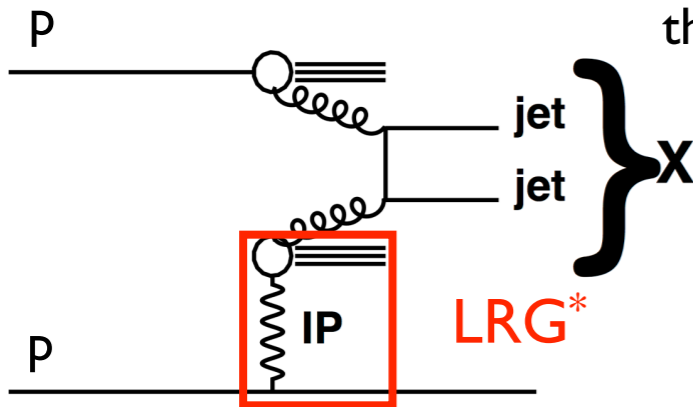


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Diffractive Di-jets



Measure hard diffractive process and compare to pQCD-based theory predictions (gap-survival probability at 7 TeV).

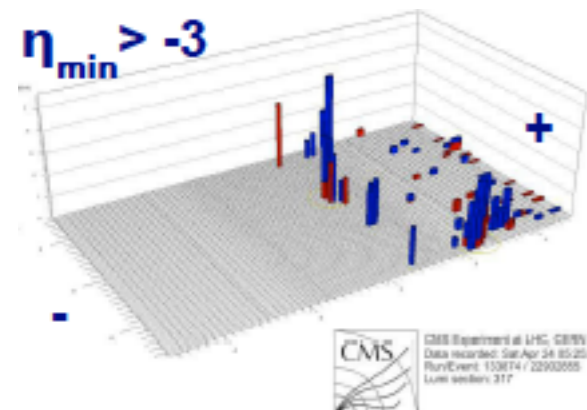


- Analysis based on 2010 data (2.7 nb^{-1}) with negligible PU.
- Single-jet trigger, anti-kt 0.5, vertex.
- At least 2 jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 4.4$
- Based on Particle Flow objects (tracking + calorimetry).

Large Rapidity Gap (LRG): require most forward (or backward) PF object in the events to satisfy $\eta_{max} < 3$ (or $\eta_{min} > -3$).

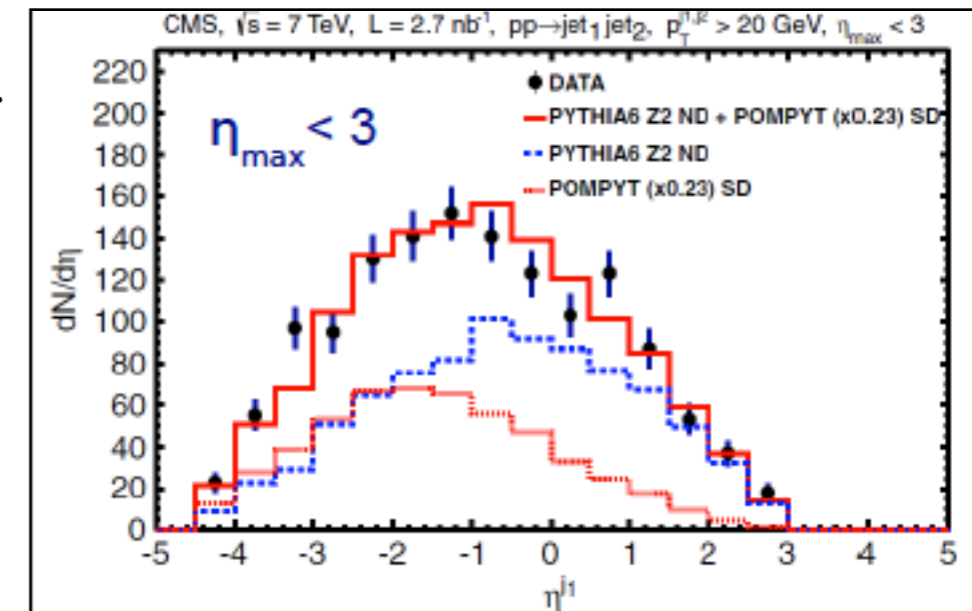
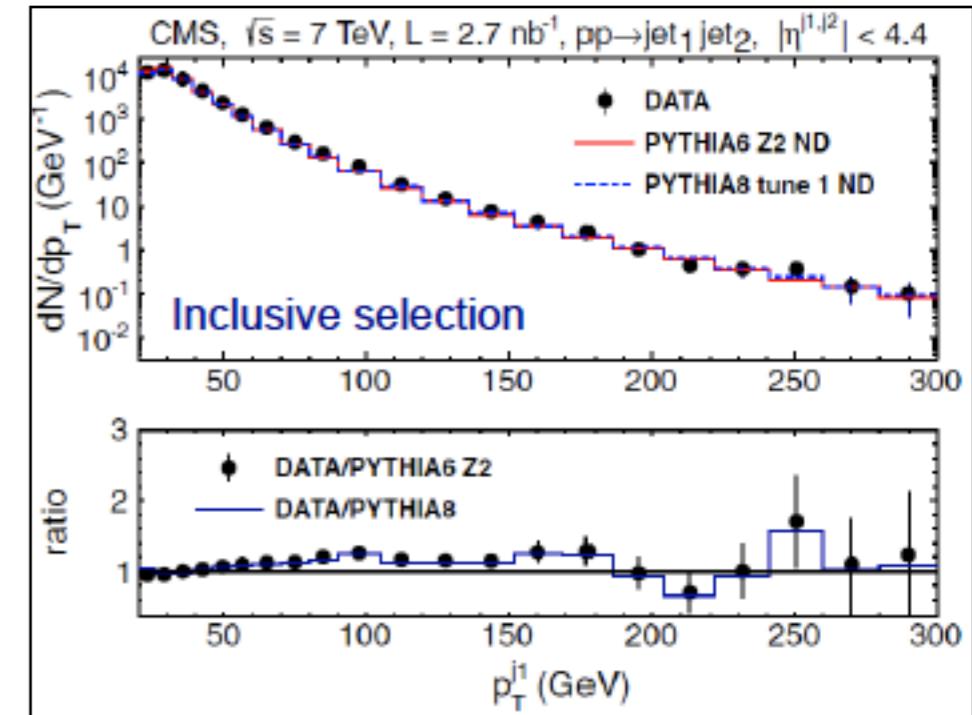
η_{max} (η_{min})- highest (lowest) η of the particle reconstructed in the central detector.

Corresponds to no individual energy deposit above 4GeV; in HF+ (or HF-).
Rapidity gap of 1.9 units in the central CMS detector.



LRG data described by a combination of diffractive (POMPTY) and non-diffractive samples (PYTHIA6 Z2).

relative fraction from the fit to the data.





Diffractive Di-jets Cross Section



CMS-FWD-10-004
PRD 87 (2013) 012006

Inclusive di-jets cross section extracted in 3 bins of ξ .

$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p_z^i)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

For single diffractive events!

Proton fraction momentum loss.

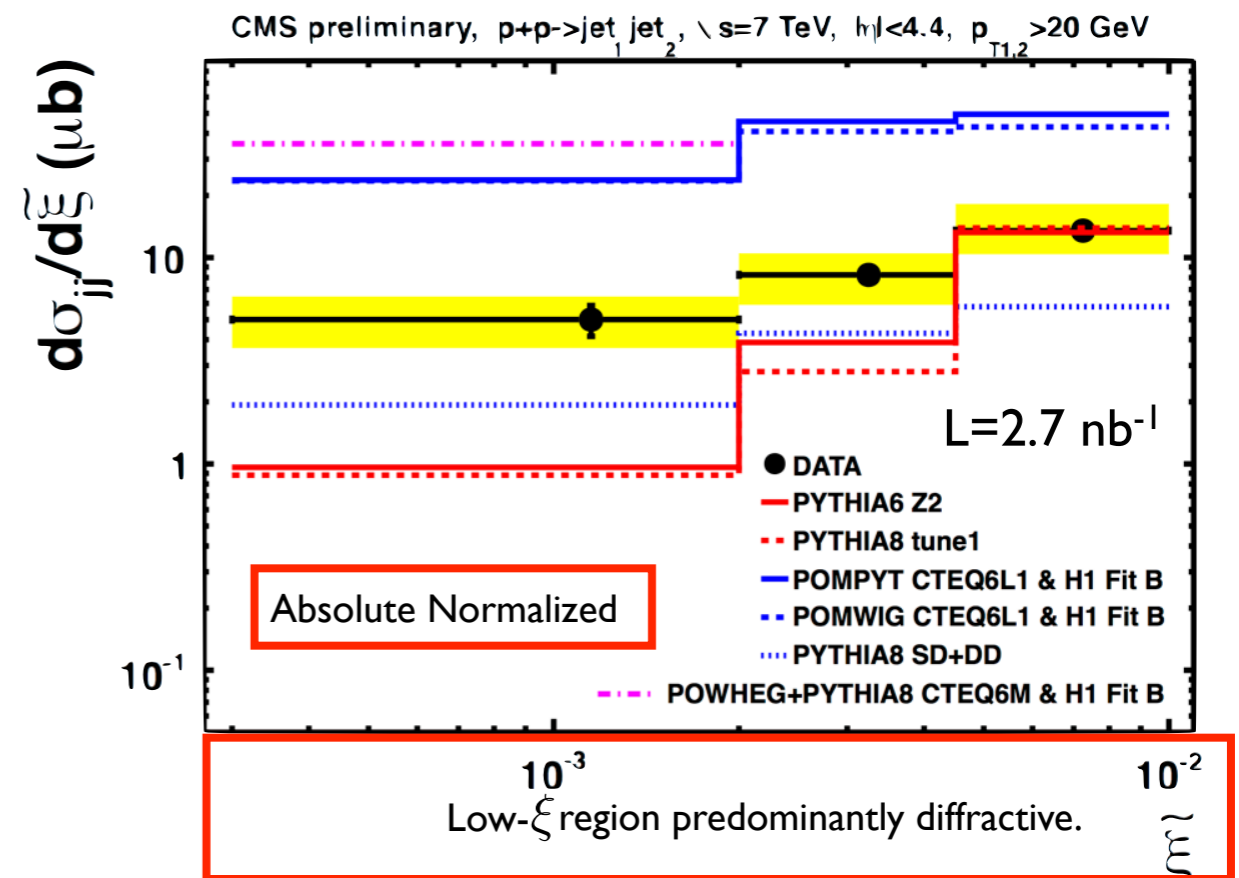
- Reconstructed from PF objects.
- Corresponding to the gap on positive/negative side.

Excess of events in low ξ region wrt non-diffractive PYTHIA6 and PYTHIA8 MC.

POMPTY and POMWIG (LO) diffractive MCs and NLO calculated from POMWEG, using diffractive PDFs, are factor ~ 5 above the data in lowest- ξ region.

$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N_{jj}^i}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

$$A_{MC}^i = \frac{N^i(\tilde{\xi}_{Rec})}{N^i(\tilde{\xi}_{Gen})}$$



Data/MC suppression factor is: 0.21 ± 0.07 (LO MC).
 0.14 ± 0.05 (NLO MC).

After proton dissociation correction, the ratio can be interpreted in terms of rapidity gap survival probability is 0.12 ± 0.05 (LO MC).
 0.08 ± 0.04 (NLO MC).

$\tilde{\xi}$ bin	$\Delta\sigma_{jj}/\Delta\tilde{\xi} (\mu\text{b})$
$0.0003 < \tilde{\xi} < 0.002$	$5.0 \pm 0.9(\text{stat.})^{+1.5}_{-1.4}(\text{syst.})$
$0.002 < \tilde{\xi} < 0.0045$	$8.2 \pm 0.9(\text{stat.})^{+2.3}_{-2.3}(\text{syst.})$
$0.0045 < \tilde{\xi} < 0.01$	$13.5 \pm 0.9(\text{stat.})^{+4.7}_{-3.1}(\text{syst.})$



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Outlook: ongoing in 2012/2013

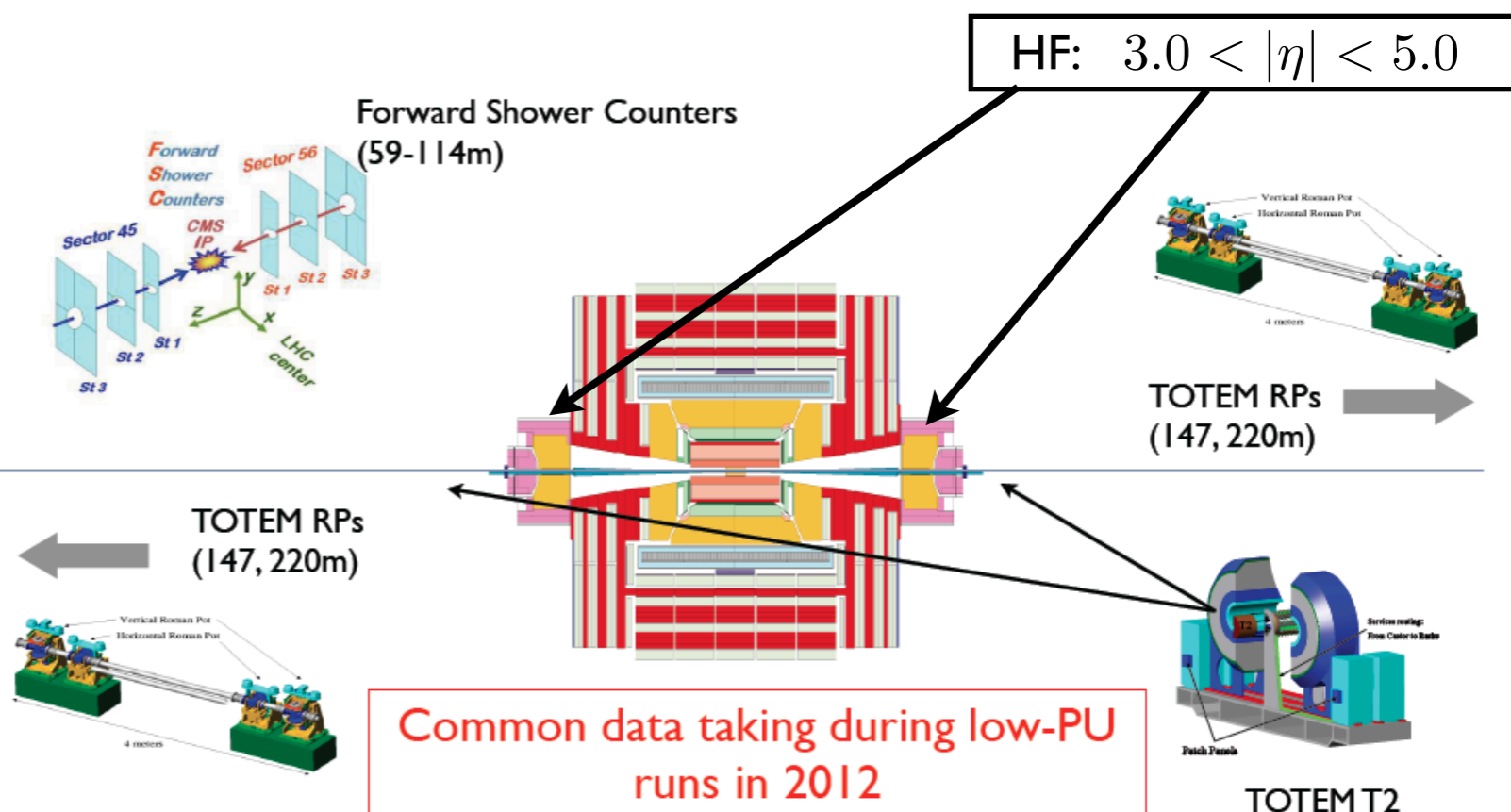


- Common CMS-TOTEM data taking at low PU with 50 nb^{-1} (July 2012 using 8TeV and $\beta^* 90 \text{ m}$)

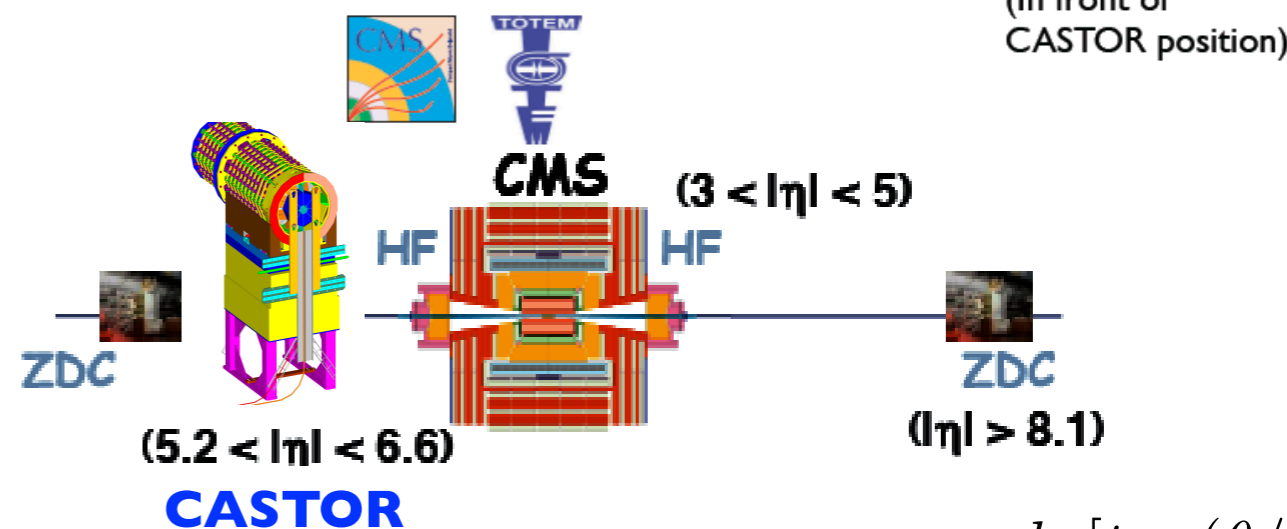
- TOTEM Roman Pots (RPs): detect proton scattering from diffractive and photon induced processes

- TOTEM T1/T2 tracking at very forward angles

- Forward Shower Counters (FSC) covering $|\eta| \approx 6 - 8$



Common data taking during low-PU runs in 2012

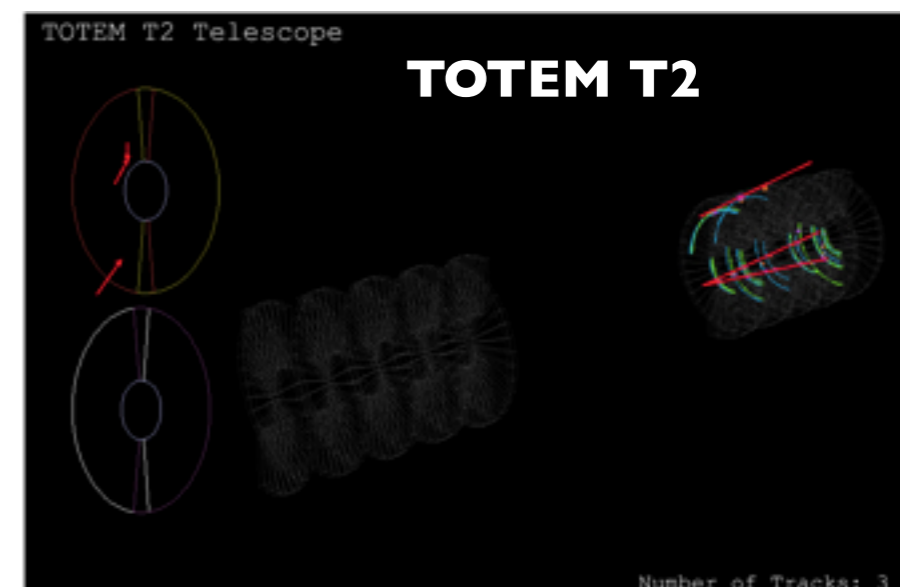
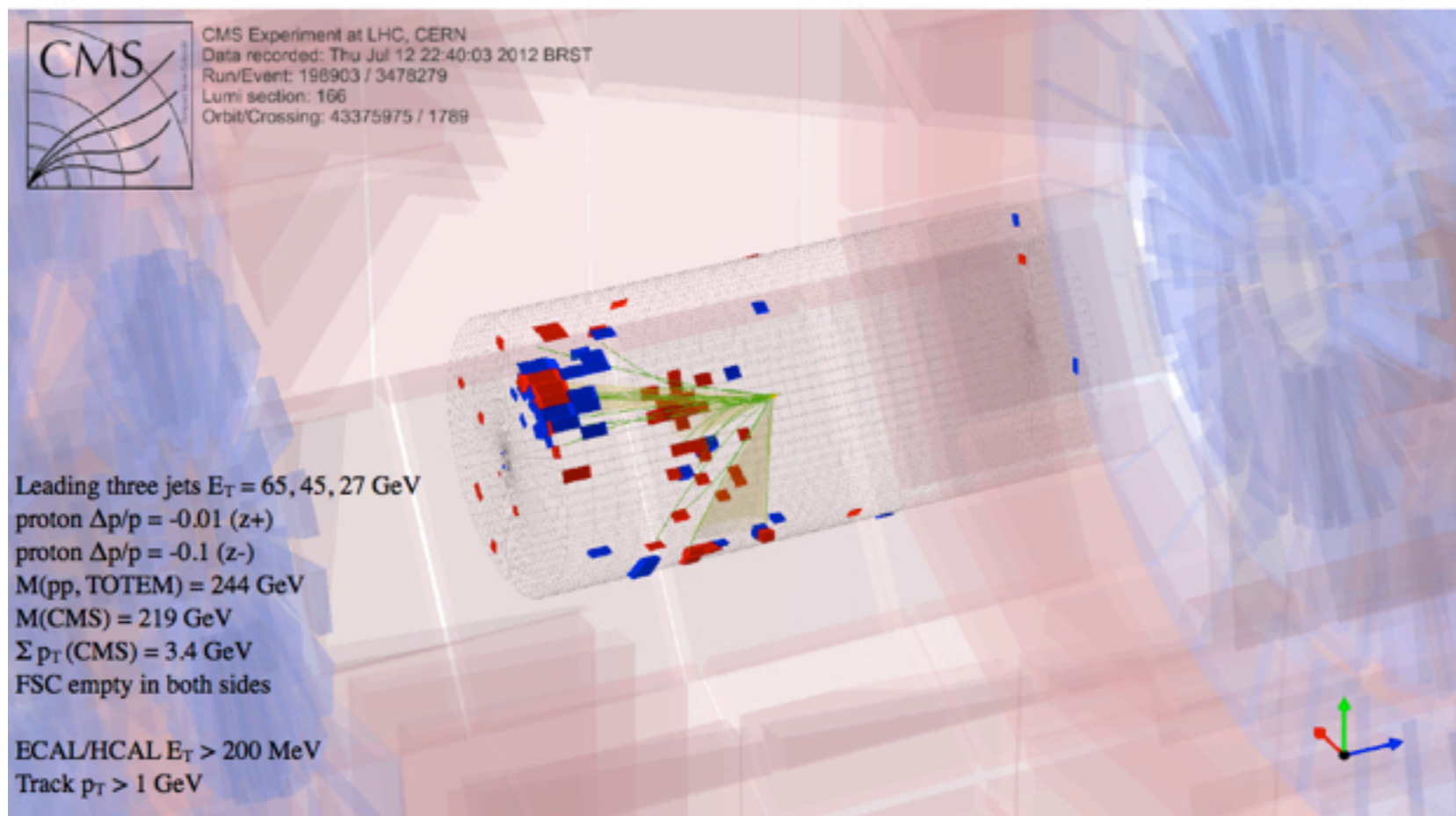


TOTEM T2	$5.3 < \eta < 6.5$
TOTEM T1	$3.1 < \eta < 4.7$

$$\eta = -\ln[\tan(\theta/2)]$$

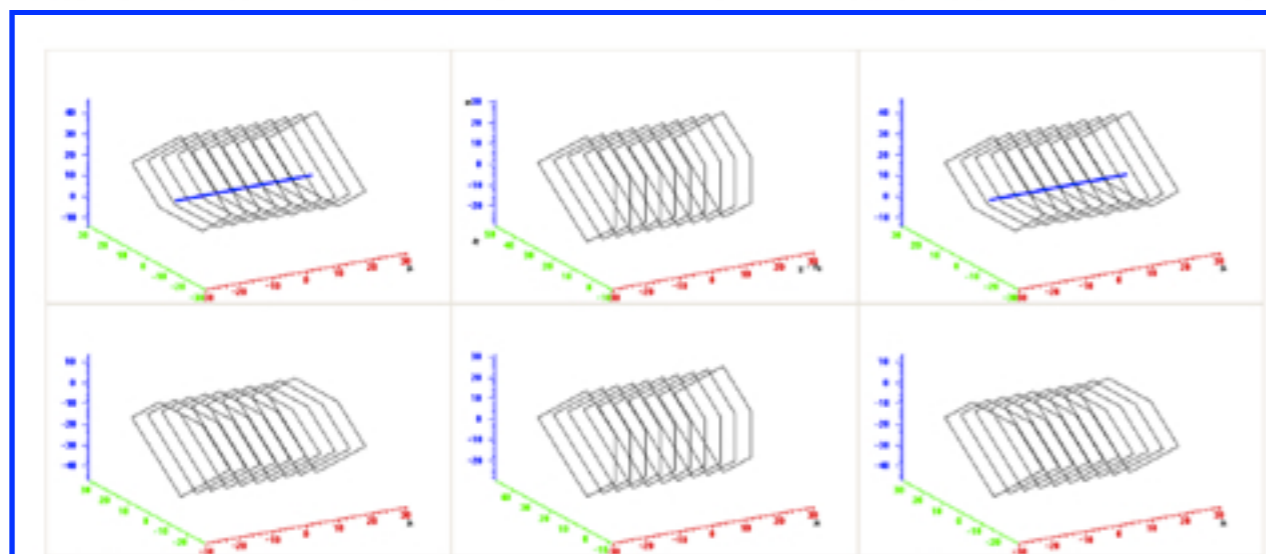


Central Dijets Events candidate with Two Leading Protons



CMS-DP 2013/004

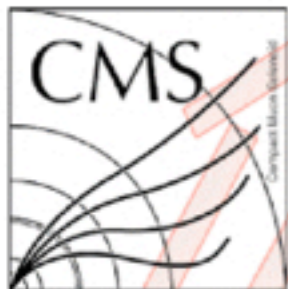
CMS-DP 2013/006



← TOTEM Roman Pots
Stations- Section 4-5

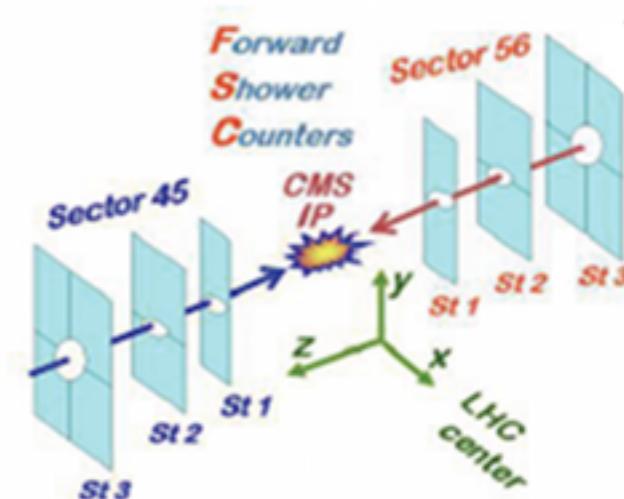
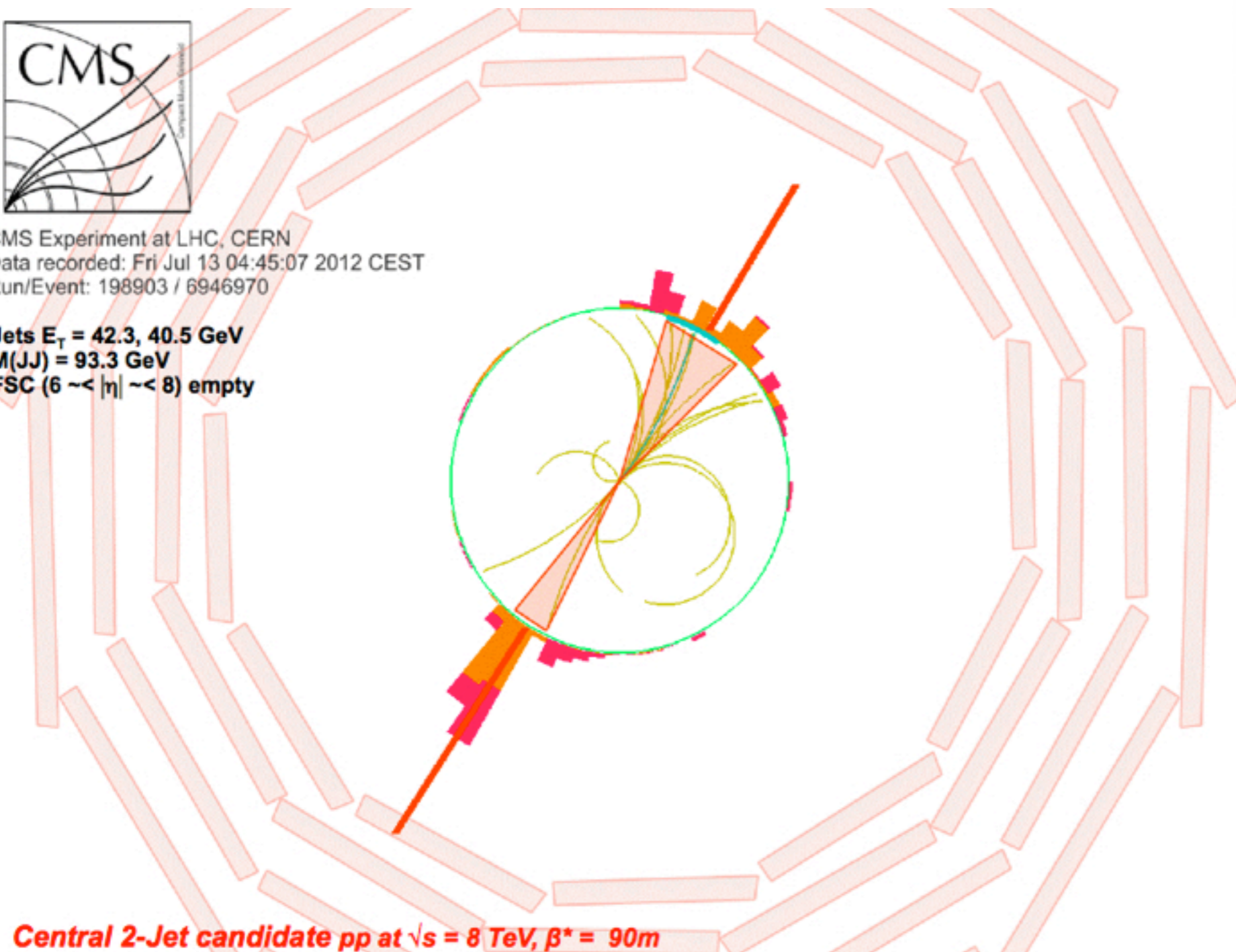


Central High-pT jet Production During Low PU Run@ $\sqrt{s} = 8\text{TeV}$



CMS Experiment at LHC, CERN
Data recorded: Fri Jul 13 04:45:07 2012 CEST
Run/Event: 198903 / 6946970

Jets $E_T = 42.3, 40.5\text{ GeV}$
 $M(JJ) = 93.3\text{ GeV}$
FSC ($6 \lesssim |\eta| \lesssim 8$) empty



CMS-DP 2013/004
CMS-DP 2013/006

Central 2-Jet candidate pp at $\sqrt{s} = 8\text{ TeV}$, $\beta^* = 90\text{m}$



Summary



- Measurement of the exclusive two-photon production of WW pairs in pp collisions at 7 TeV, based on samples of events collected during 2011 physics runs.
- Provide unique sensitivity to anomalous quartic couplings of the gauge bosons (AQCG). Extending the experimental reach by several orders of magnitude with respect to the best limits so far obtained at LEP.
- Inclusive SD and DD diffractive cross section measured at 7 TeV. MC prediction are in agreements with data using several theoretical models.



Summary



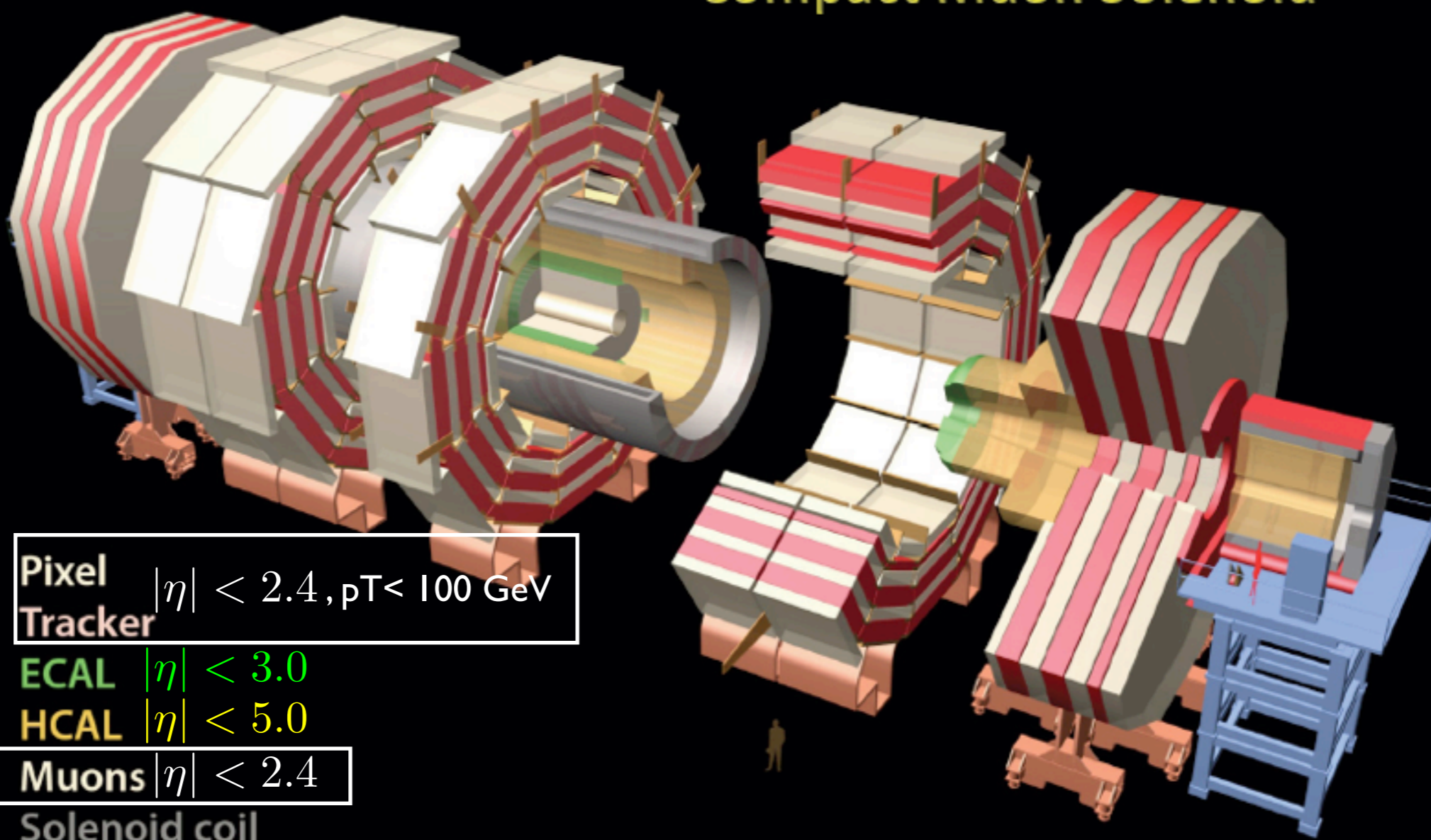
- The differential cross section has been measured and as a function of the variable (ξ) that approximates the momentum loss of protons in diffractive events.
- Diffractive di-jets events dominate the low- ξ . Comparing the measured cross section to diffractive MC prediction based on dPDFs from HERA an estimate of the survival probability was obtained.
- Results obtained using common data taking CMS-TOTEM and FSC at low PU with 50 nb^{-1} (July 2012 using 8TeV and $\beta^* 90 \text{ m}$).
- First “forward proton spectrometer” associated with complete central coverage region at LHC.



Extra Slides

CMS Detector

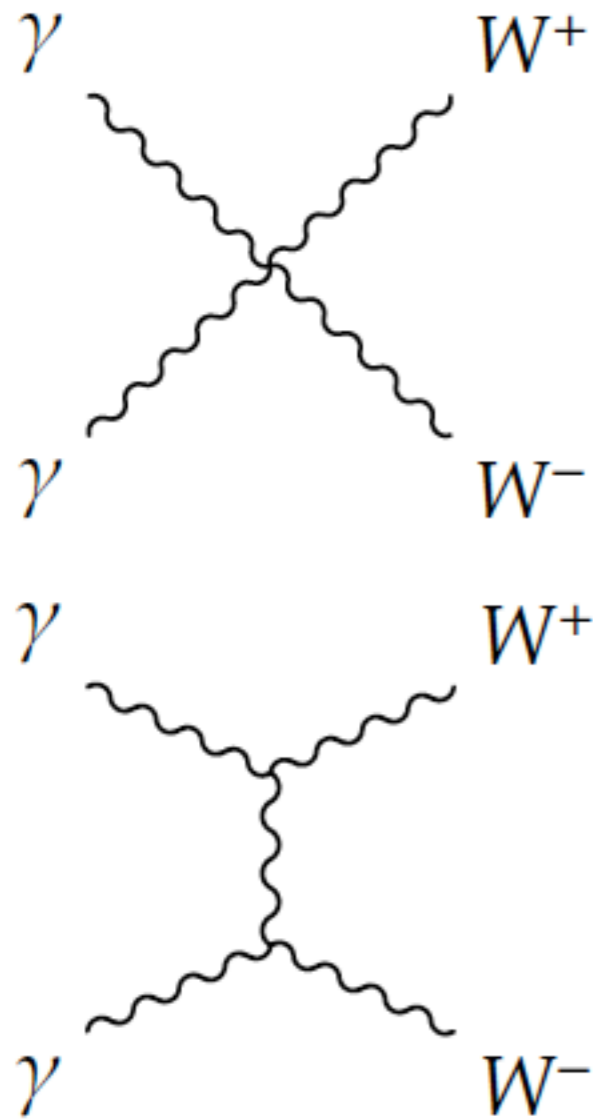
Compact Muon Solenoid



| Weight: 14.000 ton. | Diameter: 15 m | Length: 21,6 m | Magnetic Field: 4 Tesla |

$$\gamma\gamma \rightarrow W^+W^-$$

CMS PAS FSQ-12-010



$$\begin{aligned} \mathcal{L} = & a_1 F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{\alpha}^{-} \\ & + a_2 F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha} \\ & + a_3 F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta} \\ & + a_4 F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{\beta}^{-} + W^{-\alpha} W_{\beta}^{+}) \end{aligned}$$

$$\gamma\gamma \rightarrow W^+W^-$$

CMS PAS FSQ-12-010

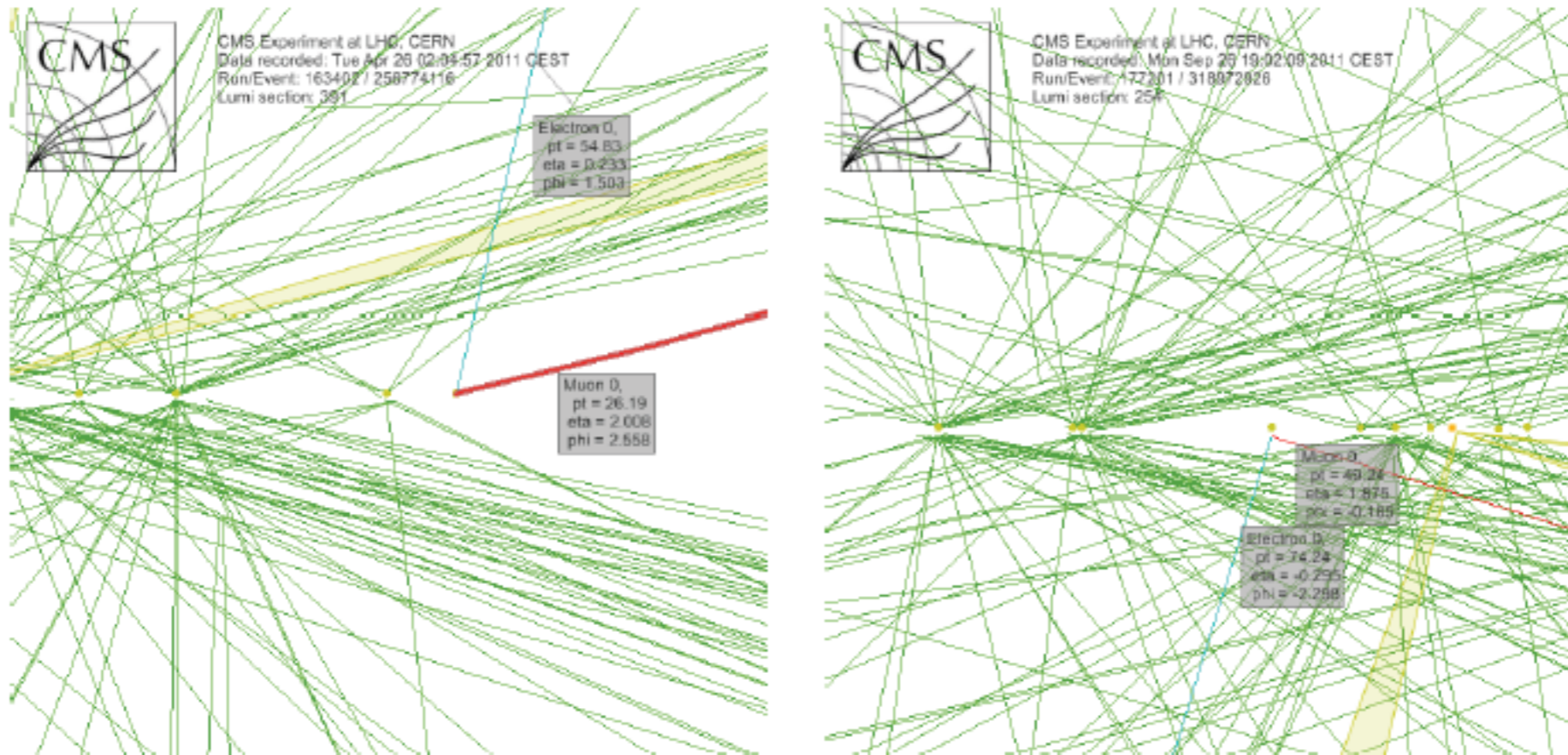


Figure 45: Event displays of the two events passing all selection criteria with $p_T(\mu^\pm e^\mp) > 30$ GeV.



$$\gamma\gamma \rightarrow W^+ W^-$$

CMS PAS FSQ-12-010

	Uncertainty
Trigger and lepton identification	4.2%
Luminosity	2.2%
Vertexing efficiency	1.0%
Exclusivity and pile-up dependence	10.0%
Proton dissociation factor	20.0%

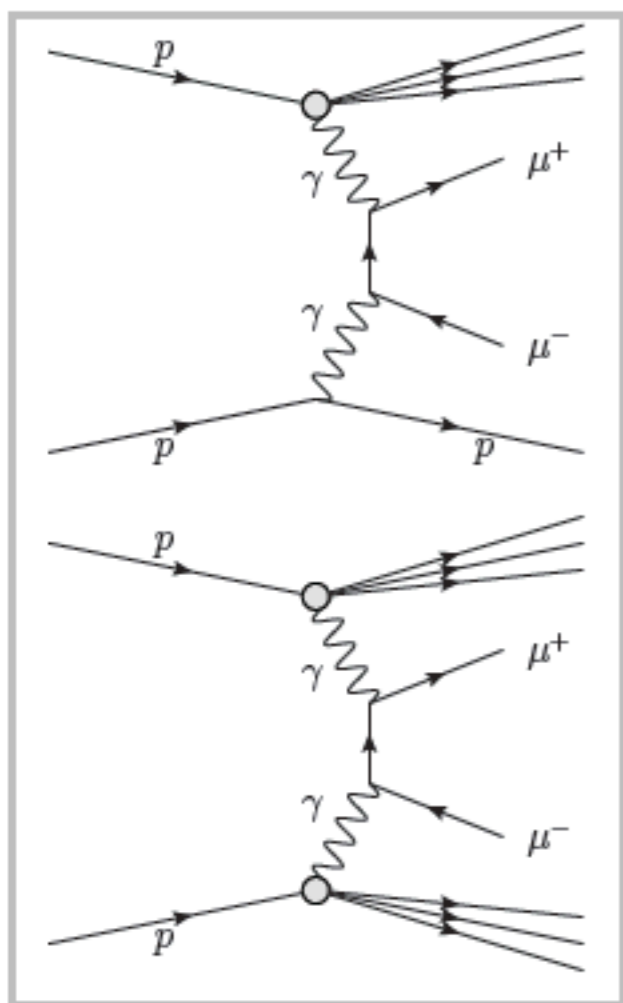
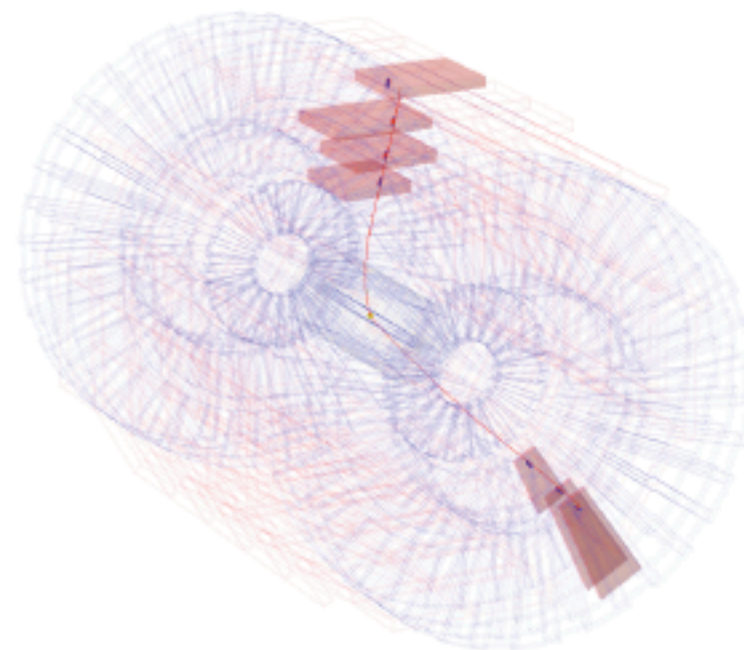
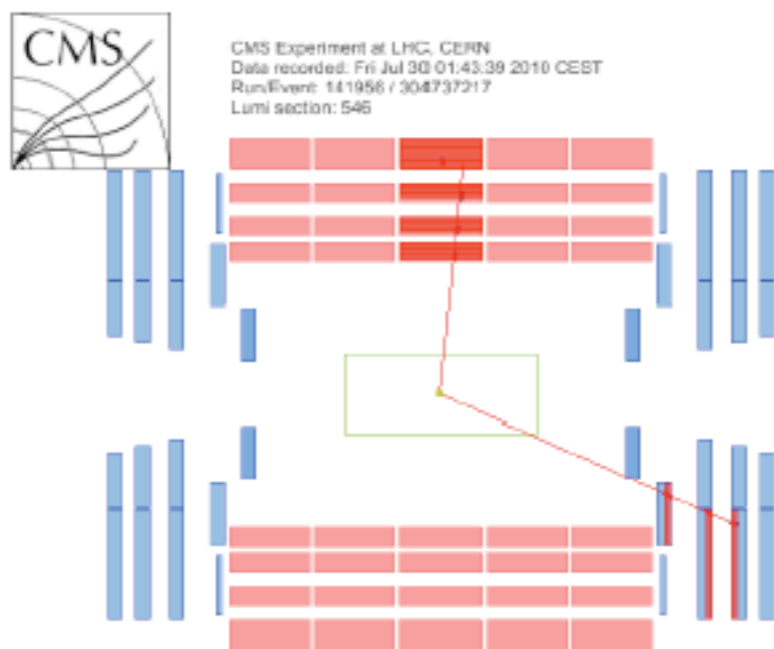
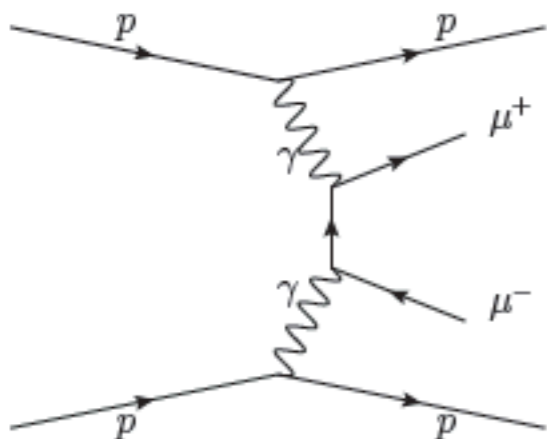
Table 4: Summary of systematic uncertainties affecting the signal.



Exclusive production: $\gamma\gamma \rightarrow \mu^+\mu^-/e^+e^-$

CMS FWD-10-005

[*J. High Energy Phys.* 01 \(2012\) 052](#)



Exclusive two-photon events: 2 muons/electrons and *nothing else*

Main background to pure QED process from single and double proton dissociation processes, where the proton fragments in a low mass state

Standard candle for exclusive processes at the LHC

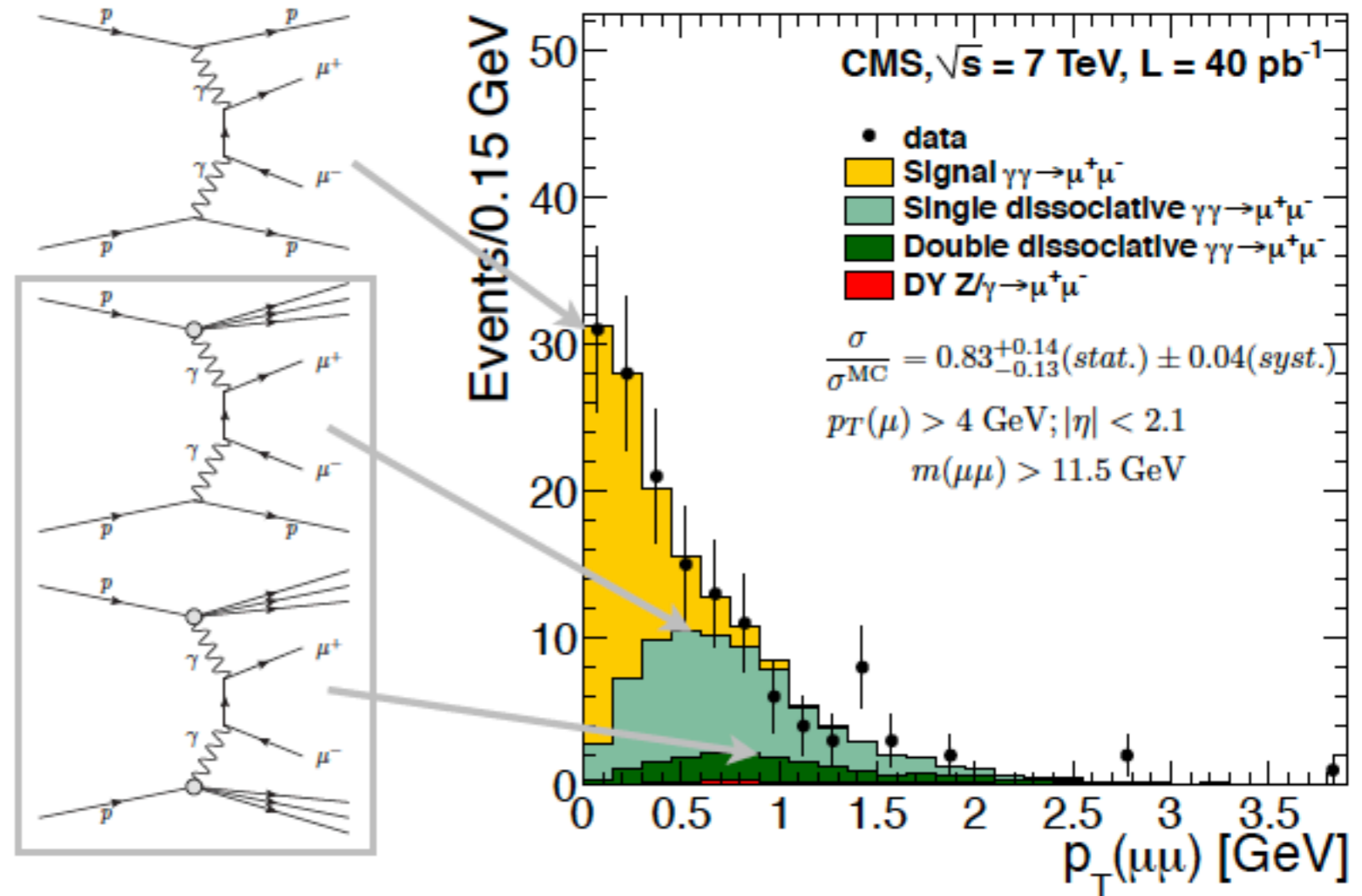
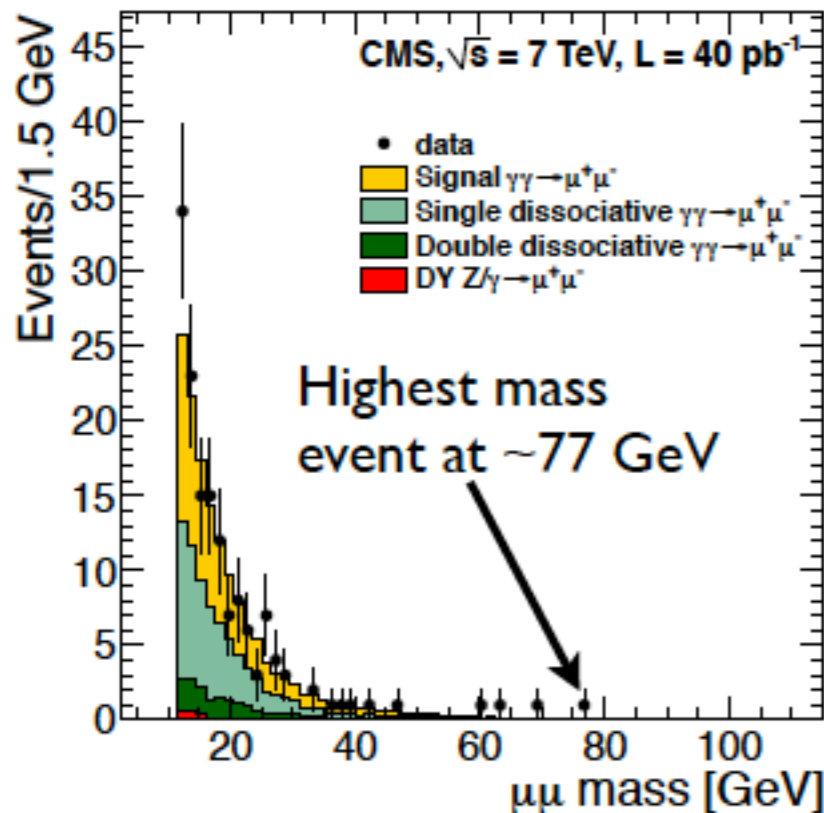


Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production

Measurement restricted to well controlled kinematic region ($p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$), rejecting Υ photo-production

Exclusivity condition requires a primary vertex with exactly 2 muons and no other track within 2 mm

Signal extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution



$$\sigma(p + \mu\mu + p) = 3.38^{+0.58}_{-0.55}(stat.) \pm 0.16(syst.) \pm 0.14(lum.) \text{ pb}$$

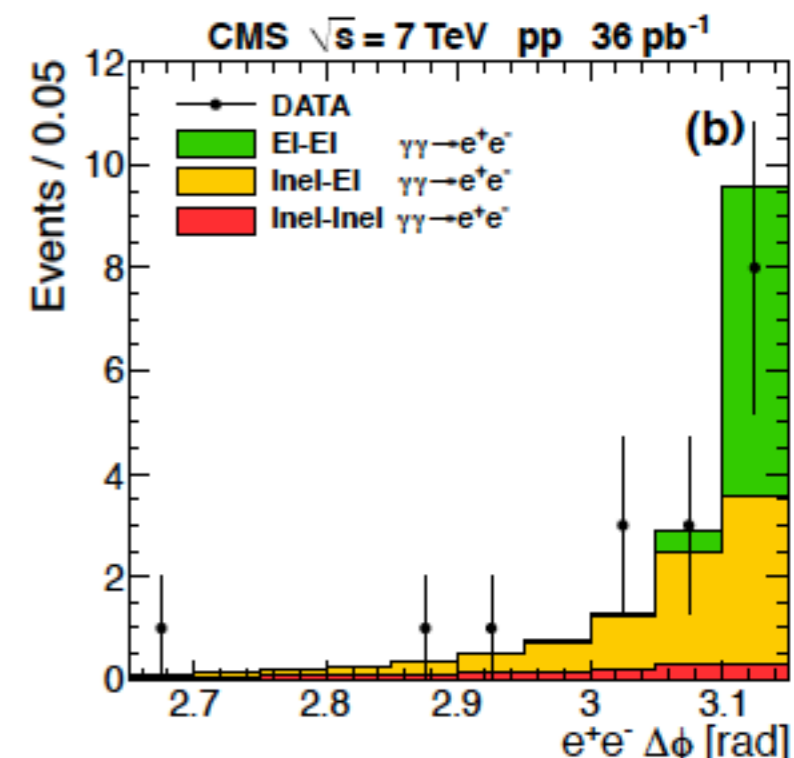
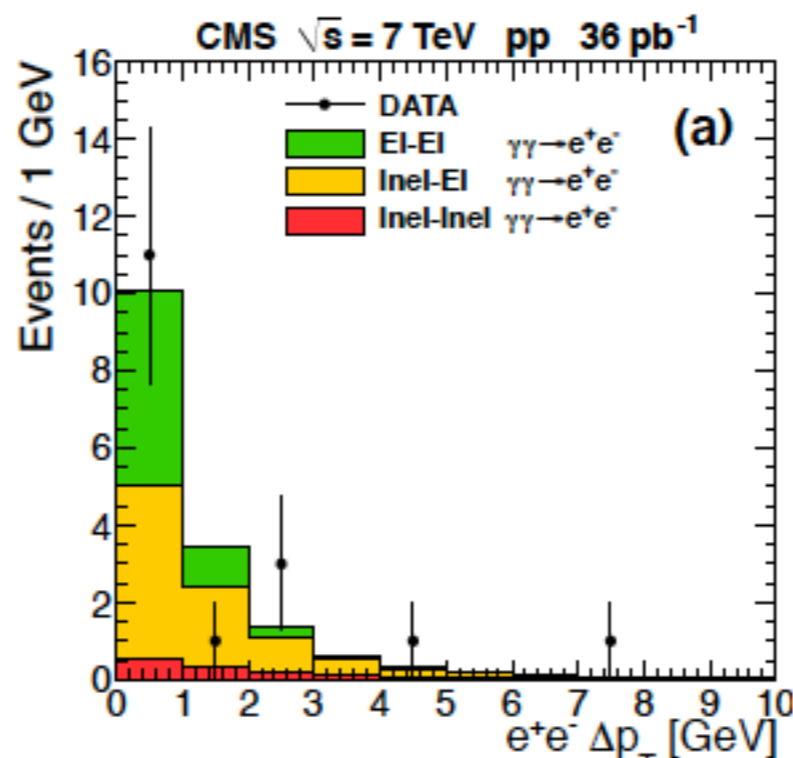
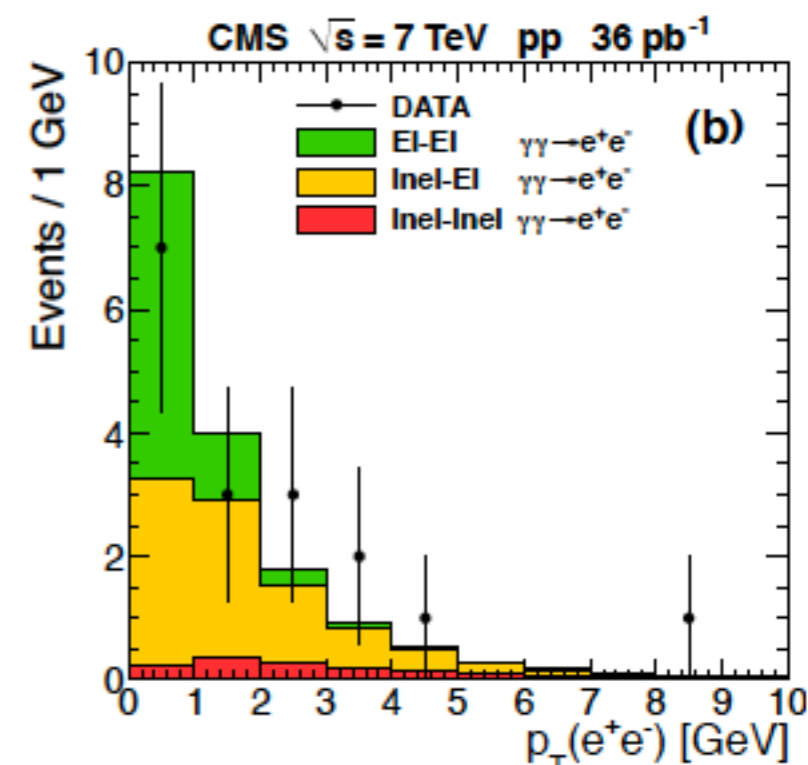
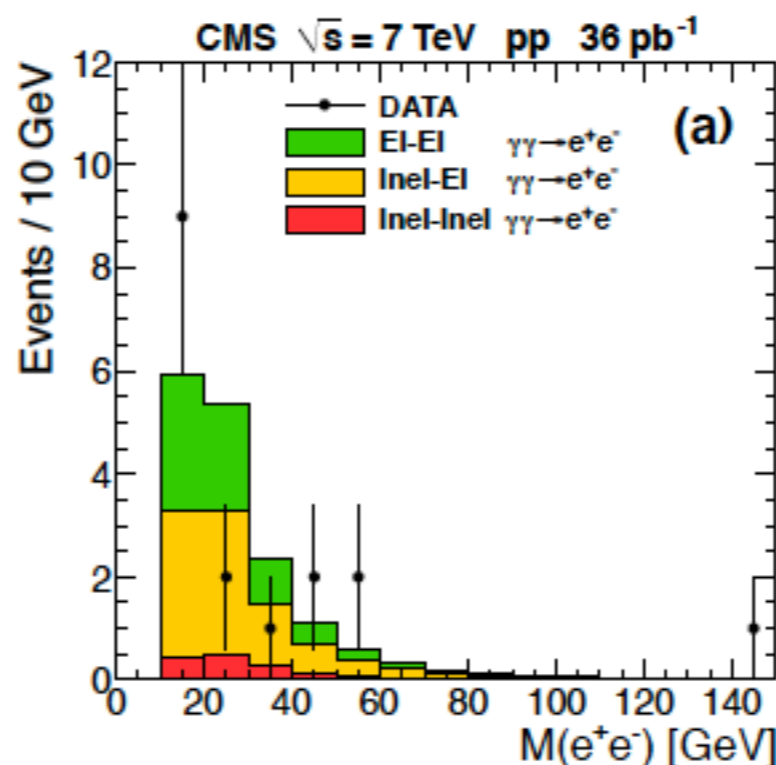
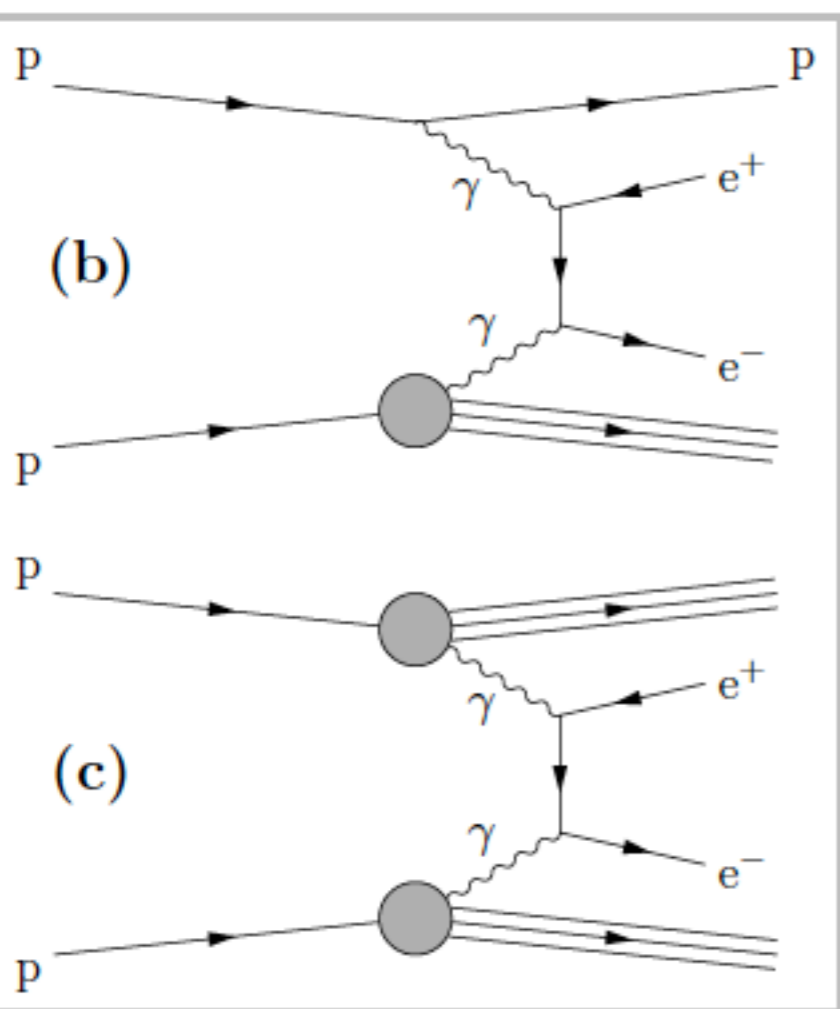
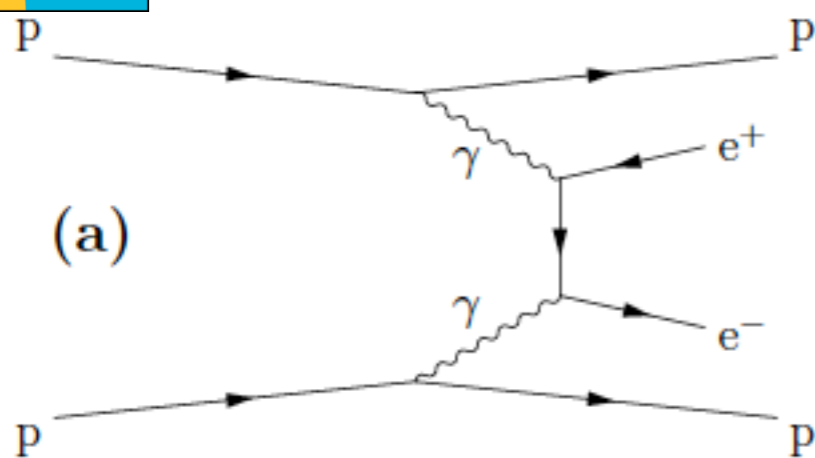
Largest systematics from track veto efficiency (data driven - pile-up sensitive)

Good agreement between data and LPAIR MC (signal and proton dissociation)

Potential for luminosity monitor at the LHC



Exclusive $\gamma\gamma \rightarrow e^+e^-$ production



CMS FWD-I I-004

J. High Energy Phys. 11 (2012) 080



Diffraction Di-jets Cross Section



[CMS-FWD-10-004](#)
[PRD 87 \(2013\) 012006](#)

TABLE I. Monte Carlo generators used in this work with details on their model ingredients.

Model	PDF	dPDF	Parameter tune	Process
PYTHIA6	CTEQ6L1	none	Z2, D6T	Nondiffractive jets
PYTHIA8	CTEQ5L	H1 fit B	Tune 1	Diffraction plus nondiffractive jets
POMPYT	CTEQ6L1	H1 fit B	PYTHIA6 D6T	Diffraction jets only
POMWIG	CTEQ6L1	H1 fit B	HERWIG	Diffraction jets only
POWHEG	CTEQ6M	H1 fit B	PYTHIA8 tune 1	Diffraction jets only



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Diffraction Di-jets Cross Section

TABLE II. Contributions to the systematic uncertainty on the dijet cross section in the three lowest $\tilde{\xi}$ bins considered. The total systematic uncertainty calculated as the quadratic sum of the individual contributions is given in the last row.

Uncertainty source	$0.0003 < \tilde{\xi} < 0.002$	$0.002 < \tilde{\xi} < 0.0045$	$0.0045 < \tilde{\xi} < 0.01$
1. Jet energy scale	(+ 26; -19)%	(+ 21; -20)%	(+ 28; -16)%
2. Jet energy resolution	(+ 6; -4)%	(+ 4; -3)%	(+ 3; -2)%
3. PF energy, p_T threshold, C	(+ 7; -15)%	(+ 14; -8)%	(+ 12; -11)%
4. MC model uncertainty	(+ 5; -3)%	(+ 2; -14)%	(+ 3; -1)%
5. One-vertex selection	(+ 6; -0)%	(+ 0; -1)%	(+ 1; -0)%
6. Jet objects (Calorimeter, PF)	(+ 0; -4)%	(+ 0; -4)%	(+ 2; -4)%
7. $\tilde{\xi}^+$, $\tilde{\xi}^-$ difference	$\pm 8\%$	$\pm 8\%$	$\pm 11\%$
8. Trigger efficiency	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
9. Luminosity	$\pm 4\%$	$\pm 4\%$	$\pm 4\%$
Total error	(+ 30; -26)%	(+ 27; -29)%	(+ 33; -23)%



Soft Diffraction Cross Sections

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Systematic Uncertainties

- HF energy scale: varied in MC by $\pm 10\%$.
- PF energy thresholds: raised by 10% .
- CASTOR energy scale: changed in MC by $\pm 20\%$.
- CASTOR energy threshold in each sector: changed from 4σ to 3.5σ and 4σ to 5σ , where σ is the pedestal width;
- CASTOR alignment uncertainty: systematic uncertainties of 8% and 2% are added to the measurements of the DD and SD cross sections with and without a CASTOR tag, respectively.
- trigger efficiency uncertainty: estimated from a comparison of the efficiency curves between data (measured using the Zero-Bias sample) and MC.
- hadronization and diffraction model: the hadronization parameters in the nominal PYTHIA8-MBR MC sample are tuned to describe the multiplicity and p_T spectra of diffractive systems [10]. The uncertainty in hadronization is evaluated by comparing with the PYTHIA8-4C simulation and symmetrizing the differences wrt the nominal analysis. This procedure takes also into account the difference between diffraction models of PYTHIA8-MBR and PYTHIA8-4C.
- background subtraction: backgrounds from DD and ND in SD and from ND in DD events are obtained from the PYTHIA8-MBR predictions (cf. Fig. 6), with the uncertainty estimated by varying their relative contributions by -10% and $+10\%$. Contribution from SD in DD and from CD in SD and DD are negligible.
- an uncertainty in luminosity measurement of $\pm 4\%$ is taken into account.