Exclusive production in CMS

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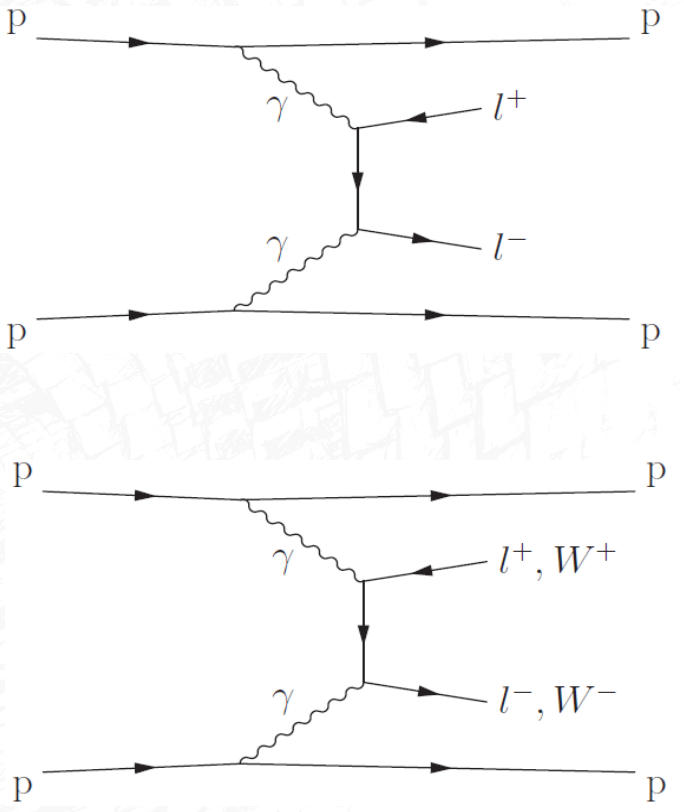
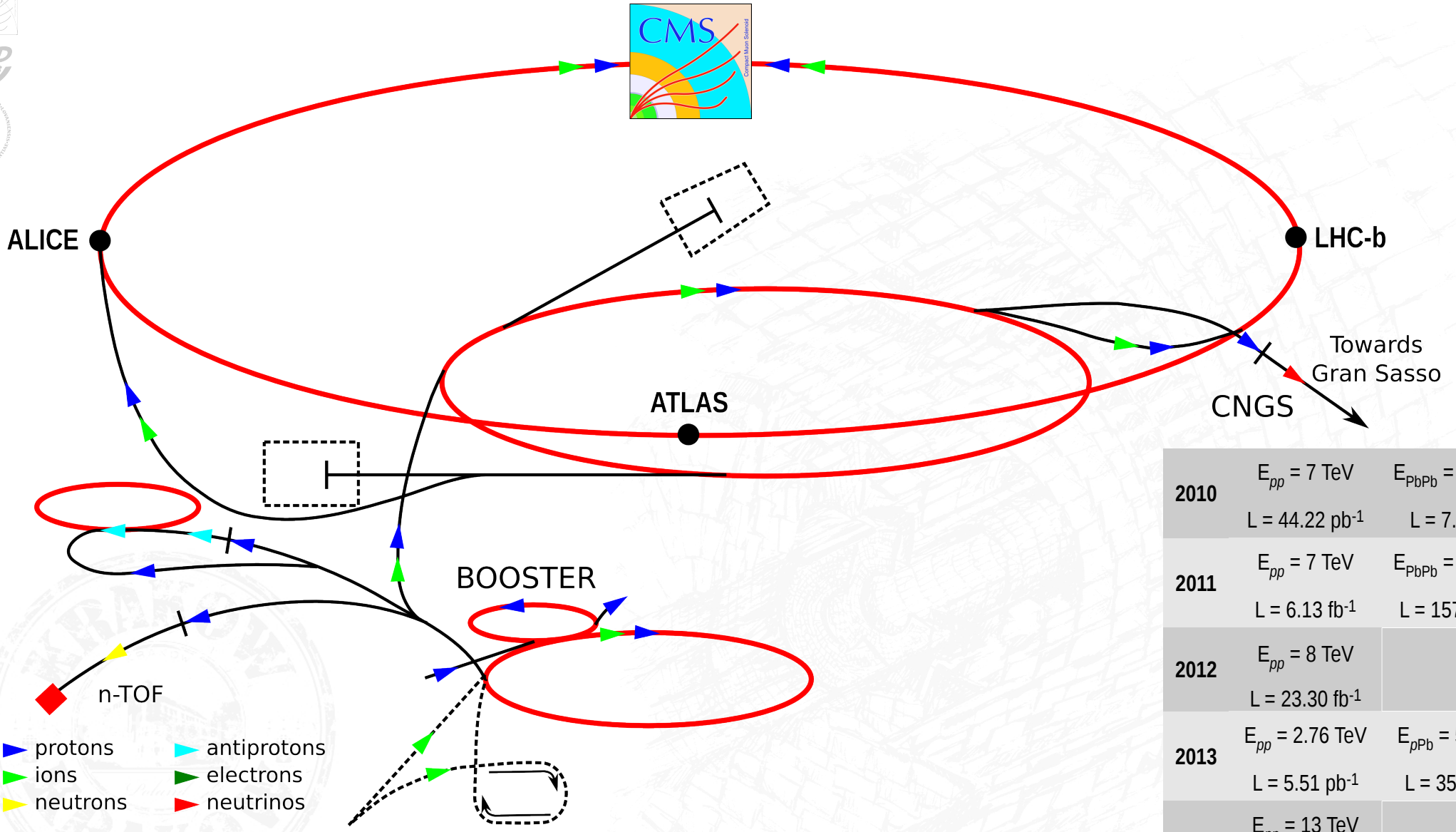
on behalf of the CMS Collaboration

Outline

- CMS detector and capabilities for forward physics;
- Possibilities of meson photo-production in CMS;
- Probing central exclusive processes at high-energies;
  - Measurement of exclusive $\gamma\gamma \to e^+e^-$, $\mu^+\mu^-$ production;
- Measurement of exclusive $\gamma\gamma \to \mu^+\mu^-$ at large masses;
- Exclusive production of massive electroweak-boson pairs;
  - Search for exclusive $\gamma\gamma \to W^+W^-$ production;
  - Limits on anomalous quartic gauge couplings.



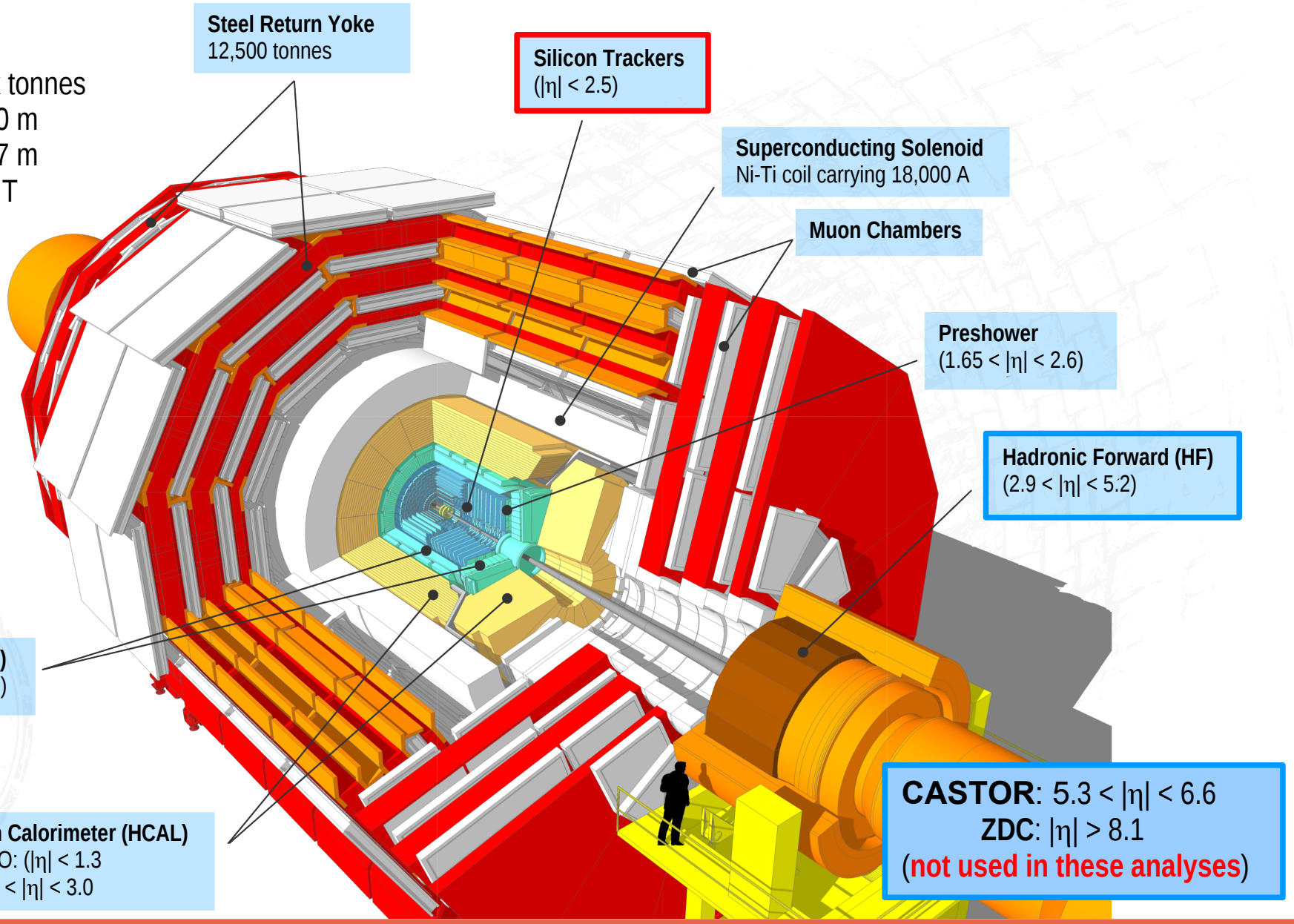
Large Hadron Collider



2010	E_{pp} = 7 TeV L = 44.22 pb^{-1}	E_{PbPb} = 2.76 TeV L = 7.00 μb^{-1}
2011	E_{pp} = 7 TeV L = 6.13 fb^{-1}	E_{PbPb} = 2.76 TeV L = 157.57 μb^{-1}
2012	E_{pp} = 8 TeV L = 23.30 fb^{-1}	-
2013	E_{pp} = 2.76 TeV L = 5.51 pb^{-1}	E_{pPb} = 5.02 TeV L = 35.50 nb^{-1}
2015	E_{pp} = 13 TeV L ~ 50.00 fb^{-1}	(expected)

The CMS experiment

Total weight : 14k tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



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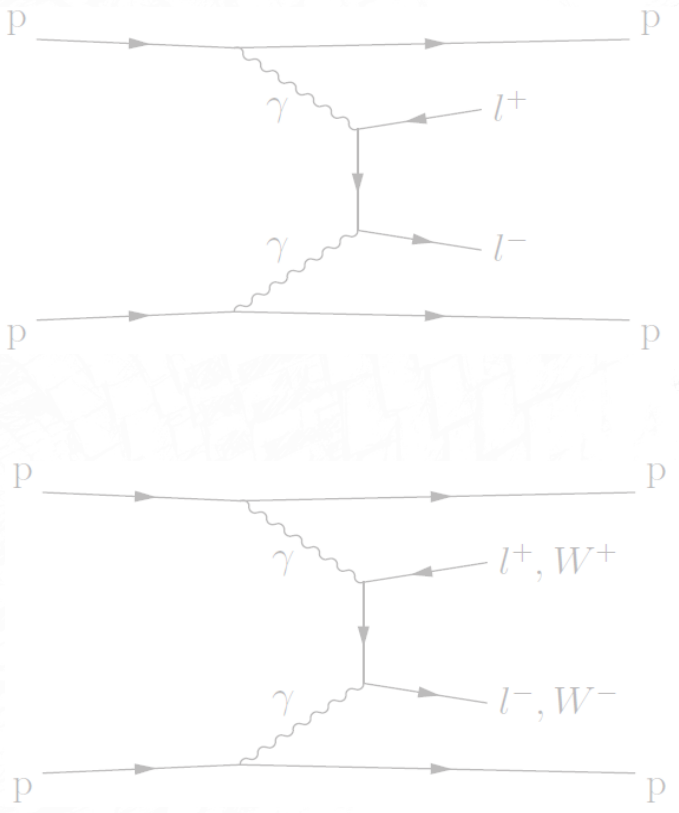
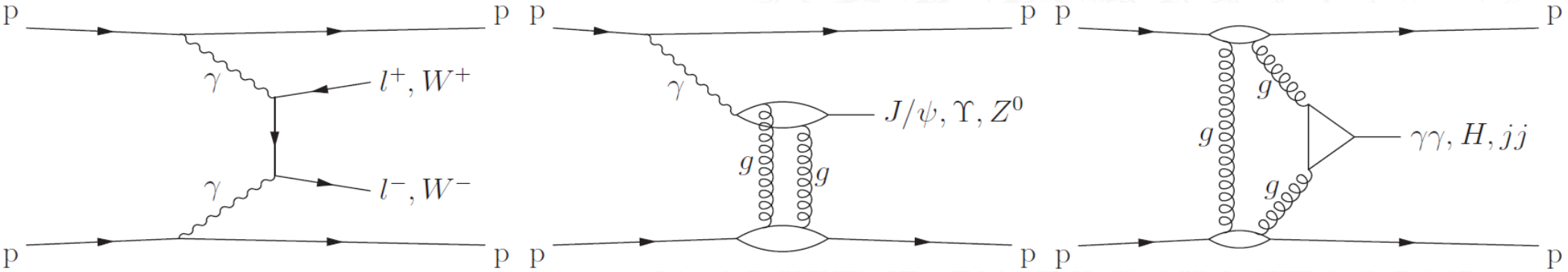


Exclusive processes at the LHC

- The exclusive production of light and heavy pairs is represented by:

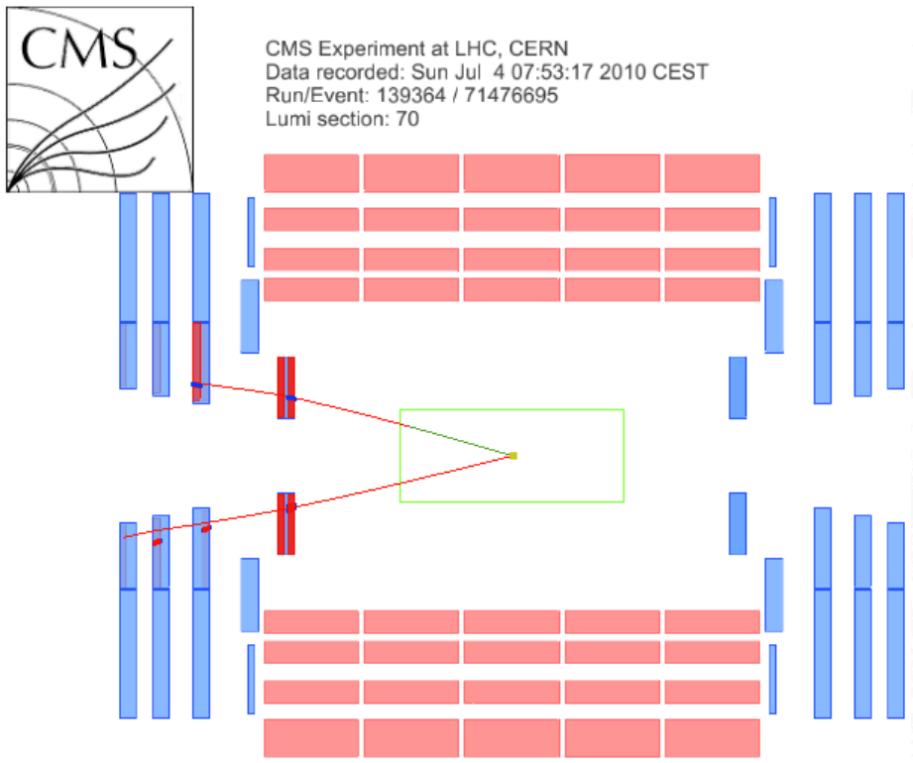
$$pp \rightarrow p^{(*)} + (\gamma\gamma, \ell^+\ell^-, \mathrm{W}^+\mathrm{W}^-) + p^{(*)}$$

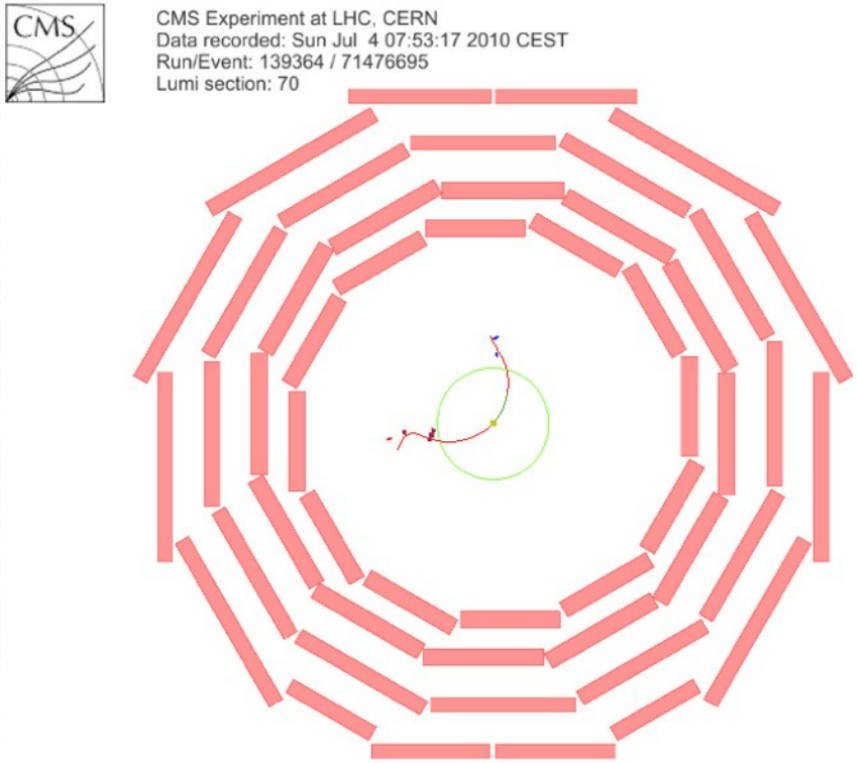


- Intact protons in the final states, however also accounting for **proton dissociation p^***;
- **No other particles in the final states**;
- $\gamma\gamma$: tests for theoretical prediction for **exclusive Higgs production** and to measure **gluon density at small-x**;
- $\ell^+\ell^-$: comparison to precision QED predictions and to study of **proton dissociation**;
- $\mathrm{W}^+\mathrm{W}^-$: study of exclusive processes at high mass and constraint of **anomalous couplings**.

Meson photo-production in CMS: $J/\psi \rightarrow \mu^+\mu^-$

- Simulation with exactly 2 opposite-sign muon tracks with no other tracks;
- Consider exclusivity cuts of $\Delta\phi(\mu\mu)/\pi > 0.9$ and $\Delta p_T(\mu\mu) < 1.5$ GeV.

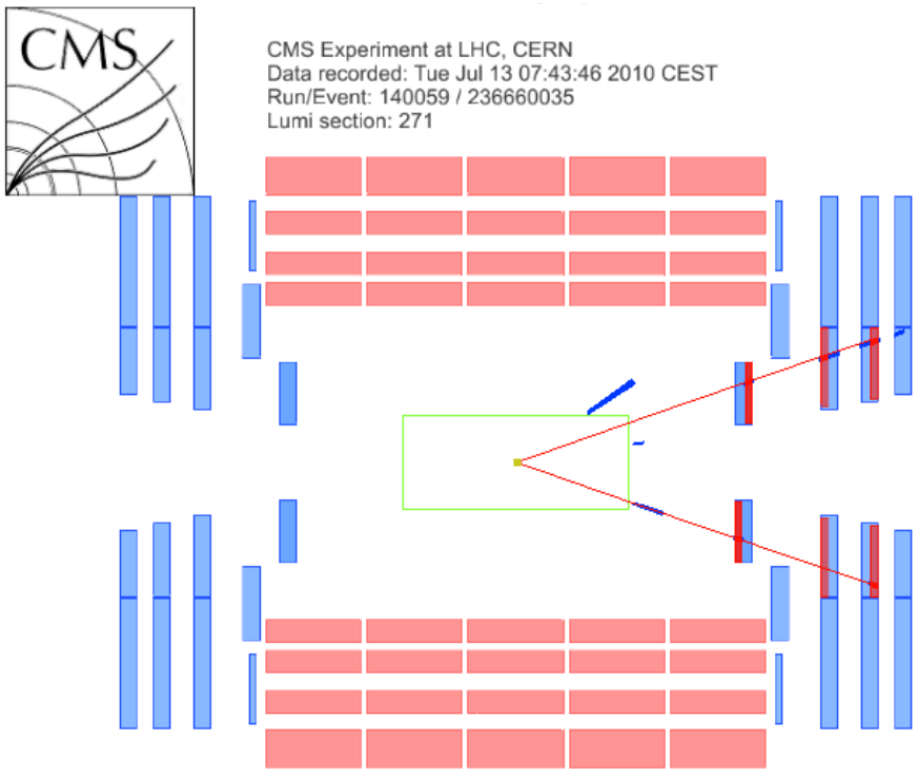


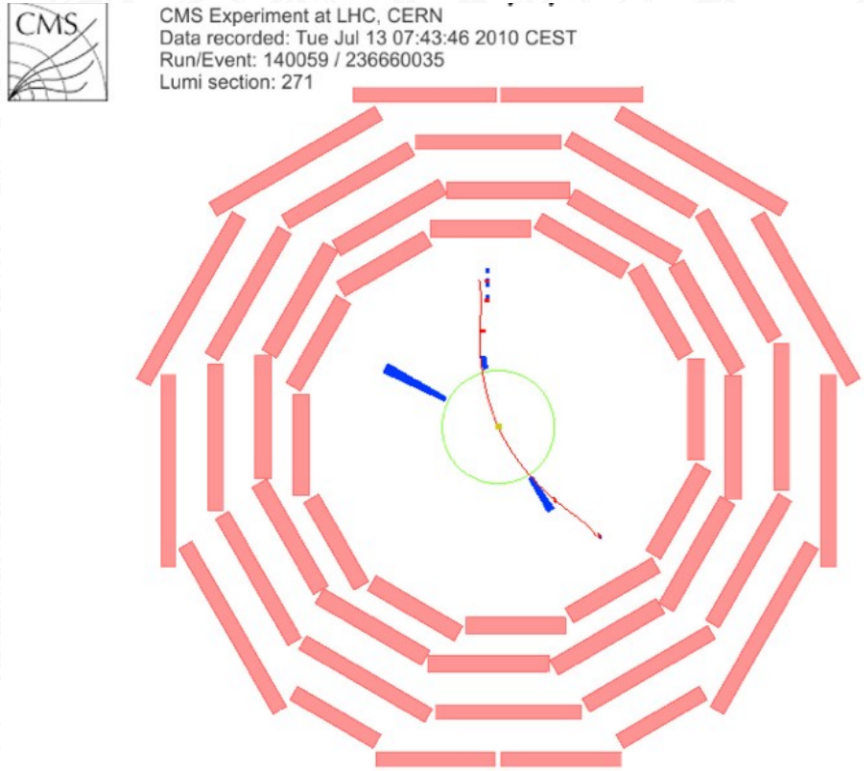


m = 3.05 ± 0.03 GeV	$\Delta\phi(\mu\mu)/\pi$ = 0.98	$\Delta p_T(\mu\mu)$ = 0.05 GeV
Track: p_T > 0 GeV	HCAL: E > 4 GeV	ECAL: E > 2.5 GeV

Meson photo-production in CMS: $\Upsilon \rightarrow \mu^+\mu^-$

- Studies in the **Upsilon mass** range with exactly 2 opposite-sign muon tracks with no other tracks in the event;
- Consider exclusivity cuts of $\Delta\phi(\mu\mu)/\pi > 0.9$ and $\Delta p_T(\mu\mu) < 1.5$ GeV.

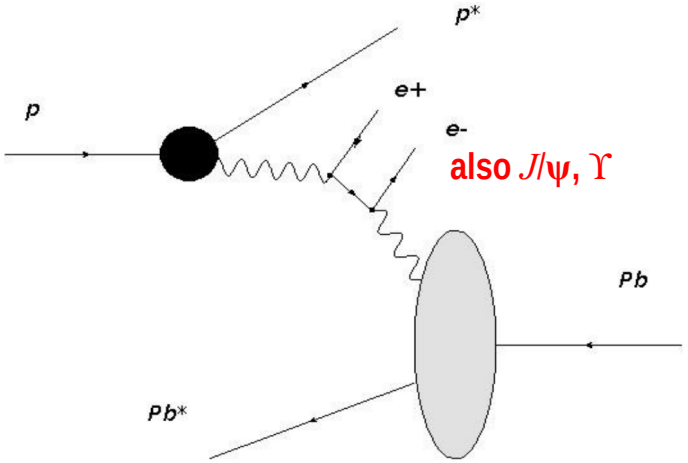




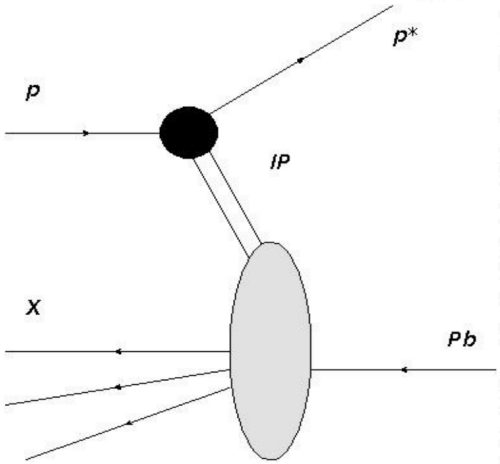
m = 9.44 ± 0.08 GeV	$\Delta\phi(\mu\mu)/\pi$ = 0.99	$\Delta p_T(\mu\mu)$ = 0.20 GeV
Track: p_T > 0 GeV	HCAL: E > 4 GeV	ECAL: E > 2.5 GeV

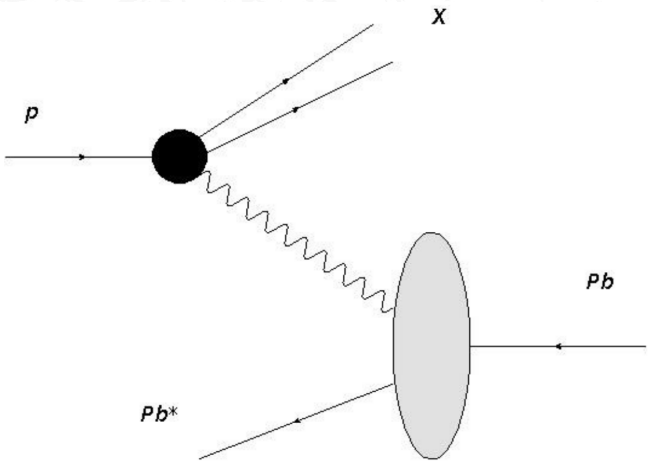
Future prospects in *p*-Pb collisions

- Possibility of parallel data taking of CMS and TOTEM;
  - Combination of CMS **central detector** and TOTEM **roman pots**.

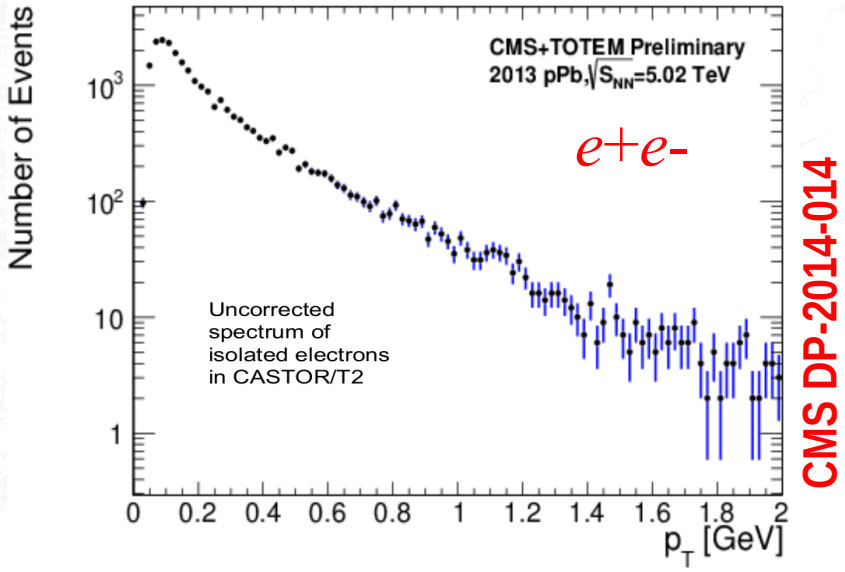


also J/ψ, Υ





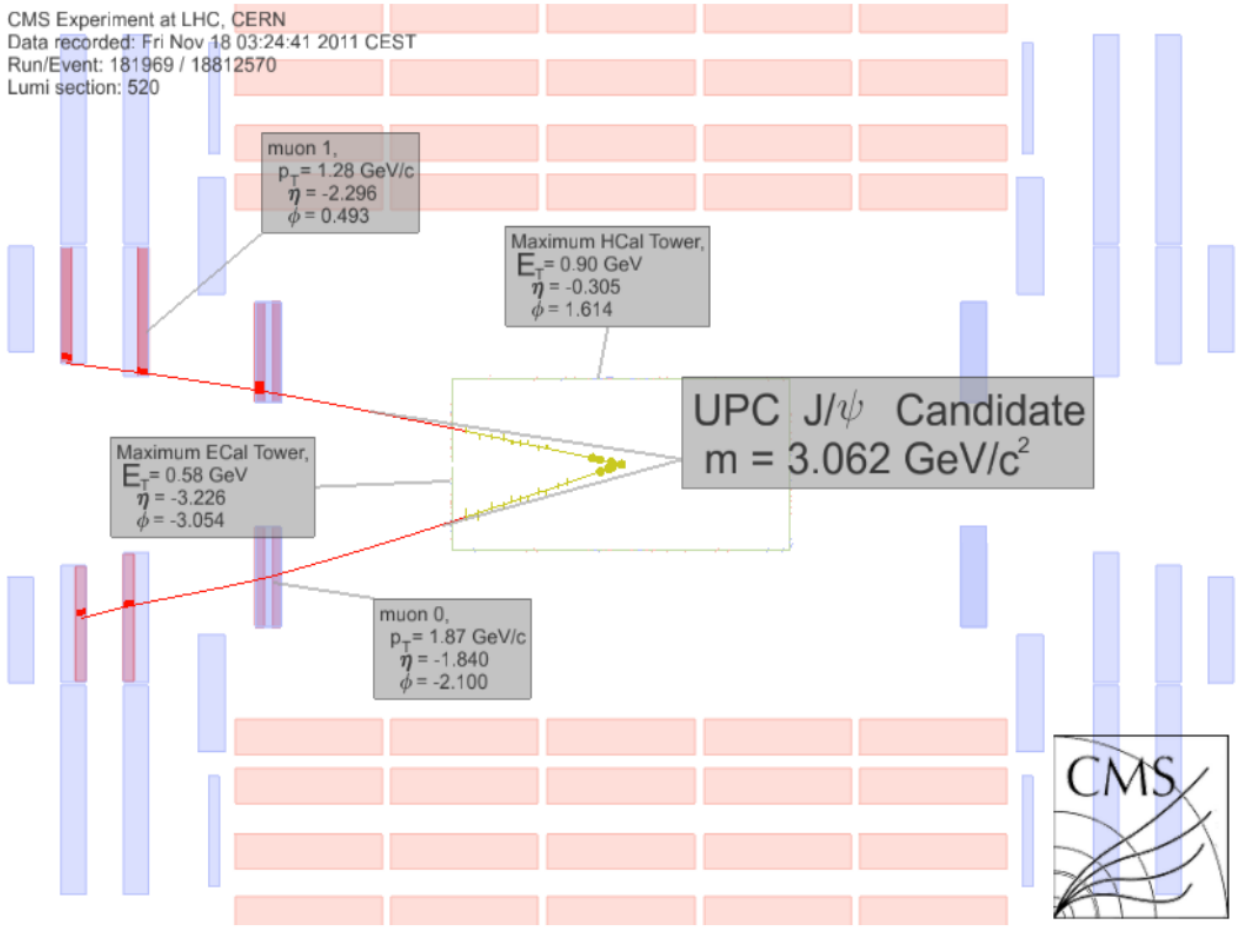
- Photo-nuclear processes can be measured by the activity in the central detector and no activity in the forward calorimeter and ZDC;
  - Pb beam **intact** after interaction with proton break-up.



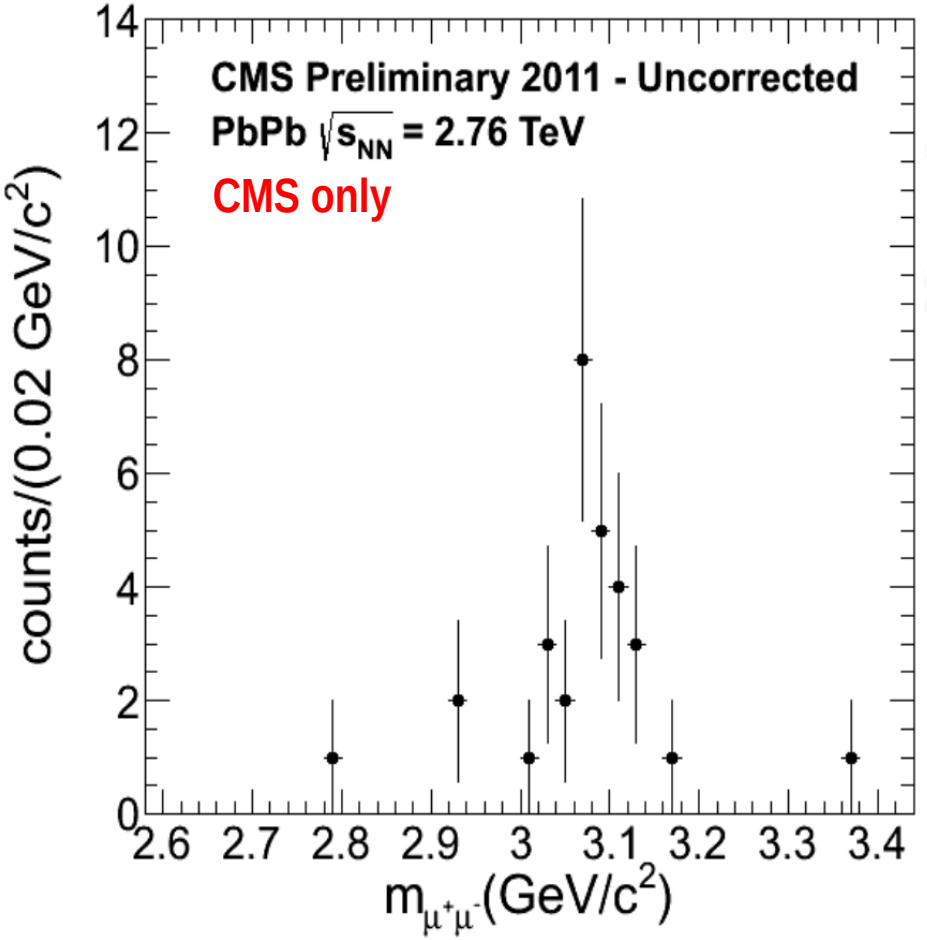
From presentation by I. Katkov, PhotonLHC 2014

Future prospects in Pb-Pb collisions

- Possibility of measurements in CMS with **foward calorimeter**;
  - Data can be obtained with single muon trigger and with the ZDC information.



CMS DP-2012-017



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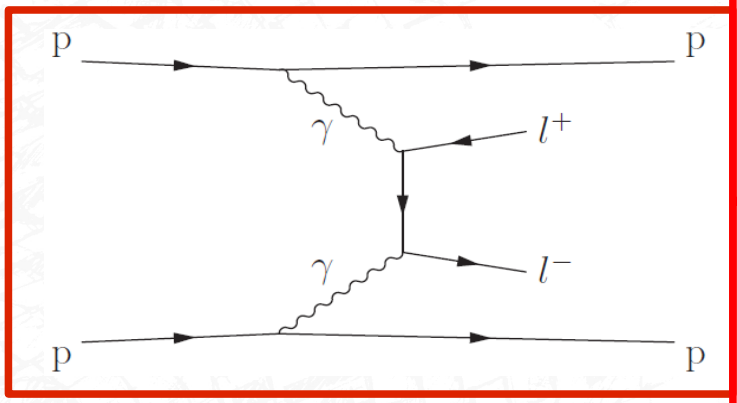

JHEP 11 (2012) 080

JHEP 01 (2012) 052

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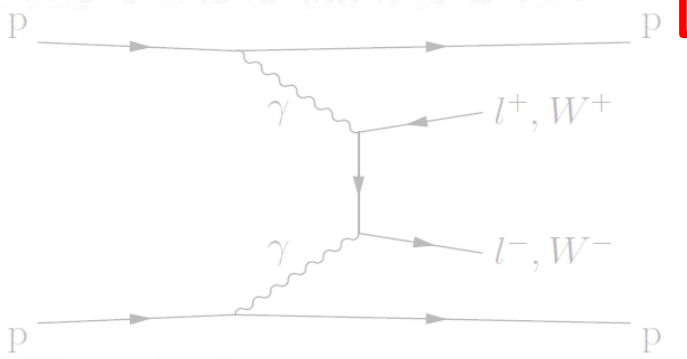
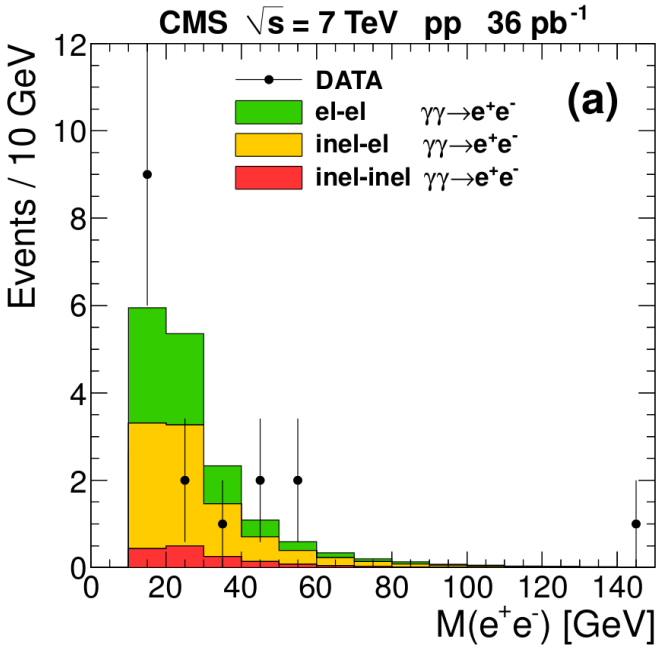
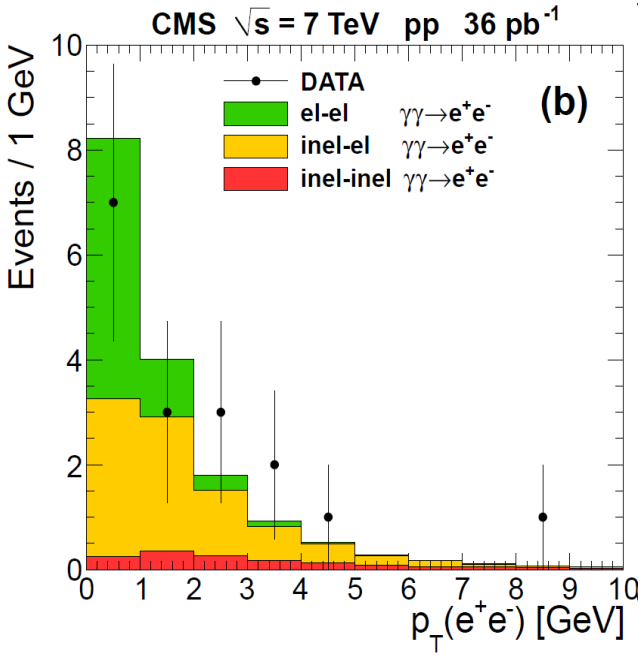
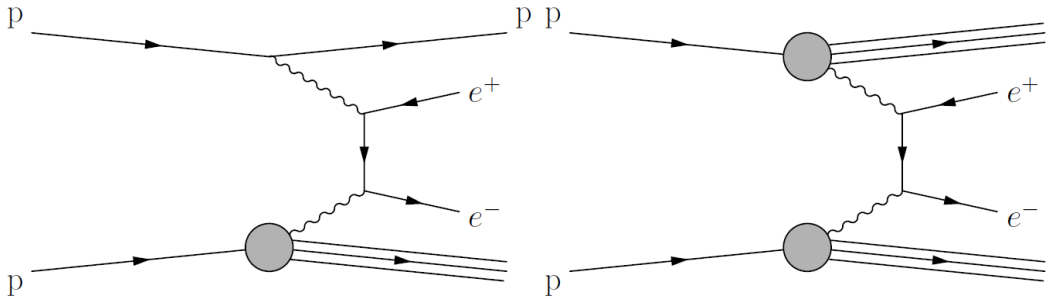


Exclusive production of e^+e^- pairs



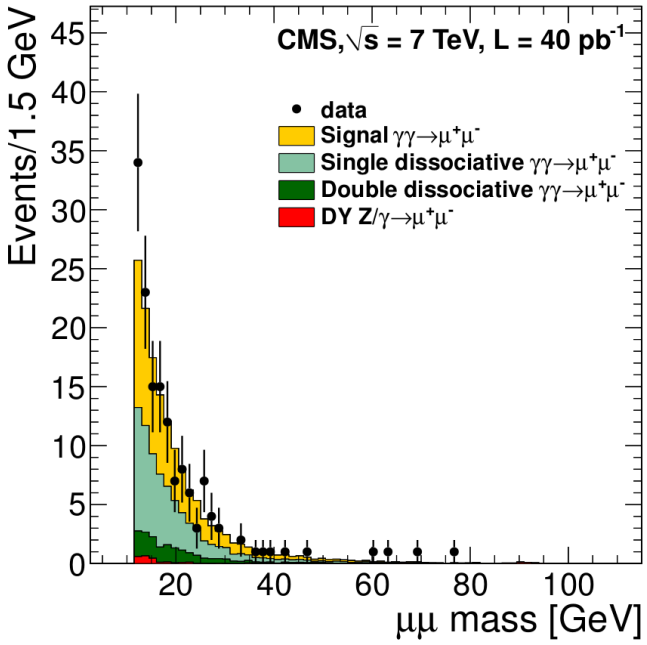


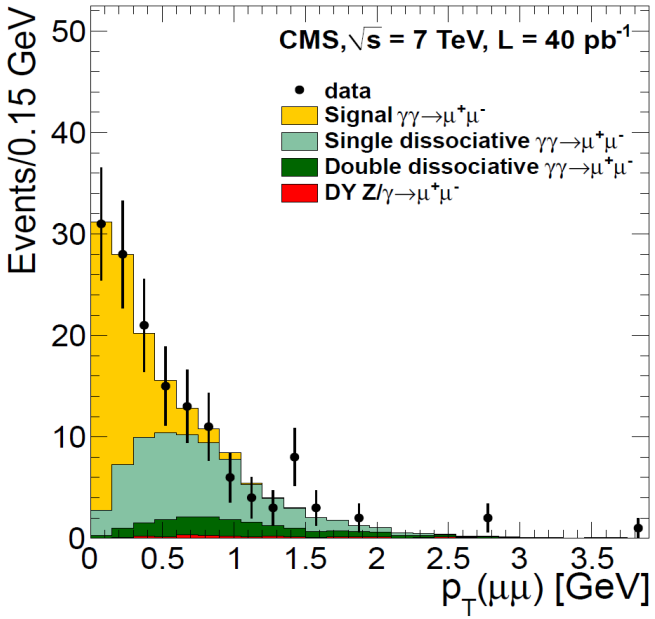
- Selection requires vertex with two leptons tracks & **nothing else**;
  - $E_T(e) > 5.5$ GeV and $|\eta(e)| < 2.5$;
  - No additional tracks in the Tracker;
  - No additional towers above noise threshold in the calorimeters.
- MC predictions include **elastic** processes and contribution from **proton dissociation**:



- In the exclusive production of e^+e^- pairs, it has been observed **17** (semi-)exclusive events in 36 pb^{-1};
- **Good agreement** between LPAIR and the data.

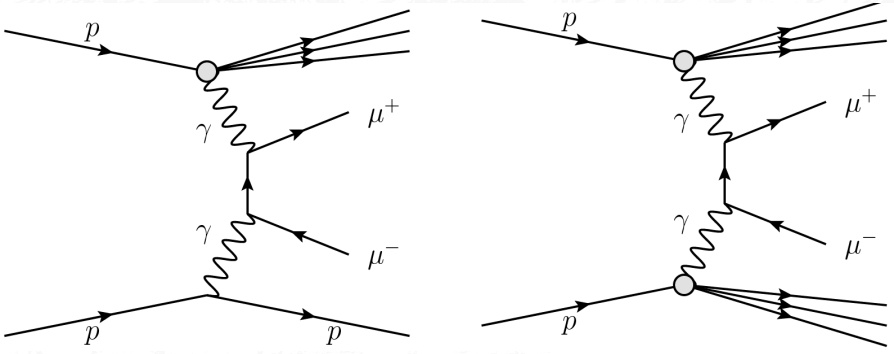
Exclusive production of $\mu^+\mu^-$ pairs



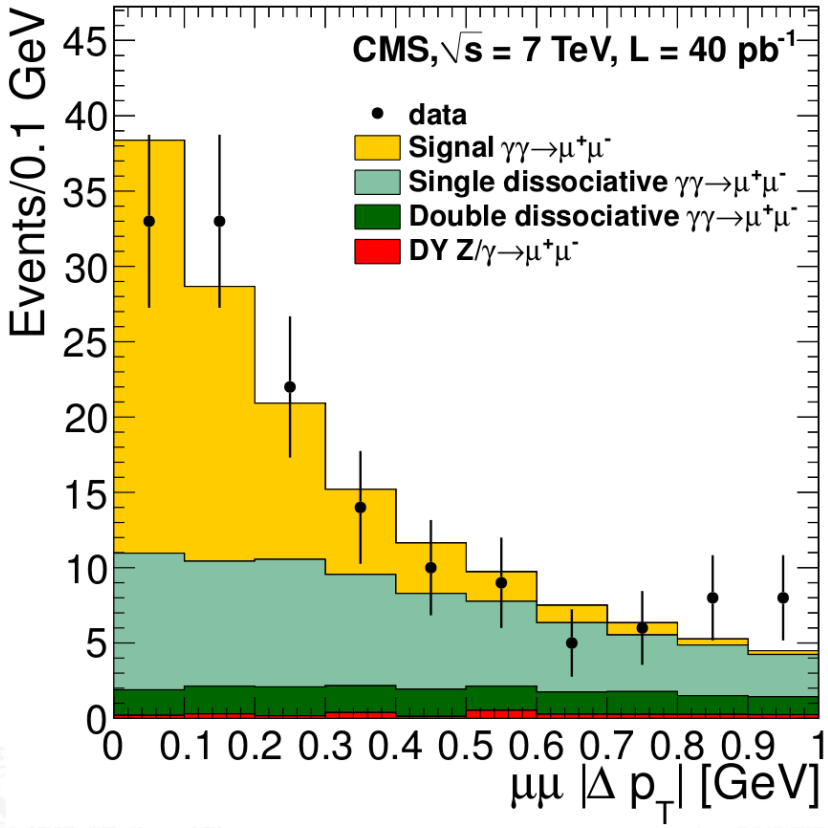


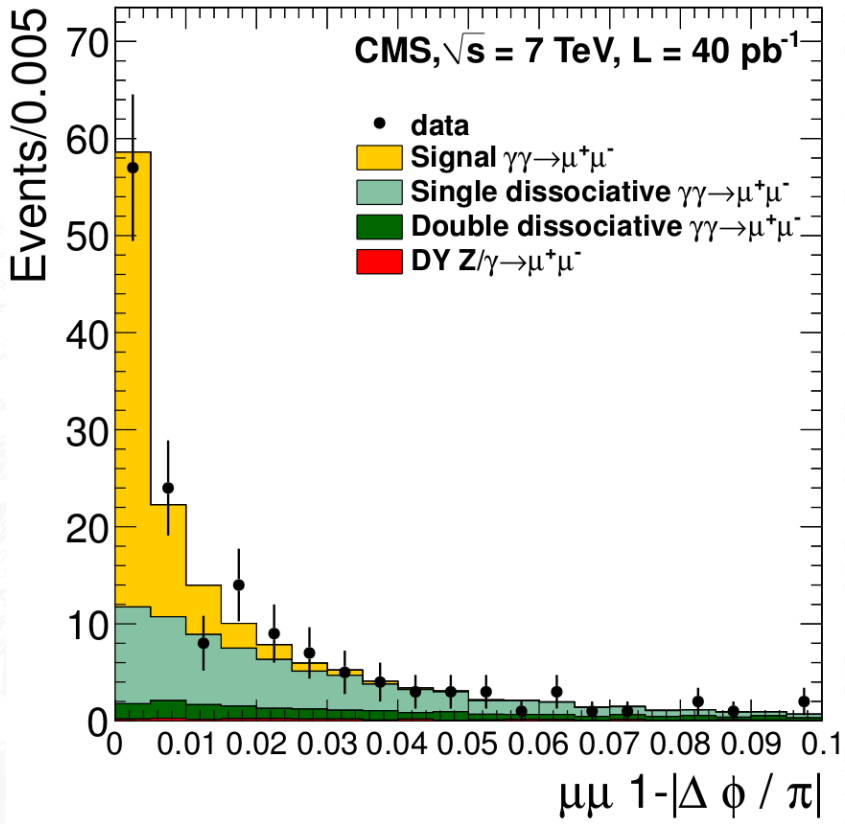
- Selection requires vertex with two leptons tracks & **nothing else**:
  - Information from the Pixel and Silicon Tracker;
  - $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$;
  - $m(\mu^+\mu^-) > 11.5$ GeV to neglect Υ resonances;
  - **Exclusivity cuts**: $1 - |\Delta\varphi/\pi| < 0.1$ and $|\Delta p_T| < 1.0$ GeV

- The contribution from **proton dissociation** is included:



Cross section for $\mu^+\mu^-$ pair production





- Measurement of exclusive $\mu^+\mu^-$ pairs results in 40 pb^{-1}:

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

- **Good agreement** between LPAIR and the data in the whole kinematic region.

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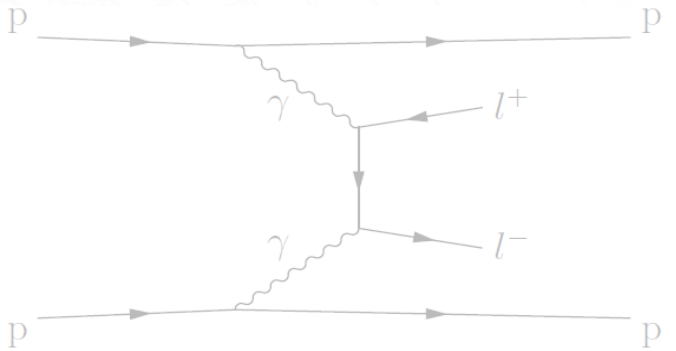

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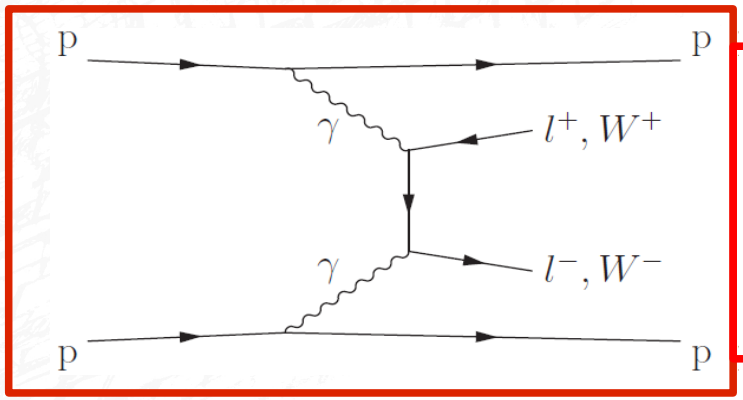


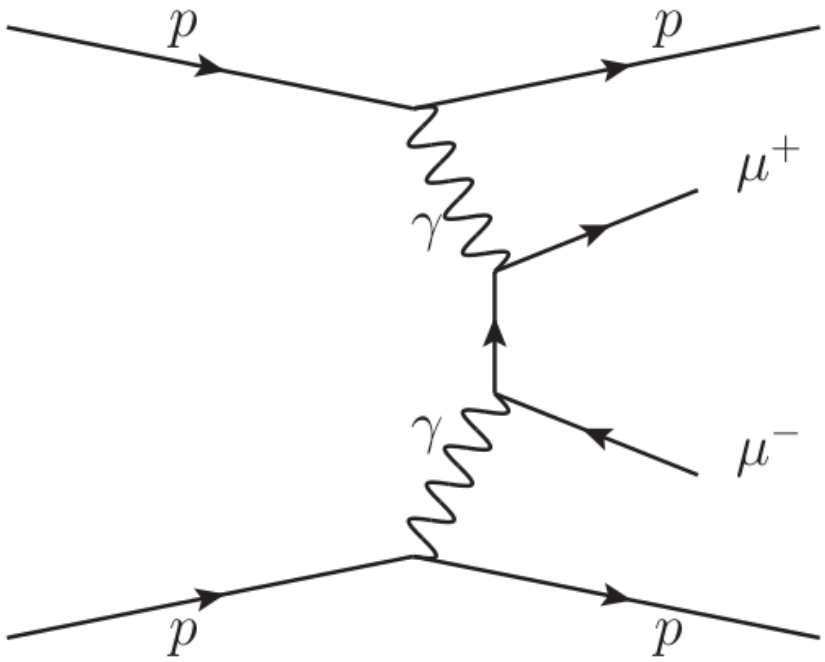
JHEP 07 (2013) 116

Selection for $\mu^+\mu^-$ events at large mass

- Data collected in 2011 by the CMS detector at 7 TeV:
  - Events with opposite-sign muons corresponding to **5.24 fb^{-1}**.

- Muons are selected with the requirements:
  - $p_T(\mu) > 15$ GeV and $|\eta(\mu)| < 2.4$;
  - $m(\mu^+\mu^-) > 20$ GeV and $p_T(\mu^+\mu^-) > 30$ GeV;

- An exclusivity selection is applied to each event:
  - $p_T(\mu)$ balance below 1 GeV;
  - Back-to-back leptons with $\Delta\varphi(\mu\mu) > 0.9\pi$
  - **No extra tracks** in the vertex apart of the leptons.



Measurement of $\gamma\gamma \rightarrow \mu^+\mu^-$

- The study is performed in **two different kinematic regions** in order to discritminate the dominant contributions of elastic and inelastic interactions;

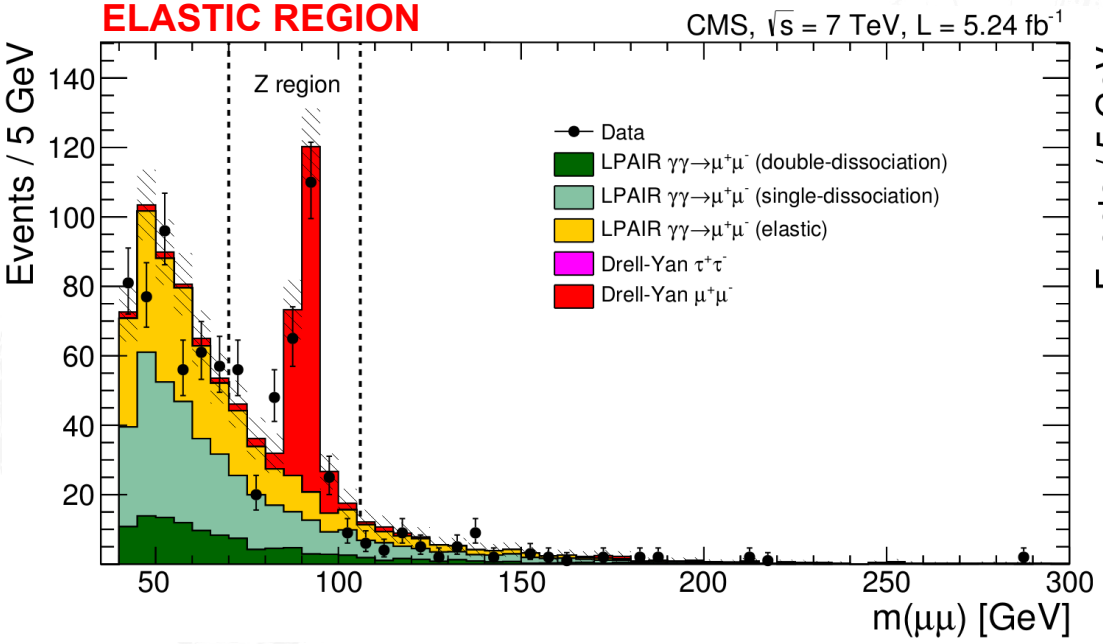
- The regions are defined as follows:

Good agreement with LPAIR

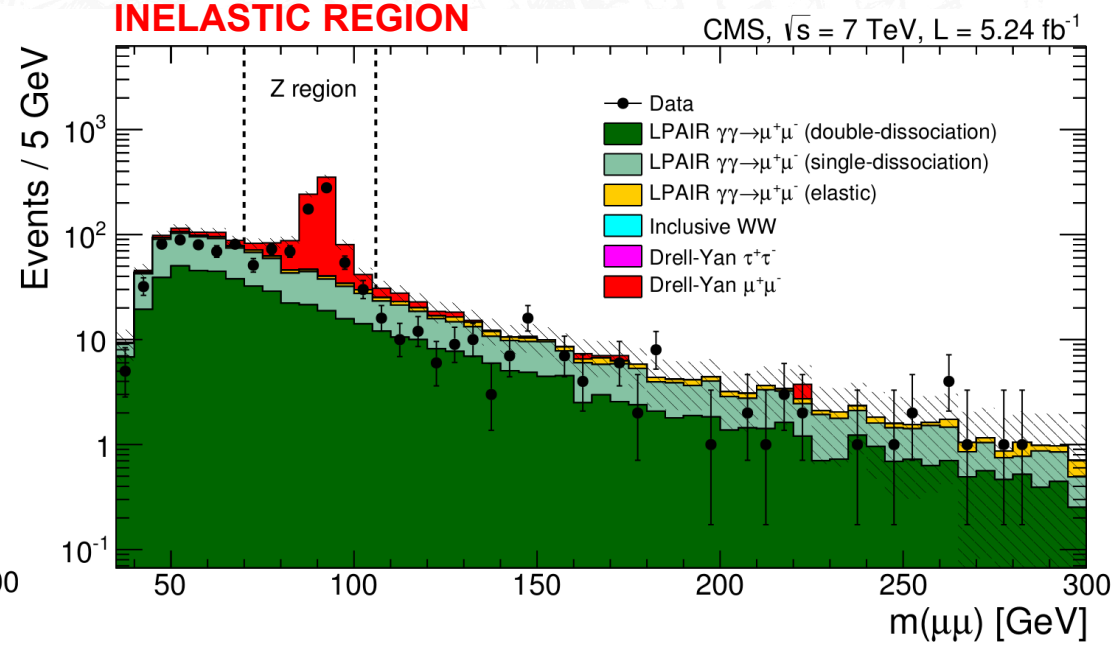
Elastic	Inelastic (quasi-exclusive)
$1-\lvert\Delta\varphi(\mu^+\mu^-)/\pi\rvert < 0.1$ $\lvert\Delta p_T(\mu^+\mu^-)\rvert < 1.0$	$1-\lvert\Delta\varphi(\mu^+\mu^-)/\pi\rvert > 0.1$ $\lvert\Delta p_T(\mu^+\mu^-)\rvert > 1.0$

Dissociation dominates

ELASTIC REGION

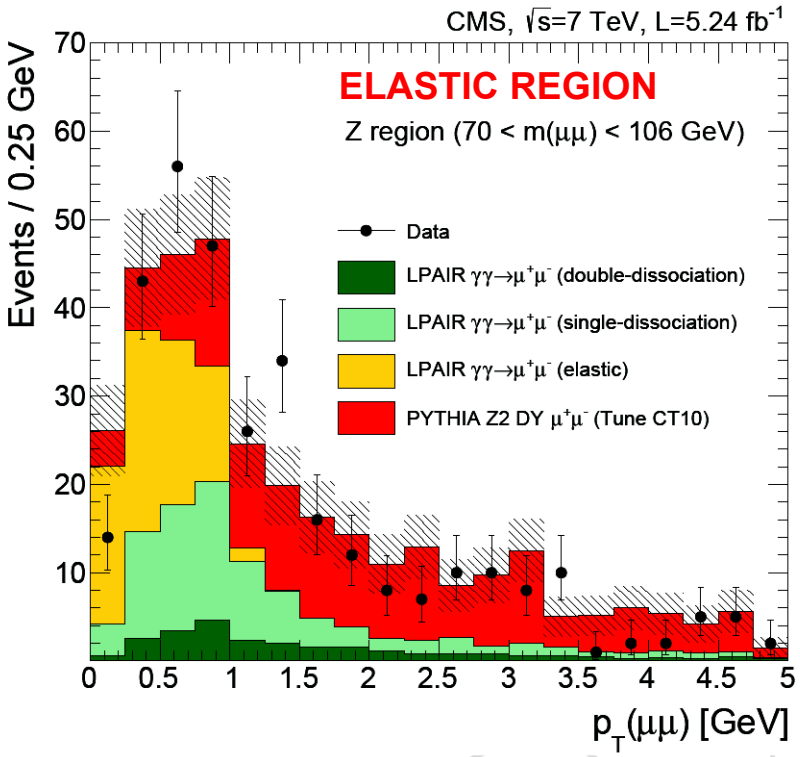


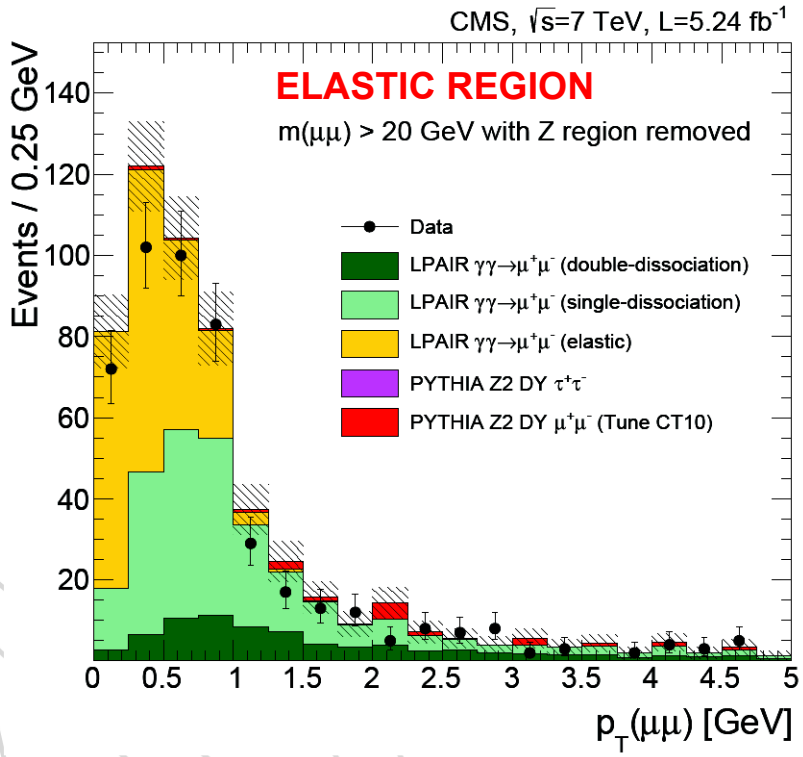
INELASTIC REGION



Elastic region for $\gamma\gamma \rightarrow \mu^+\mu^-$

- The elastic region presents a good agreement with the MC predictions:





- The contribution from both regions can be accounted in Data and MC:

$1-|\Delta\varphi(\mu^+\mu^-)/\pi| < 0.1$
$|\Delta p_T(\mu^+\mu^-)| < 1.0$

deficit observed in the data compared to LPAIR MC

Region	Data	Simulation	Data/Simulation
Elastic	820	906 ± 9	0.91 ± 0.03
Dissociation	1312	1830 ± 17	0.72 ± 0.02
Total	2132	2736 ± 19	0.78 ± 0.02

Proton dissociation in inelastic $\gamma\gamma \rightarrow \mu^+\mu^-$

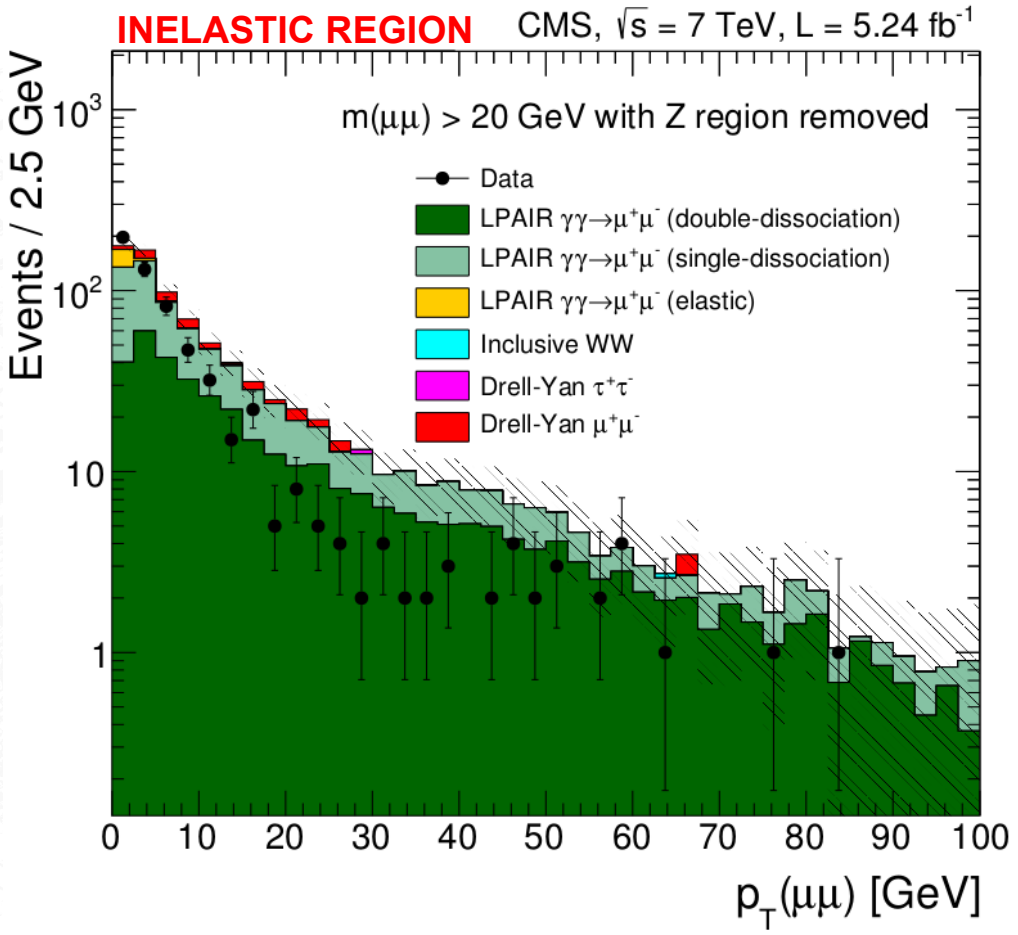
- A deficit is observed in data which is **not** predicted by LPAIR – **rescattering effects** not included to the predictions;

- Proton dissociation in LPAIR is **loosely** constrained experimentally – a normalization factor is naturally employed for this component;

- We estimate a normalization factor for masses larger than the W-pair mass:

$$F = \left. \frac{N_{\mu\mu\ data} - N_{DY}}{N_{elastic}} \right|_{m(\mu^+\mu^-)>160\ \mathrm{GeV}}$$

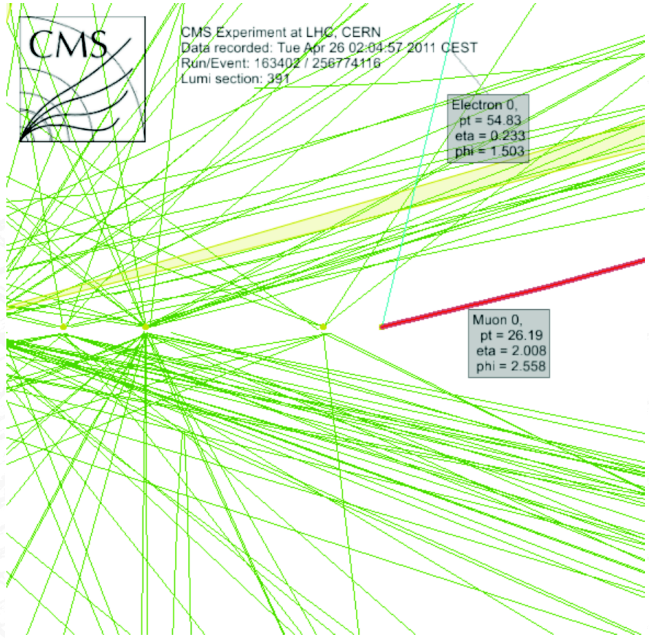
$$= \boxed{3.23 \pm 0.53.}$$

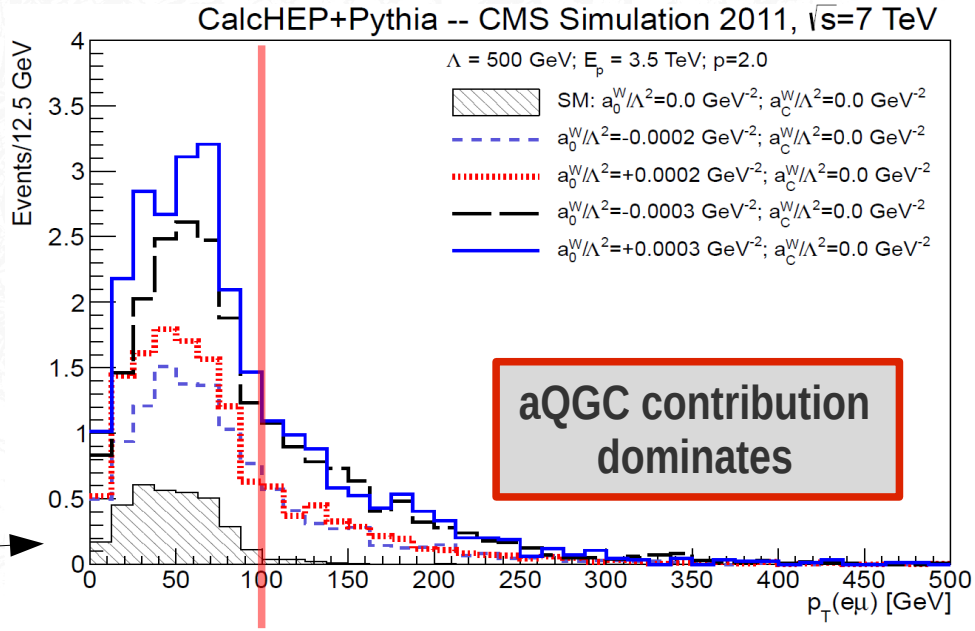


- This factor is then used to re-scale the signal cross section in order to include the contribution from the **proton dissociation**.

Search for $\gamma\gamma \rightarrow W^+W^-$ production

- Data collected in 2011 by the CMS detector at 7 TeV:
  - Final state: $W^+W^- \rightarrow e^{\pm}\mu^{\mp}\nu\nu$ to suppress DY bkg;
  - Events with opposite-sign and flavor leptons: **5.05 fb^{-1}**.
- Leptons are selected with the requirements:
  - $p_T(\ell) > 15$ GeV and $|\eta(\ell)| < 2.4$;
  - $m(\ell^+\ell^-) > 20$ GeV and $p_T(\ell^+\ell^-) > 30$ GeV;
- Exclusivity selection:
  - $p_T(\ell)$ balance below 1 GeV;
  - Back-to-back leptons with $\Delta\varphi > 0.9\pi$
  - No extra tracks in the vertex apart of the leptons.
- **aQGC**: search is performed in the kinematical region with $p_T(\mu e) > 100$ GeV.



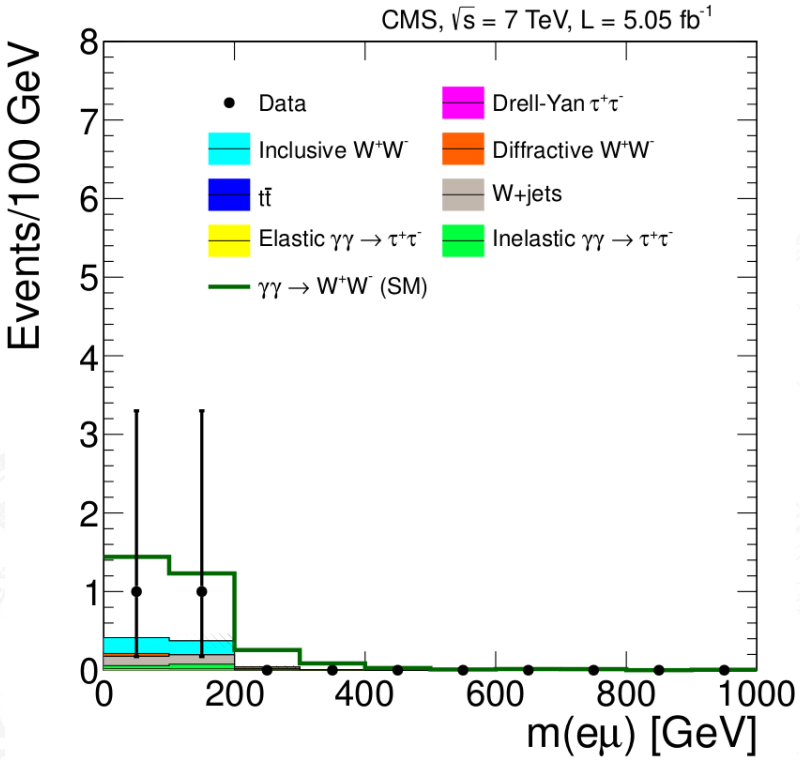


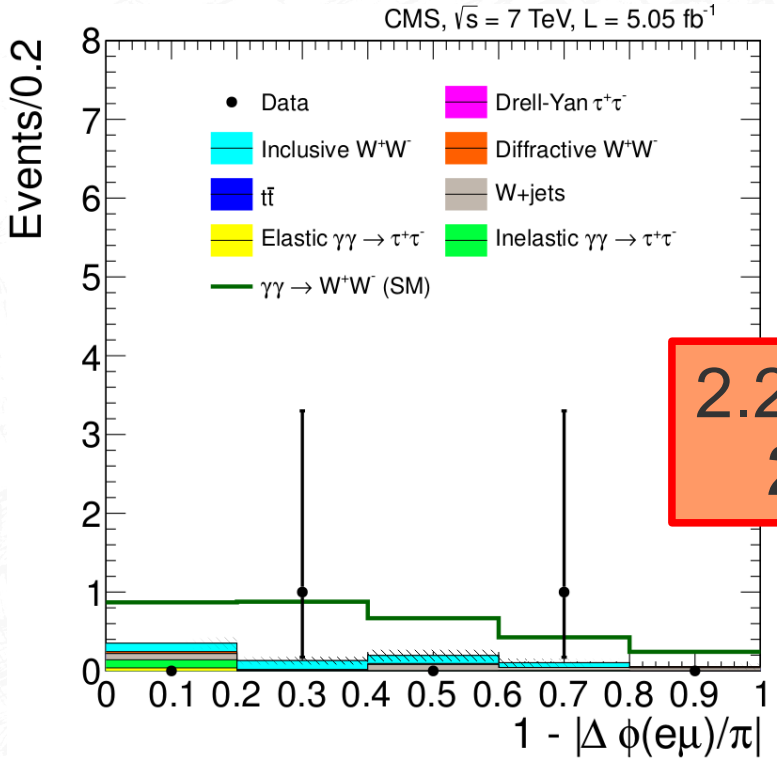
Signal from $W^+W^- \to \mu^\pm e^\mp \nu\bar{\nu}$

- Events passing all the requirements:

Signal: **2.2 ± 0.4 evt**
Bkg: **0.84 ± 0.15 evt**

Selection step	Signal $\epsilon \times A$	Events in data
Trigger and preselection	28.5%	9086
$m(\mu^\pm e^\mp) > 20$ GeV	28.0%	8200
Muon ID and Electron ID	22.6%	1222
$\mu^\pm e^\mp$ vertex with 0 extra tracks	13.7%	6
$p_T(\mu^\pm e^\mp) > 30$ GeV	10.6%	2





2.2 evt expected
2 observed

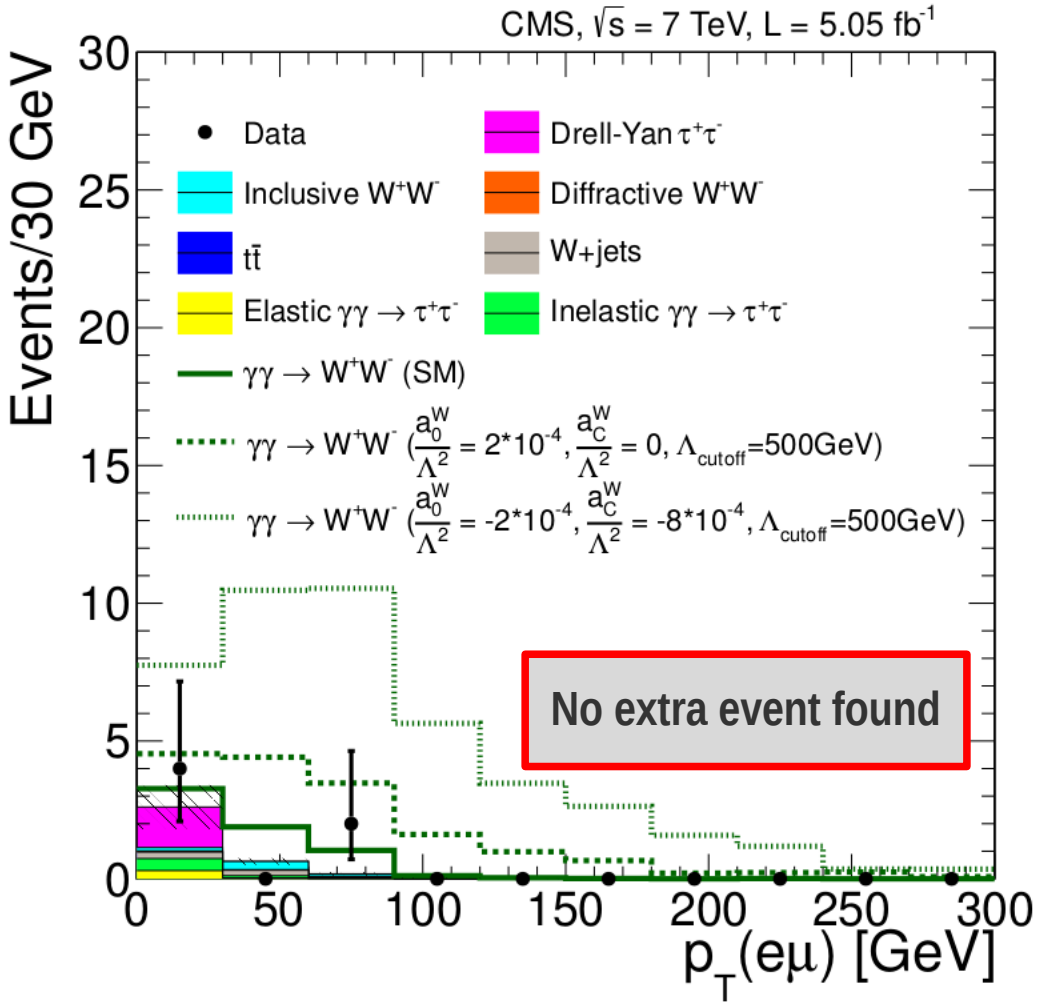
SM: 4.0 ± 0.7 fb

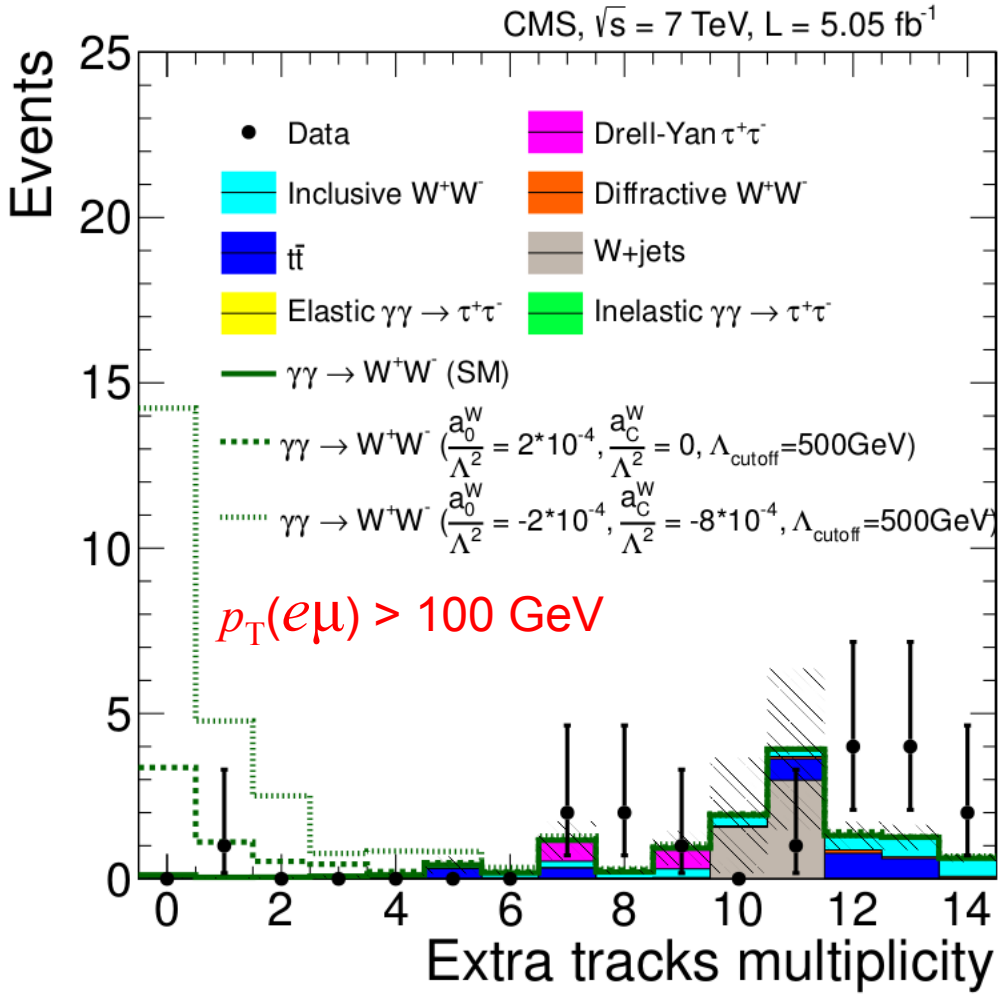
σ · BR with 95% CL: $\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.1^{+3.1}_{-1.9}$ fb

Search for aQGC

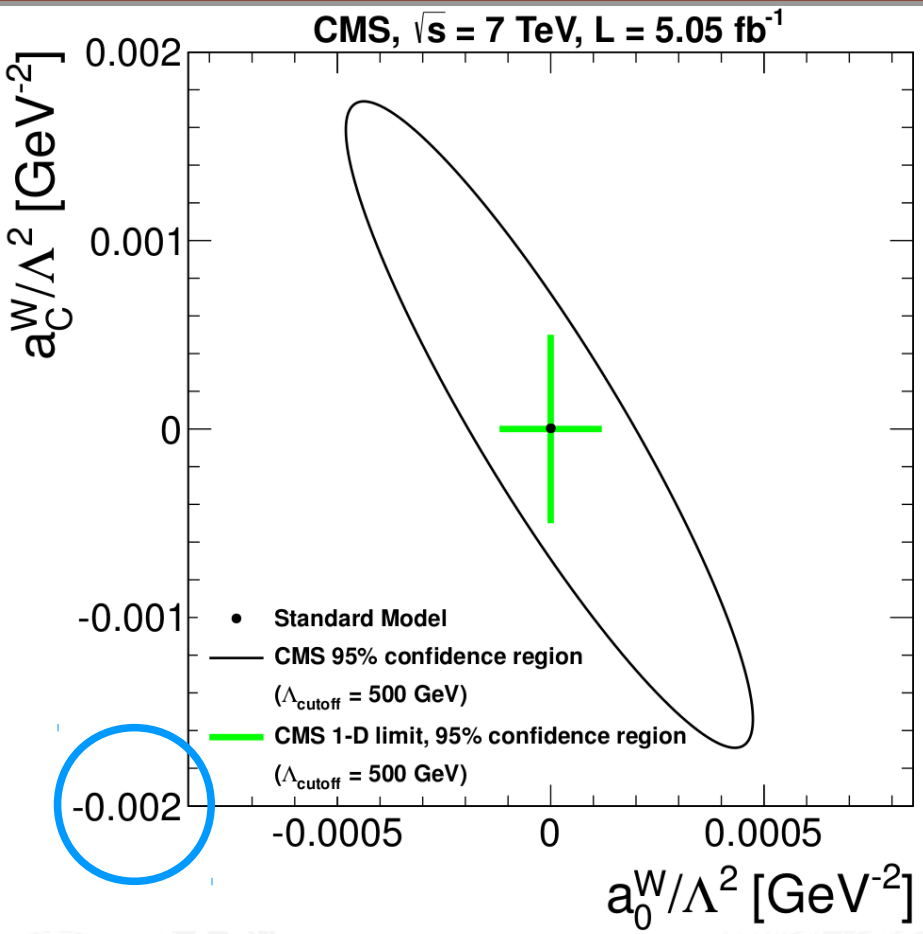
- The upper limit on the cross section times Branching fraction is found as

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) < 10.6\,\text{fb}$$





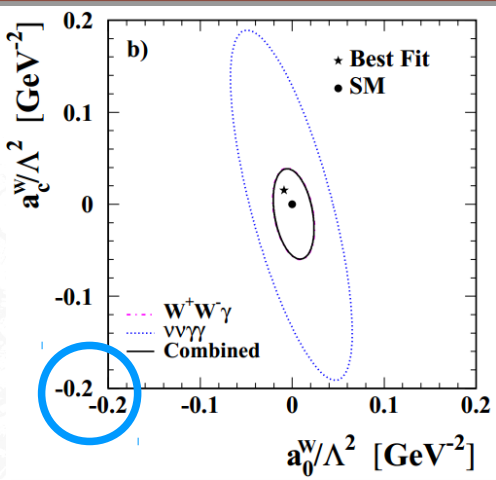
Limits on aQGC

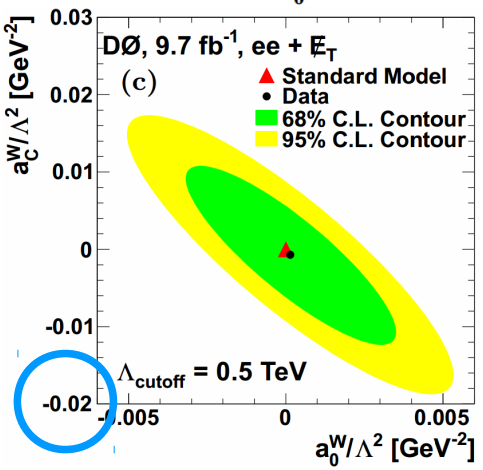


OPAL

Scales differ by a factor of **10** and **100**

DØ





- The upper limit on the cross section times Branching fraction is found as

$$-0.00015 < a_0^{\mathrm{W}}/\Lambda^2 < 0.00015\,\mathrm{GeV}^{-2}\ (a_C^{\mathrm{W}}/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}),$$
$$-0.0005 < a_C^{\mathrm{W}}/\Lambda^2 < 0.0005\,\mathrm{GeV}^{-2}\ (a_0^{\mathrm{W}}/\Lambda^2 = 0, \Lambda_{\mathrm{cutoff}} = 500\,\mathrm{GeV}).$$

$$-4.0 \times 10^{-6} < a_0^{\mathrm{W}}/\Lambda^2 < 4.0 \times 10^{-6}\,\mathrm{GeV}^{-2}\ (a_C^{\mathrm{W}}/\Lambda^2 = 0, \text{no form factor}),$$
$$-1.5 \times 10^{-5} < a_C^{\mathrm{W}}/\Lambda^2 < 1.5 \times 10^{-5}\,\mathrm{GeV}^{-2}\ (a_0^{\mathrm{W}}/\Lambda^2 = 0, \text{no form factor}).$$

Limits 2 orders of magn. more stringent than those from LEP

Summary

- Encouraging results showing **excellent** forward capabilities of the CMS detector;
- Studies show the possibility to measure exclusive **meson photo-production** in CMS;
  - Photo-production of J/ψ and Υ to be explored in *p*-*p*, *p*-Pb and Pb-Pb collisions.
- CMS has successifully measured exclusive processes at **low** and **high** masses;
  - The observed cross sections are in agreement with the QED predictions:

17 (semi-)exclusive events in exclusive production of e^+e^- pairs

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

- The search for the exclusive production of W pairs results in **two potential candidates** with observed cross section in agreement with the SM expectation:

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

- AQGC limits: **two orders of magnitude** more stringent than the limits of LEP & Tevatron;

Backup slides

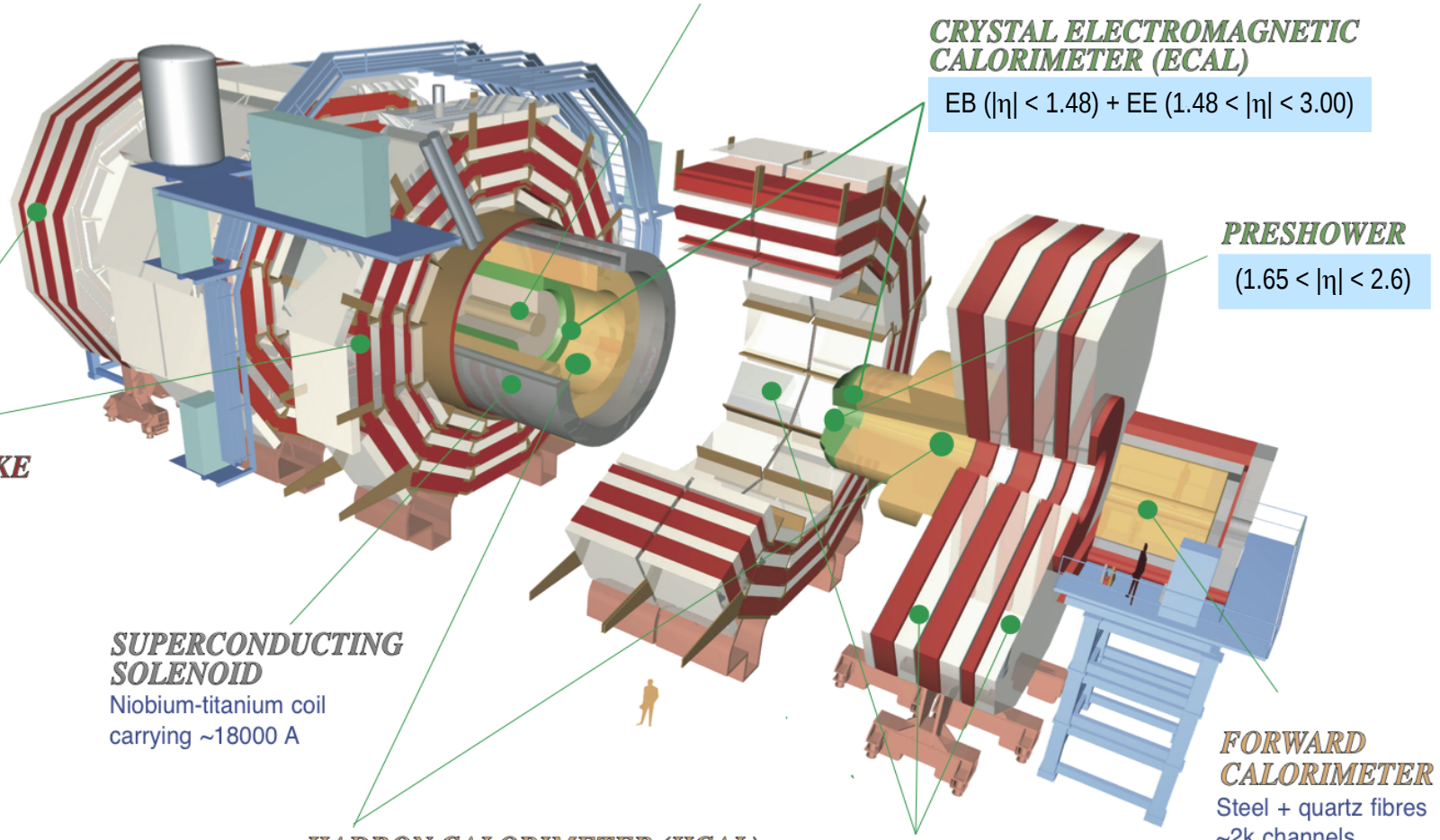
The CMS experiment

CASTOR: 5.3 < |η| < 6.6
ZDC: |η| > 8.1
(**not used in these analyses**)

SILICON TRACKER
(|η| < 2.5)

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
EB (|η| < 1.48) + EE (1.48 < |η| < 3.00)

PRESHOWER
(1.65 < |η| < 2.6)



STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
HB + HO: (|η| < 1.3
HE: 1.3 < |η| < 3.0
HF: 3.0 < |η| < 5.2

MUON CHAMBERS

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

$\gamma\gamma \to e^+e^-$: cutflow & efficiency

Dielectron analysis	
Selection criterion	Events remaining
Trigger	3 023 496
Electron reconstruction	132 271
Electron identification	1 668
Cosmic-ray rejection	1 321
Exclusivity requirement	17

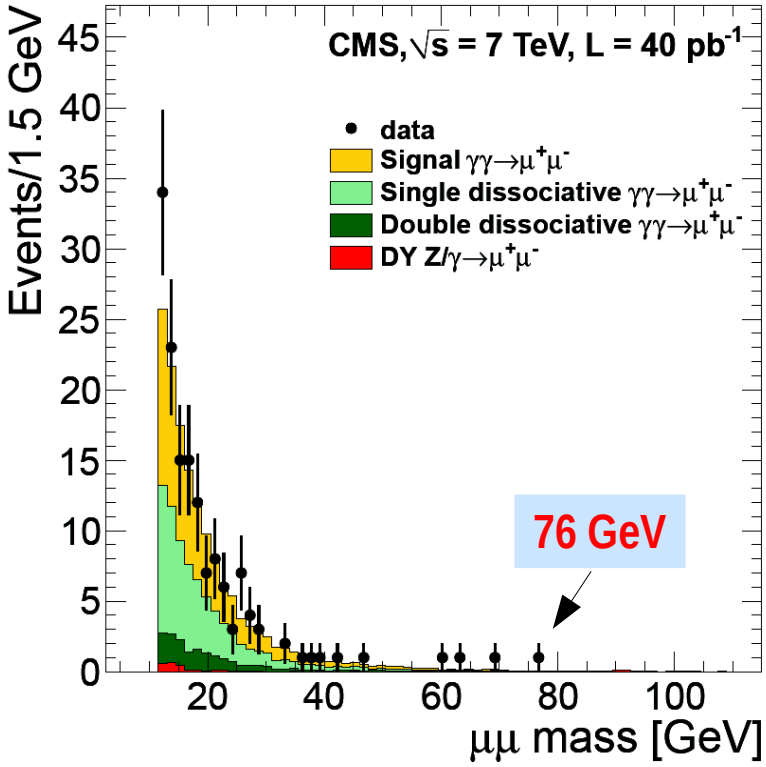
Dielectron analysis		
el-el	inel-el	inel-inel
0.371 ± 0.037	0.438 ± 0.035	0.430 ± 0.030
0.979 ± 0.009	0.822 ± 0.008	0.639 ± 0.006
0.927 ± 0.005	0.666 ± 0.049	0.299 ± 0.041
0.143 ± 0.008	0.143 ± 0.008	0.143 ± 0.008
0.0481 ± 0.0055	0.0343 ± 0.0042	0.0117 ± 0.0019

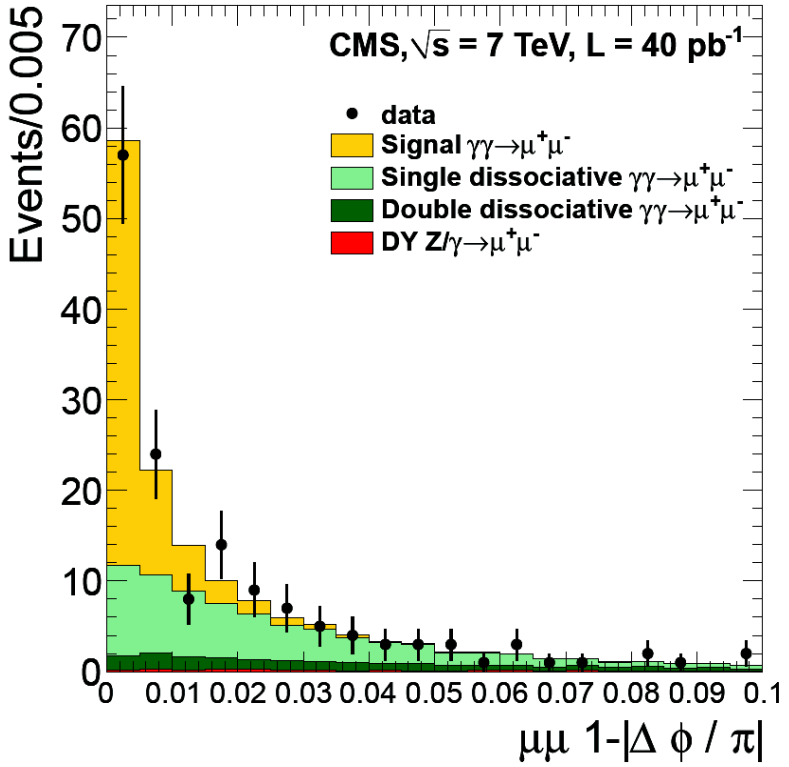
$\gamma\gamma \to e^+e^-$: background expectation

Dielectron analysis	
Background	Events
Non-exclusive	0.80 ± 0.28
Exclusive Υ(1S,2S,3S) $\to e^+e^-$	Negligible
Cosmic ray	0.05 ± 0.01
Exclusive $\pi^+\pi^-$	Negligible
Total	0.85 ± 0.28

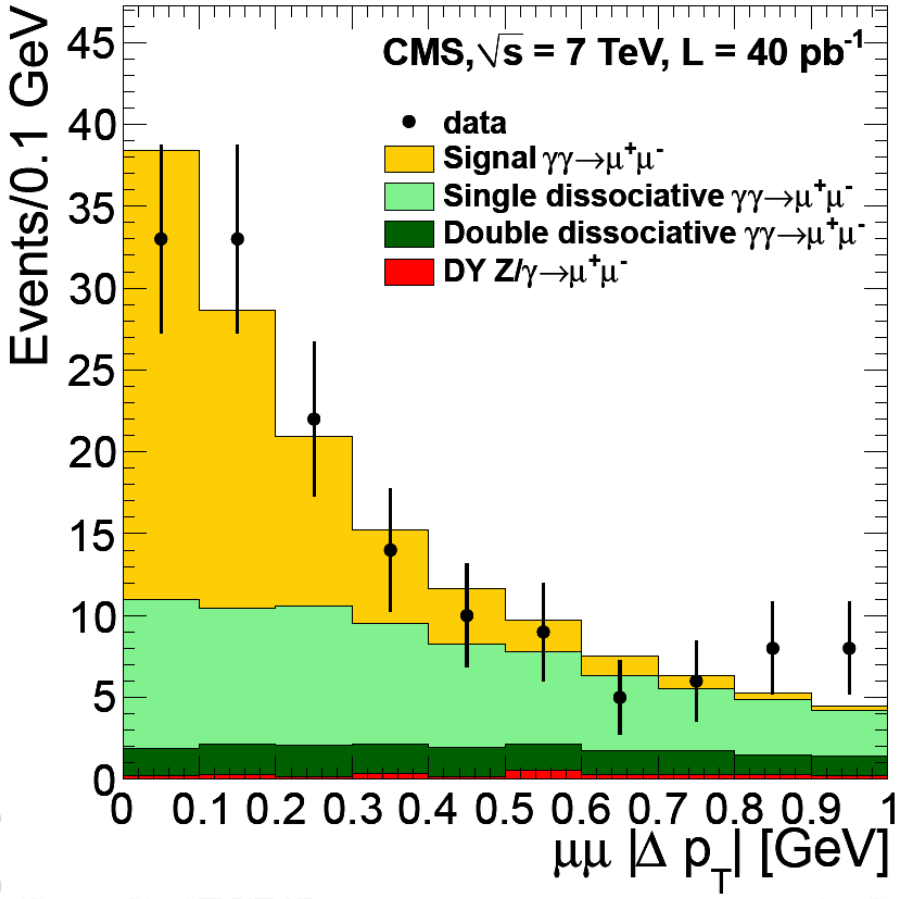
Low mass $\gamma\gamma \to \mu^+\mu^-$: cutflow

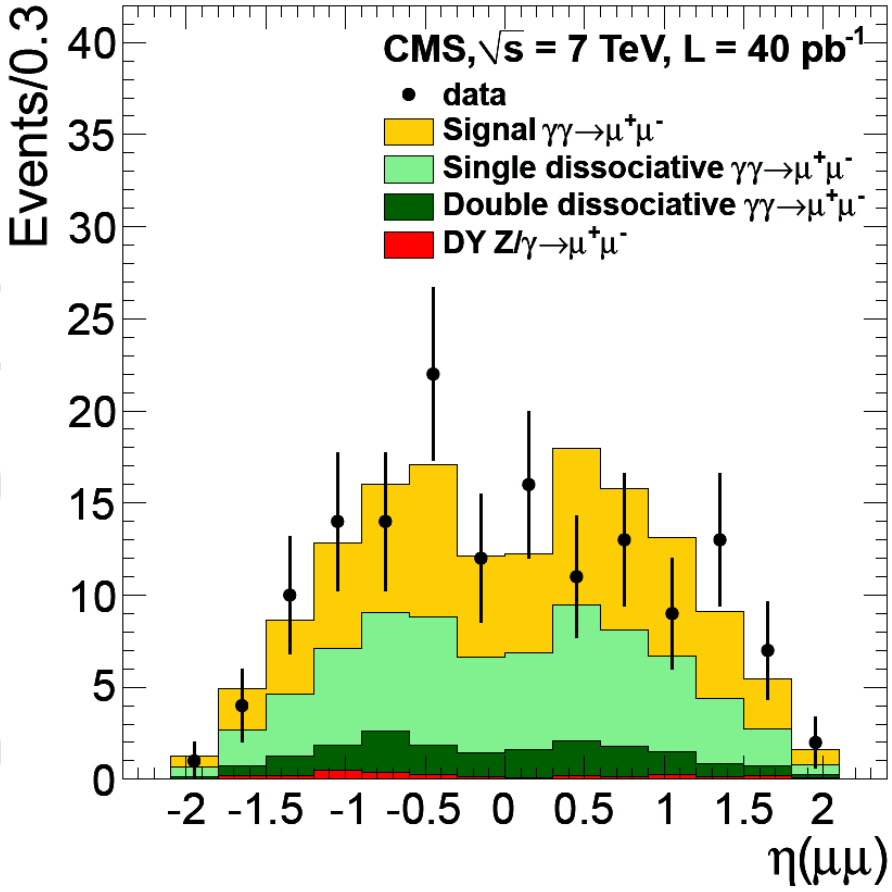
Selection	Data	Signal	Single-pdiss.	Double-pdiss.	DY	Total
Vertex and track-exclusivity	921	247	437	197	56	937
Muon ID	724	193	336	160	53	741
$p_T > 4\,\text{GeV}$, $\lvert\eta\rvert < 2.1$	438	132	241	106	20	499
$m(\mu^+\mu^-) > 11.5\,\text{GeV}$	270	95	187	86	13	380
$3D$ angle $< 0.95\pi$	257	87	178	83	12	361
$1 - \lvert\Delta\phi/\pi\rvert < 0.1$	203	87	126	41	8	263
$\lvert\Delta p_T\rvert < 1.0\,\text{GeV}$	148	86	79	16	3	184



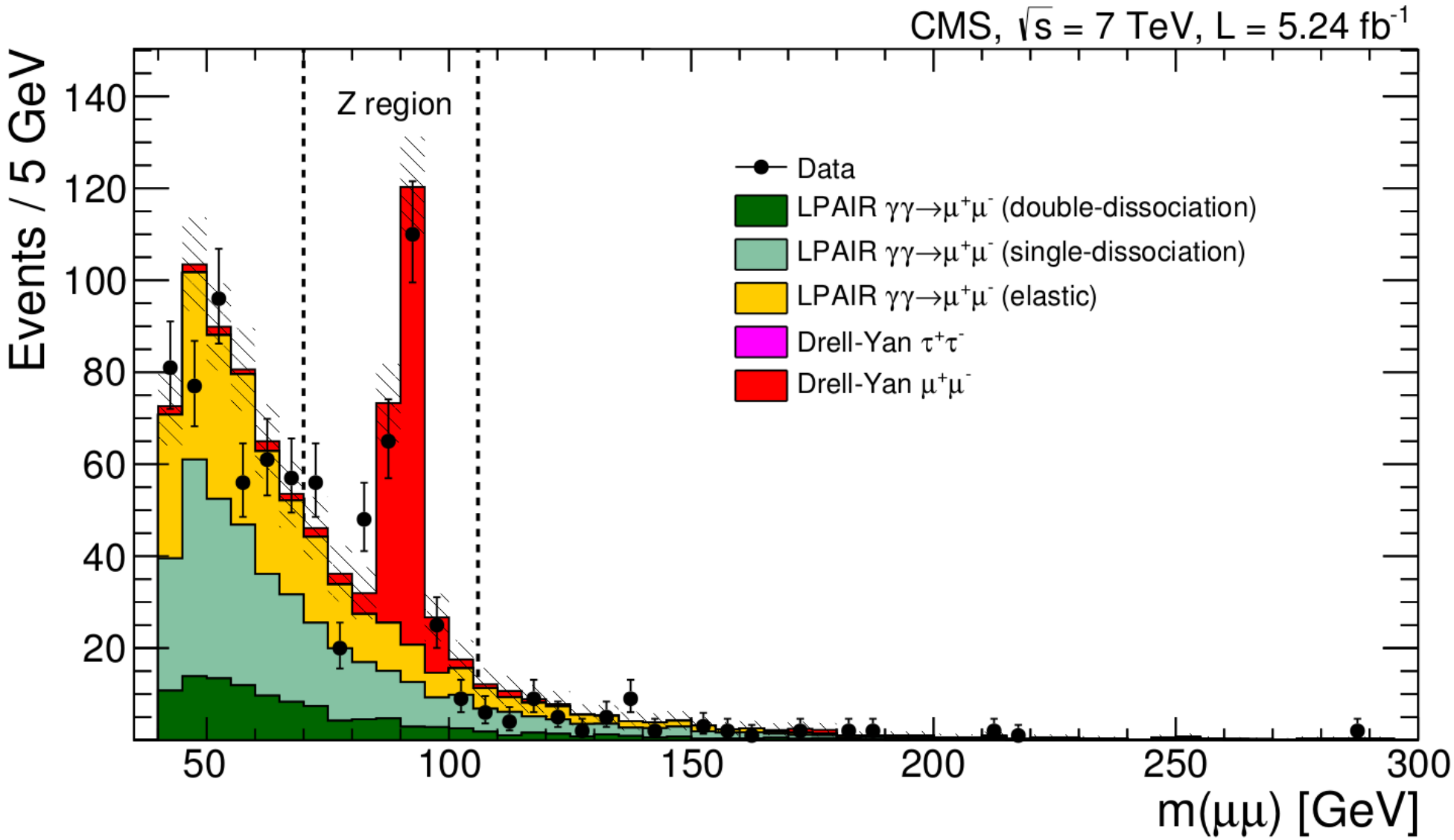


Low mass $\gamma\gamma \to \mu^+\mu^-$: distributions

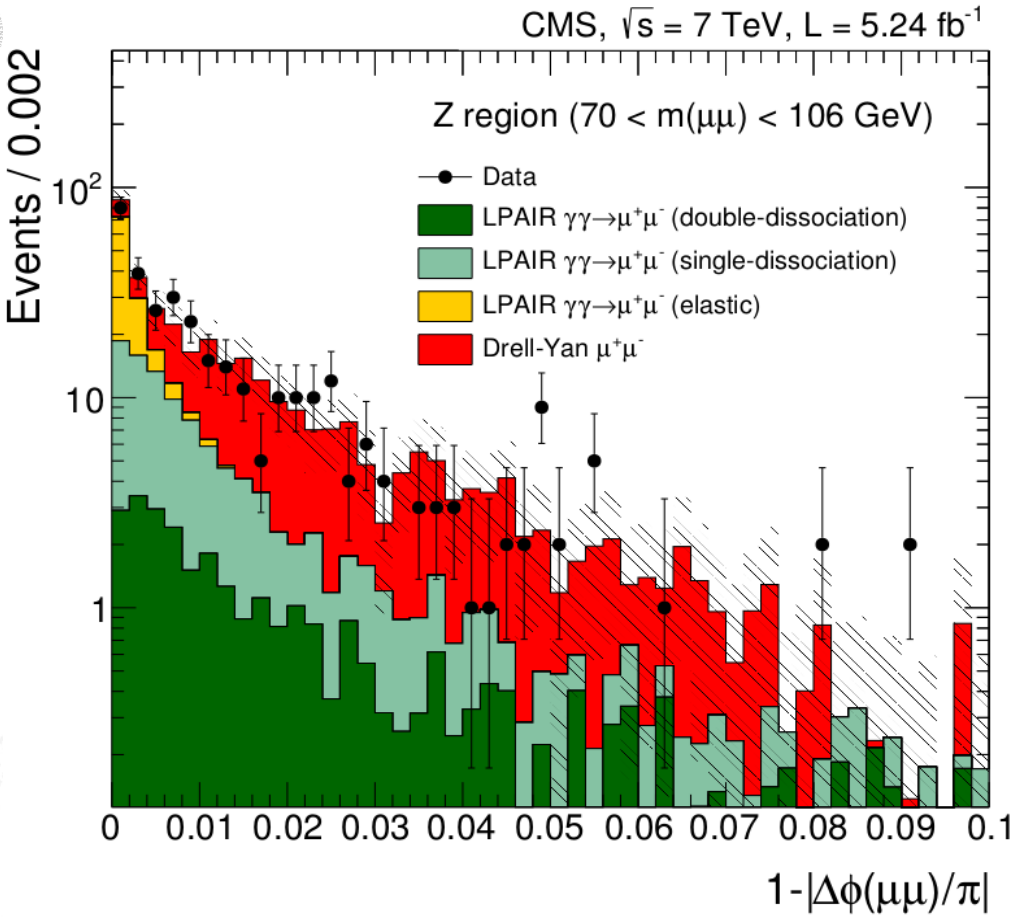


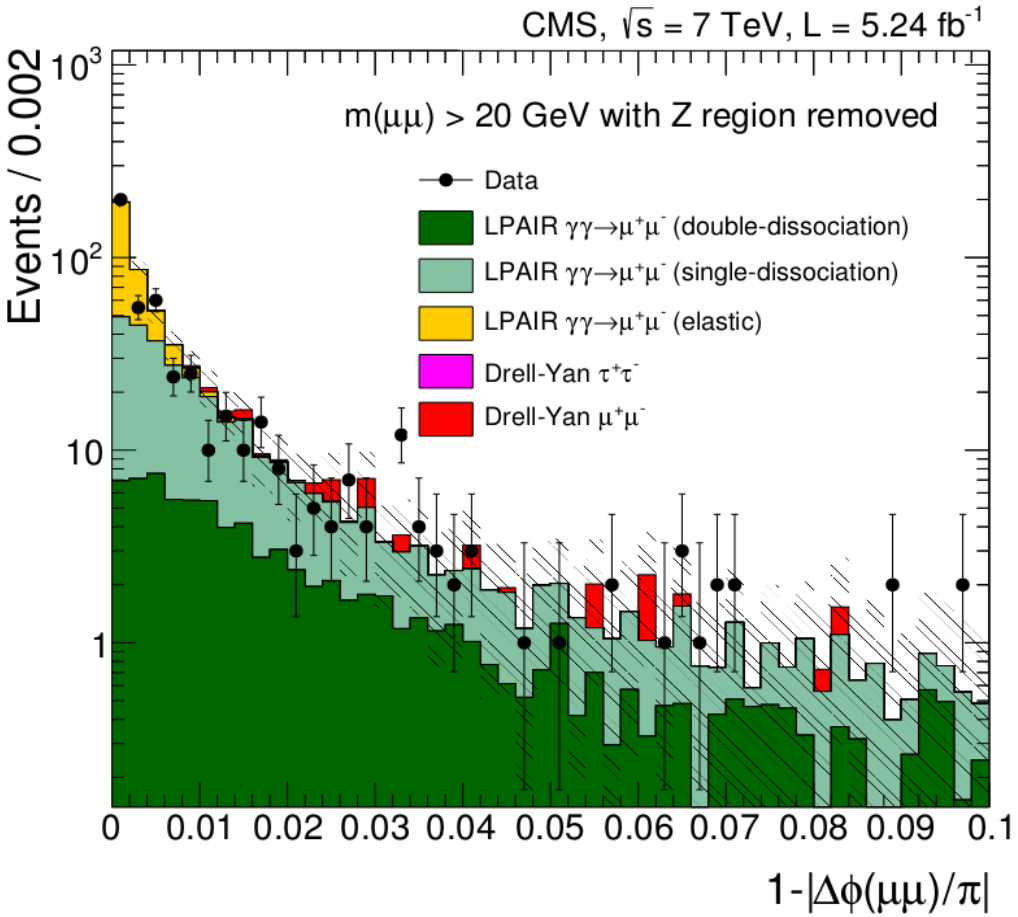


High mass $\gamma\gamma \to \mu^+\mu^-$: invariant mass

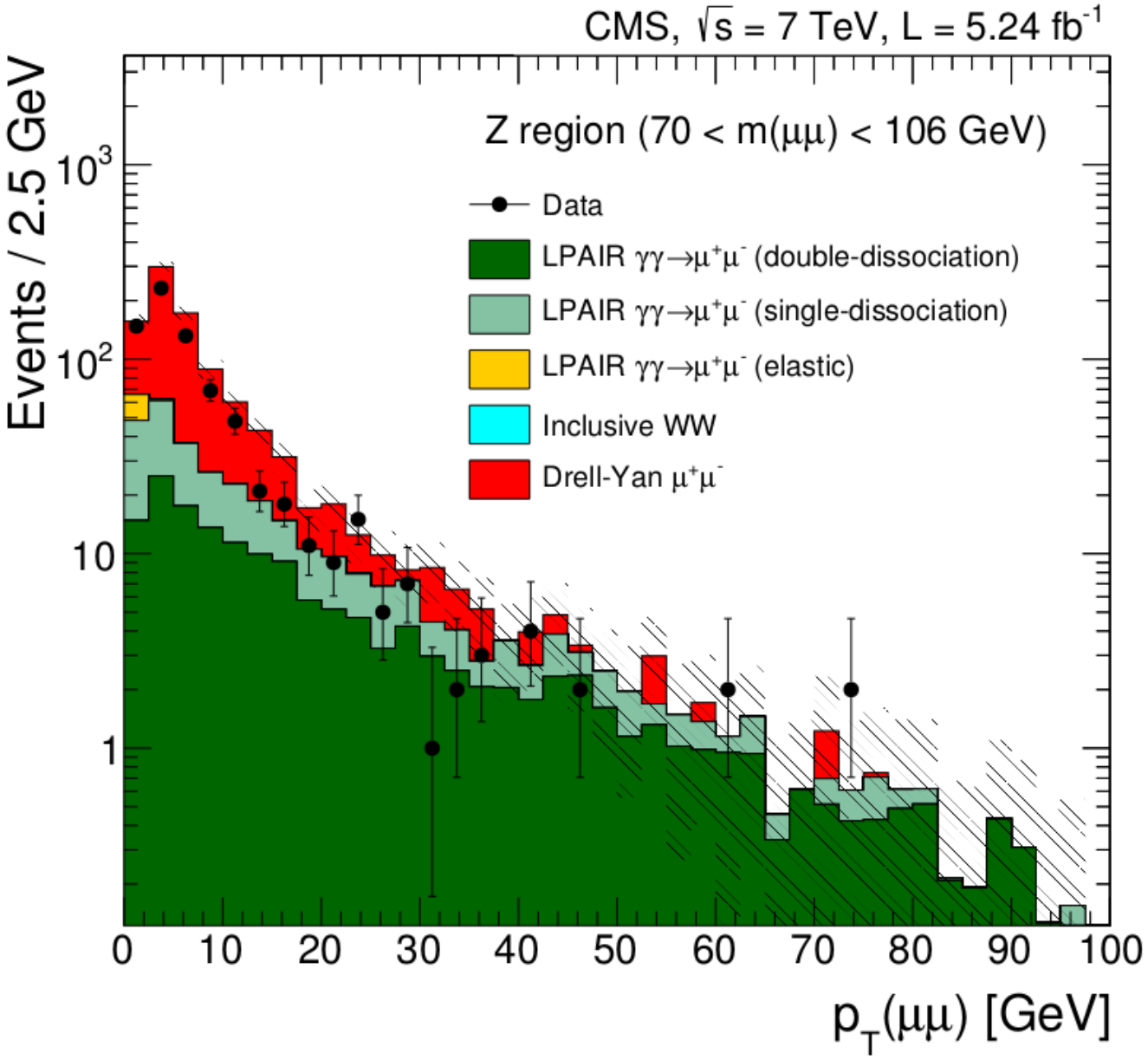


High mass $\gamma\gamma \to \mu^+\mu^-$: acoplanarity





High mass $\gamma\gamma \to \mu^+\mu^-$: transv. momentum



$\gamma\gamma \to W^+W^-$: efficiencies

Selection step	Signal $\epsilon \times A$	Visible cross section (fb)	Events in data
Trigger and preselection	28.5%	1.1	9086
$m(\mu^{\pm}e^{\mp}) > 20\,\text{GeV}$	28.0%	1.1	8200
Muon ID and Electron ID	22.6%	0.9	1222
$\mu^{\pm}e^{\mp}$ vertex with zero extra tracks	13.7%	0.6	6
$p_T(\mu^{\pm}e^{\mp}) > 30\,\text{GeV}$	10.6%	0.4	2

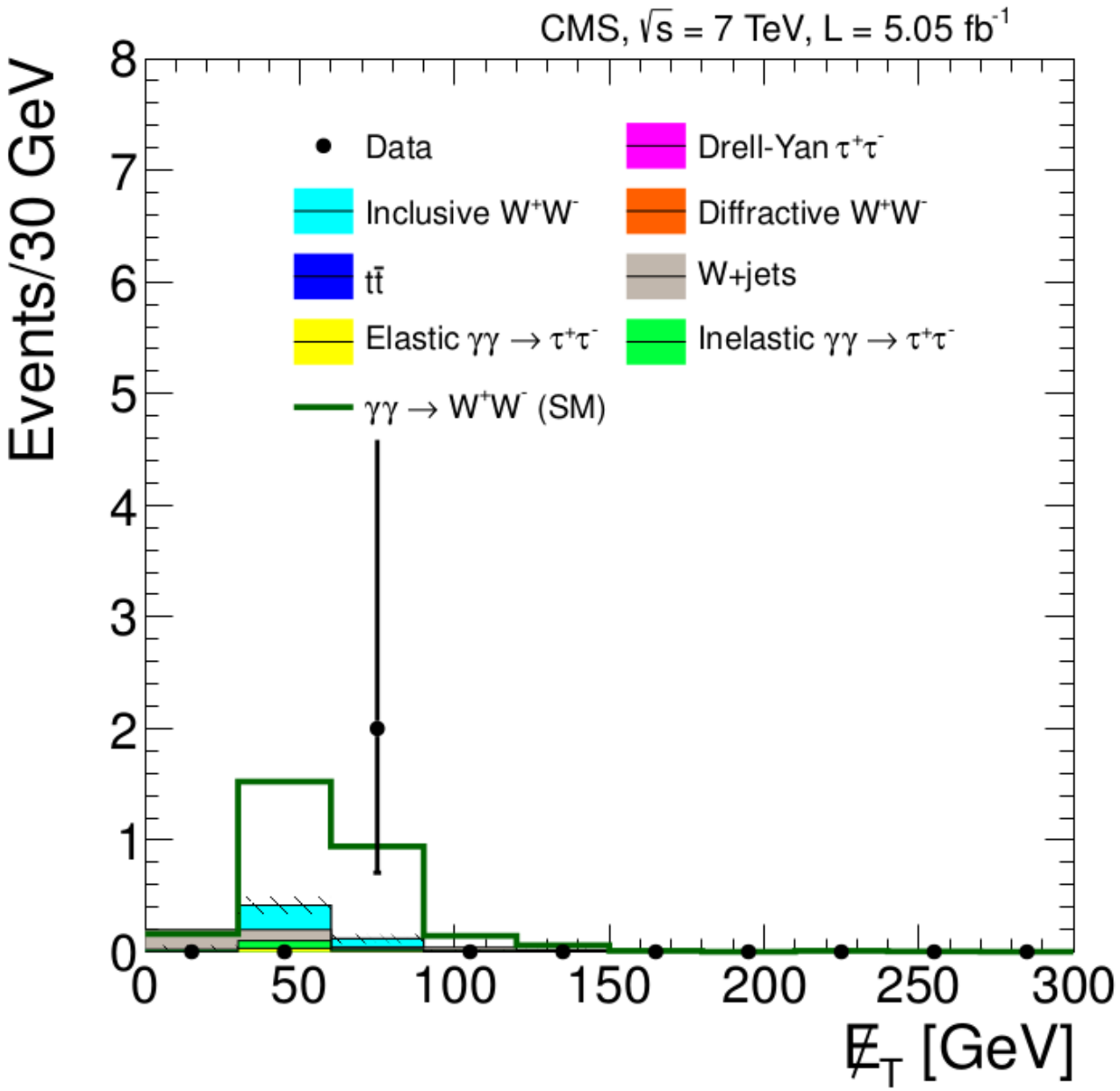
$\gamma\gamma \to W^+W^-$: background expectation

Region	Background process	Data	Sum of backgrounds	$\gamma\gamma \to W^+W^-$ signal
1	Inclusive W^+W^-	43	46.2 ± 1.7	1.0
2	Inclusive Drell-Yan $\tau^+\tau^-$	182	256.7 ± 10.1	0.3
3	$\gamma\gamma \to \tau^+\tau^-$	4	2.6 ± 0.8	0.7

$\gamma\gamma \to W^+W^-$: systematic uncertainties

	Signal uncertainty	Background uncertainty (events)
Trigger and lepton identification	4.2%	0.02
Luminosity	2.2%	0.005
Vertexing efficiency	1.0%	0.005
Exclusivity and pileup dependence	10.0%	0.05
Proton dissociation factor	16.3%	0.02

$\gamma\gamma \rightarrow W^+W^-$: missing E_T



Efficiencies in aQGC

a_0^W/Λ^2	$[\mathrm{GeV}^{-2}]$	0	2×10^{-4}	-2×10^{-4}	7.5×10^{-6}	0
a_C^W/Λ^2	$[\mathrm{GeV}^{-2}]$	0	0	-8×10^{-4}	0	2.5×10^{-5}
Λ	[GeV]	—	500	500	No form factor	No form factor
Efficiency		$30.5 \pm 5.0\%$	$29.8 \pm 2.1\%$	$31.3 \pm 1.8\%$	$36.0 \pm 1.7\%$	$36.3 \pm 1.8\%$