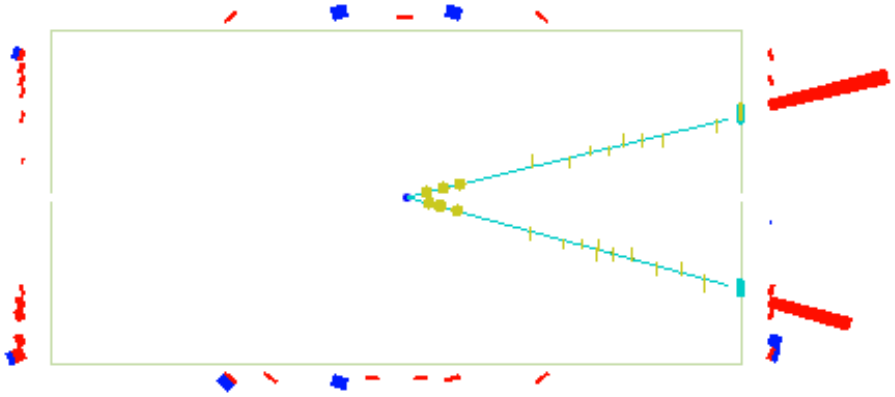


CMS results on central exclusive production

Wenbo Li

Peking University
(for the CMS Collaboration)

Diffraction 2012, Sep. 15, Spain

Outline

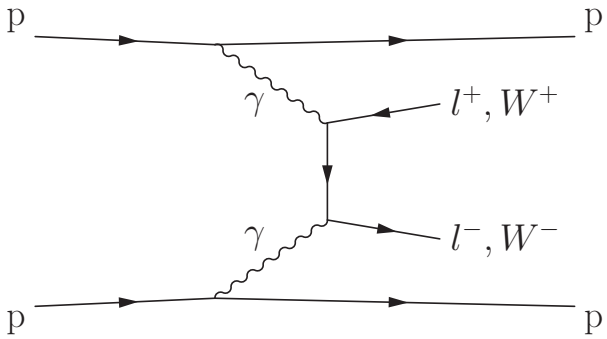
- Introduction
- The CMS Detector
- Exclusive dipohoton and dielectron production
  - Event selection
  - Result
- Exclusive dimuon production
  - Event selection
  - Signal extraction
  - Result
- Summary & Outlook

Central Exclusive Production

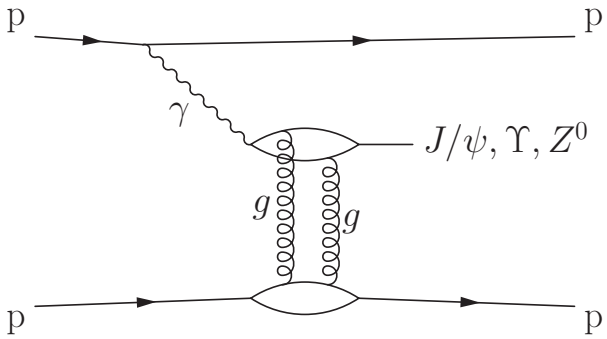
- Central exclusive production:

$$pp \to p + X + p$$

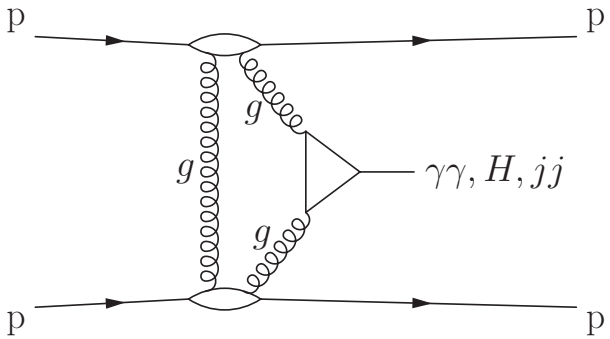
- Both protons emerge intact from the interaction
- X: a simple fully measured system
- Exclusive: no other particles produced & large rapidity gaps
- Cleanest and simplest inelastic pp collision
- Physics processes involved: γγ interactions, γIP fusion, and IPIP exchange



γγ interactions

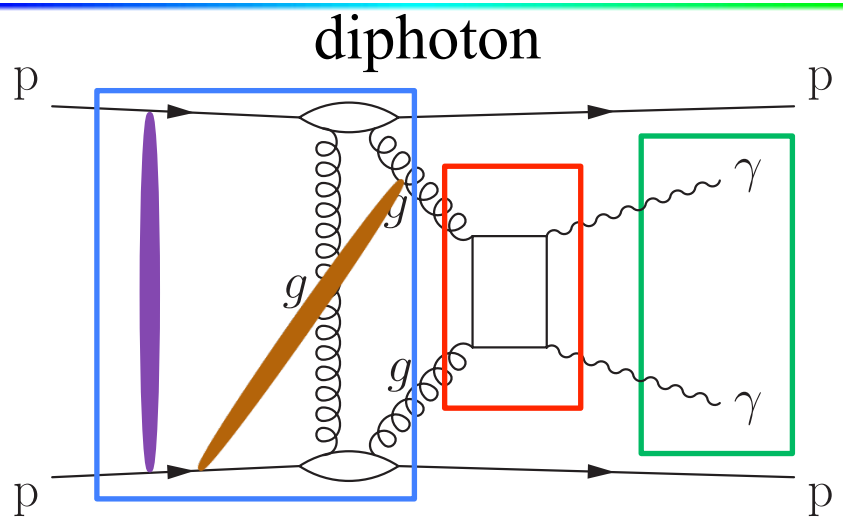


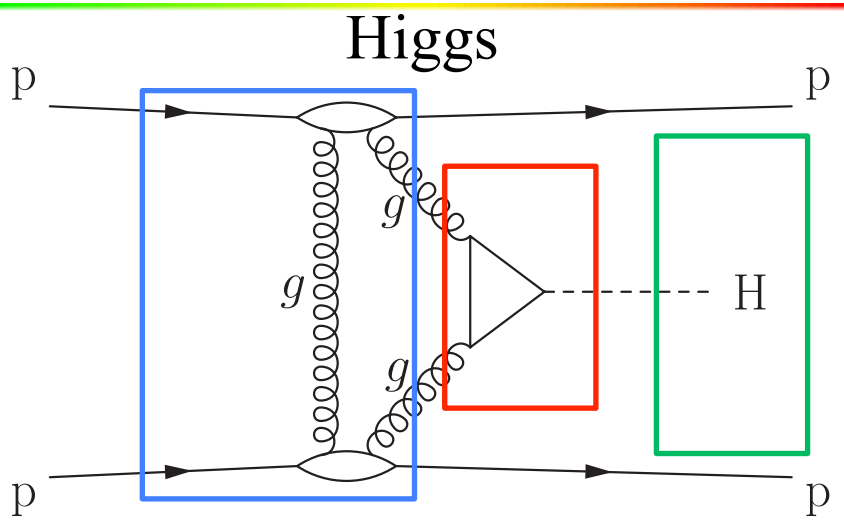
γIP fusion



IPIP exchange

Physics Motivation ($\mathbb{PP} \to \gamma\gamma$)



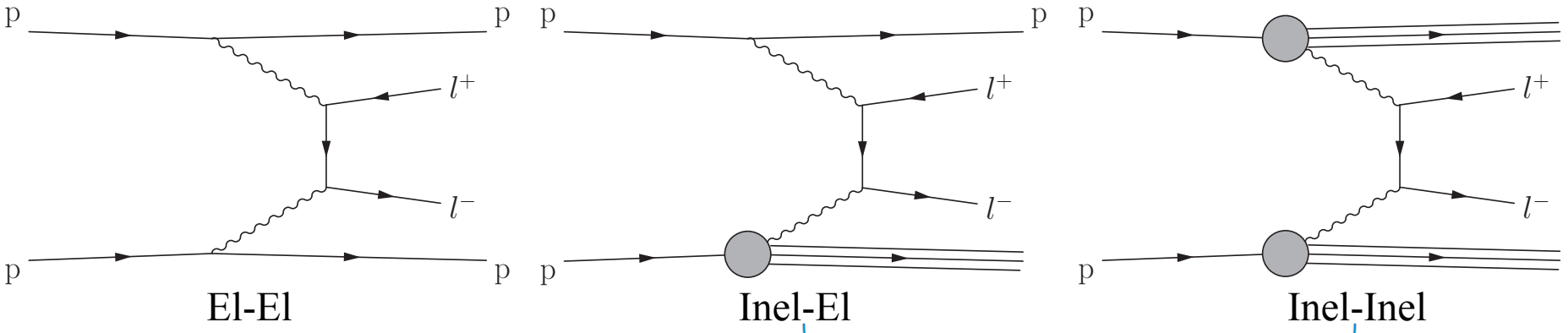


- Double pomeron exchange:
  - *gg* fusion through a quark loop to produce the central system
  - with a soft low-Q^2 screening gluon to cancel the color flow
  - Sudakov factor (no partons emitted by the interacting gluons)
  - Rapidity-gap survival probability S^2 (no additional inelastic pp scattering)

- Shed light on diffraction and double pomeron exchange
  - Low-*x* gluon density ($\sigma \sim [g(x)]^4$)
  - Rapidity-gap survival probability

- Provide excellent test of theoretical predictions for exclusive Higgs production
  - QCD calculation (blue box) is same, from which most uncertainties originate
  - Only the calculable matrix elements (red box) are different for H and γγ cases
  - $\frac{d\sigma(M_{\gamma\gamma})}{dM_{\gamma\gamma}} : \sigma_H$ should be well determined theoretically

Physics Motivation ($\gamma\gamma \to l^+l^-$)



Exclusive

Semi-exclusive

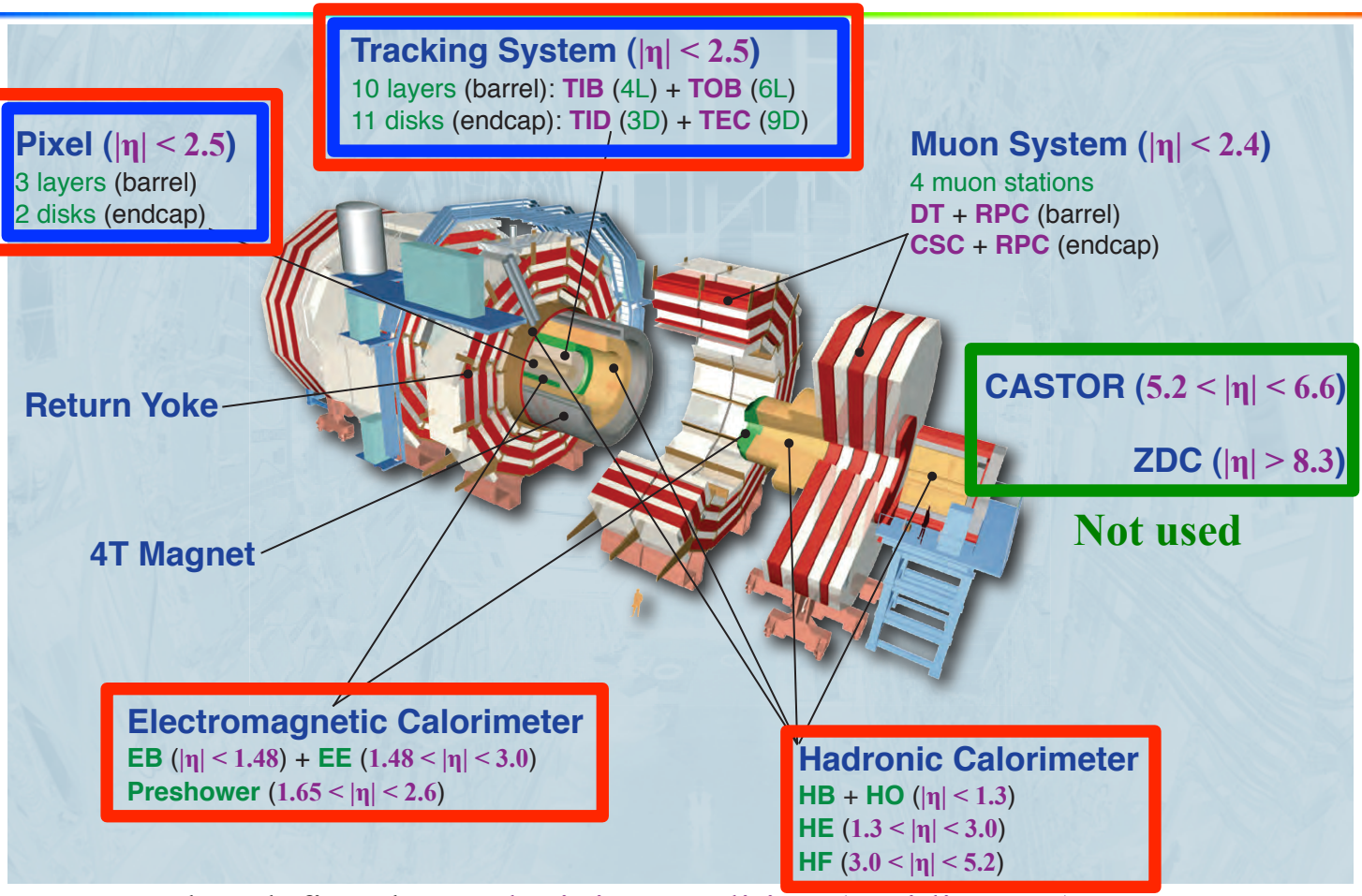
Exclusive production:

- QED process, cross section known with high accuracy at theoretical level (<1%)
- Control process for other exclusive processes
- Potentially interesting for integrated luminosity measurement (provided that semi-exclusive production is well understood or well suppressed)

Semi-exclusive production:

- Either or both protons excited and diffractively dissociated
- Much less theoretically determined
- Suppression of such events depends on the performance of the forward detectors (In CMS, this process contributes more than half of the candidates)

The CMS Detector



Subdetectors used to define the exclusivity condition (rapidity gap):

- Diphoton and dielectron analyses: Tracker (blue box) + Calo (red box) ($|\eta_{max}|$=**5.2**)
- Dimuon analysis: Tracker only (blue box) ($|\eta_{max}|$=**2.5**)

Exclusivity condition: no other particles detected aside from the two photons/leptons

Exclusive $\gamma\gamma$ & e^+e^- Production

FWD-11-004

arXiv:1209.1666 (submitted to JHEP)

Event Selection

- Any other inelastic interaction overlapping with an exclusive interaction would spoil the exclusivity condition and make the exclusive interaction unobservable
- Only 2010 data sample used (low pileup contamination) (36 pb^{-1})

- Trigger: 2 EM showers with $E_T > 5$ GeV
- Photon (electron) selection:
  - Exactly two identified photons (electrons) with $E_T > 5.5$ GeV and $|\eta| < 2.5$
- Cosmic ray rejection criteria:
  - EM timing of the two photons (electrons)
    - $|t_1| < 2$ ns and $|t_2| < 2$ ns
    - $|t_1 - t_2| < 2$ ns
  - $\Delta\varphi > 2.5$ rad
- Exclusivity selection criteria (overriding part):
  - No additional tracks ($|\eta| < 2.5$)
  - No additional towers above noise thresholds in EB, EE, HB, HE and HF ($|\eta| < 5.2$)
  - No track segments in the DTs and CSCs

Additional: not associated to the two central photons (electrons)

Exclusivity efficiency (fraction of events with single interaction): 14.3%

Result

Number of events remaining after each selection:

Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Number of background events:

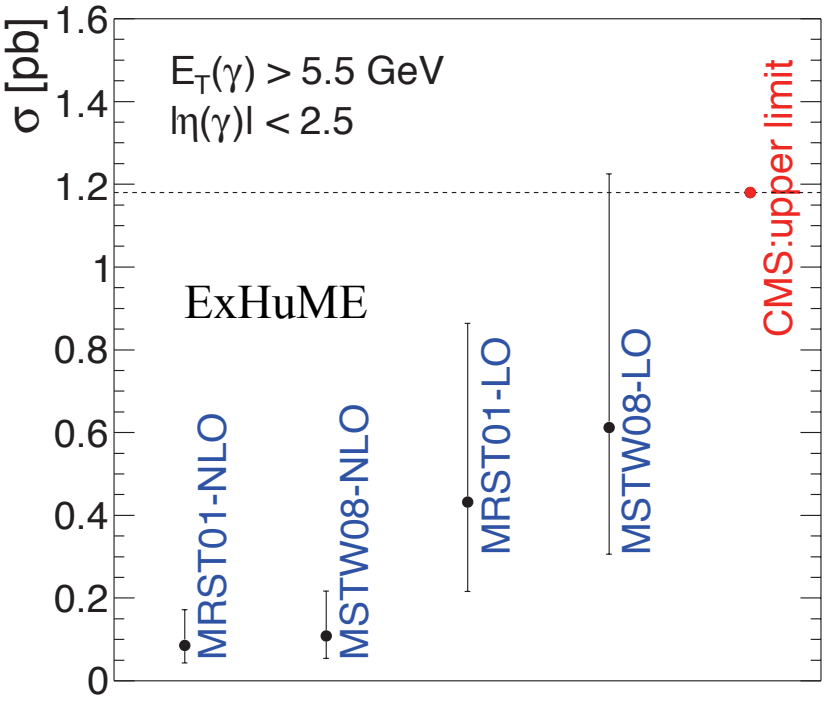
Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive $\Upsilon(1S,2S,3S) \to e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$ and $\eta\eta$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28

Result ($\gamma\gamma$)

- 95% confidence level upper limit:

$$\sigma(E_T(\gamma) > 5.5\,\text{GeV},\ |\eta(\gamma)| < 2.5) < 1.18\,\text{pb}$$

- This upper limit is on the sum of the cross sections for
  - exclusive (el-el) production
  - semi-exclusive (inel-el and inel-inel) production with no particles from the proton dissociation having $|\eta| < 5.2$. (difficult to calculate its contribution precisely) (but is expected to be of magnitude similar①)



- Predictions: exclusive (el-el) only; higher by a factor of ~2① if contribution from semi-exclusive included
- LO vs NLO: different low-x gluon density

	MRST01		MSTW08	
	LO	NLO	LO	NLO
ExHuME	0.432	0.086	0.612	0.109
SuperCHIC		0.103	0.472	
New①		0.039	0.18	

①: from Valery (arXiv: 1204.4803)

Result (e^+e^-)

Number of candidates expected:

S^2 not included in σ

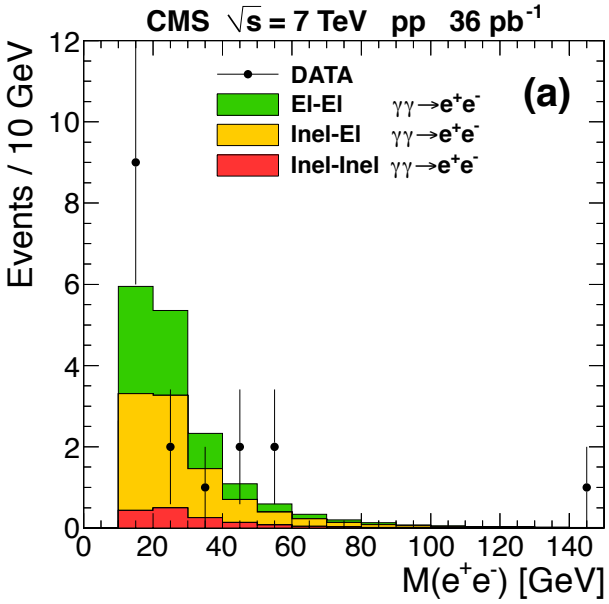
Process	$\mathcal{L}$ (pb^{-1})	σ (pb)	ε	Yield (events)
el-el	36.2±1.4	3.74	0.0481±0.0055	6.51±0.79 (syst.)
inel-el		6.68	0.0343±0.0042	8.29±1.07 (syst.)
inel-inel		3.52	0.0117±0.0019	1.49±0.25 (syst.)
Total				16.3±1.3 (syst.)

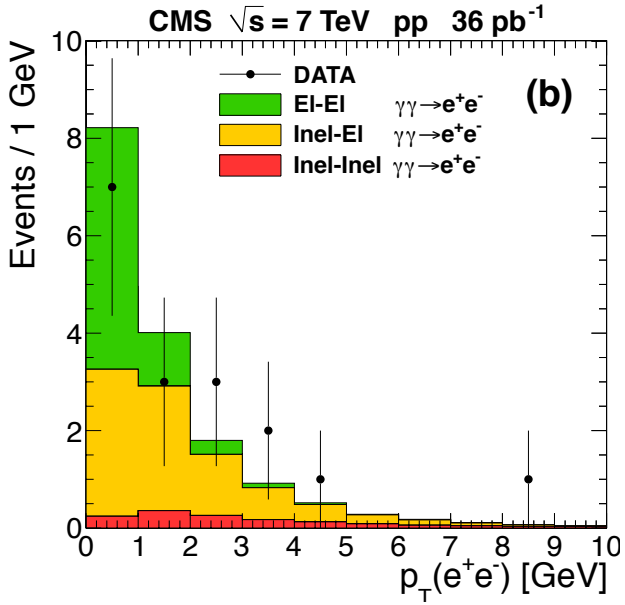
- 17 (semi-)exclusive e^+e^- events on a background of 0.85±0.28 events are observed.
- The theoretical prediction is 16.3±1.3 events.
- Observation in agreement with QED prediction (LPAIR generator).

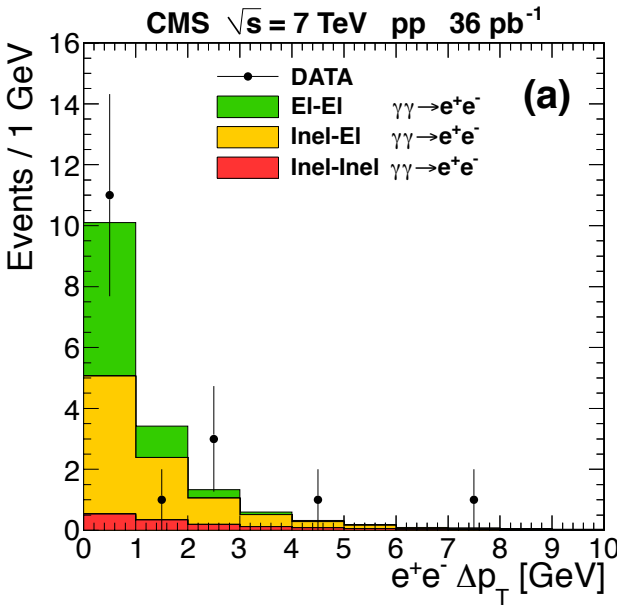
- Rapidity-gap survival probability is not included in LPAIR.
- From Valery:

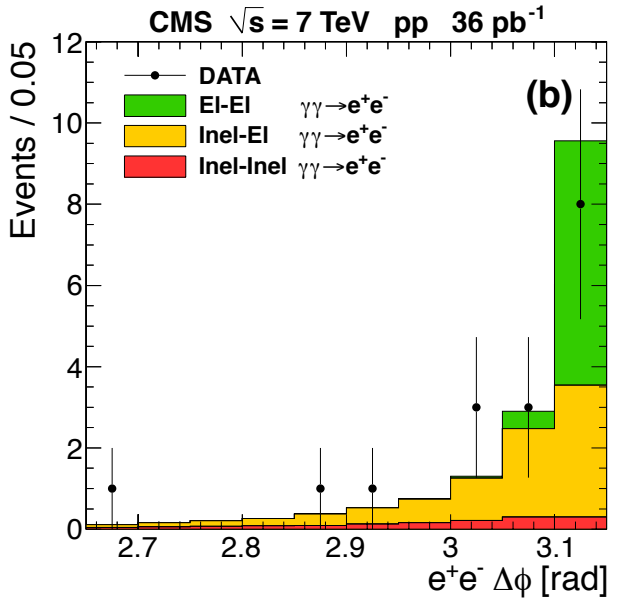
Process	State	S^2
el-el		1
inel-el	low mass (M_X < 2–2.5 GeV)	0.86±0.03
	high mass	0.81±0.03
inel-inel	low mass + low mass	0.3–0.45
	low mass + high mass	0.2–0.28
	high mass + high mass	0.08–0.16

Result (e^+e^-)

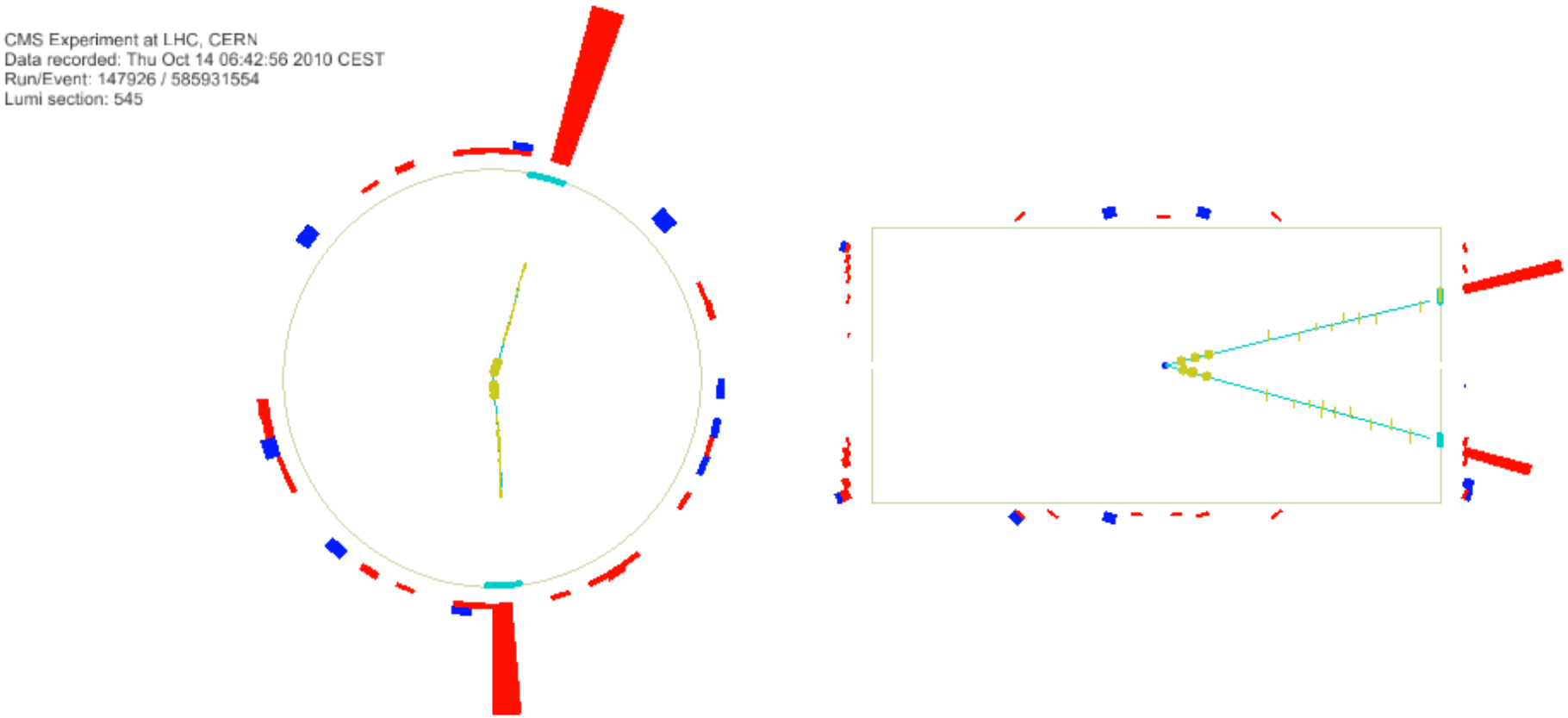

CMS √s = 7 TeV pp 36 pb-1
DATA
EI-EI γγ→e+e-
Inel-EI γγ→e+e-
Inel-Inel γγ→e+e-
(a)
Events / 10 GeV
M(e+e-) [GeV]


CMS √s = 7 TeV pp 36 pb-1
DATA
EI-EI γγ→e+e-
Inel-EI γγ→e+e-
Inel-Inel γγ→e+e-
(b)
Events / 1 GeV
pT(e+e-) [GeV]


CMS √s = 7 TeV pp 36 pb-1
DATA
EI-EI γγ→e+e-
Inel-EI γγ→e+e-
Inel-Inel γγ→e+e-
(a)
Events / 1 GeV
e+e- ΔpT [GeV]


CMS √s = 7 TeV pp 36 pb-1
DATA
EI-EI γγ→e+e-
Inel-EI γγ→e+e-
Inel-Inel γγ→e+e-
(b)
Events / 0.05
e+e- Δφ [rad]

Display of one exclusive event



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

FWD-10-005

JHEP 01 (2012) 052

Event Selection

- 2010 data sample (low pile-up contamination) (40 pb^{-1})
- Both events with and without pileup are used (vertex exclusivity only)

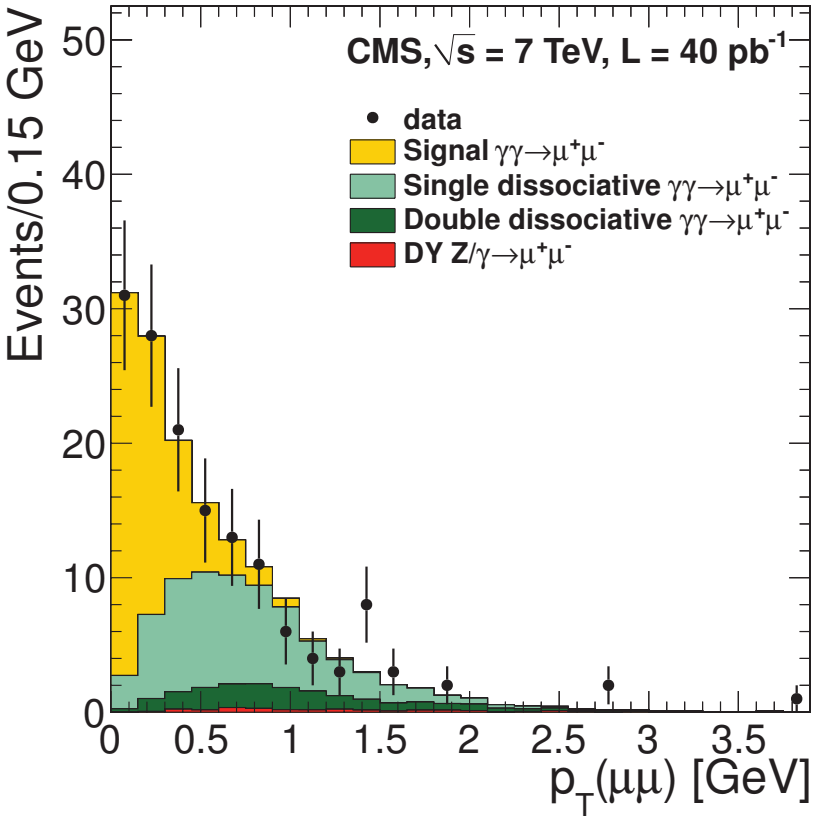
- Unlike dielectron analysis, only exclusive (el-el) events are considered as signal here

- Trigger: 2 muons with $p_T > 3$ GeV
- Muon selection:
  - Two muons with $p_T > 4$ GeV and $|\eta| < 2.1$
  - Both pass tight identification cuts
  - Coming from the same primary vertex
- Muon pair kenimatics:
  - $\Delta p_T(\mu\mu) < 1.0$ GeV (balanced in p_T) } Suppress non-exclusive and
  - $1-|\Delta\phi(\mu\mu)| < 0.1$ (back to back in ϕ) } semi-exclusive background
  - $m(\mu\mu) > 11.5$ GeV (Reject Y(1S,2S,3S) photoproduction)
  - 3D opening angle $> 0.95\pi$ (Reject cosmic ray events)
- Exclusivity selection criteria (vertex exclusivity only):
  - no additional tracks from the dimuon primary vertex
  - no other tracks within 2 mm of the dimuon vertex

- Exclusivity efficiency: 92.3%

much higher than the case using ideal exclusivity requirements (Tracker + Calo) (15%)

Signal Extraction

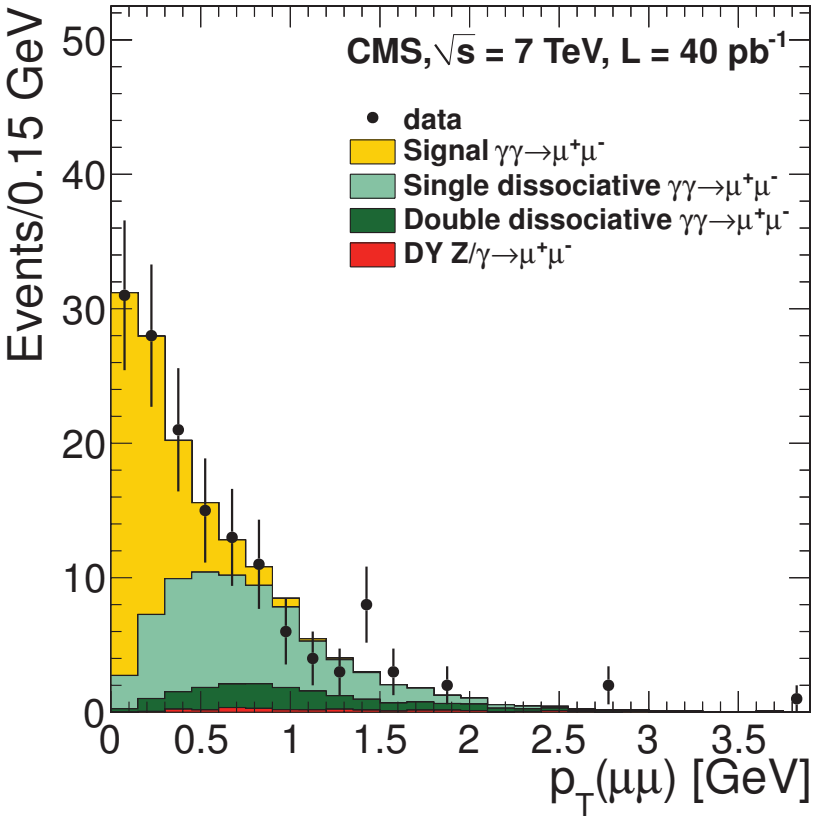


- After all selections, 148 events remain (~50% expected to be from proton dissociation)
- Signal (el-el) is extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution with 3 free parameters:
  - Signal yield
  - Single proton dissociation (inel-el) yield
  - Correction factor to the shape of single proton dissociation events
- Shape and yield of double proton dissociation (inel-inel) and Drell-Yan production are fixed from simulation (Varied as systematic uncertainties)

Fit function (free parameters in red):

$$N\cdot f = N_{\text{el-el}}\cdot f_{\text{el-el}} + N_{\text{inel-el}}\cdot f_{\text{inel-el}}\cdot e^{-a\cdot p_T^2} + N_{\text{inel-inel}}\cdot f_{\text{inel-inel}} + N_{\text{DY}}\cdot f_{\text{DY}}$$

Signal Extraction



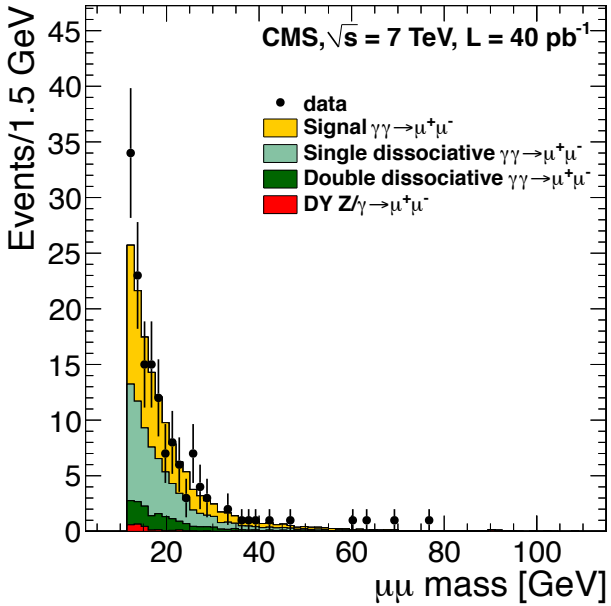
- After all selections, 148 events remain (~50% expected to be from proton dissociation)
- Signal (el-el) is extracted with a binned maximum likelihood fit to the $p_T(\mu\mu)$ distribution with 3 free parameters:
  - Signal yield
  - Single proton dissociation (inel-el) yield
  - Correction factor to the shape of single proton dissociation events
- Shape and yield of double proton dissociation (inel-inel) and Drell-Yan production are fixed from simulation (Varied as systematic uncertainties)

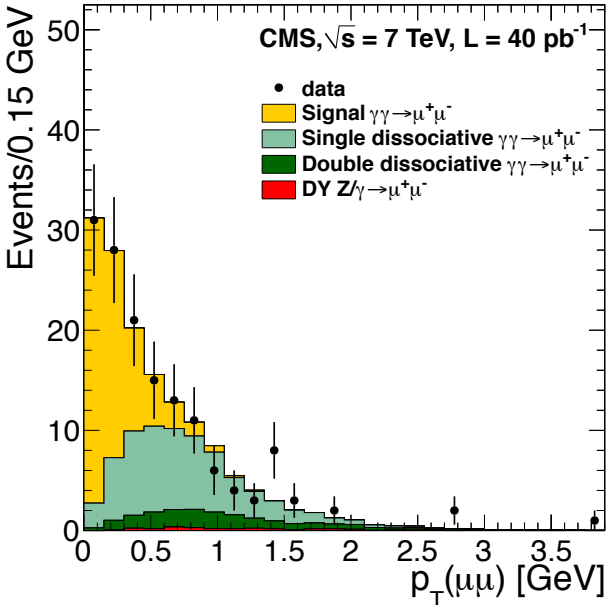
For $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$ and $m(\mu\mu) > 11.5$ GeV, the measured cross section and the ratio to the LPAIR prediction are:

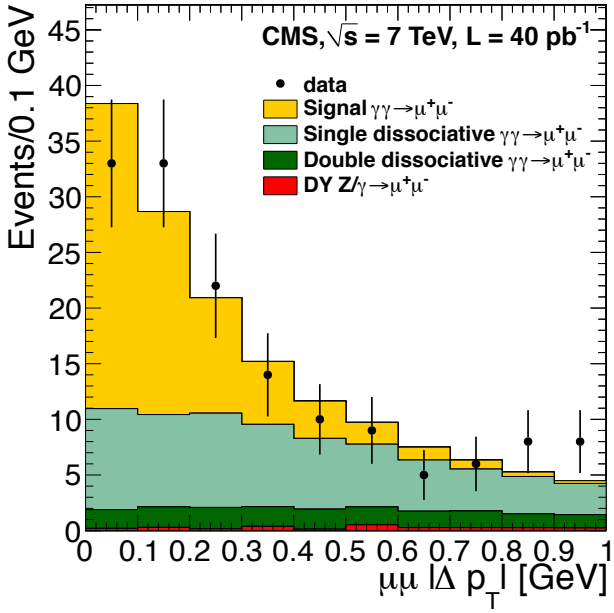
$$\sigma = 3.38^{+0.58}_{-0.55}(\text{stat.}) \pm 0.16(\text{syst.}) \pm 0.14(\text{lumi.})\ \text{pb}$$

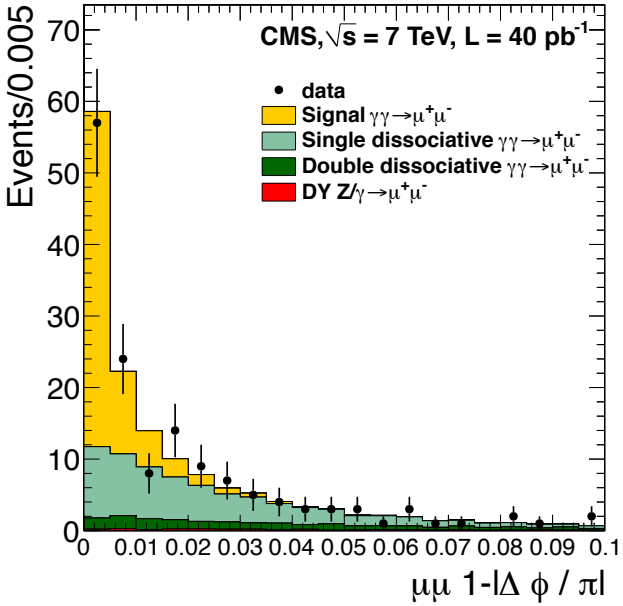
$$R = 0.83^{+0.14}_{-0.13}(\text{stat.}) \pm 0.04(\text{syst.}) \pm 0.03(\text{lumi.})$$

Kinematic distributions









Conclusion

- No diphoton events survive the selection criteria.
- An upper limit on the cross section is set at 1.18 pb with 95% confidence level.

- 17 exclusive or semi-exclusive dielectron candidates are observed, with an estimated background of 0.85 events, while the prediction is 16.3 events.
- Both the number of candidates and the kinematic distributions are in agreement with the QED prediction evaluated with LPAIR.

- For $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$ and $m(\mu\mu) > 11.5$ GeV, a cross section of exclusive dimuon production is measured:

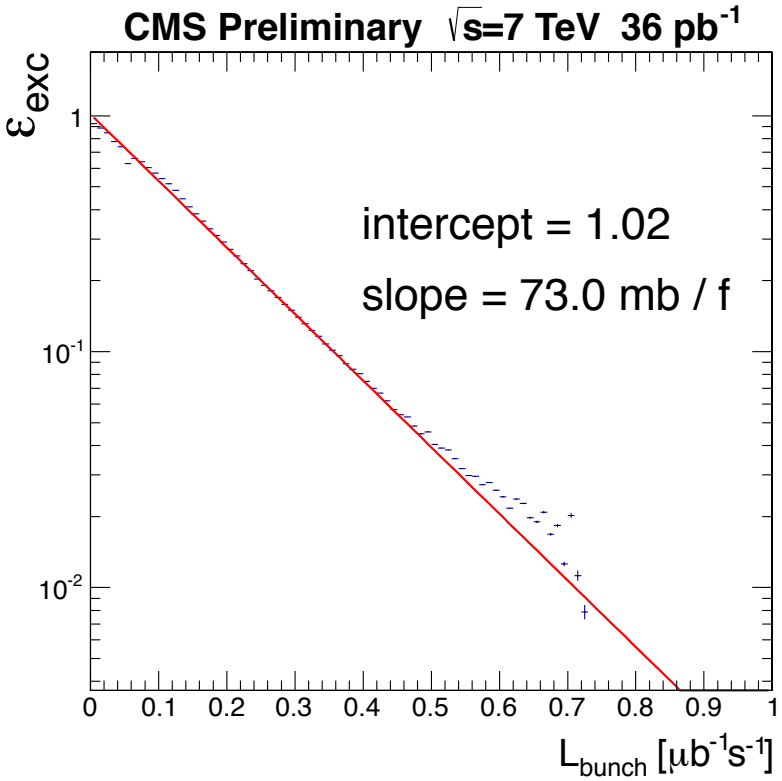
$$\sigma = 3.38^{+0.58}_{-0.55}(\text{stat.}) \pm 0.16(\text{syst.}) \pm 0.14(\text{lumi.})\,\text{pb}$$

Outlook:

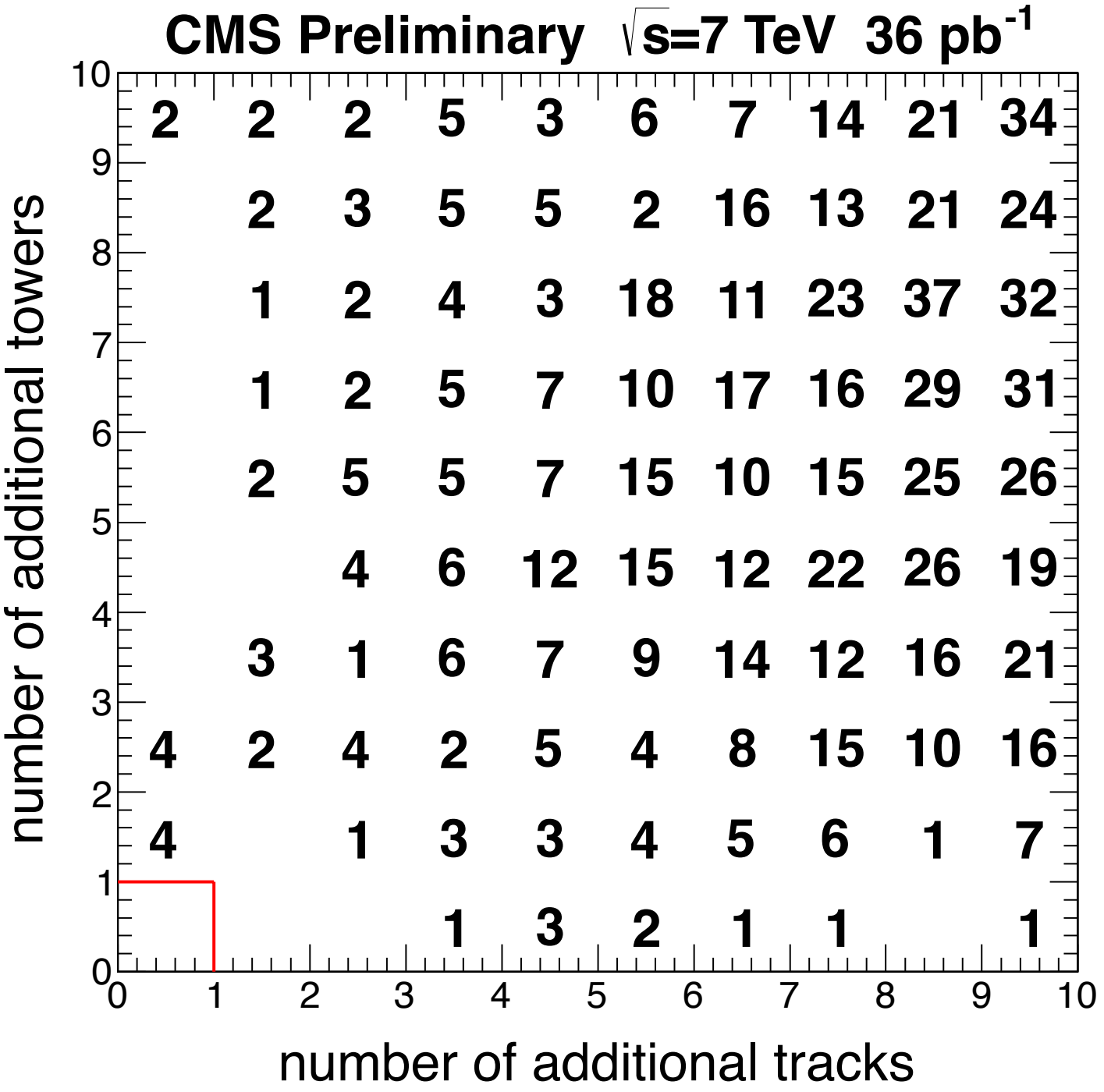
- Exclusive W^+W^- production via $\gamma\gamma$ interactions
- Exclusive Z production via γIP fusion
- Exclusive $\pi^+\pi^-$ production via IPIP exchange

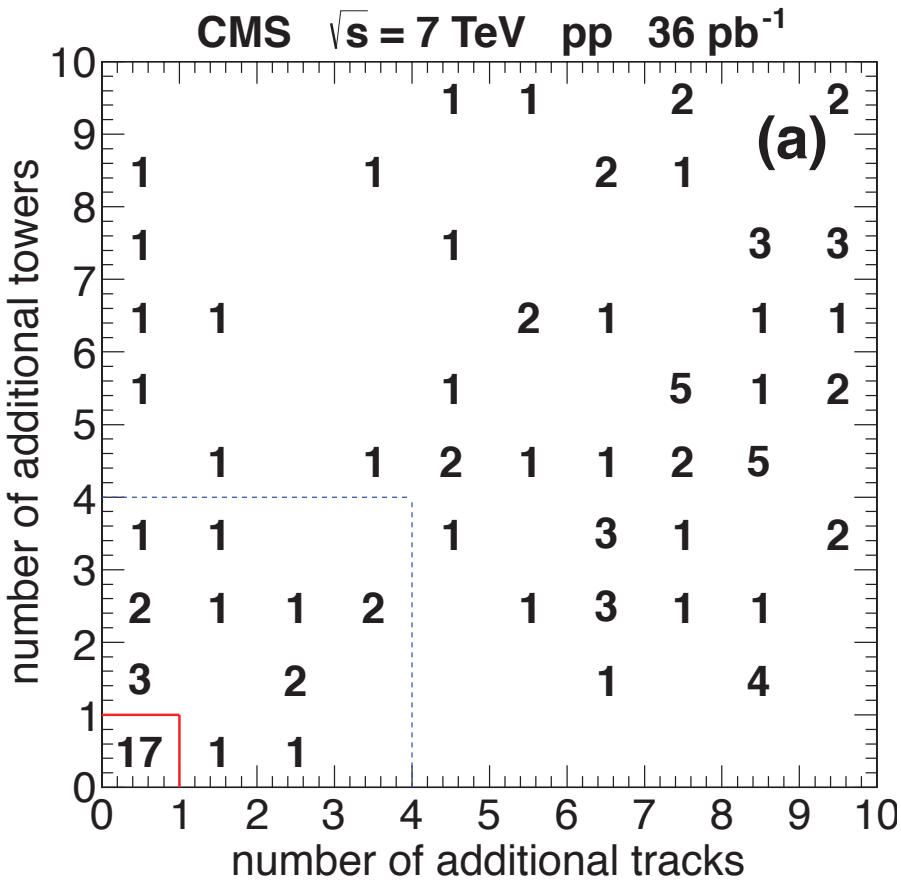
Thank you !

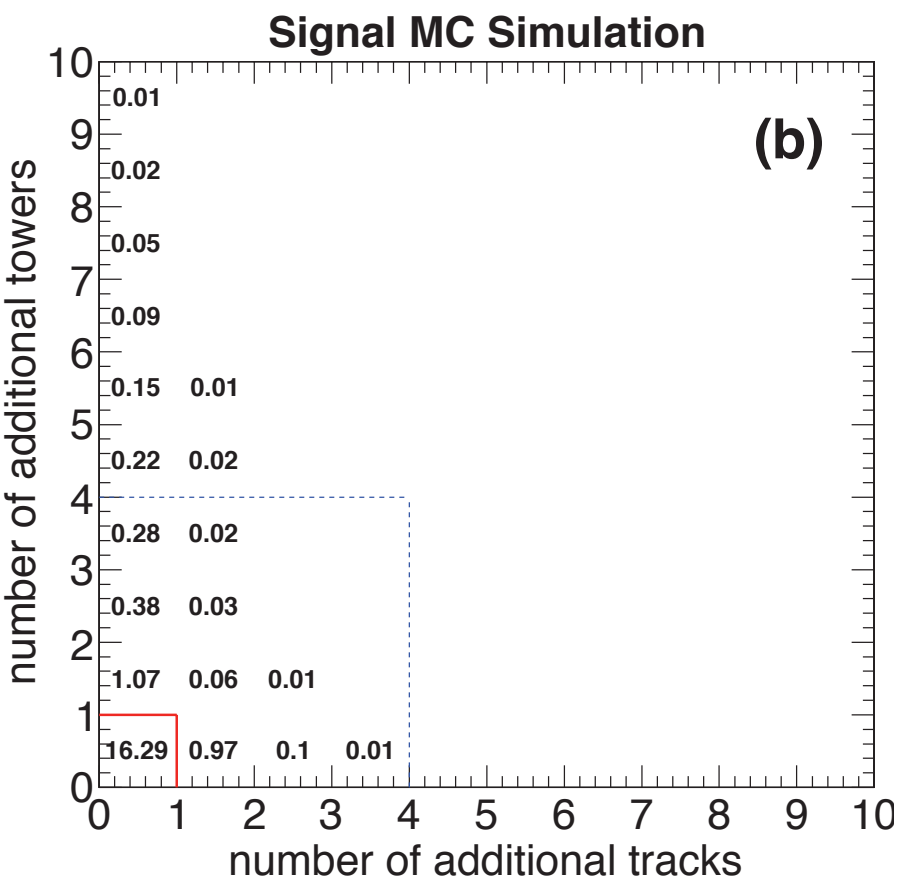
$$\varepsilon_{\text{exc}}(\mathcal{L}_{\text{bunch}}) = \frac{N^{\text{exc}}_{\text{zero-bias}}(\mathcal{L}_{\text{bunch}})}{N_{\text{zero-bias}}(\mathcal{L}_{\text{bunch}})} \approx \mathrm{e}^{-\overline{n}} = \mathrm{e}^{-\mathcal{L}_{\text{bunch}} \cdot \sigma_{\text{inelastic}} / f}$$

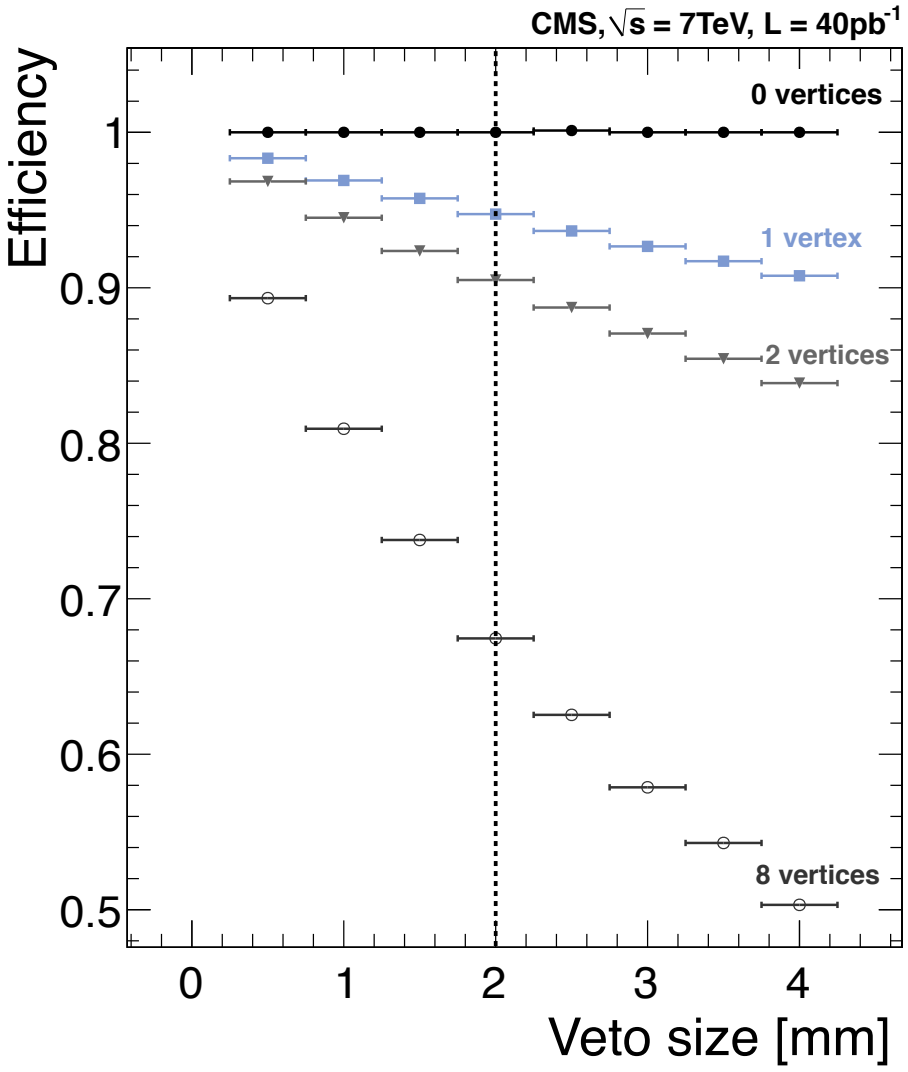


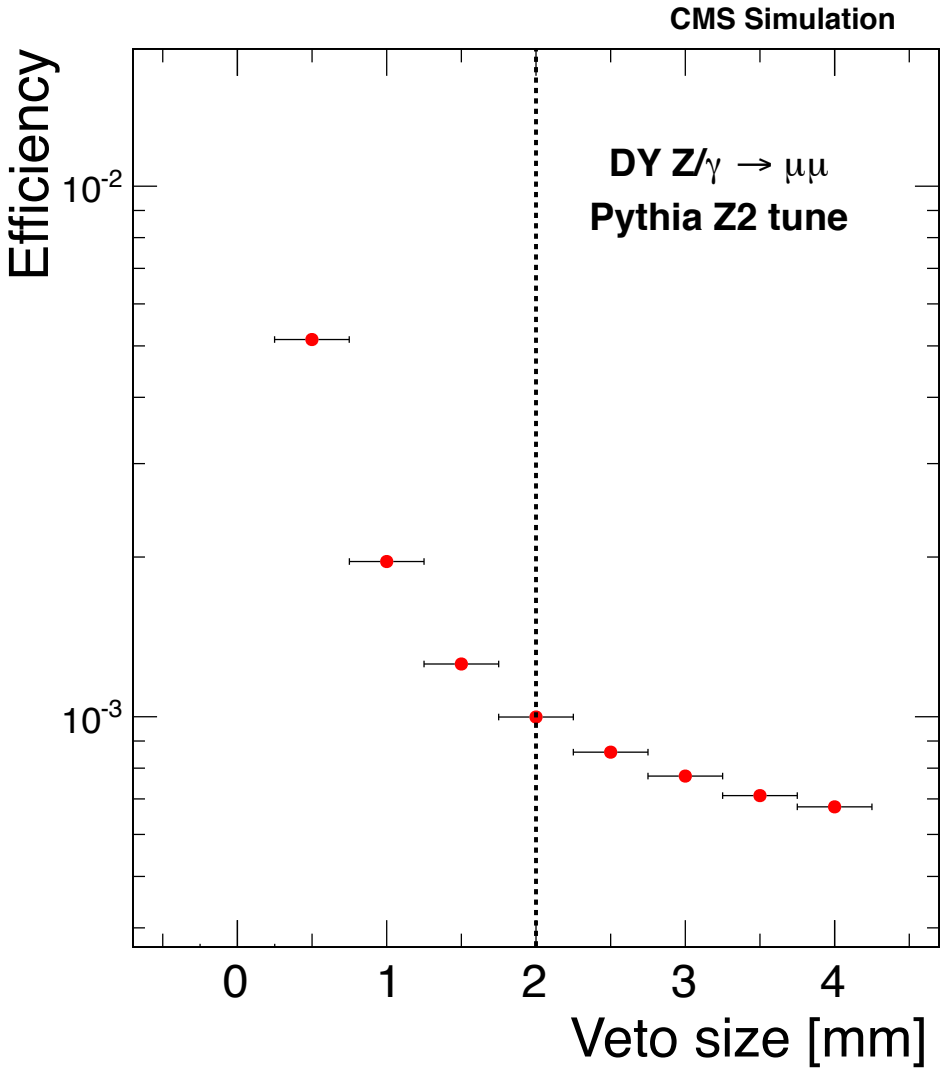
$$\varepsilon_{\text{exc}} = \frac{\int \frac{\mathrm{d}N_{\text{zero-bias}}}{\mathrm{d}\mathcal{L}_{\text{bunch}}} \cdot \mathcal{L}_{\text{bunch}} \cdot \varepsilon_{\text{exc}}(\mathcal{L}_{\text{bunch}}) \cdot \mathrm{d}\mathcal{L}_{\text{bunch}}}{\int \frac{\mathrm{d}N_{\text{zero-bias}}}{\mathrm{d}\mathcal{L}_{\text{bunch}}} \cdot \mathcal{L}_{\text{bunch}} \cdot \mathrm{d}\mathcal{L}_{\text{bunch}}} = 0.143 \pm 0.008$$


CMS Preliminary √s=7 TeV 36 pb-1
number of additional towers
number of additional tracks
0 1 2 3 4 5 6 7 8 9 10
2 2 2 5 3 6 7 14 21 34
2 3 5 5 2 16 13 21 24
1 2 4 3 18 11 23 37 32
1 2 5 7 10 17 16 29 31
2 5 5 7 15 10 15 25 26
4 6 12 15 12 22 26 19
3 1 6 7 9 14 12 16 21
4 2 4 2 5 4 8 15 10 16
4 1 3 3 4 5 6 1 7
1 3 2 1 1 1


CMS √s = 7 TeV pp 36 pb-1
(a)
number of additional towers
number of additional tracks
0 1 2 3 4 5 6 7 8 9 10
1 1 2 2
1 1 2 1
1 1 3 3
1 1 2 1 1 1
1 1 5 1 2
1 1 2 1 1 2 5
1 1 1 3 1 2
2 1 1 2 1 3 1 1
3 2 1 4
17 1 1


Signal MC Simulation
(b)
number of additional towers
number of additional tracks
0 1 2 3 4 5 6 7 8 9 10
0.01
0.02
0.05
0.09
0.15 0.01
0.22 0.02
0.28 0.02
0.38 0.03
1.07 0.06 0.01
16.29 0.97 0.1 0.01


CMS, $\sqrt{s}$ = 7TeV, L = 40pb^{-1}
0 vertices
1 vertex
2 vertices
8 vertices
Efficiency
1
0.9
0.8
0.7
0.6
0.5
0
1
2
3
4
Veto size [mm]


CMS Simulation
DY Z/γ → μμ
Pythia Z2 tune
Efficiency
10^{-2}
10^{-3}
0
1
2
3
4
Veto size [mm]

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
$p_{\mathrm{T}} > 4\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.1$	438	132	241	106	20	499
$m(\mu^+\mu^-) > 11.5\,\mathrm{GeV}$	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
$\lvert\Delta p_{\mathrm{T}}\rvert < 1.0\,\mathrm{GeV}$	148	86	79	16	3	184

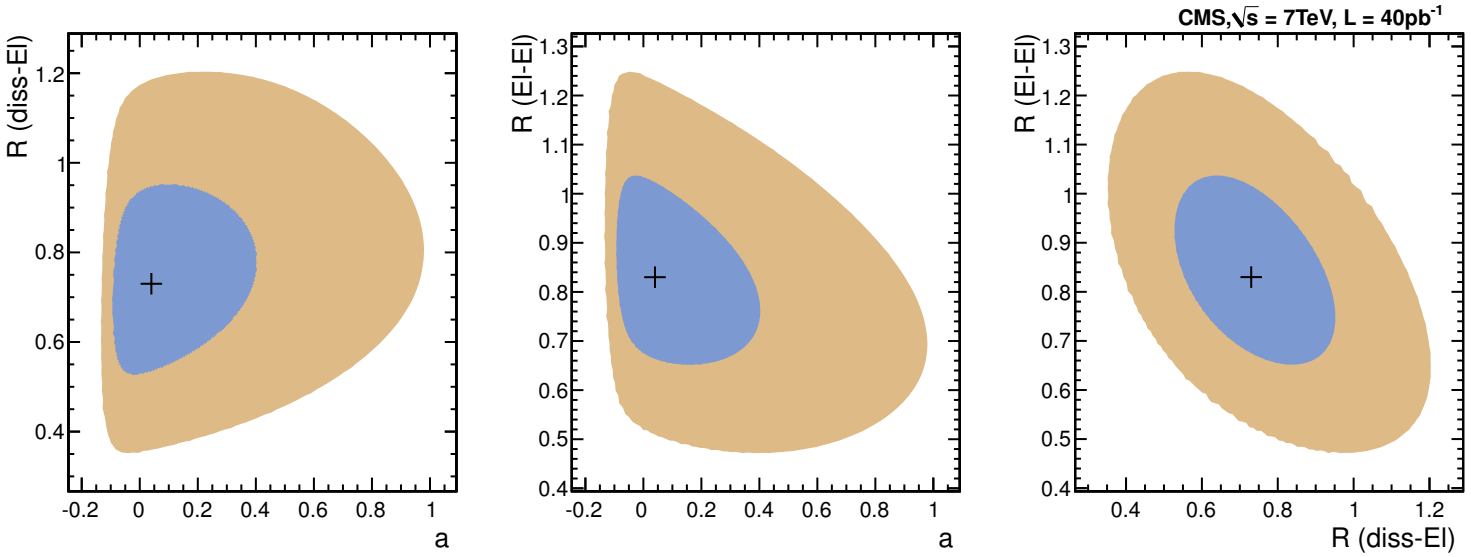


Figure 5. One and two standard-deviation contours in the plane of fitted parameters for the proton-dissociation yield ratio vs. modification parameter a (left), the data-theory signal ratio vs. modification parameter a (center), and the data-theory signal ratio vs. proton-dissociation yield ratio (right). The contours represent 39.3% and 86.5% confidence regions, where the cross indicates the best-fit point.

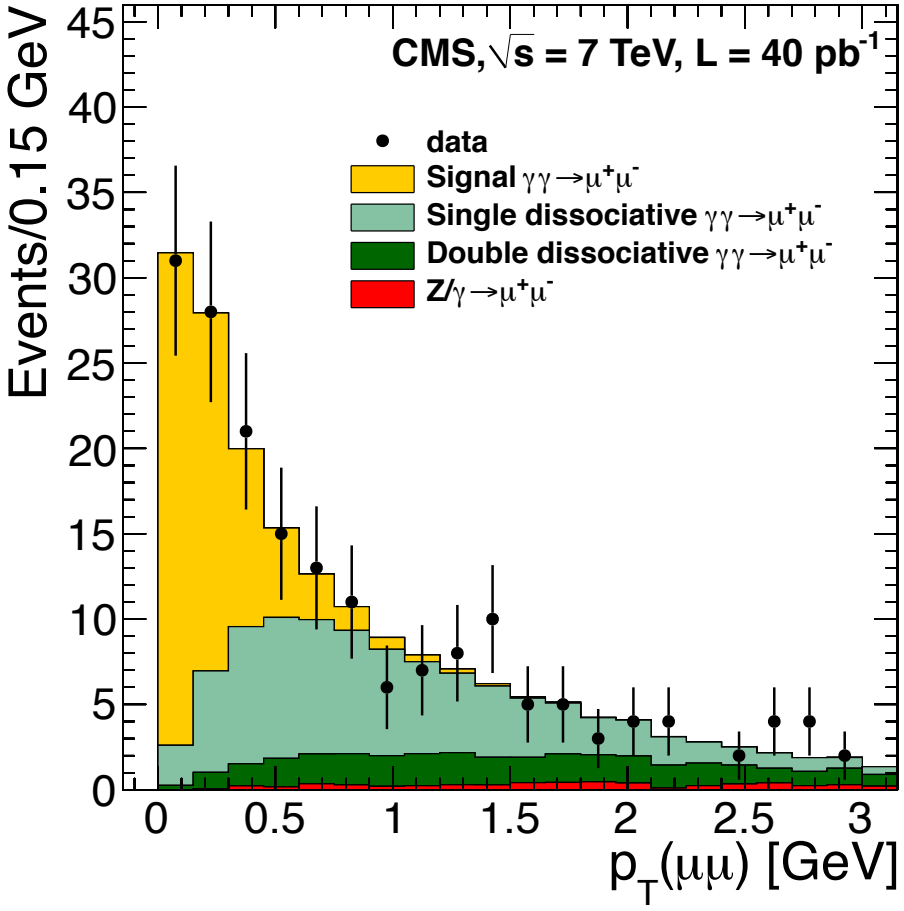
data-theory signal ratio: $R_{\mathrm{El-El}} = 0.83^{+0.14}_{-0.13}$;

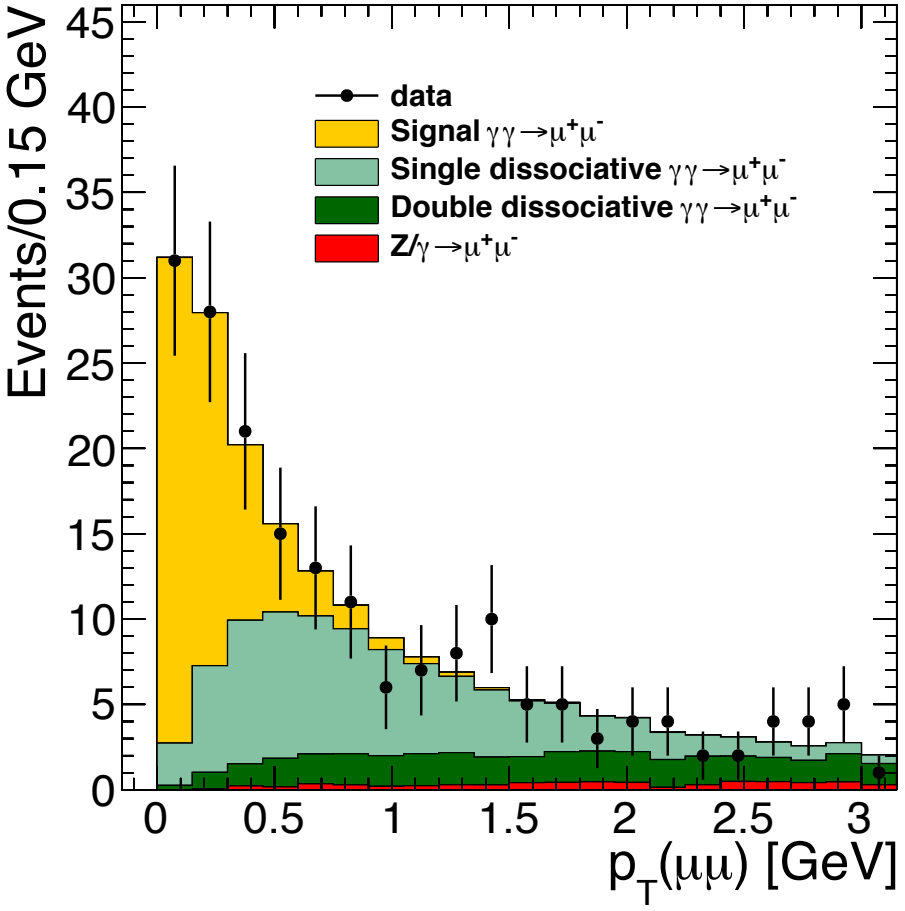
single-proton dissociation yield ratio: $R_{\mathrm{diss-El}} = 0.73^{+0.16}_{-0.14}$;

modification parameter: $a = 0.04^{+0.23}_{-0.14}\,\mathrm{GeV}^{-2}$

Selection	Variation from nominal yield
Track veto criteria	3.6%
Track quality	2.5%
DY background	0.4%
Double-proton dissociation background	0.9%
Crossing angle	1.0%
Tracking efficiency	0.1%
Vertexing efficiency	0.1%
Momentum scale	0.1%
Efficiency correlations in J/ψ control sample	0.7%
Muon and trigger efficiency statistical uncertainty	0.8%
Total	4.8%

Table 3. Relative systematic uncertainties.





Selection	$R_{\mathrm{El-El}}$	$R_{\mathrm{diss-El}}$
All selection criteria applied	$0.83^{+0.14}_{-0.13}$	$0.73^{+0.16}_{-0.14}$
No $\lvert\Delta p_{\mathrm{T}}\rvert$ requirement	$0.82^{+0.13}_{-0.13}$	$0.63^{+0.11}_{-0.10}$
Both $\lvert\Delta p_{\mathrm{T}}\rvert$ and $1-\lvert\Delta\phi/\pi\rvert$ requirements removed	$0.81^{+0.13}_{-0.13}$	$0.45^{+0.08}_{-0.07}$

Table 2. Best-fit values of $R_{\mathrm{El-El}}$ and $R_{\mathrm{diss-El}}$ for the nominal selection, and with the requirements on $\lvert\Delta p_{\mathrm{T}}(\mu^+\mu^-)\rvert$ and $1-\lvert\Delta\phi(\mu^+\mu^-)/\pi\rvert$ removed.