

Exclusive measurements with CMS

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on behalf of the CMS collaboration

QCD at LHC: forward physics and UPC collisions of heavy ions, Trento, Italy

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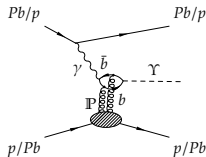
- Exclusive production of Υ mesons in pPb collisions: [CMS-PAS-FSQ-13-009](#)
- Measurement of exclusive $\pi^+\pi^-$ production in pp collisions: [CMS-PAS-FSQ-12-004](#)
- Searches for $\gamma\gamma \rightarrow W^+W^-$ processes and limits on anomalous quartic gauge couplings: [JHEP08\(2016\) 119](#) and [arXiv:1604.04464](#) [hep-ex]

Documentation

Complete list of CMS Forward, small- x , and QCD results available on

- cern.ch/cms-results/public-results/publications/FSQ, and
- twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Exclusive production of Υ mesons in pPb collisions



First observation ever of this process in asymmetric pPb/Pbp collisions

Main motivations:

- Photonuclear cross-section sensitive to the gluon density in the nucleon:

$$d\sigma/dt \propto (x_{Bj} G(x_{Bj}, Q^2))^2$$

- Steep rising of σ with $W_{\gamma p}$
- reflection of steep rise in the gluon density with lowering of x_{Bj}
- probing the **gluon density** in the **unexplored region** of
low- $x_{Bj} = M_{\Upsilon}^2 / W_{\gamma p}^2 \simeq 10^{-2} - 10^{-4}$

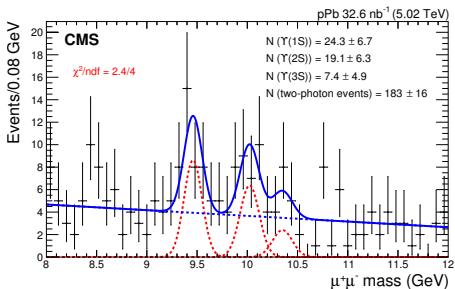
Datasets: 18.8 (13.8) nb^{-1} of pPb (Pbp) collected at $\sqrt{s_{NN}} = 5.02$ TeV

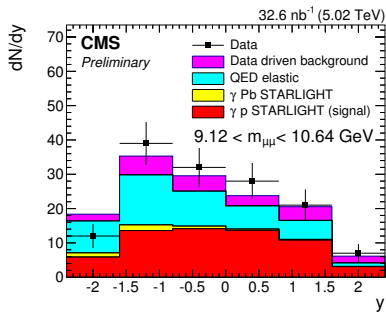
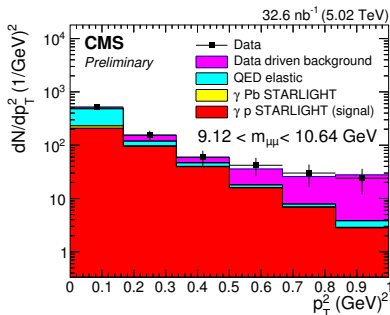
Selection:

- two opposite-sign muons, with $|\eta(\mu)| < 2.2$, $p_T(\text{single } \mu) > 3.3$ GeV
- one single dimuon vertex, no extra tracks with $p_T > 2$ GeV

- $0.1 < p_T(\mu\mu) < 1$ GeV
(remove **exclusive and inclusive backgrounds**)
- $|\gamma(\mu\mu)| < 2.2$ (high **μ -finding efficiency**)
- invariant mass fit templates:
 - linear $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum
 - Gaussian $\Upsilon(nS)$ peaks

- fit parameters: $\Upsilon(1-3s)$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum yields, $\Gamma(\Upsilon(1s))$





- Good data/MC agreement reached
- Higher γp signal with respect to γPb
 - photon flux $\phi \propto Z^2$
 - quasireal photons emission strongly enhanced for Pb

Differential cross section evaluated in:

- 5 bins of $|t| \simeq p_T^2(\mu\mu)$: $0.01 < |t| < 1 \text{ GeV}^2$
- 4 bins of $y(\mu\mu)$: $|y| < 2.2$

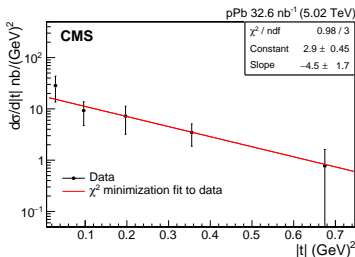
Iterative Bayesian unfolding of background-subtracted $|t|$ and y distributions, correction for experimental acceptance

$$\frac{d\sigma_\Upsilon}{d|t|} = \frac{1}{L} \frac{N^{\Upsilon(nS)}}{\Delta|t|}$$

Templated fit:

$N e^{-b|t|}$ in $0.01 < |t| < 1 \text{ GeV}^2$:

$b = 4.5 \pm 1.7 \text{ (stat.)} \pm 0.6 \text{ (syst.) GeV}^{-2}$



Compatible with pQCD predictions and HERA measurements:

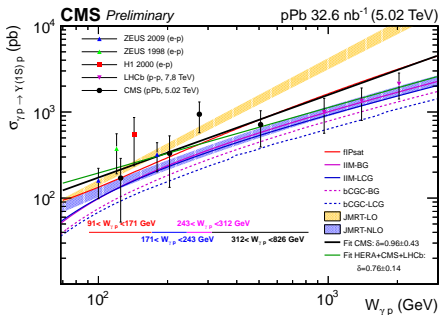
- H1: $4.73 \pm 0.25 \text{ (stat.) GeV}^{-2}$ (arXiv:hep-ex/0003020)
- ZEUS: $4.3_{-1.3}^{+2.0} \text{ (stat.) GeV}^{-2}$ (arXiv:1111.2133)

Power law dependance of the resonance production cross-section with γp CoM energy:

$$\sigma_{\gamma p} = \frac{1}{\phi} \frac{d\sigma_{\Upsilon(1S)}}{dy} \propto (W_{\gamma p})^\delta$$

Photon flux $\phi = \phi(y)$ from STARLIGHT (no hadronic interaction)

Experiment	δ
HERA-H1	0.83 ± 0.07
HERA-ZEUS	1.2 ± 0.8
LHC-CMS	0.96 ± 0.43
Overall fit	0.76 ± 0.14



- CMS data **consistent** with dependence of $\sigma(W_{\gamma p})$ seen in **former attempts**
- **disfavors LO pQCD** predictions.

Measurement of exclusive $\pi^+\pi^-$ production in pp collisions

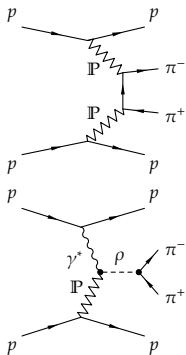
Multiple contributions to exclusive $\pi^+\pi^-$ production, e.g.

CEP, or $\gamma p \rightarrow \rho(770)p \rightarrow \pi^+\pi^-p$

Good spectroscopy tool to probe low-mass scalar resonances

Samples and selection:

- Low-pileup, zero bias data collected at $\sqrt{s} = 7$ TeV:
450 pb^{-1}
- $p_T(\pi^\pm) > 200$ MeV, $|y(\pi^\pm)| < 2.0$, identification through dE/dx of low-momentum tracks in silicon tracker
- Exclusivity condition: **2 tracks** only on vertex, calorimeter signal veto (noise thresholds on ECAL and HCAL)

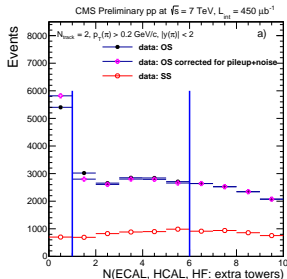


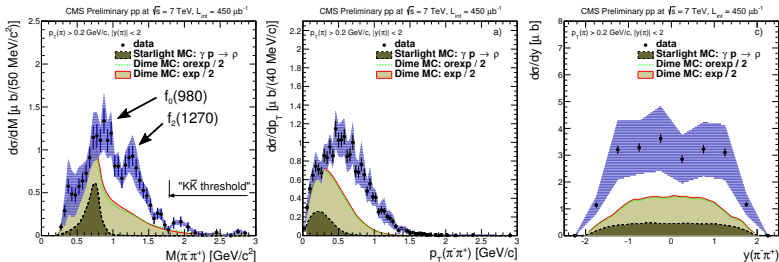
Simulation:

- Single- and double- dissociation, DPE with **Pythia8+MBR**
- $\gamma p \rightarrow \rho(770)p$ with **Starlight**
- $pp \rightarrow p^{(*)}\pi^+\pi^-p^{(*)}$ continuum (no resonances) with Durham's **Dime MC**

Data-driven background estimation:

- background yield and shape extracted from events with 1–5 extra towers above threshold
- same procedure applied on same-sign events (background only) as a closure test
 - 754 ± 12 events predicted in 0 extra towers-region, with 700 ± 27 observed events





Differential cross sections overestimate the exclusive $\pi^+\pi^- + \rho$ photoproduction predictions at $p_T(\pi^+\pi^-) > 0.4$ GeV

Unfolded cross sections ($p_T(\pi^\pm) > 0.2$ GeV):

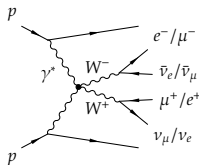
- $|y(\pi^\pm)| < 2.0$: $\sigma_{\text{vis}} = 20.5 \pm 0.3$ (stat.) ± 3.1 (sys.) ± 0.8 (lumi) μb

Predicted value: 12.7 μb (Pythia8 MBR) / 13.8 μb (Pythia8 4C tune), without **low-mass proton dissociation** nor **intermediate resonances** contributions

- $|y(\pi^\pm)| < 1.0$: $\sigma_{\text{vis}} = 8.1 \pm 0.2$ (stat.) ± 1.2 (sys.) ± 0.3 (lumi) μb

Searches for $\gamma\gamma \rightarrow W^+W^-$ processes and limits on
anomalous quartic gauge couplings

Upgrade at $\sqrt{s} = 8$ TeV of the previous 7 TeV search
(JHEP 07 (2013) 116)



Strategy:

- search for $pp \rightarrow p^{(*)}(\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu \bar{\nu})p^{(*)}$ events
- using central CMS information only:
 - track-based exclusivity condition to enhance two-photon production process
- detect deviations on production rate to probe anomalous couplings

Anomalous models:

Gauge boson self-couplings in SM: $SU(2) \times U(1)$ structure of electroweak sector.
Anomalous (T/Q)GCs predicted by many SM extensions: additional gauge bosons, SUSY, ...

Can be introduced as a $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{ext}}$ up to a fixed energy scale Λ .

- dimension-6, “LEP legacy” model

$$\mathcal{L}_{\text{AQGC}} \ni \begin{cases} \mathcal{L}_6^c = -\frac{e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^{-\beta} - W^{-\alpha} W^{+\beta}) \\ \quad - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^\alpha Z_\beta \\ \mathcal{L}_6^0 = -\frac{e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-\alpha} - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha \end{cases}$$

- 2 parameters handling the $\gamma\gamma W^+W^-$ coupling: $a_{0,C}^W$ (SM limit: $a_{0,C}^W = 0$)
- dimension-8, suitable for LHC energies
 - 4 parameters handling the $\gamma\gamma W^+W^-$ coupling: $f_{M,0-3}$ (SM limit: $f_{M,0-3} = 0$)

Dataset: 19.7 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$ (combined with 5.05 fb^{-1} at 7 TeV)

Selection:

- opposite charge electron-muon pair,

- $p_T(\mu), E_T(e) > 20 \text{ GeV}$,
 - $|\eta(e, \mu)| < 2.4$

- associated to a common primary vertex

- $m(e\mu) > 20 \text{ GeV}$

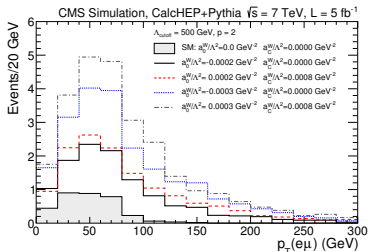
- track-based exclusivity condition

- **no additional tracks** on the dilepton vertex

- signal region: high- $p_T(e\mu)$

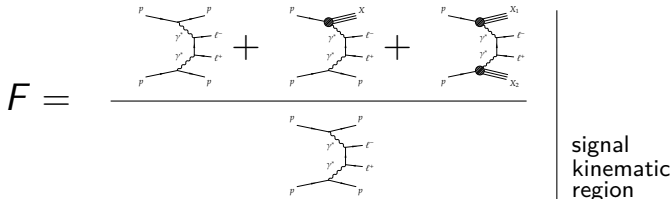
- Photon-induced process at a pp collider: **3 sub-processes** to consider in signal:

- **elastic** two-photon production
 - **single-** and **double-proton dissociation**



Elastic component simulated (EPA), **data-driven method** to account for other contributions (high-statistics channels: $\gamma\gamma \rightarrow \mu^+\mu^-$, $\gamma\gamma \rightarrow e^+e^-$):

$$\sigma_{\gamma\gamma}^{\text{total}} = F \times \sigma_{\gamma\gamma}^{\text{elastic}} \text{ with}$$

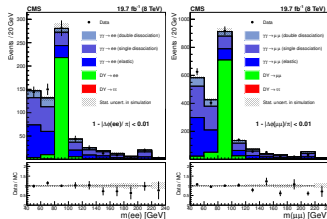


Experimentally, F factor extracted as:

$$F = \frac{n_{\text{data}}^{\mu\mu} - n_{\text{MC}}^{\text{bckgrd}}}{n_{\text{MC}}^{\text{elastic}}} \Bigg|_{\text{presel.} + m(\mu\mu) > 160 \text{ GeV} \simeq 2M_W}$$

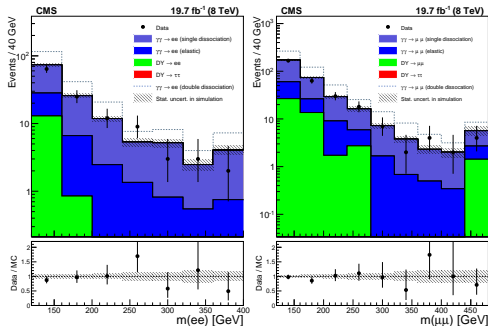
$$= 3.23 \pm 0.53 \text{ (stat.) (7 TeV)}$$

$$= 4.10 \pm 0.43 \text{ (stat.) (8 TeV)}$$



Intermission: Overestimation of the survival factor in LPAIR matrix-element description of the $\gamma\gamma \rightarrow \ell^+\ell^-$ process cross section

- Data shows better agreement with large suppression of double-dissociative component in this kinematic region
- Example: 0% gap survival probability for DD:



Search for $\gamma\gamma \rightarrow W^+W^-$ events...



Cut flows for the two analyses:

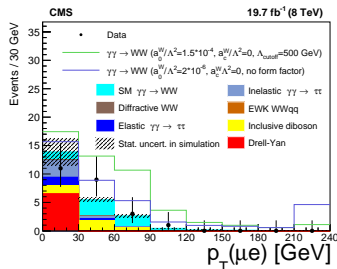
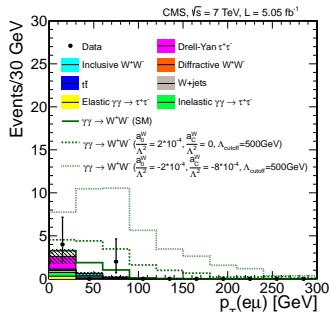
Selection step	7 TeV	8 TeV
Trigger/presel.	9086	19406
$m(e\mu) > 20$ GeV	8200	18466
Leptons identif.	1222	6541
No extra tracks	6	24
$p_T(e\mu) > 30$ GeV	2	13

Observed cross sections (\times branching fraction) for the $pp \rightarrow p^{(*)}(\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu \bar{\nu})p^{(*)}$ process:

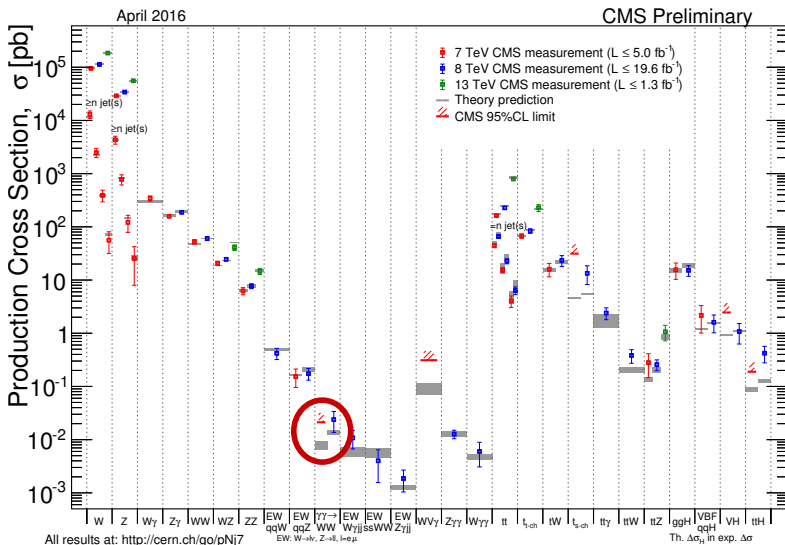
- at 7 TeV: $\sigma_{\text{obs}} = 2.2_{-2.0}^{+3.3}$ fb, $\sigma_{\text{SM}} = 4.0 \pm 0.7$ fb
- at 8 TeV: $\sigma_{\text{obs}} = 11.9_{-4.5}^{+5.6}$ fb, $\sigma_{\text{SM}} = 6.9 \pm 0.6$ fb

Consistent with the SM

Combined significance for 7 + 8 TeV combination (over background-only hypothesis): **3.4σ**



Still among the lowest cross sections reachable at the LHC



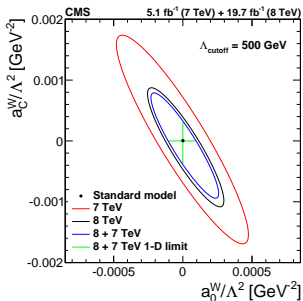
- Using the $p_T(e\mu)$ distribution of SM and AQCc $\gamma\gamma \rightarrow W^+W^-$ behaviour, extract constraints on AQCcs

Example: 1-dimensional limits on (dim-6) AQCc

parameters:

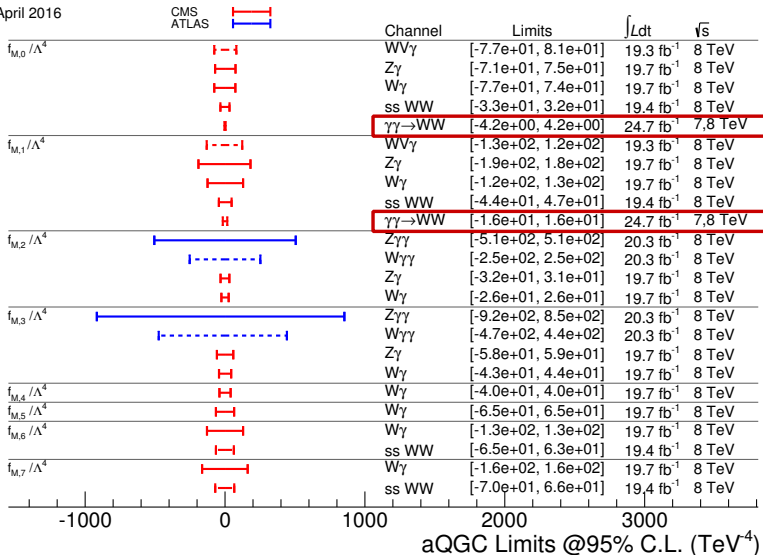
- applying unitarity restoring form factor
 - $a_{0,C}^W \rightarrow a_{0,C}^W / (1 + W_{\gamma\gamma}^2 / \Lambda_{\text{cutoff}}^2)$,
 $\Lambda_{\text{cutoff}} = 500 \text{ GeV}$

Param.	7 TeV	8 TeV	Combined
a_0^W / Λ^2	$[-1.5, 1.5]$	$[-1.1, 1.0]$	$[-0.9, 0.9]$
a_C^W / Λ^2	$[-5, 5]$	$[-4.2, 3.4]$	$[-3.6, 3.0]$
	$\times 10^{-4} \text{ GeV}^{-2}$	$\times 10^{-4} \text{ GeV}^{-2}$	$\times 10^{-4} \text{ GeV}^{-2}$



- Most stringent limits on these operators
 - two orders of magnitude tighter than LEP-II limits

April 2016



(plot from twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC)

Exclusive production of Υ in pPb collisions

- **Differential cross sections** in $|t|$ and y distributions
- Better picture of **gluon density evolution** at low- x_{Bj}

Exclusive $\pi^+\pi^-$ production in pp collisions

- Differential and integrated cross sections extracted at $\sqrt{s} = 7$ TeV
 - $|y(\pi^\pm)| < 2.0$: $\sigma_{\text{vis}} = 20.5 \pm 0.3$ (stat.) ± 3.1 (sys.) ± 0.8 (lumi) μb
 - $|y(\pi^\pm)| < 1.0$: $\sigma_{\text{vis}} = 8.1 \pm 0.2$ (stat.) ± 1.2 (sys.) ± 0.3 (lumi) μb
 - Diff. cross sections above exclusive $\pi^+\pi^- + \rho$ photoproduction predictions for $p_T(\pi^+\pi^-) > 0.4$ GeV

Search for AQGCs in $\gamma\gamma \rightarrow W^+W^-$

- **Evidence set** for this process (3.7σ observed significance)
- **Most stringent limits** so far on anomalous quartic $\gamma\gamma W^+W^-$ couplings

Backup

Systematics	Uncertainty
Background estimation	7.2%
Tracking efficiency (pion pair)	7.8%
Unfolding	10.3%
HF energy scale	2.0%
Barrel, endcaps energy scale	3.9%
Integrated luminosity	4.0%
Total	15.9%

Selection	Data: Events Left
High-Level Trigger ZeroBias	33214795
Exactly two tracks	215139
Track Purity	170990
$ y(track) < 2$	128375
$p_T(track) > 0.2 \text{ GeV}/c$	103038
Vertex with 2 tracks	58468
$ z_{vertex} < 15 \text{ cm}$	57602
$E_{EB} < 0.52 \text{ GeV}$	49462
$E_{EE} < 2.18 \text{ GeV}$	42988
$E_{HB} < 1.18 \text{ GeV}$	41703
$E_{HE} < 1.95 \text{ GeV}$	32565
$E_{HF^+} < 4.0 \text{ GeV}$	14037
$E_{HF^-} < 4.0 \text{ GeV}$	6102
Opposite Sign (OS)	5402
Same Sign (SS)	700

Summary of systematics in the signal region for the 8 TeV analysis:

Systematics	Uncertainty
Proton dissociation factor	10.5%
Efficiency correction for no add. tracks	5.0%
Trigger and lepton identification	2.4%
Integrated luminosity	2.3%
Total	12.2%

Cut flows for the 8 TeV analysis:

Selection step	Data	Excl. $\gamma\gamma \rightarrow W^+W^-$	Backgr.
Trigger/presel.	19406	26.9 ± 0.2	22180 ± 1890
$m(e\mu) > 20$ GeV	18466	26.6 ± 0.2	21590 ± 1850
Leptons identif.	6541	22.5 ± 0.2	6640 ± 93
No extra tracks	24	6.7 ± 0.2	15.2 ± 2.5
$\rho_{\text{T}}(e\mu) > 30$ GeV	13	5.3 ± 0.1	3.9 ± 0.5

