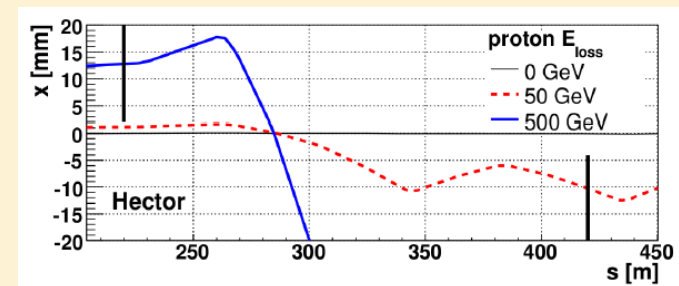
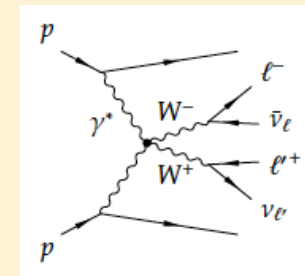
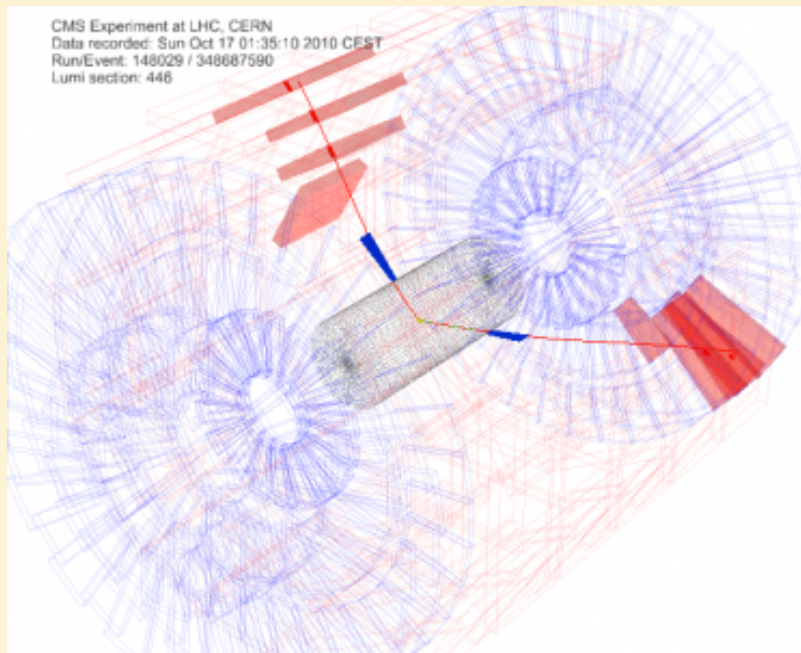


Exclusive physics at the LHC

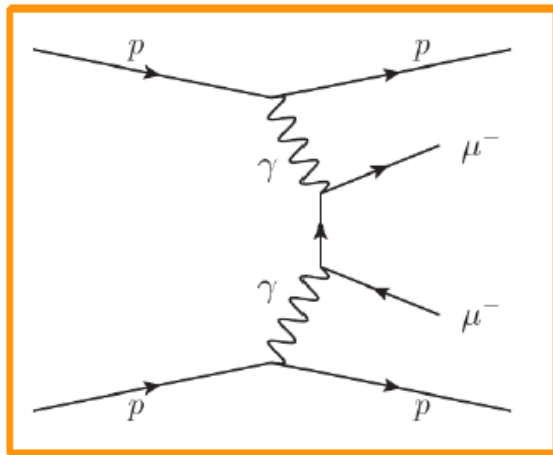
Krzysztof PIOTRZKOWSKI

Université Catholique de Louvain



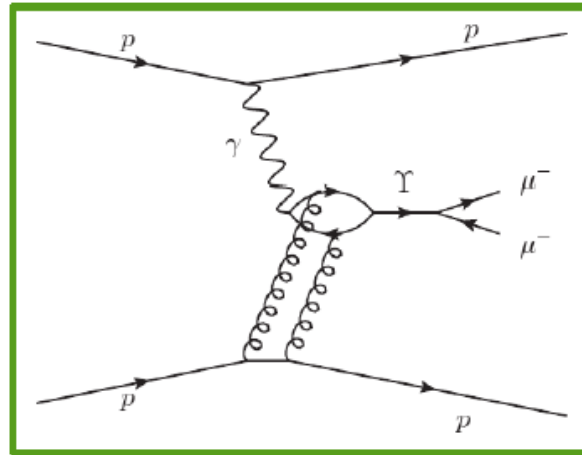
CP3 lunch seminar
December 19, 2012

Two-photon production



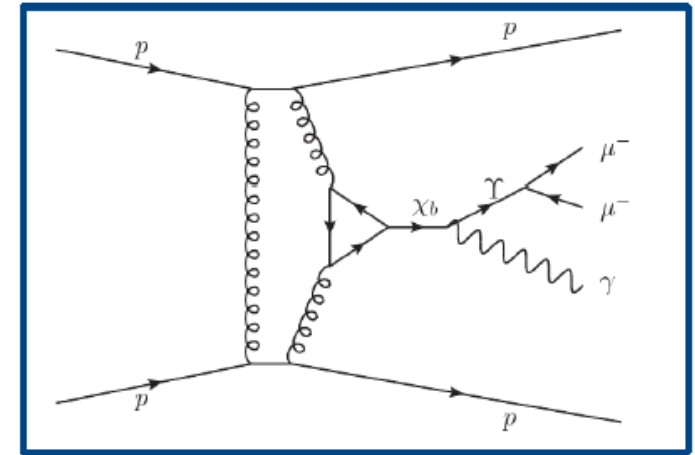
$\mu^+\mu^-$, e^+e^- , $\pi^+\pi^-$
 W^+W^- , H^+H^- , $\tilde{l}^+\tilde{l}^-$, ...

Photo-production



ρ , J/Ψ , Y , Z , ...

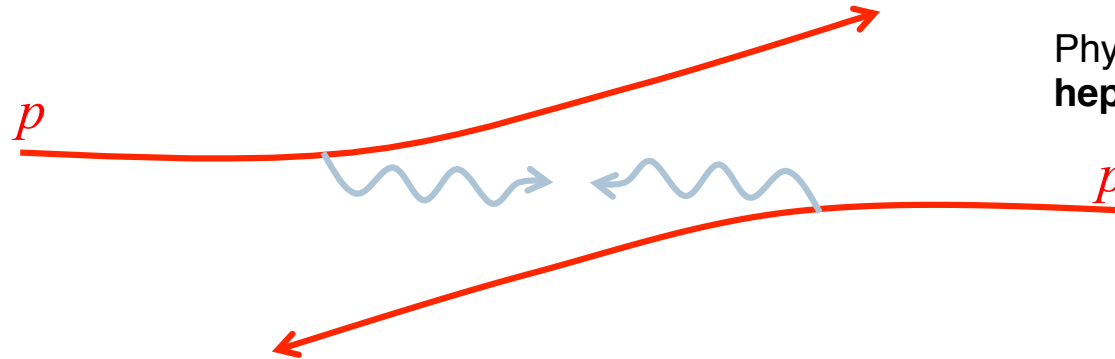
Central Exclusive Production



χ_c , χ_b , $\pi^+\pi^-$, dijets, $\gamma\gamma$,
Higgs, ...

- **Present**: studies of the SM physics and BSM searches by imposing exclusivity conditions using central detectors of CMS
- **Future**: detect also (both) forward scattered protons with the proposed 'High Precision Spectrometer' (HPS)

LHC as a High Energy $\gamma\gamma$ Collider



Phys. Rev. **D63** (2001) 071502(R)
hep-ex/0201027

Observation:

Provided efficient measurement of very forward-scattered protons one can study high-energy $\gamma\gamma$ collisions at the LHC

Highlights:

- $\gamma\gamma$ CM energy W up to/beyond 1 TeV (and under control)
- Large photon flux F therefore significant $\gamma\gamma$ luminosity
- Complementary (and clean) physics to pp interactions, eg studies of exclusive production of heavy particles might be possible ➡ opens new field high energy $\gamma\gamma$ (and γp) physics a la LEP...

Kinematics/EPA

Virtuality Q^2 of colliding photons vary between kinematical minimum $= M_p^2 x^2 / (1-x)$ where x is fraction of proton momentum carried by a photon, and $Q_{\max}^2 \sim 1/\text{proton radius}^2$

EQUIVALENT PHOTON APPROXIMATION (EPA) allows representing a pp process involving the two-photon exchange, as a convolution of two photon fluxes and the **photon-photon** cross section at the $\gamma\gamma$ CM energy W (note that is just like use of pdf for partons...)

$$W^2 = s x_1 x_2$$

$$\text{Photon flux} \propto 1/Q^2 \text{ and } Q^2 - Q_{\min}^2 \approx s\theta^2/4$$

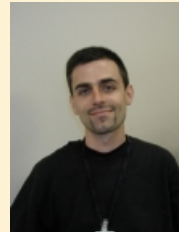
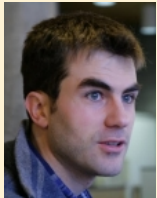


protons scattered at 'zero-degree' angle

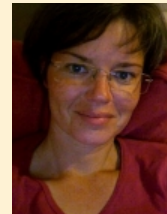
Photon fluxes are larger if one of protons is allowed to break up but virtuality increases too, $Q_{\min}^2 = M_N^2 x$

Exclusive club at CP3

Full members ($\gamma\gamma$):



Associate members (γp):



Note: 4 exclusive PhD theses so far...

Photon physics at CP3

2004: Start (from scratch) building necessary tools



2005: Join R&D effort for novel forward detectors @ LHC
(FP420 collaboration, recognized by CERN)

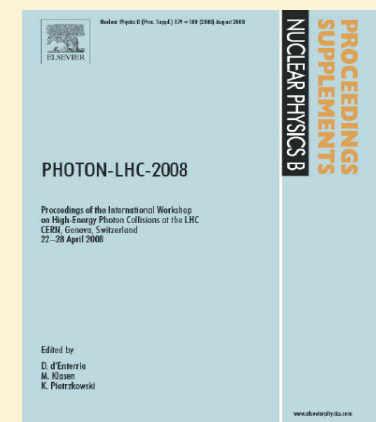
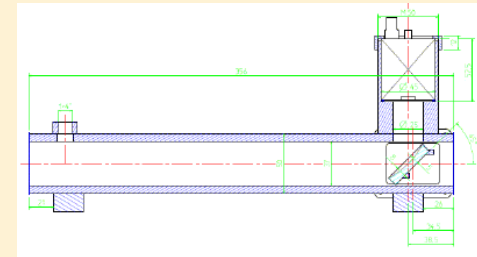
2006: Developing at CP3 - the moving pipe system and
GasToF picosecond detector

2007: Releasing HECTOR (published in JINST 2, P09005) -
A fast LHC beam-line simulation program

(note: DELPHES project initiated for γp studies)

2008: EPA model for $\gamma\gamma$ and γp interactions in pp
collisions implemented in MadGraph, CalcHEP, Pythia
and Sherpa;

Co-organization of PHOTON-LHC workshop at CERN



Photon physics at CP3

2009: FP420 report published in JINST 4 (2009) T10001 – 98 authors from 30 institutes, 10 from CP3; High Precision Spectrometer (HPS) R&D project initiated in CMS

2010: Work on exclusive triggers in CMS and observation of first $\gamma\gamma \rightarrow \mu\mu$ events

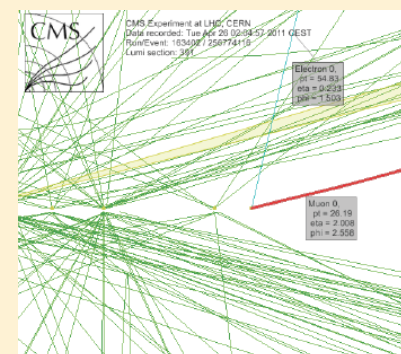
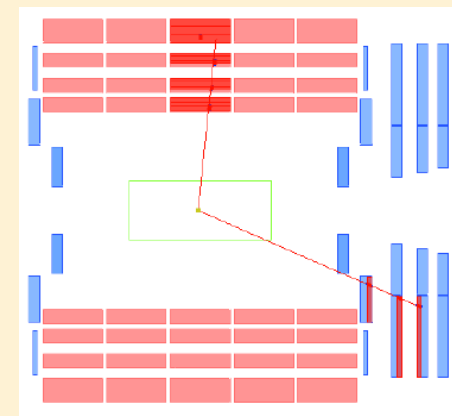
2011: First two-photon measurement in CMS (and at the LHC!) $pp \rightarrow p \mu\mu p$, AN-2011/039

Organization of the PHOTON 2011 conference in Spa

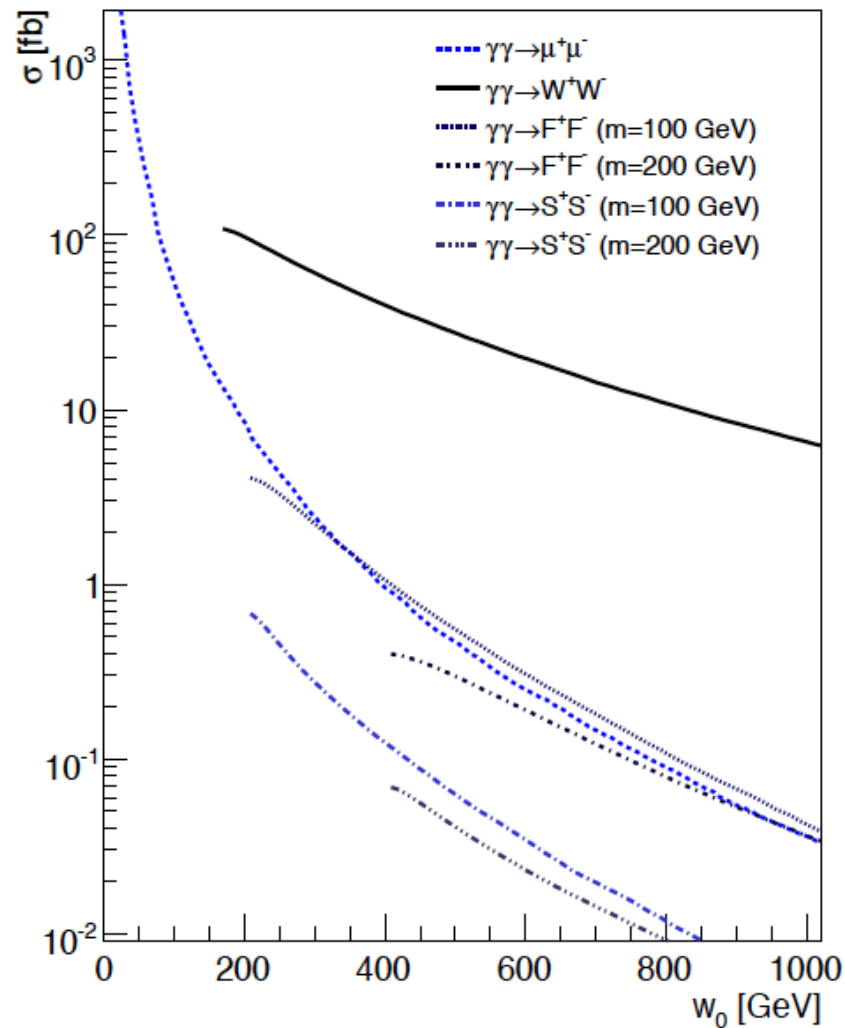
**2012: First evidence for $pp \rightarrow p WW p$
AN-2012/112**

2013: First measurement of $pp \rightarrow p WW p$

Approval and start of HPS construction?



Two-photon pair production @ LHC



Production cross-sections determined completely by the particle mass, charge and spin

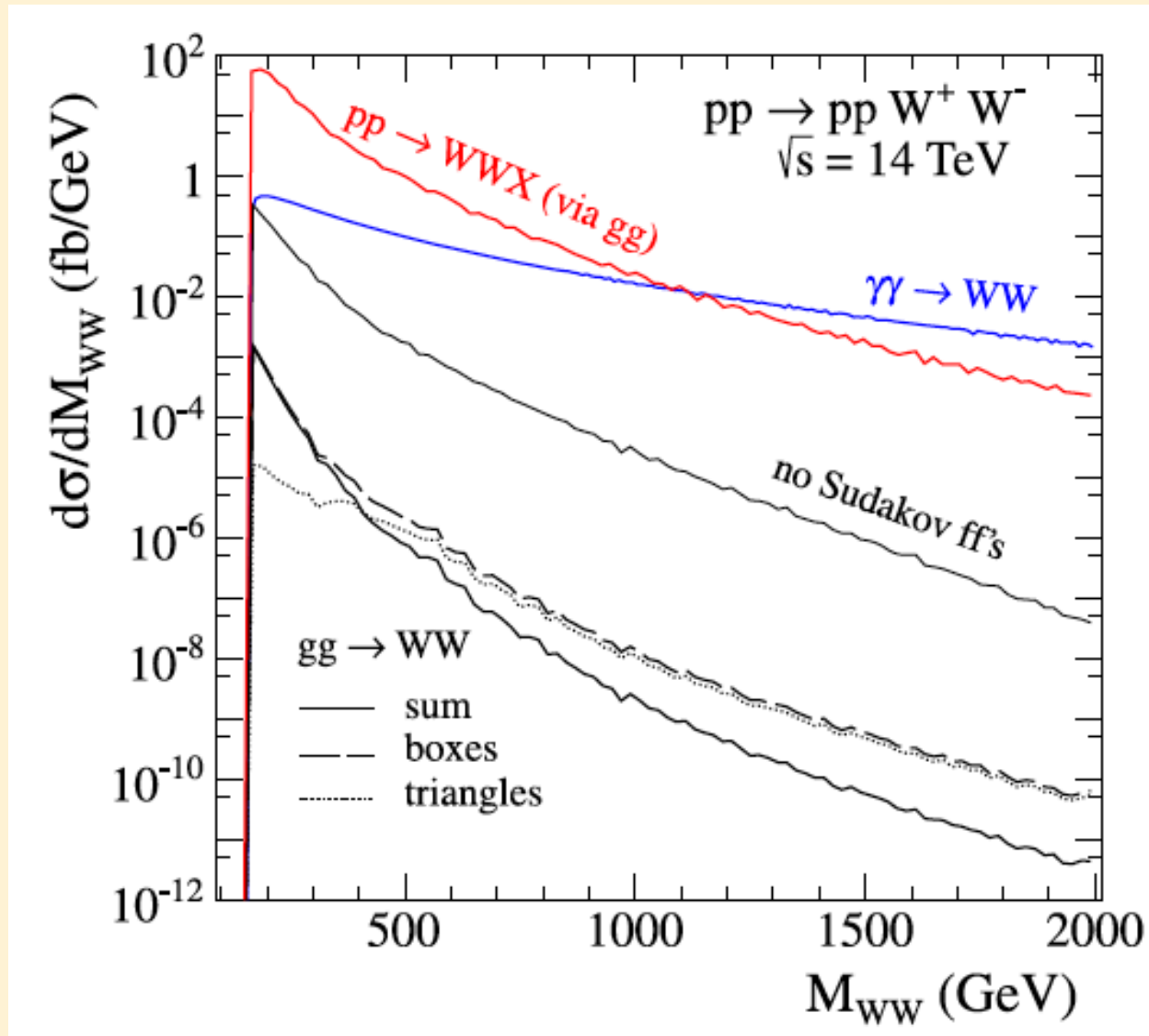
At low invariant $\gamma\gamma$ masses the $\mu\mu$ pairs dominate but at high energy WW pairs rule !

(Results for 14 TeV)

W_0 is a minimal $\gamma\gamma$ CM energy

arXiv:0908.2020v1 [hep-ph]

WW pair production @ LHC



At very high energy $\gamma\gamma$
wins over 'inclusive'
production !!

Nucl. Phys. B **867** (2013) 61

Proof-of-principle
and
Calibration candle

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

The first measurement focus on the dimuon channel – standard candle:

* **Pure QED process:**

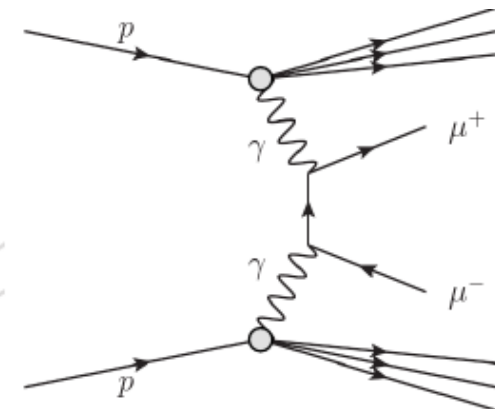
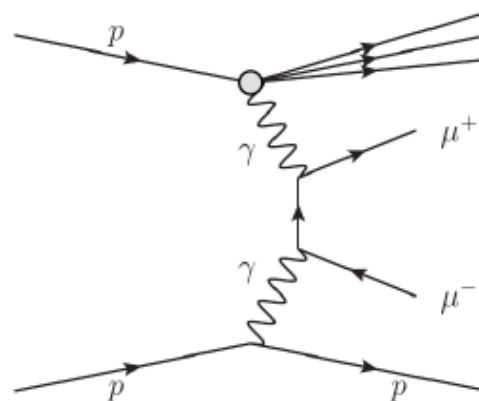
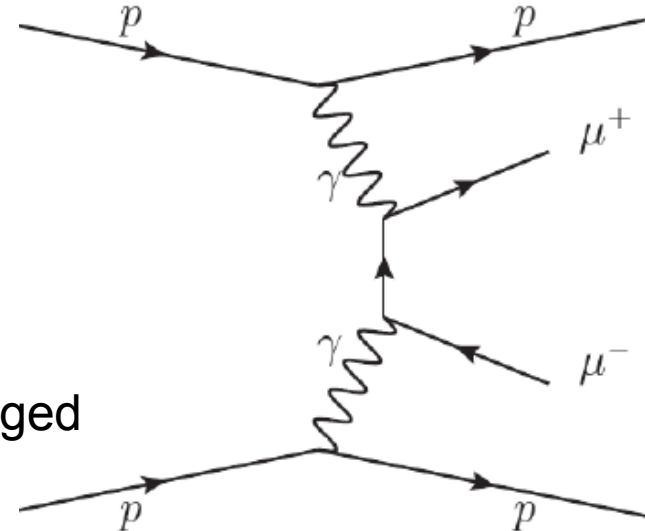
- No PDF to account for
- Small theoretical uncertainties

* **Striking kinematic distributions:**

- due to very small virtuality of the exchanged photons

* measured in previous experiments to be in agreement with the ME **LPAIR generator**

- Largest background arises from **semi-exclusive two-photon** production due to single and double proton dissociative (or inelastic) photon exchange:



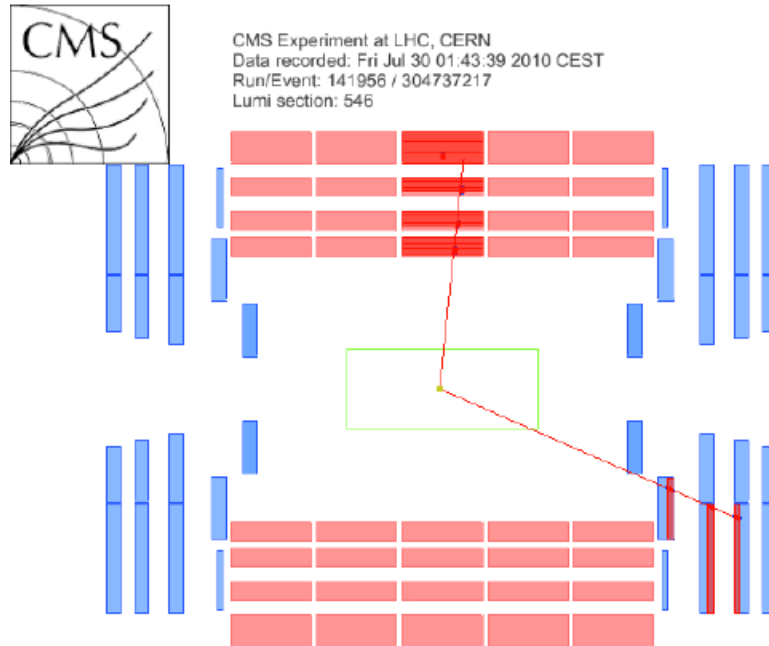


Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$



CMS-DP-2010-035

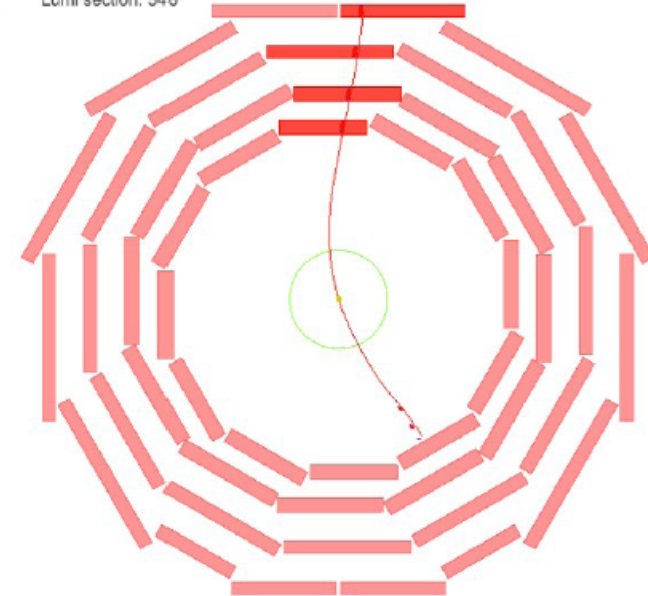
Candidates for $\gamma\gamma \rightarrow \mu\mu$ process:



$$\begin{aligned} m &= 20.51 \pm 0.2 \text{ GeV} \\ \frac{\Delta\phi}{\pi} &= 0.98 \\ \Delta p_T &= 0.48 \text{ GeV} \end{aligned}$$

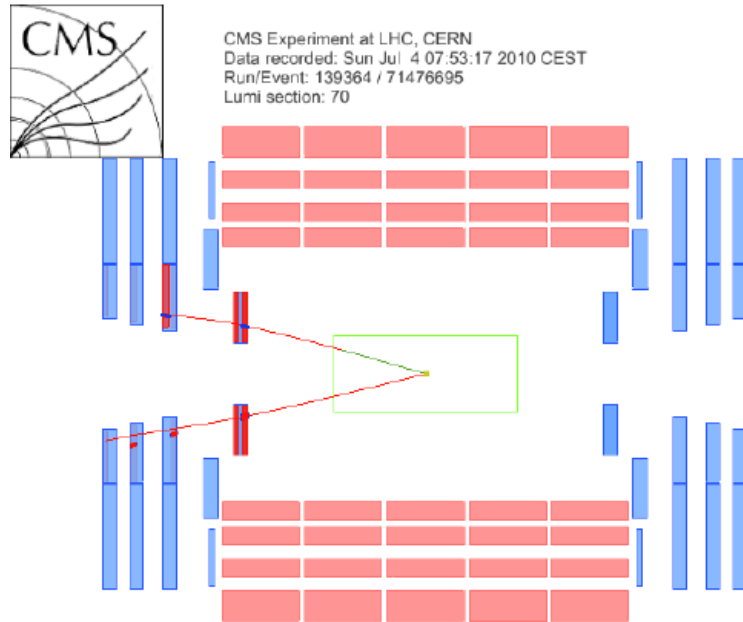


CMS Experiment at LHC, CERN
Data recorded: Fri Jul 30 01:43:39 2010 CEST
Run/Event: 141956 / 304737217
Lumi section: 546

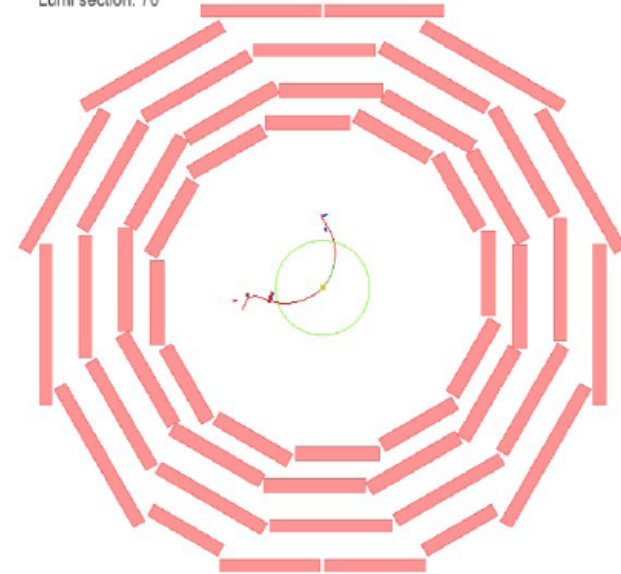


$$\begin{aligned} \text{track: } p_T &> 0 \text{ GeV} \\ \text{HCAL: } E &> 4 \text{ GeV} \\ \text{ECAL: } E &> 2.5 \text{ GeV} \end{aligned}$$

Candidates for $\gamma p \rightarrow Y p$ and $\gamma p \rightarrow J/\Psi p$ observed in CMS:



CMS Experiment at LHC, CERN
Data recorded: Sun Jul 4 07:53:17 2010 CEST
Run/Event: 139364 / 71476695
Lumi section: 70



$$\begin{aligned} m &= 3.05 \pm 0.03 \text{ GeV} \\ \frac{\Delta\phi}{\pi} &= 0.98 \\ \Delta p_T &= 0.05 \text{ GeV} \end{aligned}$$

CMS-DP-2010-035

$$\begin{aligned} \text{track: } p_T &> 0 \text{ GeV} \\ \text{HCAL: } E &> 4 \text{ GeV} \\ \text{ECAL: } E &> 2.5 \text{ GeV} \end{aligned}$$

The ideal case: 2 muons and nothing else



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



CMS Analysis Note

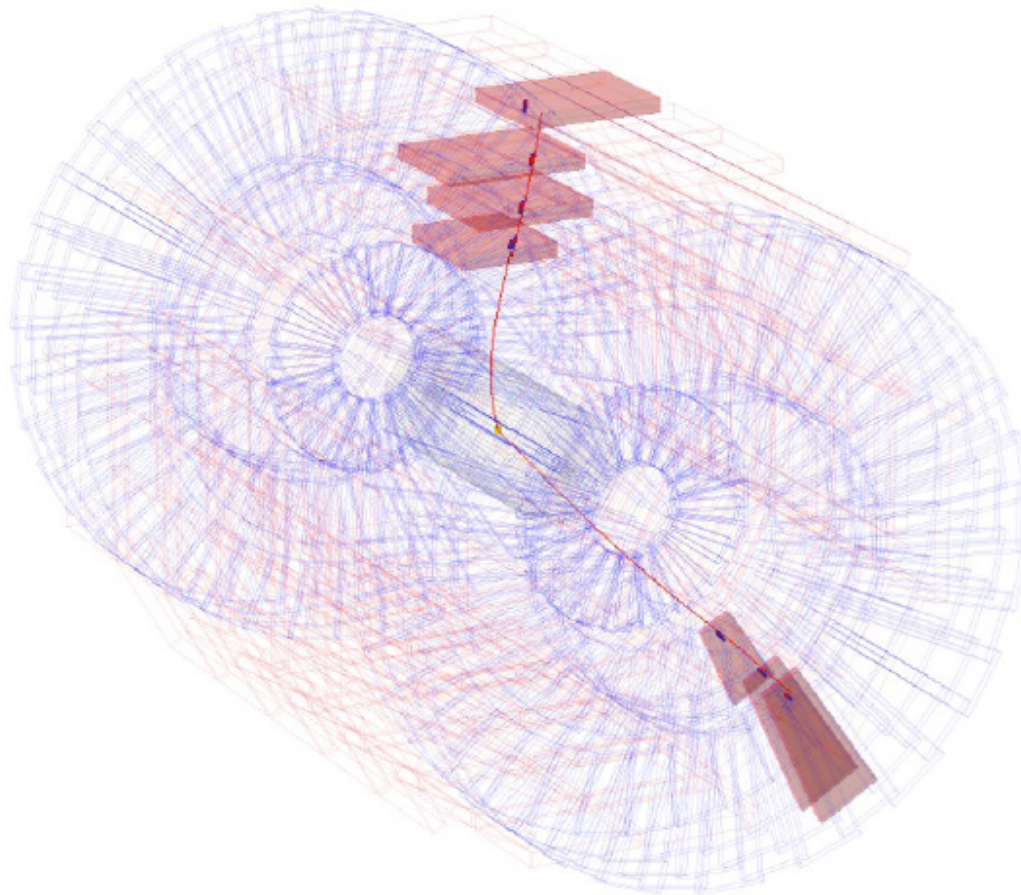
The content of this note is intended for CMS internal use and distribution only

2011/06/19

Measurement of exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production at
 $\sqrt{s} = 7$ TeV

Jonathan Hollar, Krzysztof Piotrzkowski, and Nicolas Schul
Center for Cosmology, Particle Physics and Phenomenology (CP3)
Universite catholique de Louvain, Belgium

Exclusivity conditions



In (very) low luminosity era:
2 muons and “nothing else”
in the tracker and calorimeters

In 2010, each event of interest can be
accompanied by extra “PileUp”
events
within the same bunch crossing:
~ 2-3 pileup interactions

In 2011, roughly 7-10 PU per crossing

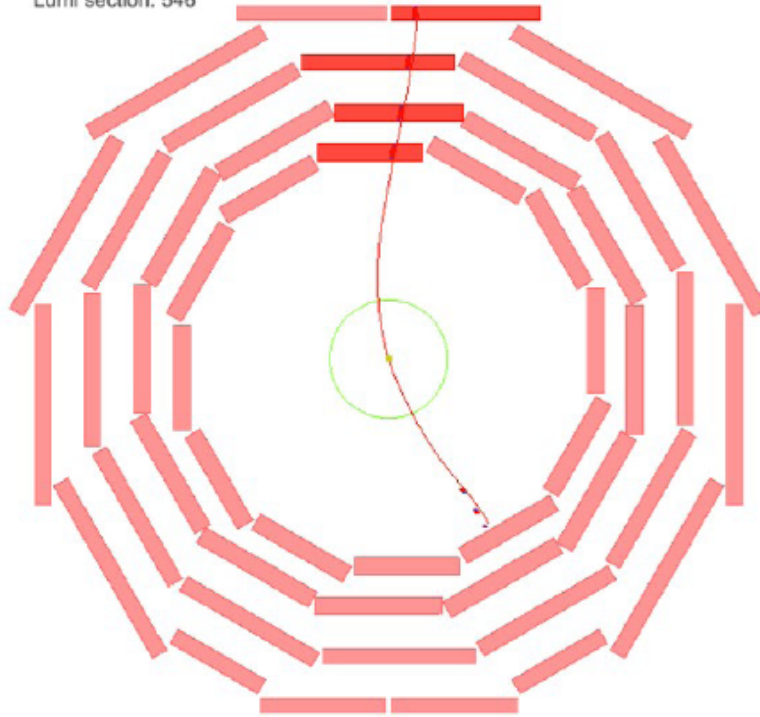
Restricting the analysis to single interactions only would have reduced the data sample to 20% of the total → **impose exclusivity using tracking only**



Kinematics selection



CMS Experiment at LHC, CERN
Data recorded: Fri Jul 30 01:43:39 2010 CEST
Run/Event: 141956 / 304737217
Lumi section: 546



- Muons are balanced in p_T :
 $|p_T(\mu^+) - p_T(\mu^-)| < 1 \text{ GeV}$

- Muons are back-to-back in the transverse plane:
 $|\phi(\mu^+) - \phi(\mu^-)| > 0.9 \pi$

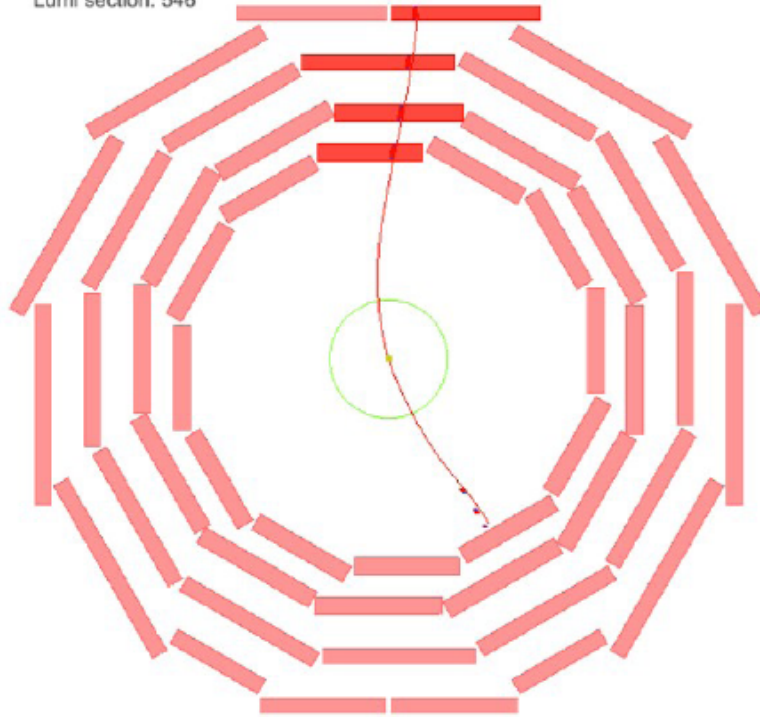
- Cosmic muon veto:
opening angle $< 0.95 \pi$



Kinematics selection



CMS Experiment at LHC, CERN
Data recorded: Fri Jul 30 01:43:39 2010 CEST
Run/Event: 141956 / 304737217
Lumi section: 546

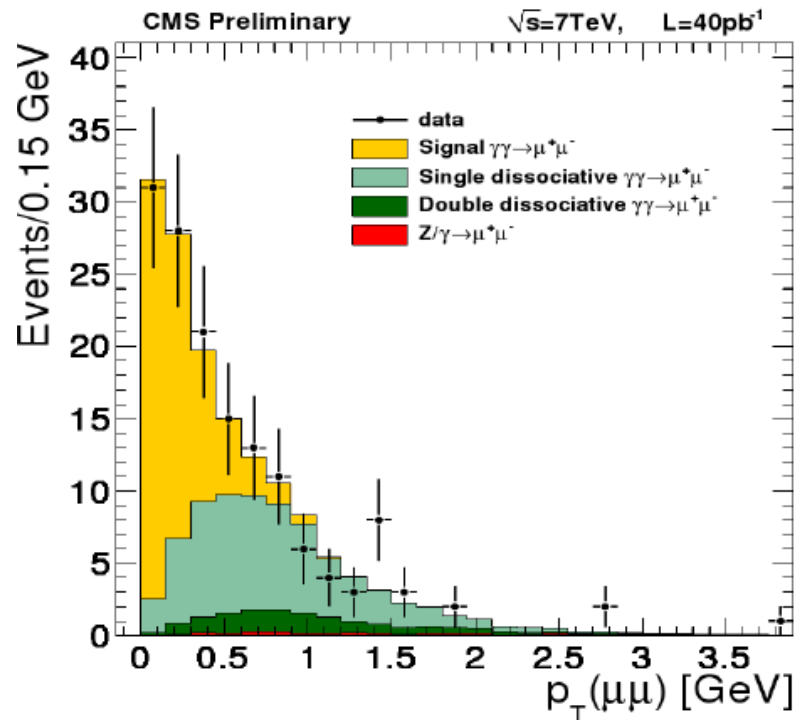


- Muons are balanced in p_T :
 $|p_T(\mu^+) - p_T(\mu^-)| < 1 \text{ GeV}$

- Muons are back-to-back in the transverse plane:
 $|\phi(\mu^+) - \phi(\mu^-)| > 0.9 \pi$

- Cosmic muon veto:
opening angle $< 0.95 \pi$

148 exclusive $\mu\mu$ candidates
passing trigger + muon ID +
exclusivity + kinematics selections



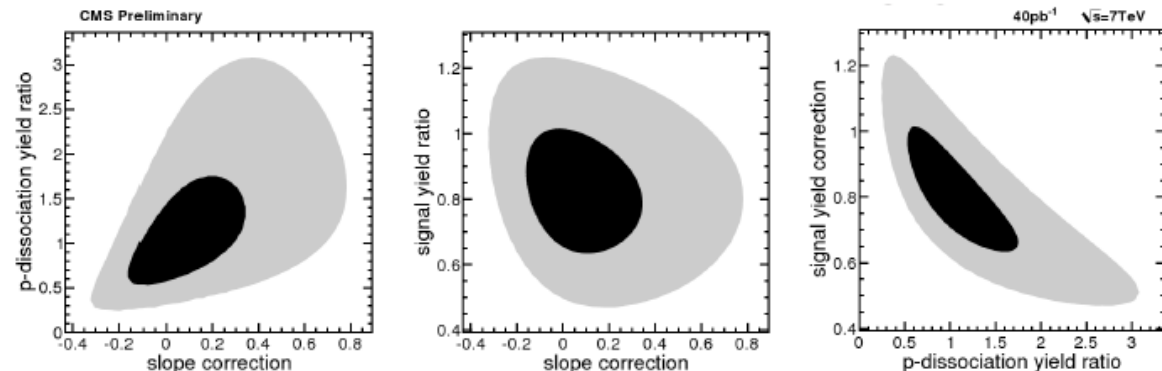
Elastic-elastic $\gamma\gamma \rightarrow \mu\mu$ signal extracted from the data by a **1D binned likelihood fit** on the $p_T(\mu\mu)$ distribution with:

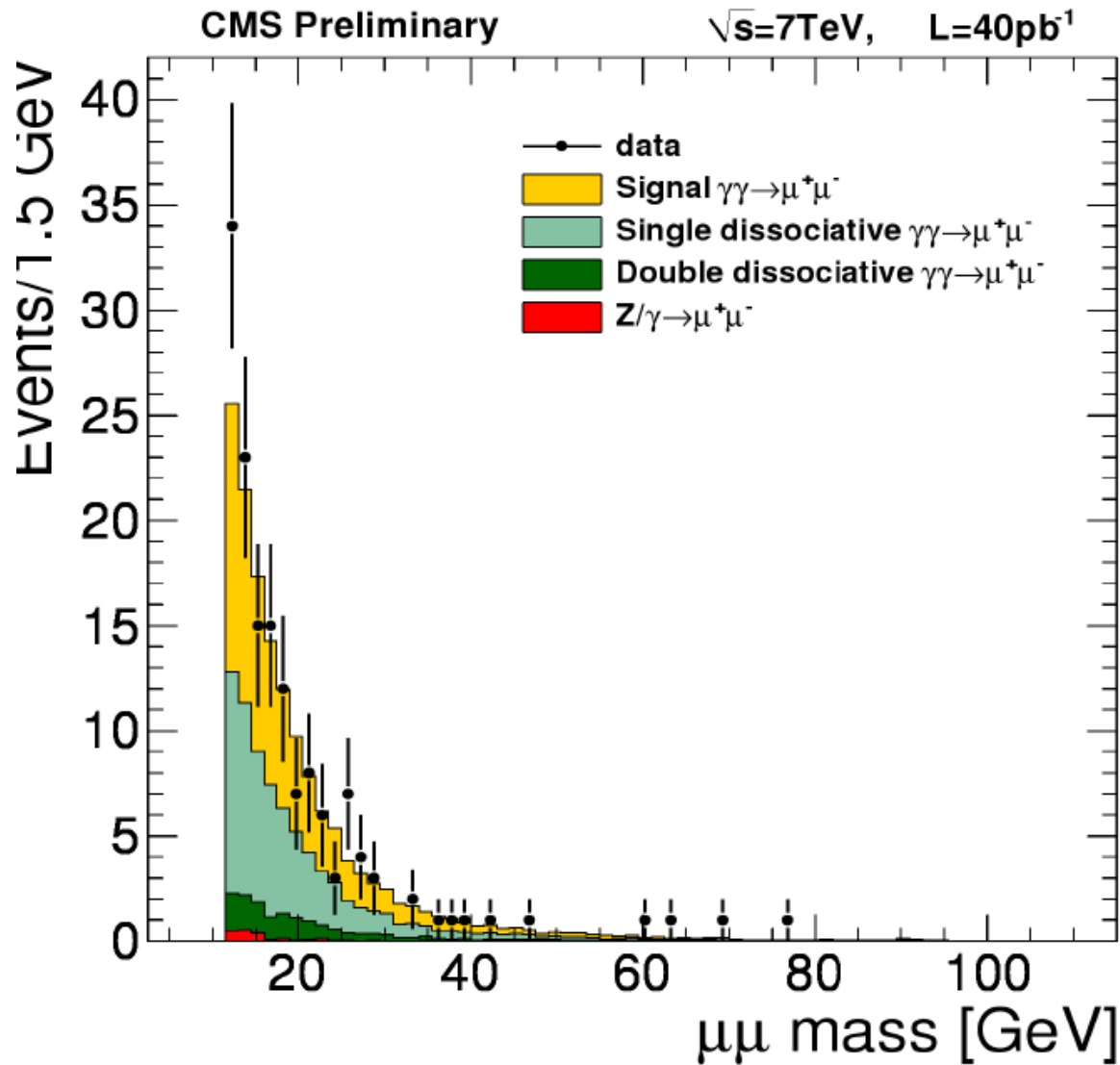
- Monte-Carlo yield ratio
- Single-inelastic yield ratio
- Correction to the exponential slope of proton dissociation

Shape for elasti-elastic taken from MC.

Shapes for Inel-Inel and inclusive DY taken from MC, normalisation varied as systematic uncertainties

1 σ and **2 σ** fit parameters contours



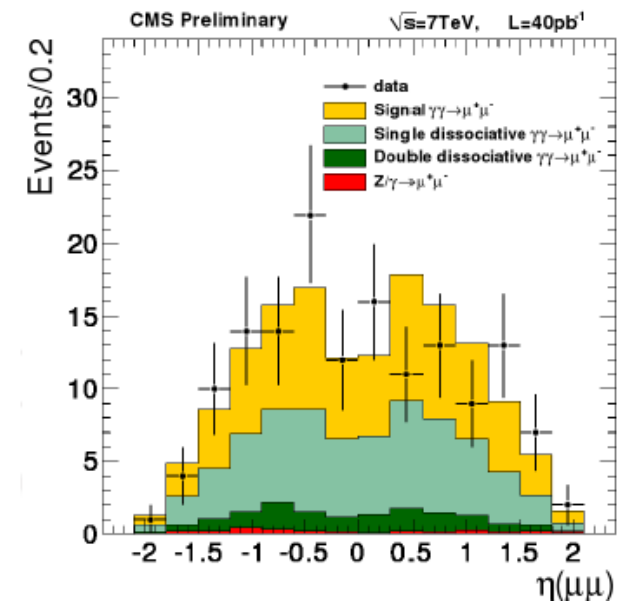


- MC normalized to best-fit value

- In agreement with LPAIR el-el, inel-el and inel-inel

-> Highest-mass event observed is 77GeV

Pair pseudo-rapidity:



Search for exclusive $\gamma\gamma \rightarrow W^+W^-$ production at $\sqrt{s} = 7 \text{ TeV}$



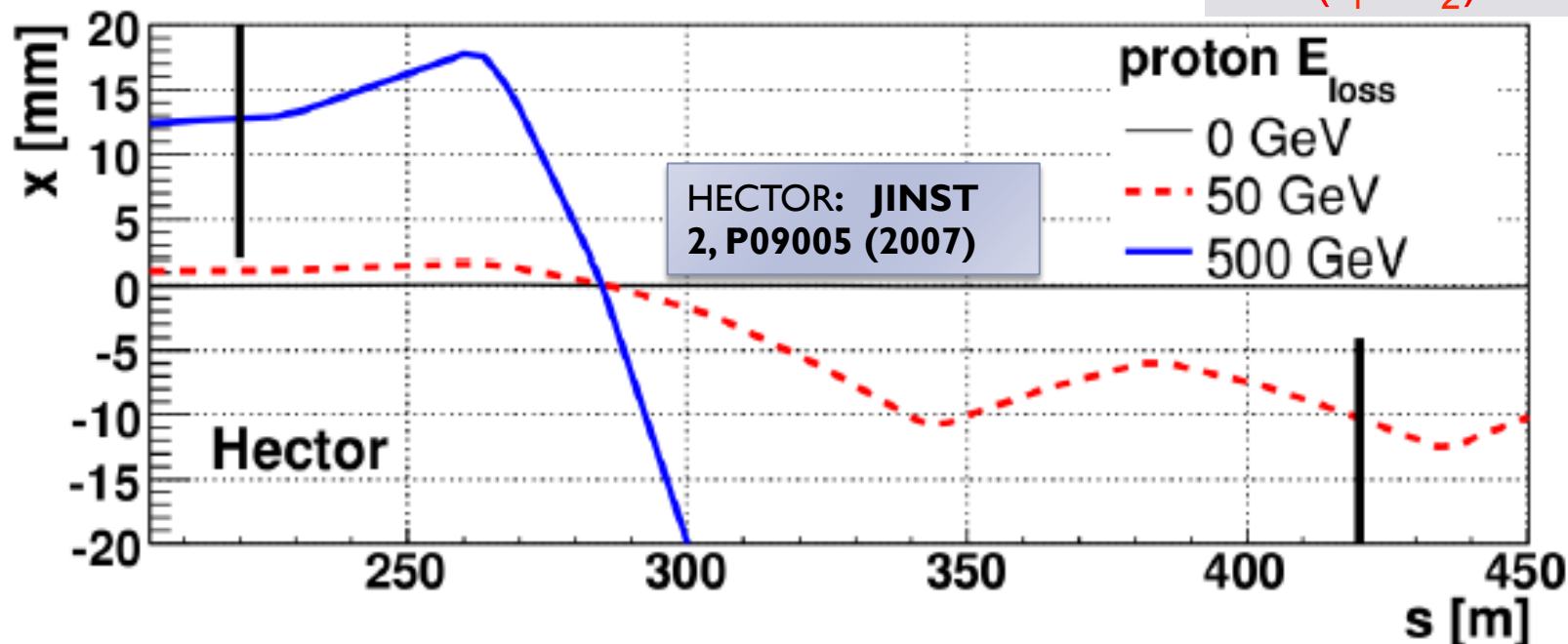
HPS for CMS ?



Picosecond ToF detectors @ LHC

Use very fast ToF detectors to measure *longitudinal vertex position* by *z-by-timing* from forward proton arrival time difference:

$$z = (t_1 - t_2)/2c$$

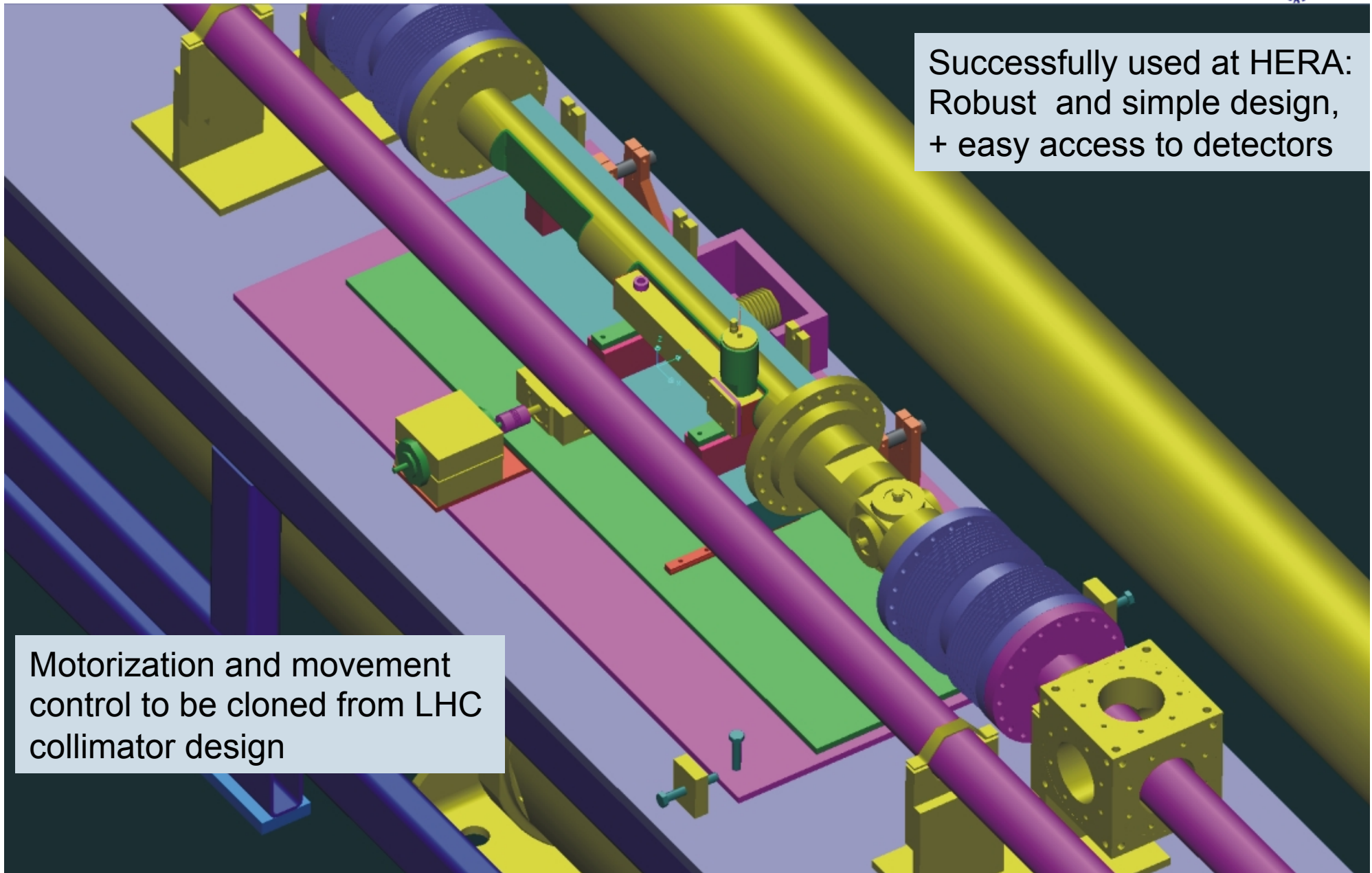


Path length differences are very small for forward protons at LHC, typically $\ll 100 \mu\text{m}$ corresponding to sub-picosecond time differences.



Ultra fast timing detectors are essential for measuring the exclusive production at LHC, $pp \rightarrow pXp$, JINST 4 (2009) T10001

Moving Hamburg pipe concept



Successfully used at HERA:
Robust and simple design,
+ easy access to detectors

Motorization and movement
control to be cloned from LHC
collimator design

What next ?

Using 2012 data at 8 TeV make first ever measurement (expect about 15 events) of $\gamma\gamma \rightarrow WW$! (+ detailed studies of $\mu\mu$, including Y photoproduction)

Repeat it in 2015 @ 13 TeV – sensitivity to aQGCs should be 10 times better wrt to present results

In 2016 hopefully HPS starts running:

Yet more sensitive studies of the $\gamma\gamma WW$ couplings will be possible, as well as for $\gamma\gamma ZZ$; even in case the $U(1) \times SU(2)$ gauge invariant models (as discussed by *O. Nachtmann et al.*) !

Search of new heavy charged particles:

- **Stable, ‘heavy muons’ (completely model independent, a la LEP) up to about 400 GeV (LEP limits are at 100 GeV)**
- **Unstable, non-strongly interacting particles (very model dependent, like sleptons or charginos)**

We must make the best of out of LHC !