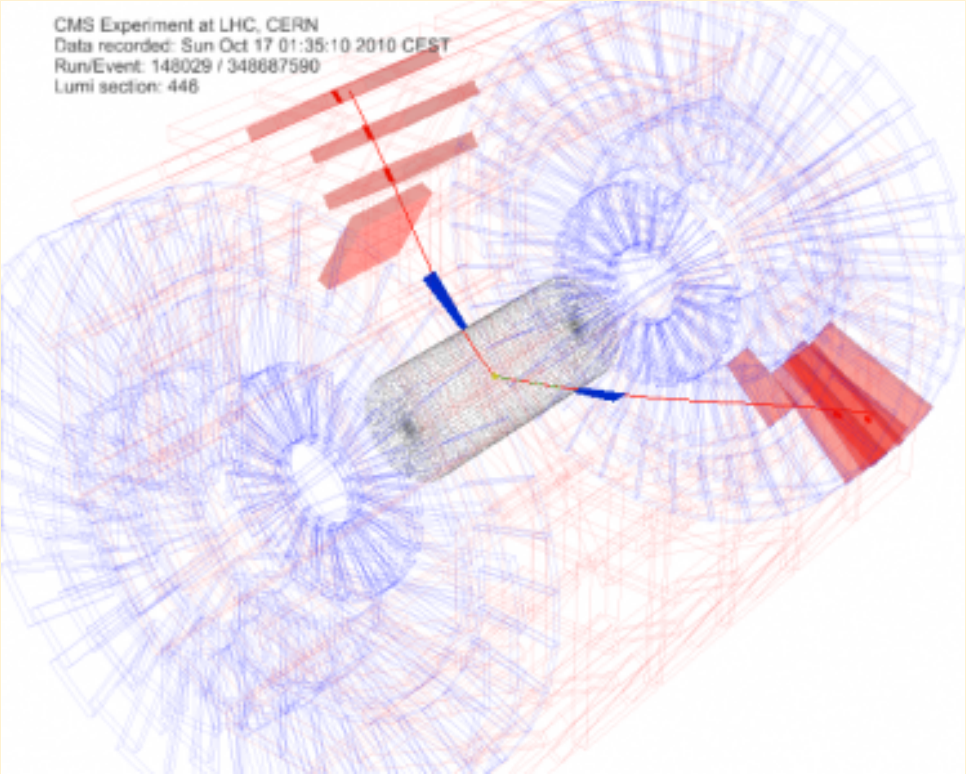
High energy γγ processes at the LHC



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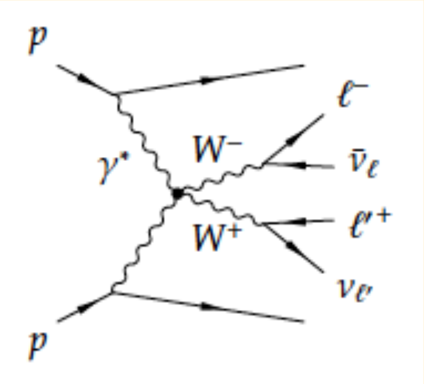
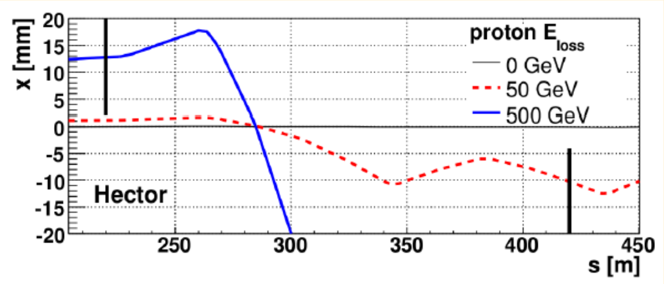




WE-HERAEUS Physics School
Bad Honnef
August 17-21, 2015

Outline

Part I: Introduction & motivation

Part II: First measurements: challenges & achievements

Part III: Future measurements - the LHC as a photon-photon collider

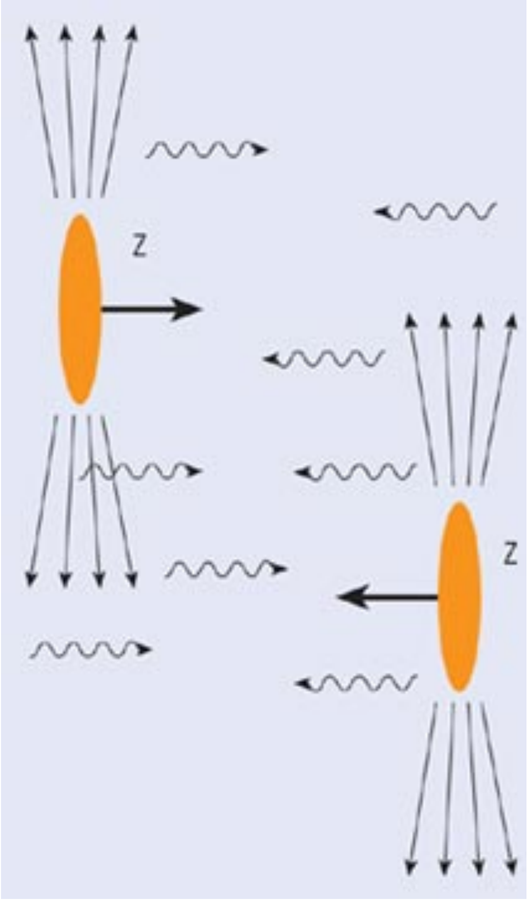
Semiclasical picture: Weizsacker-Williams approximation

Back in 1934, Weizsacker and Williams (independently) considered interactions of fast charged particles in matter by casting these processes into two steps:

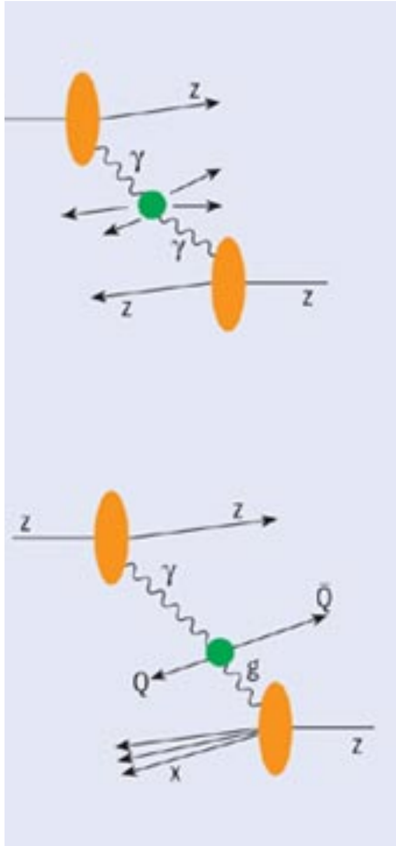
- Representing the particle electromagnetic field by a "cloud" (or flux) of virtual quanta/photons
- Calculating then photon interactions with matter

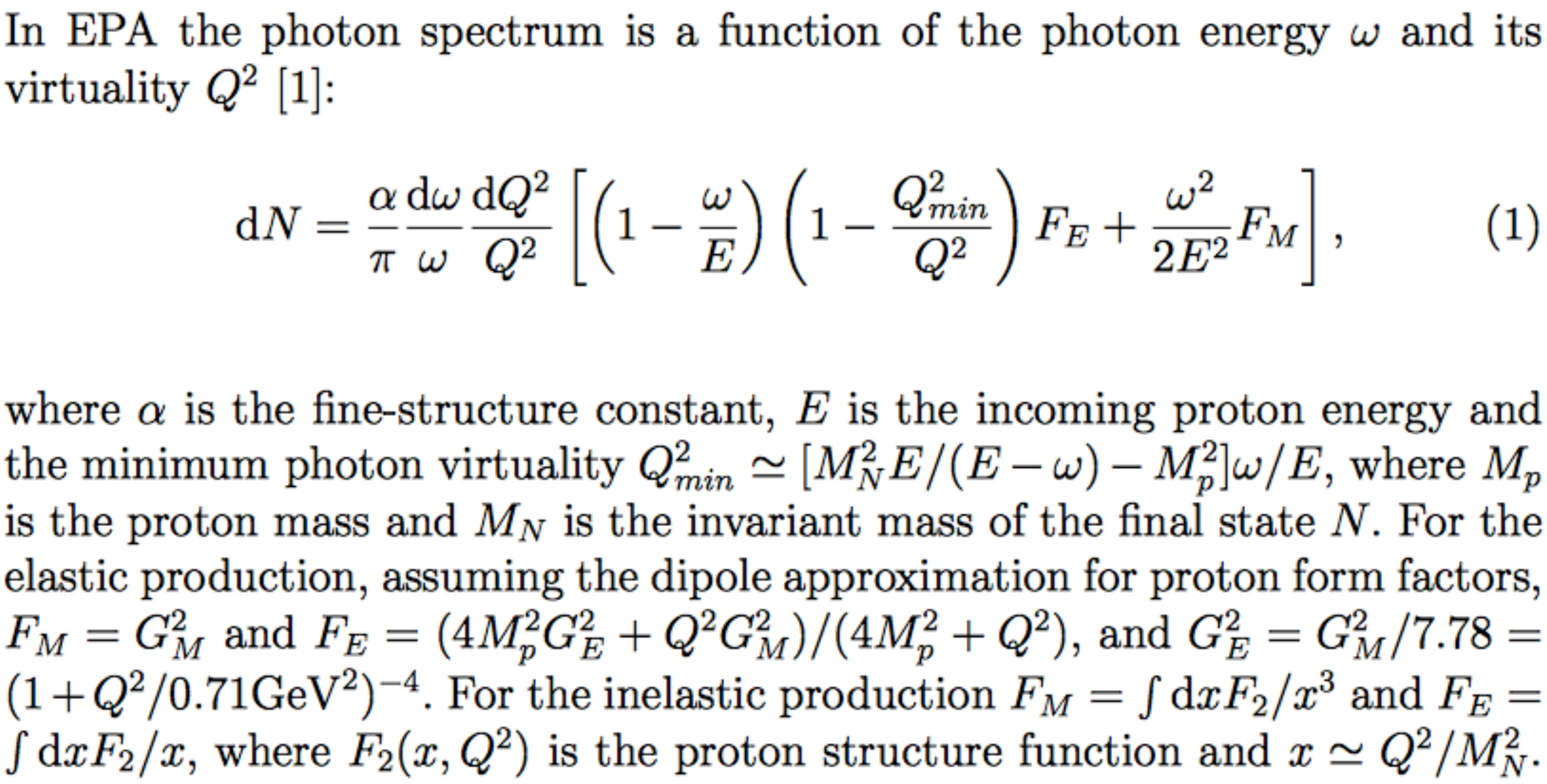
Following assumptions were made there:

- the charged particle moves uniformly
- its field gets "Lorentz-contracted", so for a "observer" at some distance b (=impact parameter) it becomes a short pulse of mostly transverse component
- field is Fourier-transformed and finally, its energy can be represented by a appropriate number of quanta (of given frequency)
- there is b_{min}, usually coming from a finite size of charge



Quantum picture: Equivalent Photon Approximation (EPA)





In EPA the photon spectrum is a function of the photon energy ω and its virtuality Q^2 [1]:

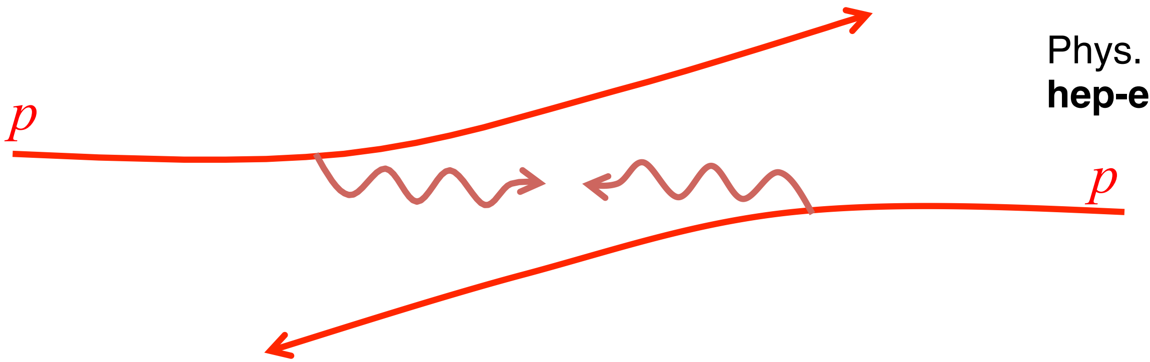
$$\mathrm{d}N = \frac{\alpha}{\pi}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}Q^2}{Q^2}\left[\left(1-\frac{\omega}{E}\right)\left(1-\frac{Q^2_{min}}{Q^2}\right)F_E + \frac{\omega^2}{2E^2}F_M\right], \qquad (1)$$

where α is the fine-structure constant, E is the incoming proton energy and the minimum photon virtuality $Q^2_{min} \simeq [M_N^2 E/(E-\omega) - M_p^2]\omega/E$, where M_p is the proton mass and M_N is the invariant mass of the final state N. For the elastic production, assuming the dipole approximation for proton form factors, $F_M = G_M^2$ and $F_E = (4M_p^2 G_E^2 + Q^2 G_M^2)/(4M_p^2 + Q^2)$, and $G_E^2 = G_M^2/7.78 = (1+Q^2/0.71\mathrm{GeV}^2)^{-4}$. For the inelastic production $F_M = \int \mathrm{d}x F_2/x^3$ and $F_E = \int \mathrm{d}x F_2/x$, where $F_2(x,Q^2)$ is the proton structure function and $x \simeq Q^2/M_N^2$.

Phys. Rev. **D63** (2001) 071502(R)

***Elastic* (or fully exclusive) production + *Inelastic,* when proton dissociates**

LHC as a High Energy γγ Collider



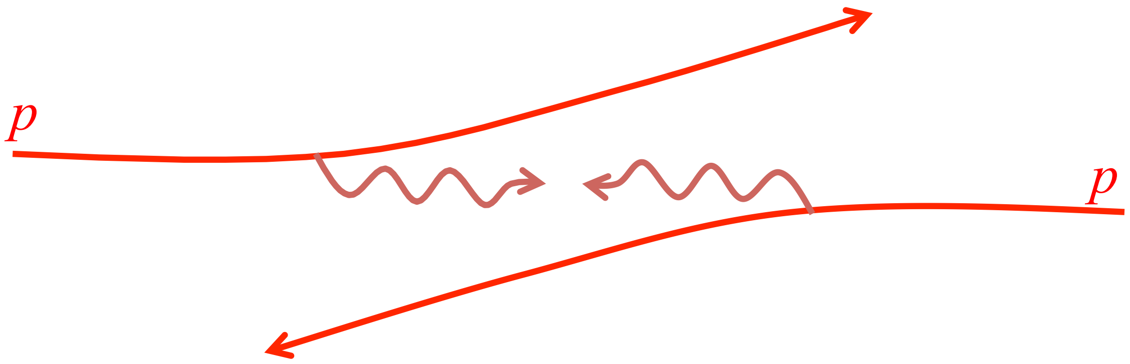
Phys. Rev. **D63** (2001) 071502(R)
hep-ex/0201027

Initial observation:
Provided efficient measurement of very forward-scattered protons one can study high-energy γγ collisions at the LHC

Highlights:

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

LHC as a High Energy γγ Collider



Two photon exclusive production:

- Very forward proton scattering ↔ large distance interactions
- Possibility of detecting whole final state → precise kinematics reconstruction; very much like in e^+e^-

Very different event topologies from typical events at the LHC

➡ must exploit that!

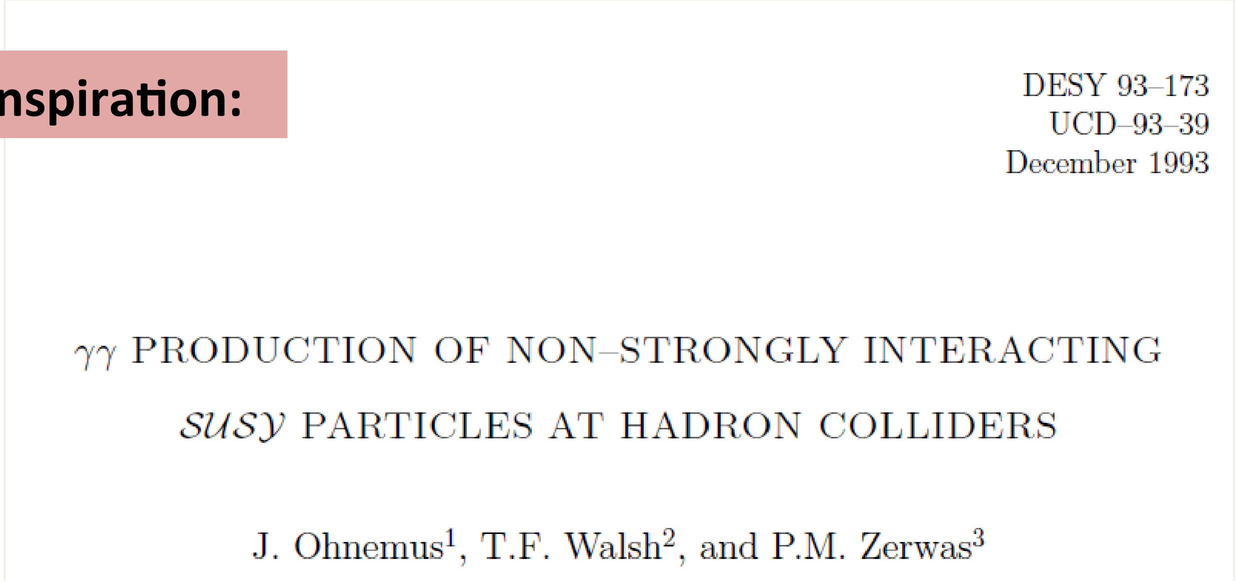
DISCLAIMER:

This is NOT meant for studying all photon interactions at the LHC but those for which the QCD (diffraction!) background can be strongly suppressed, as for example in the exclusive production of pairs of charged non-strongly interacting particles.

This IS meant for studying production of *selected* final states in photon interactions at the LHC.

Note: At Tevatron available energy too small for EW physics (but enough for lepton pairs – CDF published several measurements of exclusive two-photon production of these)

First inspiration:



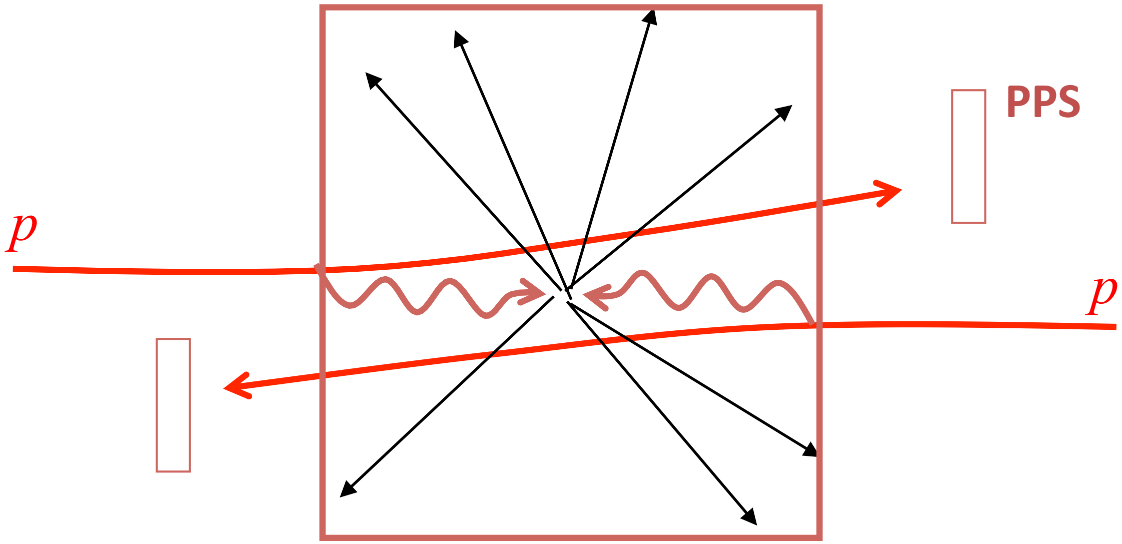
DESY 93–173
UCD–93–39
December 1993

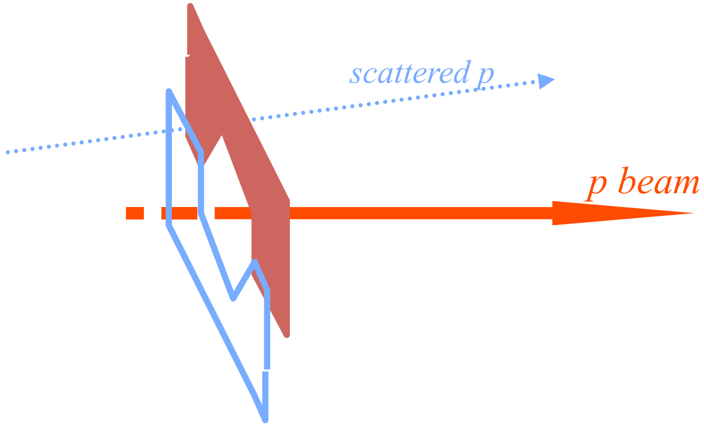
$\gamma\gamma$ PRODUCTION OF NON–STRONGLY INTERACTING $\mathcal{SUSY}$ PARTICLES AT HADRON COLLIDERS

J. Ohnemus[1], T.F. Walsh[2], and P.M. Zerwas[3]

How to measure these events?

Measure ($\gamma\gamma \rightarrow$) X in the **CMS or ATLAS** detector and scattered protons using **very forward detectors** (thanks to proton energy loss)

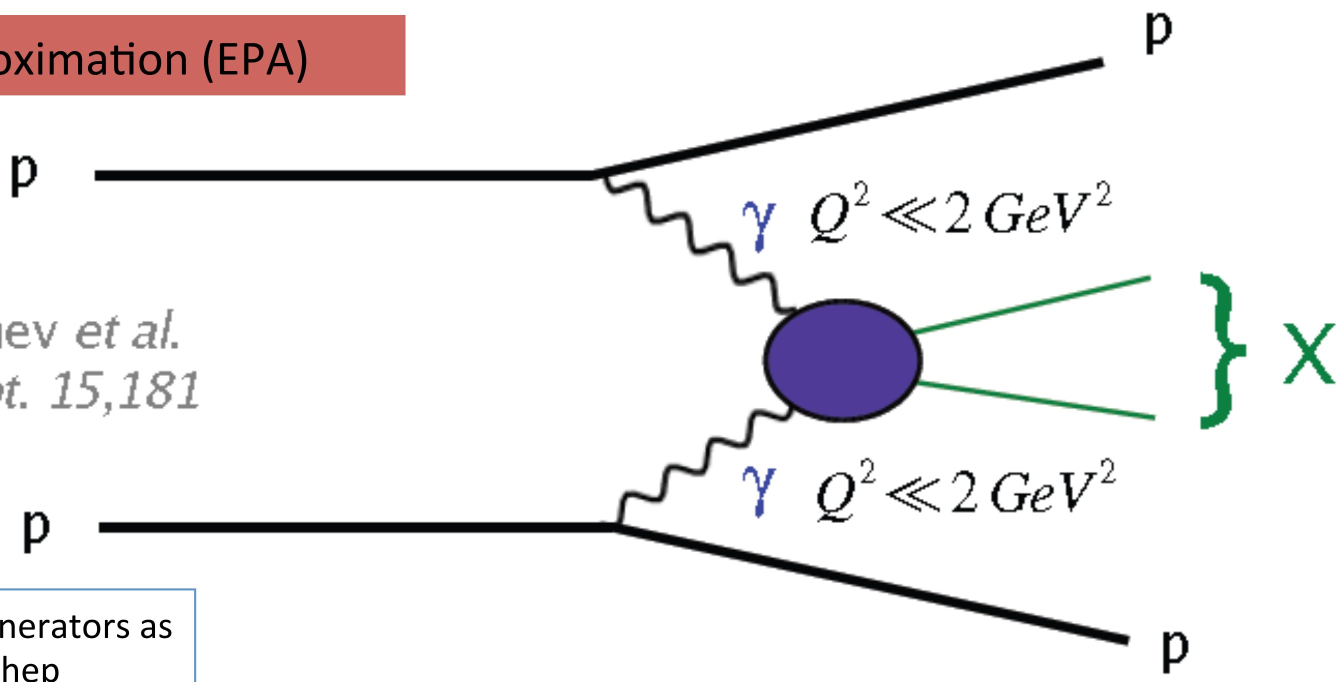




Very forward detectors needed – capable of running at high luminosity, installed as far (> 100 m) from IP and as close to the beam (≥2 mm) as possible – expected photon energy resolution can be of **2−5 GeV !**

LHC as a γγ collider

Equivalent photon approximation (EPA)



V.M.Budnev *et al.*
Phys.Rept. 15,181

…introduced to major event generators as Madgraph, Pythia, Sherpa, Calchep

$$\sigma(\,pp \rightarrow (\gamma\gamma \rightarrow X)\,pp\,)$$

low γ virtuality (typical $Q^2 \sim 0.01\,GeV^2$) $\Rightarrow$

- factorization to
  - long distance photon exchange
  - short distance $\gamma\gamma \rightarrow X$ interaction

EPA: Kinematics/γγ Luminosity

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 $Q^2_{\max} \sim 1/\text{proton radius}^2$

$$W^2 = s\, x_1\, x_2$$

(where $W \equiv M_X$)

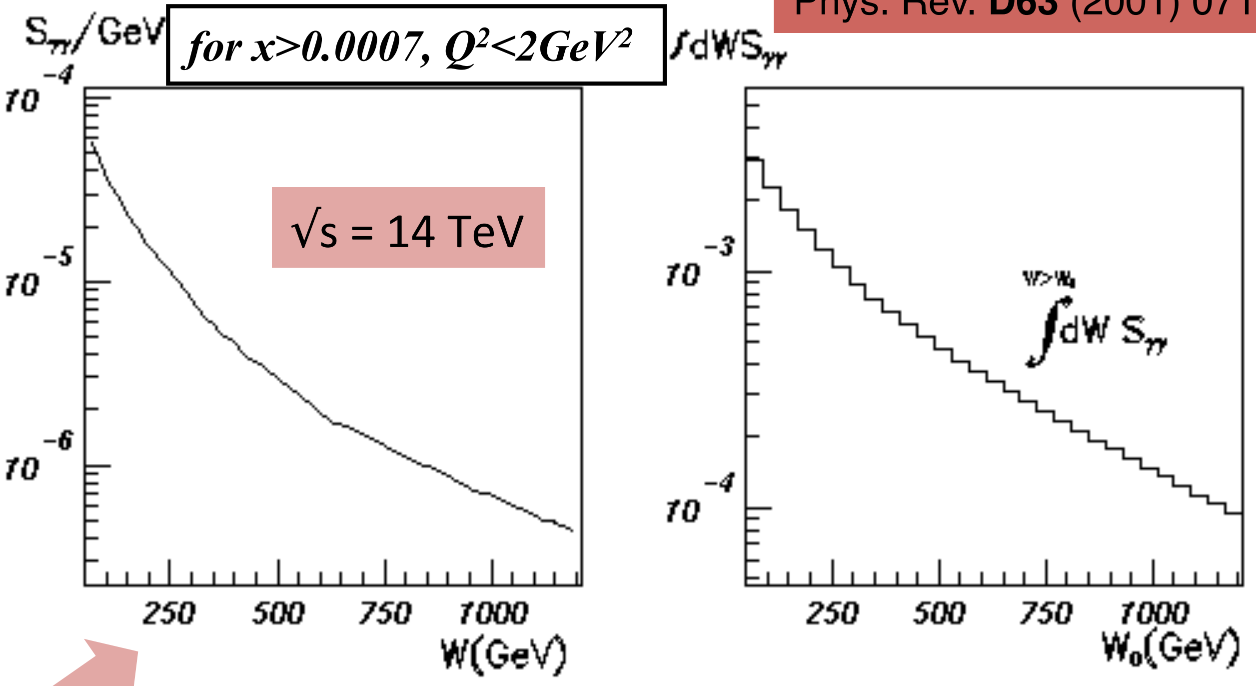
Photon flux $\propto 1/Q^2$
$Q^2 - Q^2_{\min} \approx s\theta^2/4$

protons scattered at
`zero-degree' angle

$S_{\gamma\gamma}(W) = N_\gamma(x_1) \otimes N_\gamma(x_2)$

$\sigma_{pp} = \int S\, \sigma_{\gamma\gamma}\, dW$

Phys. Rev. **D63** (2001) 071502(


for $x>0.0007$, $Q^2<2\,\text{GeV}^2$

√s = 14 TeV

Use EPA à la *Budnev et al.**

** error found in the elastic (Q^2 integrated) γ flux for protons!*

$\int dW S_{\gamma\gamma}$ = *'γγ : pp luminosity'*

Note: it's few times larger if one of protons is allowed to break up

Tagging two-photon events

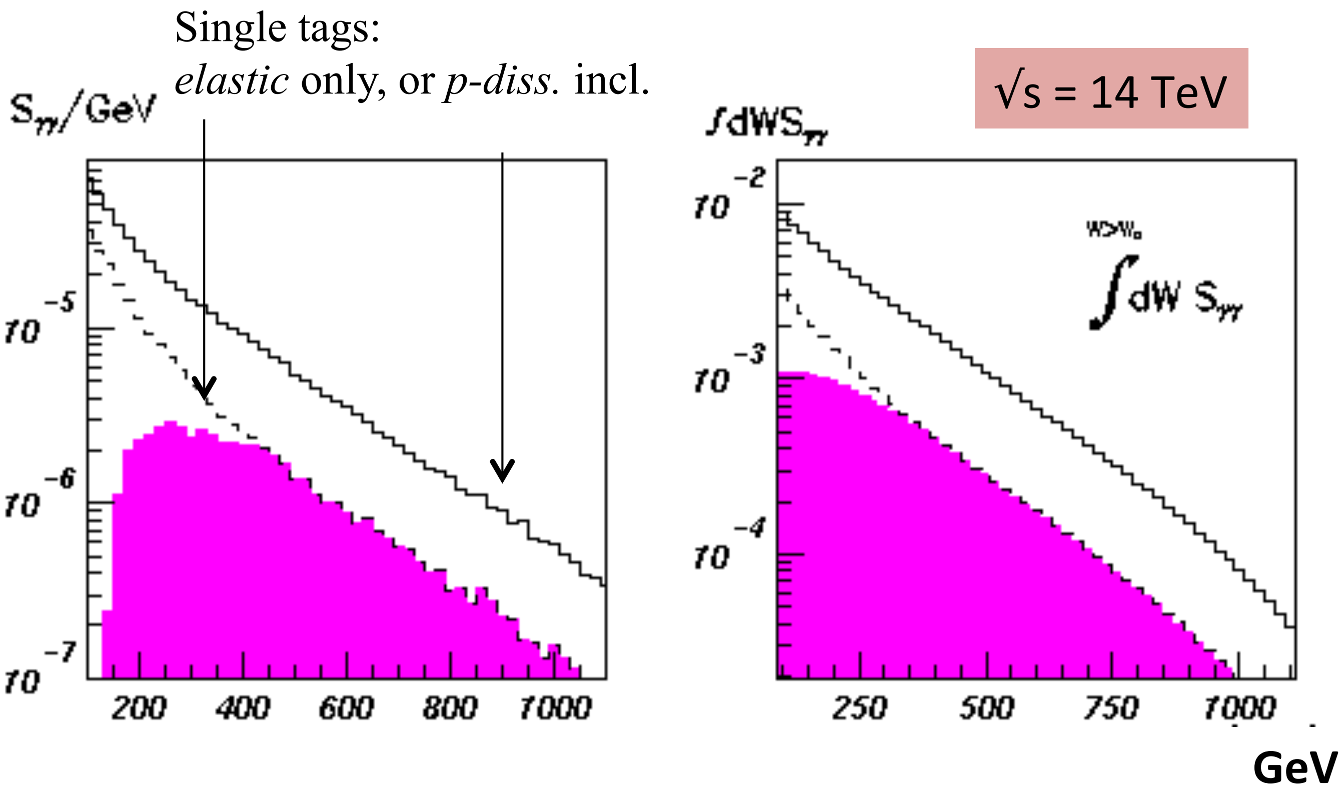
Assume detector stations at ~220 m where approximately $x > 0.01$ range accessible

Note: If only one forward p detected – single tag, but then non-elastic, p dissociative photon emission is possible

Assume 0.1>x>0.01,
and $Q^2<2$ GeV^2
and for dissociative
mass $M_N<$ 20 GeV

$$S_{\gamma\gamma}(W) = N_\gamma(x_1) \otimes N_\gamma(x_2)$$

$$\sigma_{pp} = \int S\, \sigma_{\gamma\gamma}\, dW$$



Single tags:
elastic only, or *p-diss.* incl.

√s = 14 TeV

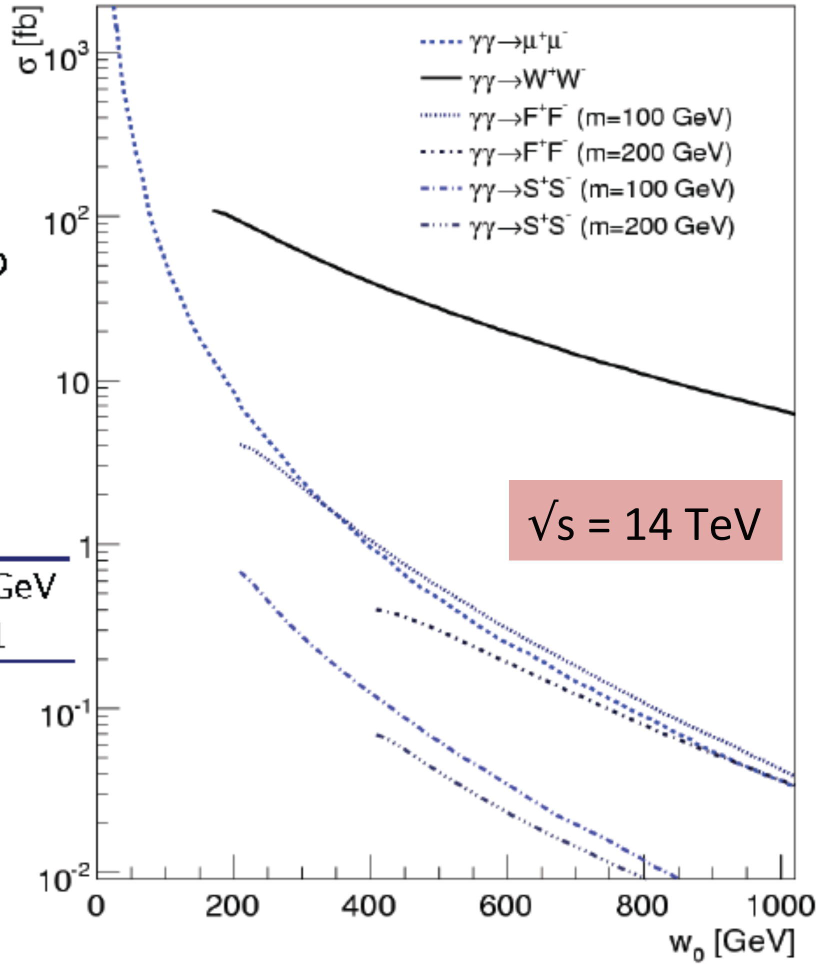
Color: double-tags, hence *elastic* scattering only

LHC as a $\gamma\gamma$ collider

arXiv:0908.2020

- $\gamma\gamma \to \mu\mu$ first $\gamma\gamma$ process to be seen
- $\gamma\gamma \to W^+W^-$ very interesting SM process 108fb
- New physics !

Processes		[fb]	Generator
$\gamma\gamma \to \mu\mu$		72 500	LPAIR pt > 2 GeV $\lvert\eta\rvert < 3.1$
$\gamma\gamma \to$ WW		108	
$\to$ FF	(m=100GeV)	4.06	MadGraph
$\to$ FF	(m=200GeV)	0.40	/
$\to$ SS	(m=100GeV)	0.68	MadEvent
$\to$ SS	(m=200GeV)	0.07	



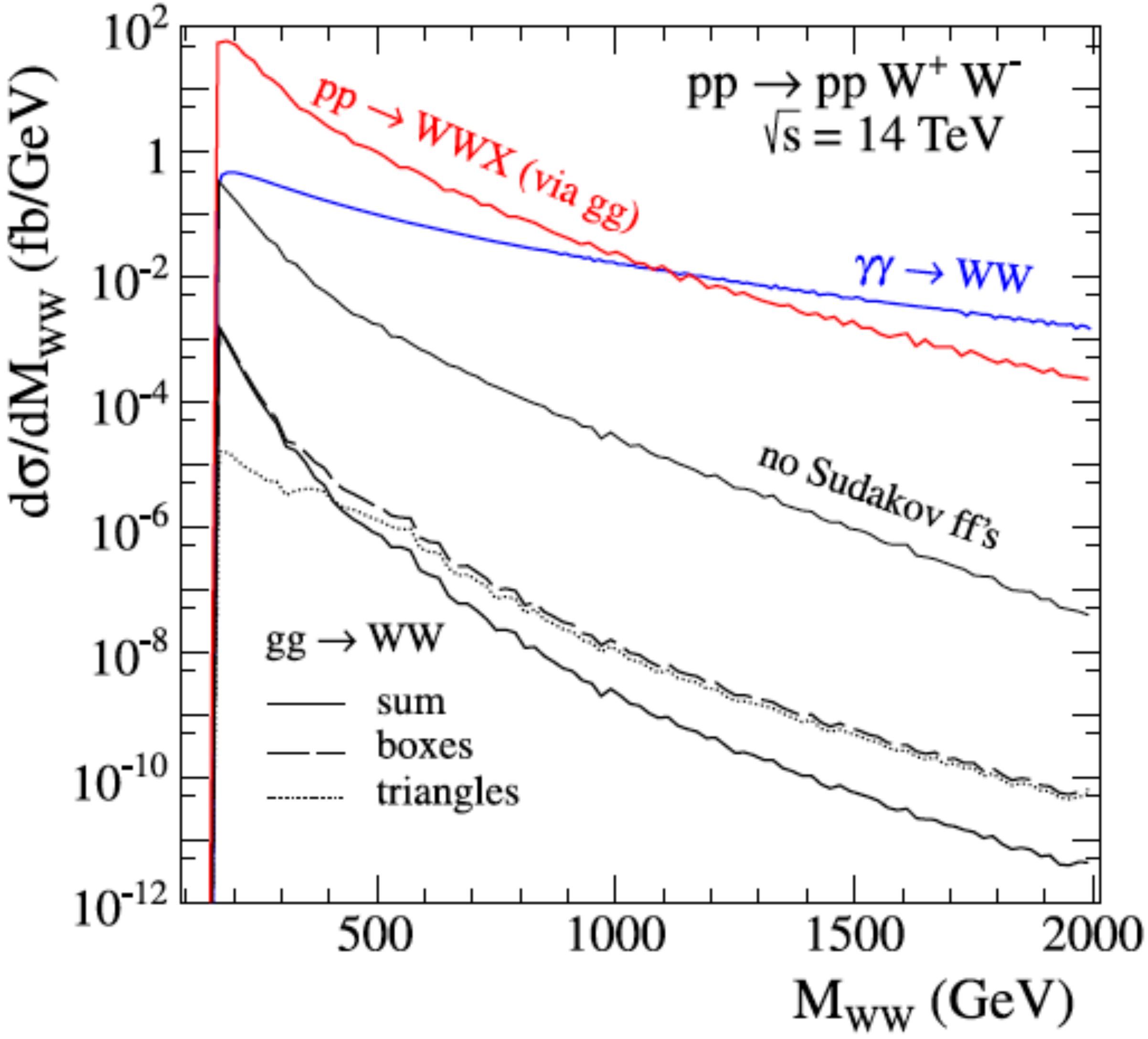
Cross sections for $\gamma\gamma$ processes as a function of the minimal $\gamma\gamma$ cms energy W_0

moreover :

lepton final states

clear signature – background suppression

WW pair production @ LHC



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

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

LHC as a $\gamma\gamma$ collider

Two-photon exclusive pair production cross-section is given just by:

- particle charge, mass and spin

for a given mass and charge it is largest for vector particles , then for fermions

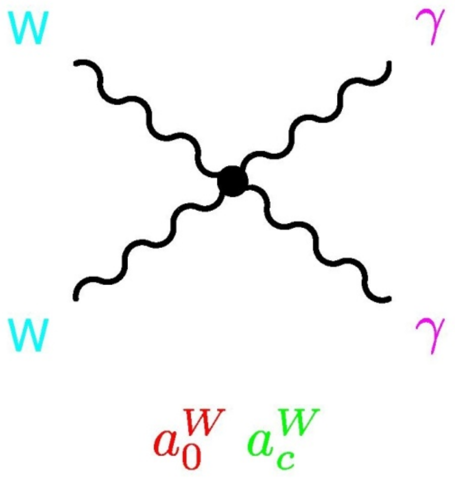
$\gamma\gamma \rightarrow$ WW pair production has very sizable cross-section at the LHC of ~100 fb (and x 4 if inelastic included)!

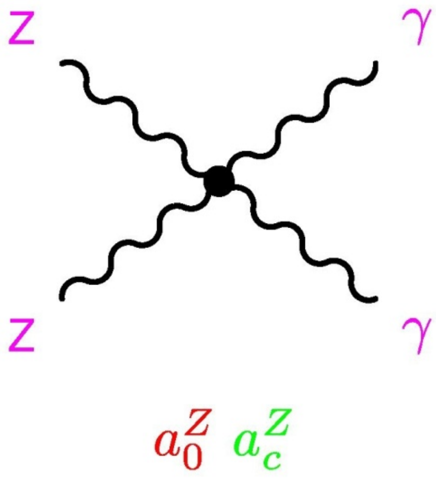
Massive fermions have sizable $\gamma\gamma$ cross-sections up to about 200 GeV masses, for scalars cross-sections are about 5 times smaller (but there is H^{++} case, for example)

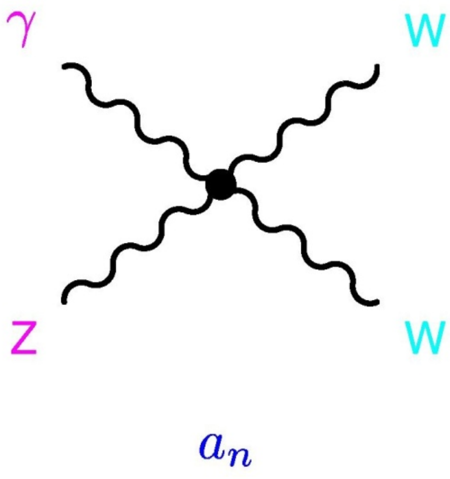
Physics with γγ → WW (and ZZ)

γγ → WW and ZZ pair as a powerful test bench for the gauge boson sector at the LHC

Search for anomalous quartic couplings







Lagrangian for aQGCs

arXiv:0908.2020

we use Lagrangian for genuine anomalous quartic vector boson couplings which conserves C, P as well as local $U(1)_{em}$ and $SU(2)_C$

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^-_\alpha - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} \left(W^{+\alpha} W^-_\beta + W^{-\alpha} W^+_\beta\right) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^\alpha Z_\beta$$

This gives a general auxiliary formula for a cross section (total or differential, with or without cuts) as a function of the anomalous parameters:

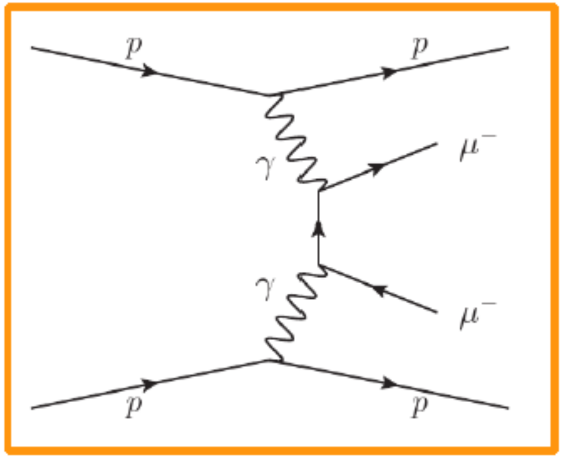
$$\sigma = \sigma_{SM} + \sigma_0 a_0 + \sigma_{00} a_0^2 + \sigma_C a_C + \sigma_{CC} a_C^2 + \sigma_{0C} a_0 a_C$$

Part II

What has been done at the LHC so far?

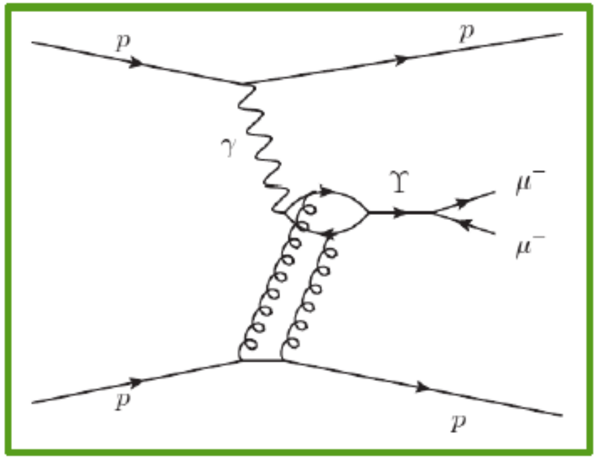
Exclusive physics @ LHC

Two-photon production



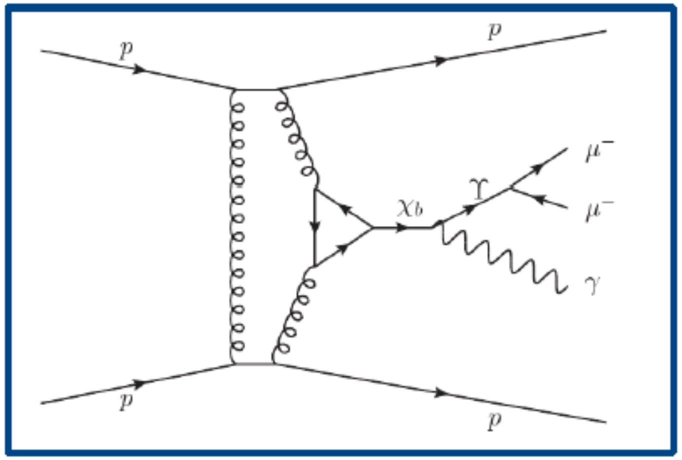
$\mu^+\mu^-$, e^+e^-, $\pi^+\pi^-$
W^+W^-, H^+H^-, $\tilde{l}^+\tilde{l}^-$, ...

Photo-production



ρ, J/Ψ, Υ, Z, ...

Central Exclusive Production



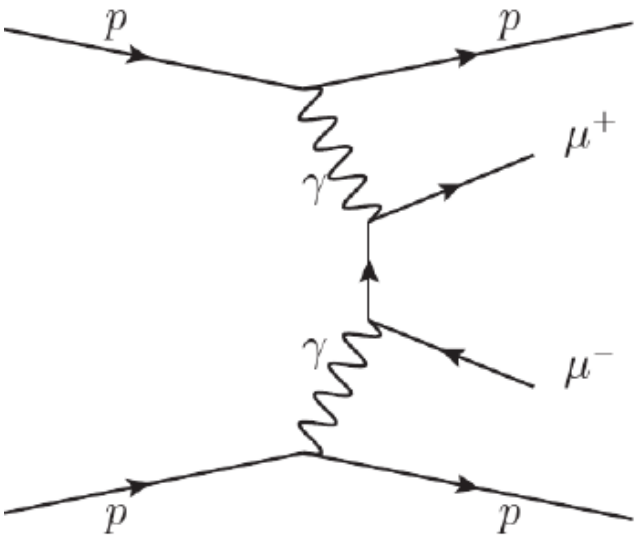
χ_c, χ_b, $\pi^+\pi^-$,dijets, γγ,
Higgs, ...

→ Early analysis: studying SM physics by imposing exclusivity conditions on the central system of CMS

→ Near Future: SM/BSM physics by detecting (both) forward scattered protons with the proposed 'Proton Precision Spectrometer' (PPS) detectors

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

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

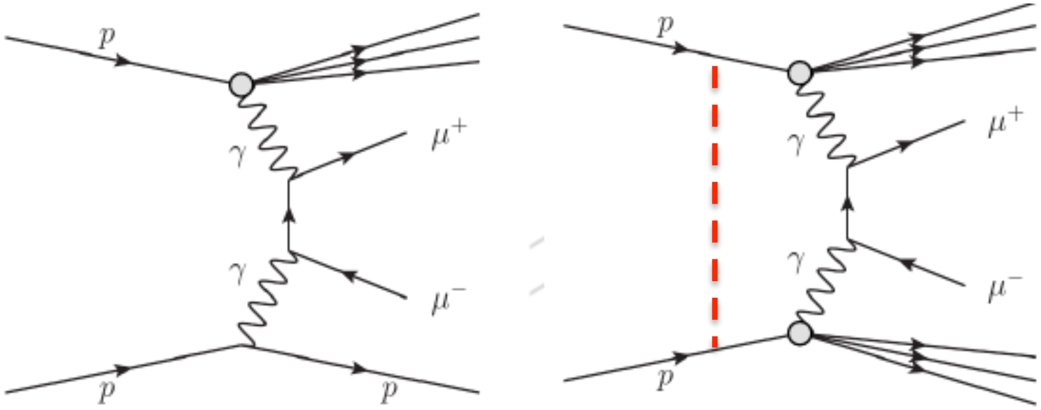


* ***Pure QED process:***
- No PDF to account for
- Small theoretical uncertainties

* ***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***

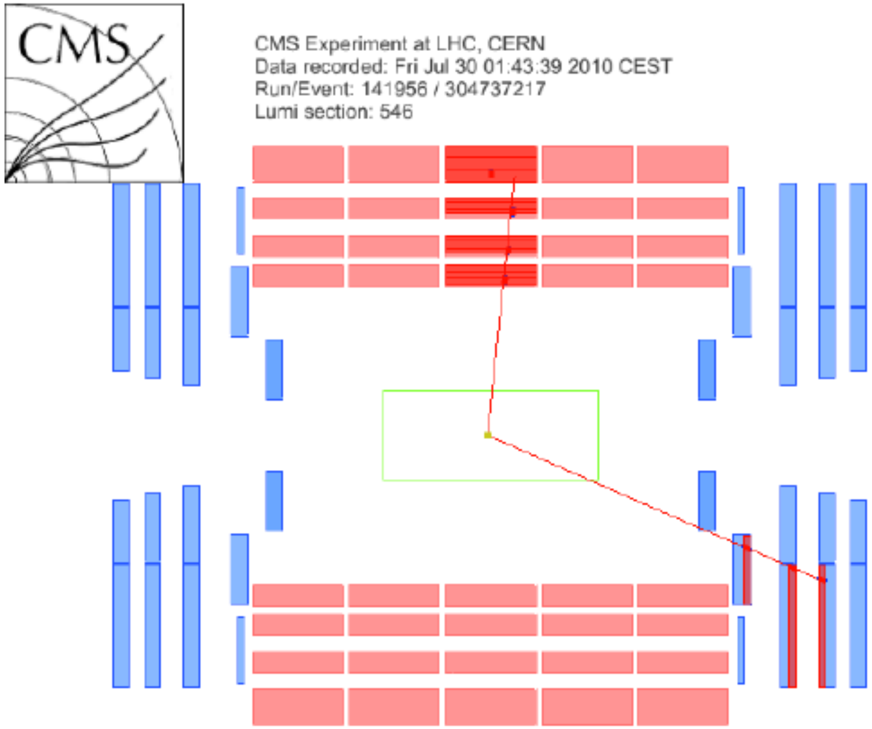
- Largest background arises from *semi-exclusive* **two-photon** production due to single and double proton dissociative (or inelastic) photon exchange:

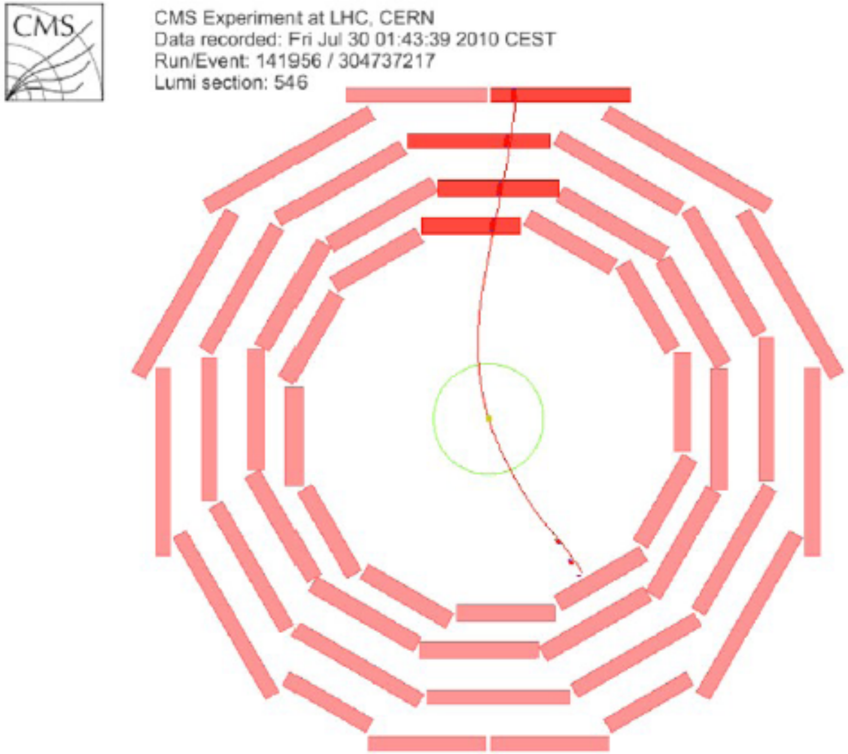


Exclusive γγ → $\mu^+\mu^-$

Candidates for γγ → μμ process:

CMS-DP-2010-035



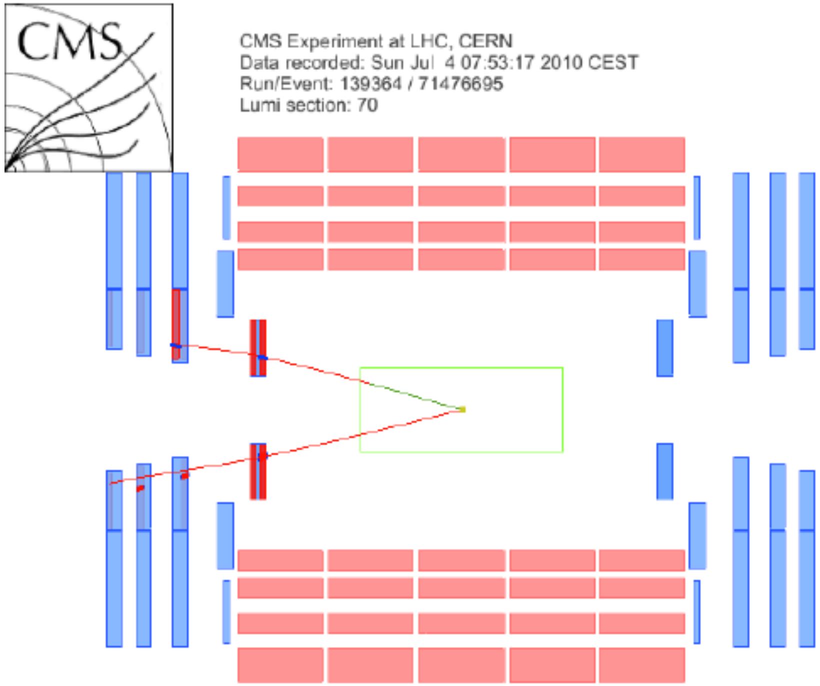


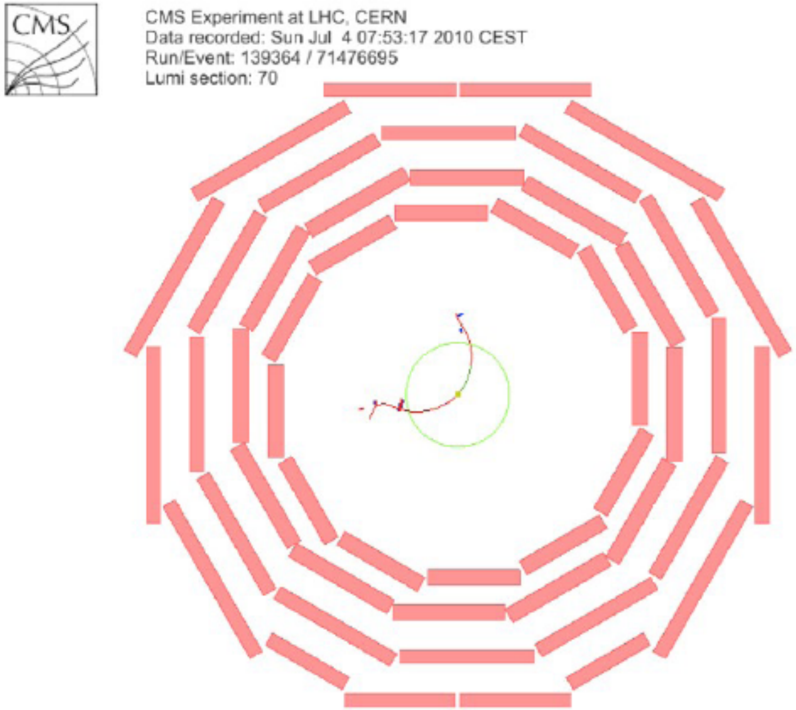
$$\begin{aligned} m &= 20.51 \pm 0.2 \text{ GeV} \\ \frac{\Delta\phi}{\pi} &= 0.98 \\ \Delta p_T &= 0.48 \text{ GeV} \end{aligned}$$

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

Exclusive vector mesons

Candidates for $\gamma p \rightarrow \Upsilon p$ and $\gamma p \rightarrow J/\Psi p$ oberved in CMS:





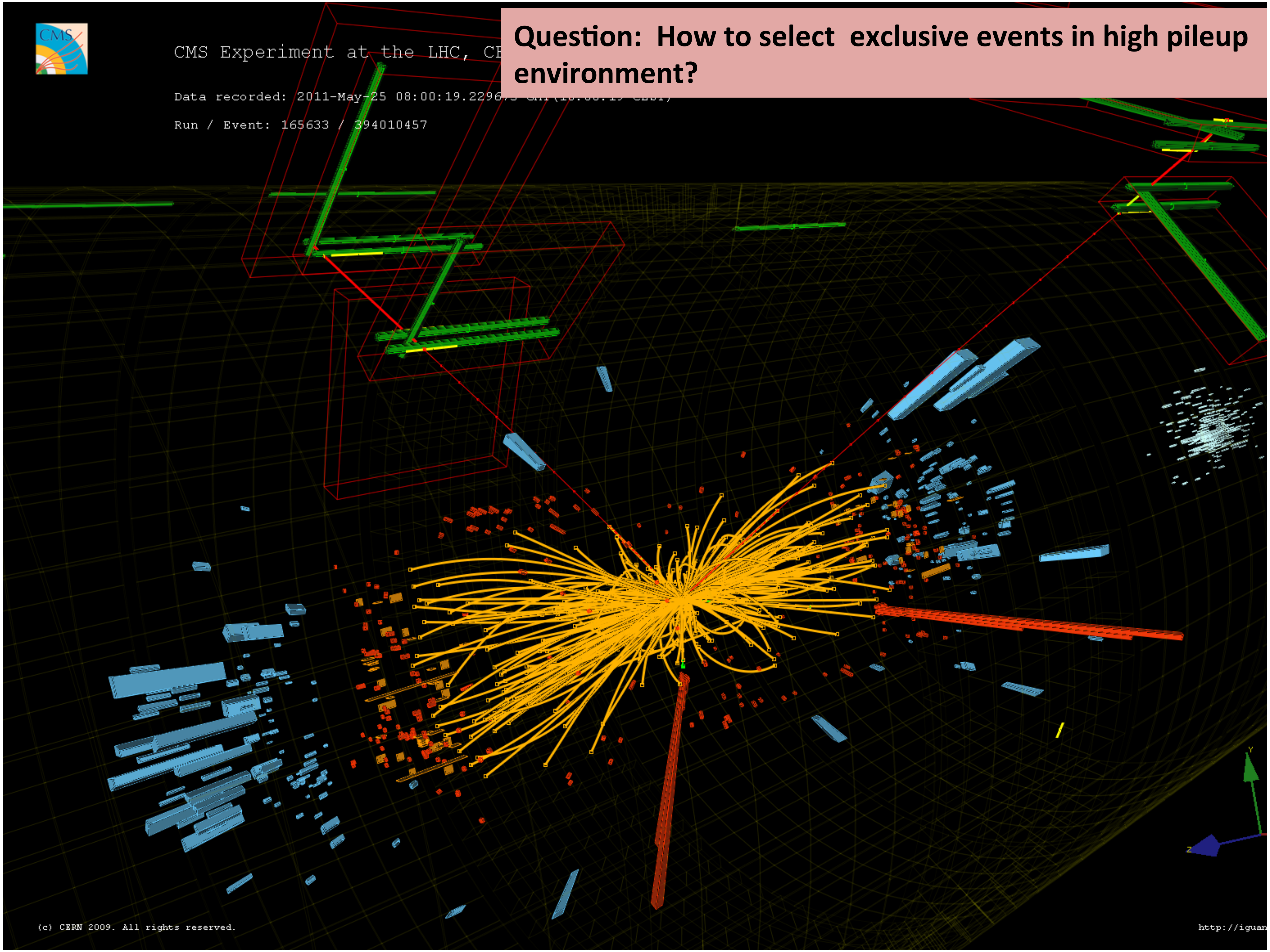
CMS-DP-2010-035

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

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

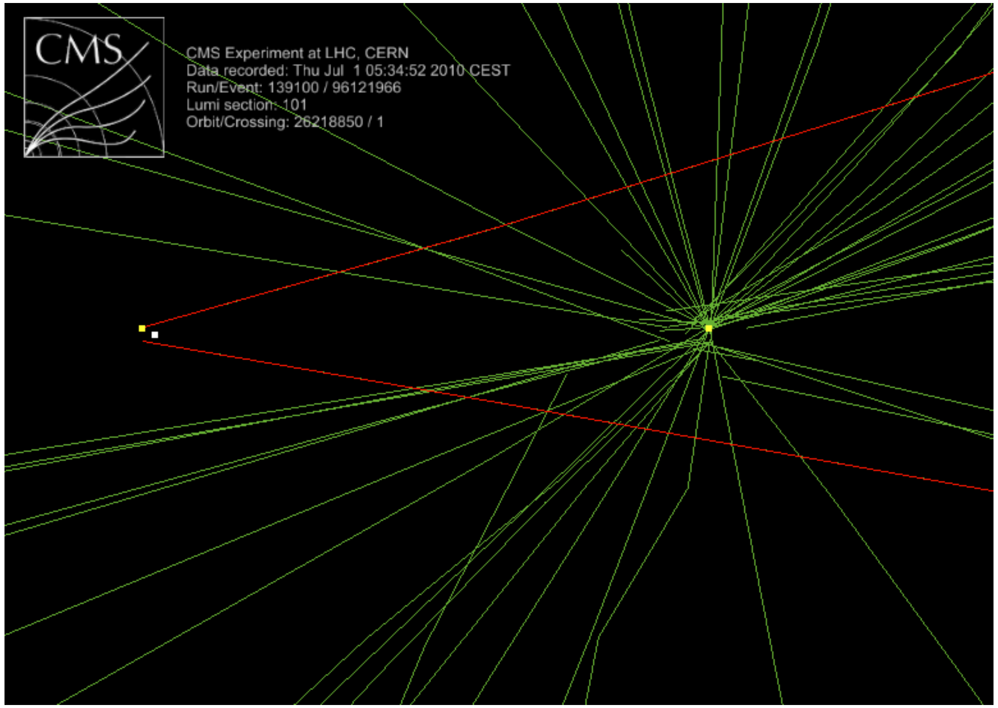
The ideal case: 2 muons and nothing else

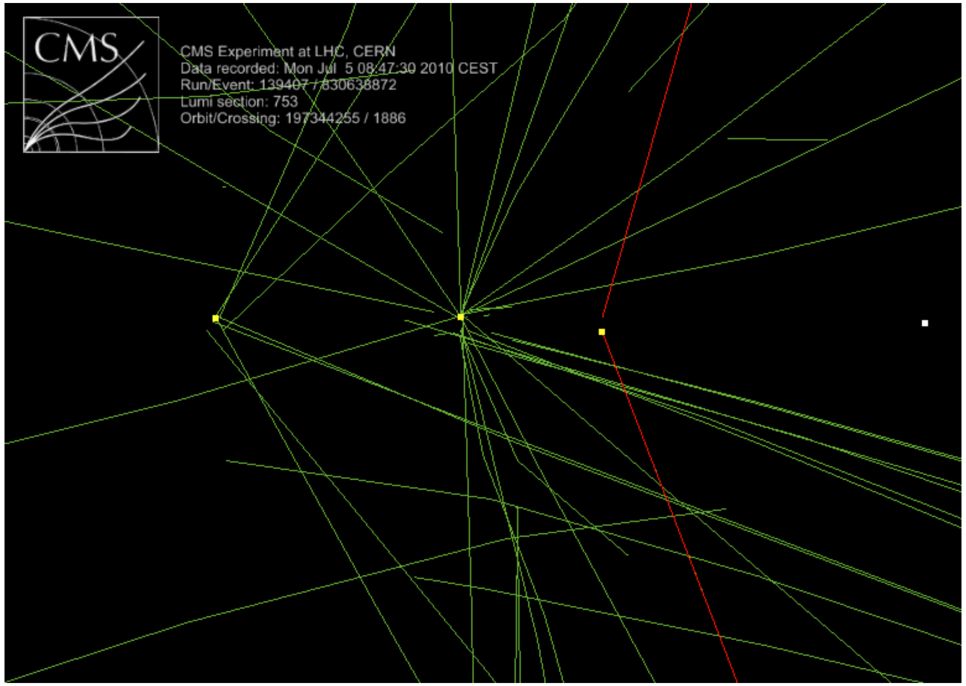
Question: How to select exclusive events in high pileup environment?



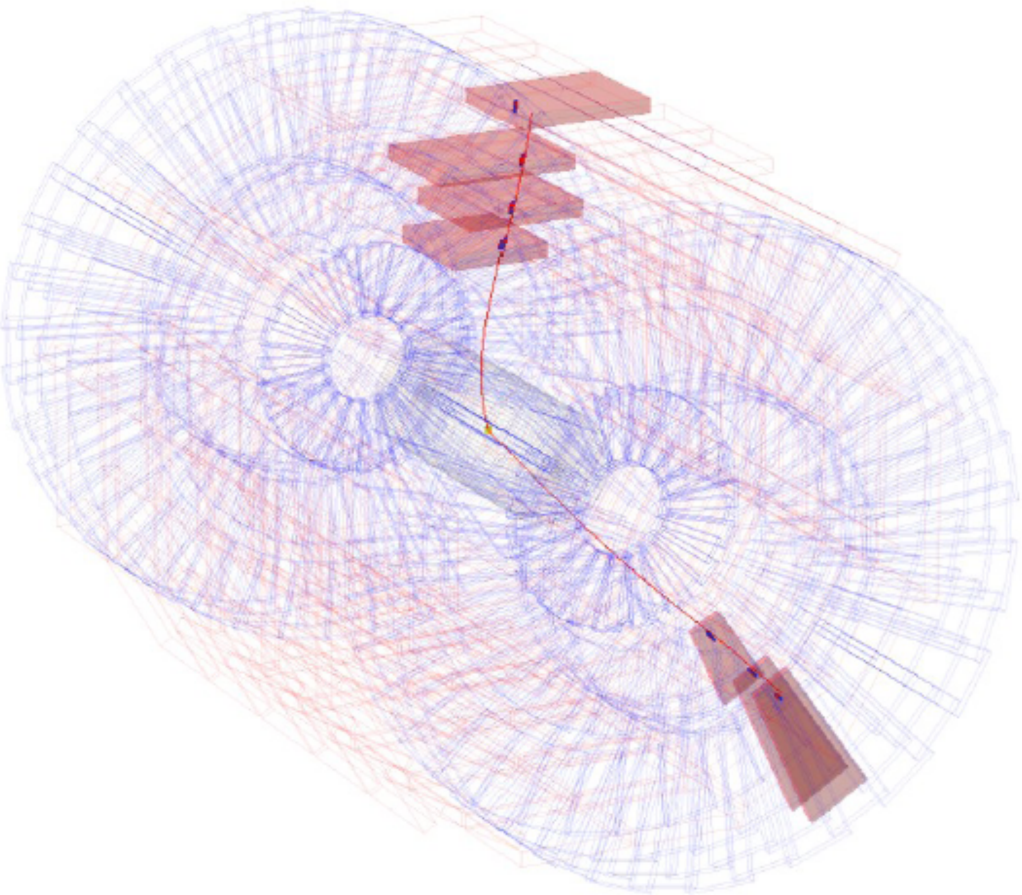
Question: How to select exclusive events in high pileup environment?

Answer: Use tracking only and zoom in onto the vertices!





Exclusivity conditions



In initial (very) low luminosity era:
2 muons and "nothing else"
in the tracker **and** calorimeters

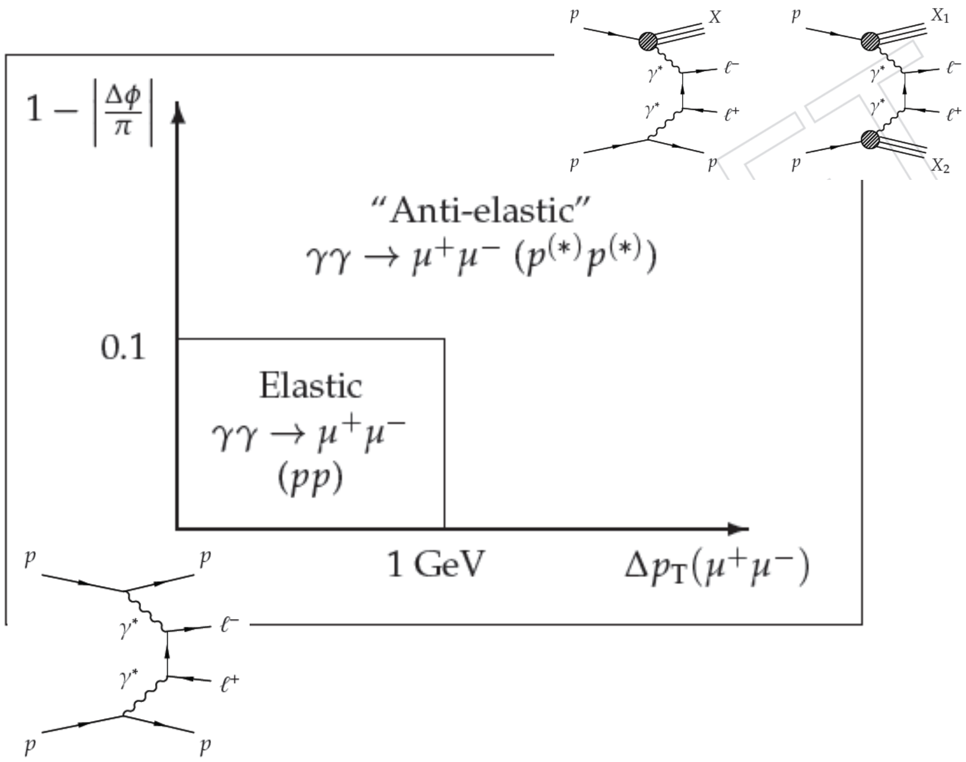
In 2010, each event of interest was accompanied by extra "PileUp" events within the same bunch crossing:
~ 2-3 pileup interactions

In 2011, roughly 7-10 PU per crossing

In 2012, PU =25 put the method to a very limit…

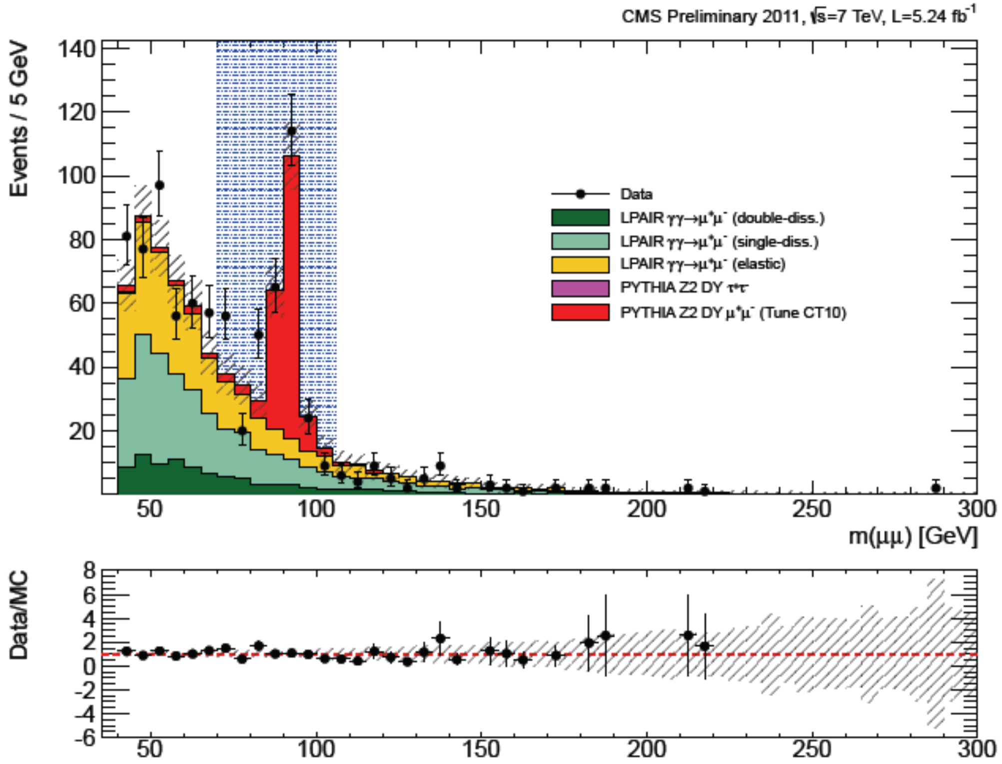
Restricting the analysis to single interactions only would have reduced the data sample a very small fraction of the total → **impose exclusivity using tracking only**

$\mu\mu$ calibration candle



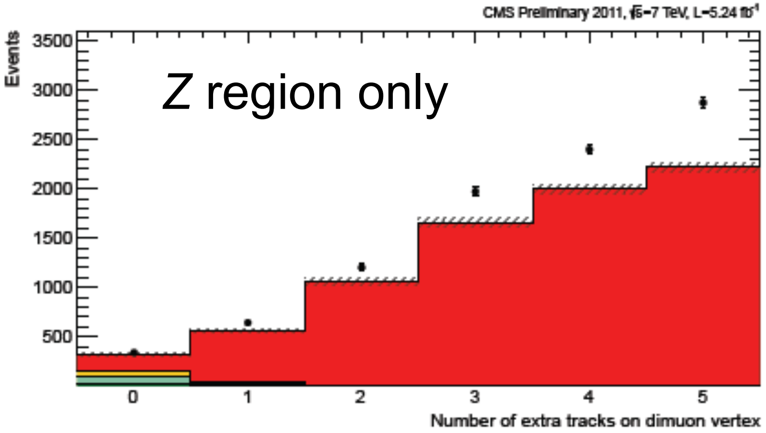
- Use Δp_T and $|1-\Delta\phi/\pi|$ to select regions enriched in elastic or inelastic events
  - Same cuts as used for 2010 $\gamma\gamma\to\mu\mu$ cross-section paper
- Also separate Z peak region (76-105GeV) to check modeling of Drell-Yan
  - $\gamma\gamma\to Z$ is suppressed at tree-level , exclusive Z is expected to be <1fb including branching fraction

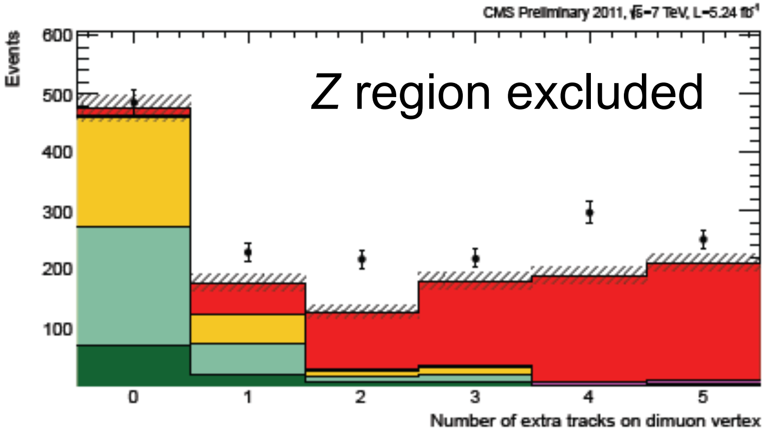
$\mu\mu$ elastic region - summary



- Total event yields in elastic $\mu\mu$ region
  - Data: 825±28.7
  - MC: 808 ±28.4
  - Ratio: 1.02±0.05

$\mu\mu$ control plots – elastic region

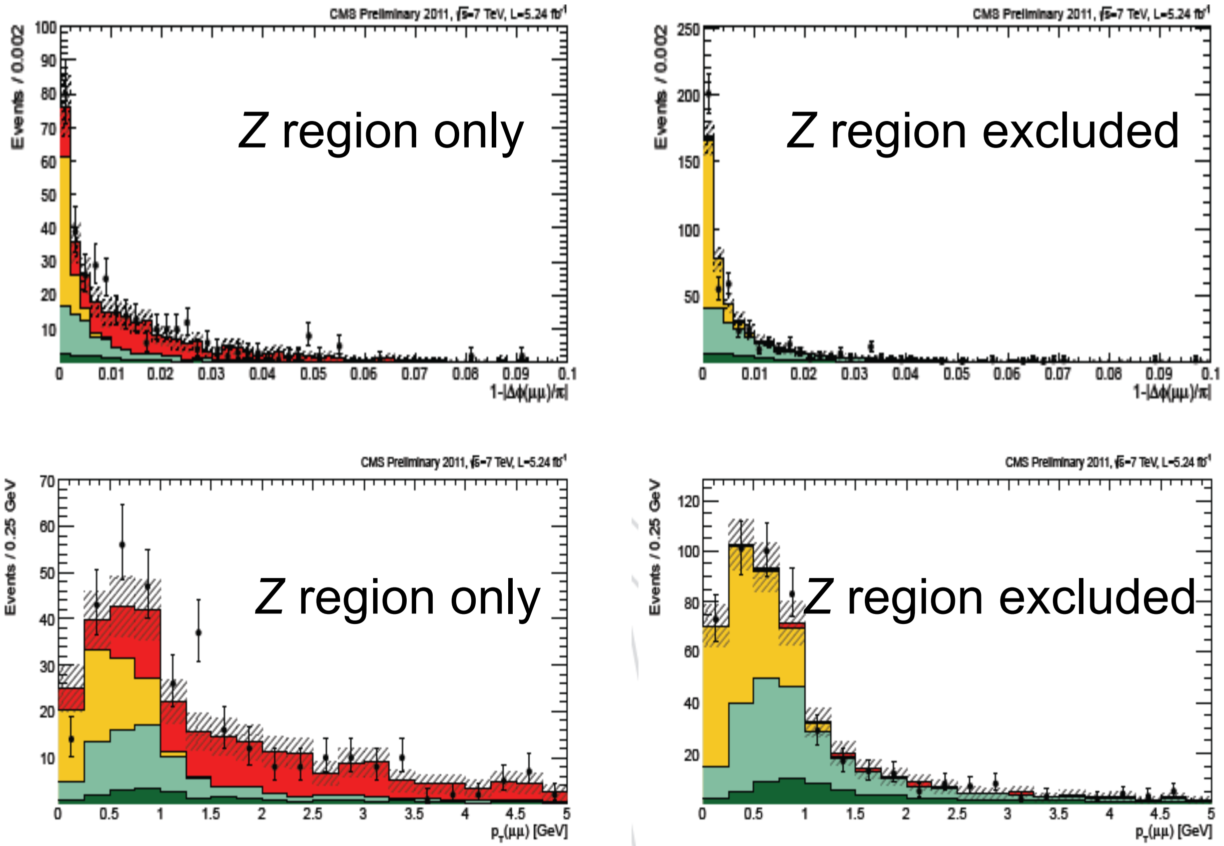




- Large excess of events with 0 extra tracks outside the *Z* region, consistent with sum of elastic and inelastic $\gamma\gamma\rightarrow\mu\mu$
- No peak at 0 in the *Z* region – consistent with large Drell-Yan component
  - NB – higher-multiplicity processes (*WW*, ttbar, *W*+jets, etc.) not shown

$\mu\mu$ control plots – elastic region

- Compare acoplanarity, $p_T(\mu\mu)$, $\Delta p_T(\mu\mu)$ distributions for events with 0 extra tracks

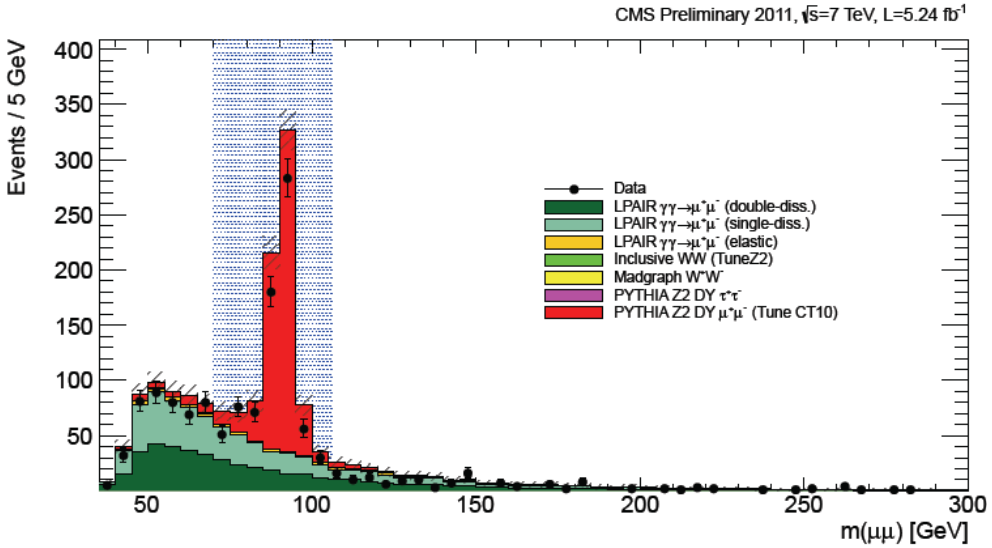


- Generally good description, both in and out of the *Z* region

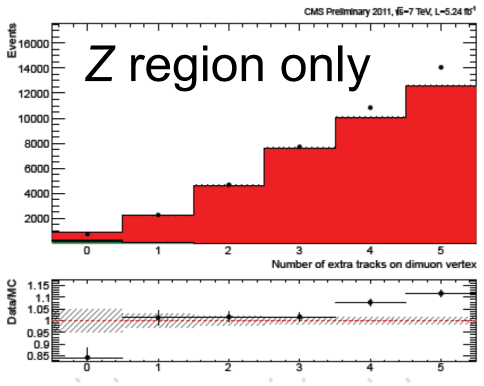
- Shaded bands indicate MC statistical errors

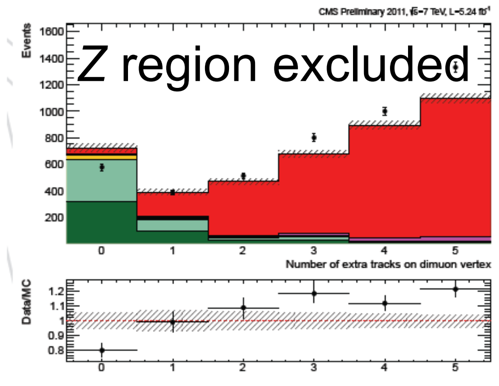
$\mu\mu$ control plots – anti-elastic region

- From MC, expect inelastic yield to be several x elastic at high mass
    - But at high p_T/mass inelastics may be suppressed by – "rescattering" (production of additional soft particles rejected by the extra tracks veto) $\Rightarrow$ extract the total/elastic ratio from the $\mu\mu$ data



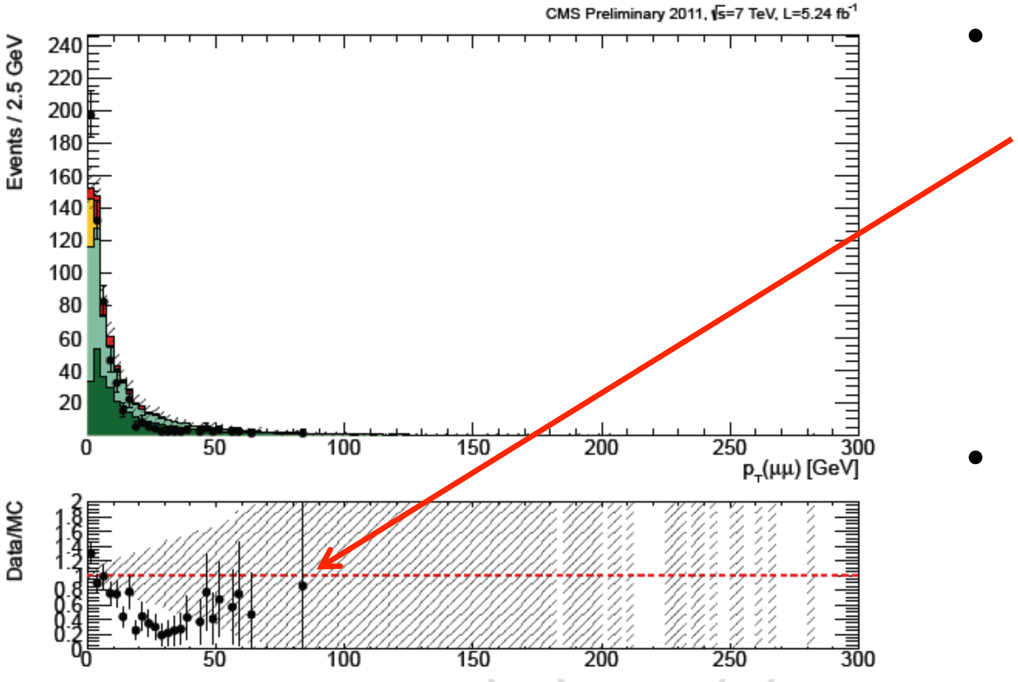
- Invert the acoplanarity and Δp_T cuts to select a region enriched in inelastic events





- Overall find a deficit of ~18% compared to MC prediction with no rescattering

$\mu\mu$ – anti-elastic region



- Further investigation – deficit mainly at high-mass/high-p_T of the pair
  - Expected to be the region most affected by rescattering corrections
- Derive a "data-driven" scale factor for total $\gamma\gamma\rightarrow\mu\mu$/elastic $\gamma\gamma\rightarrow\mu\mu$ from data with m($\mu\mu$)>160 GeV:

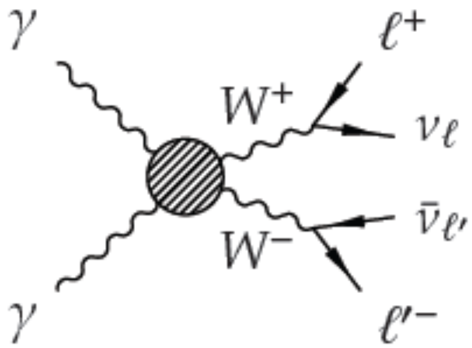
$$F = \left.\frac{N_{\mu\mu\ data} - N_{DY}}{N_{elastic}}\right|_{m(\mu^+\mu^-)>160\ \mathrm{GeV}} = \frac{56.00 - 3.01}{13.40} = 3.95.$$

- Apply this to renormalize the $\gamma\gamma\rightarrow WW$ and $\gamma\gamma\rightarrow\tau\tau$ samples in the μe analysis

$$\gamma\gamma \rightarrow WW \rightarrow \mu e \nu \nu$$

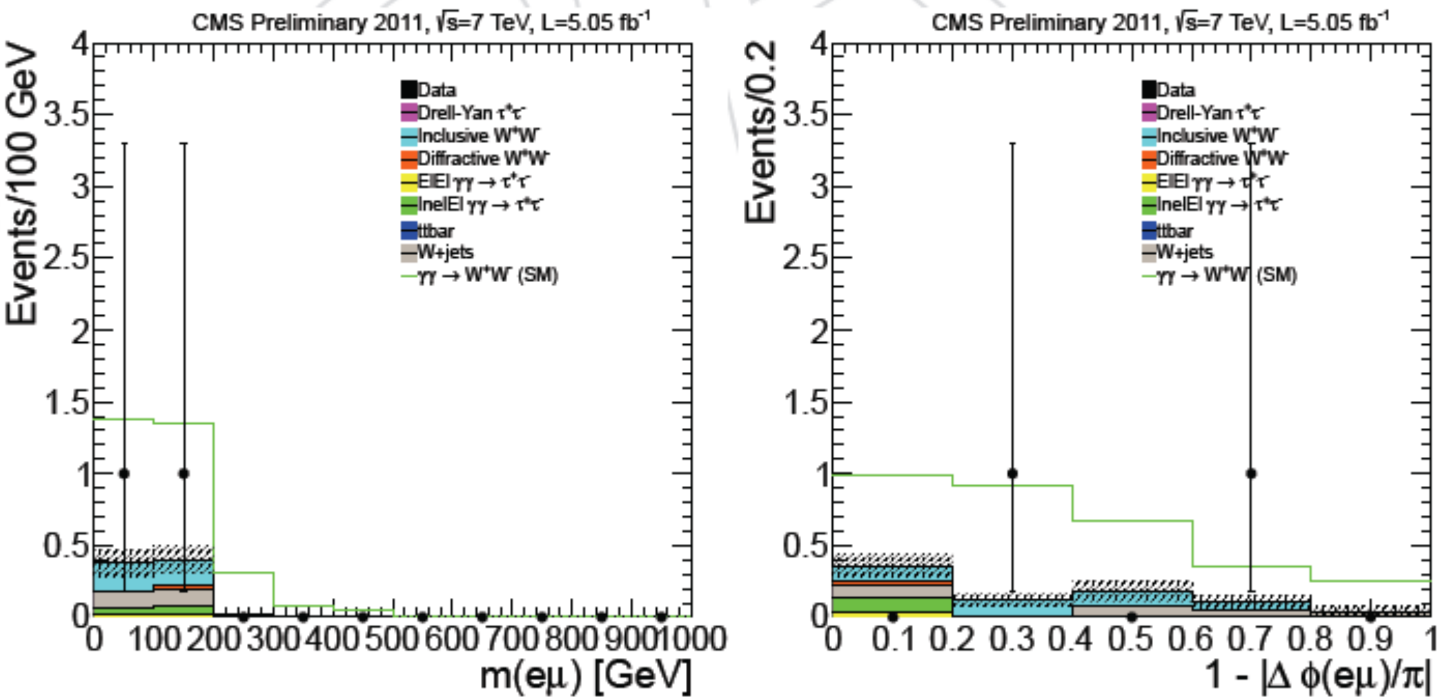
Notation

- Fully exclusive (or “elastic”): events in which both protons stay intact
  - Theoretically clean QED-like production
- Quasi-exclusive (or “inelastic” or “proton dissociation”): events in which one or both protons fragment into an undetected low-mass system $p^{(*)}$
  - Larger uncertainties, possible rescattering corrections
- Cannot separate the two contributions in a counting experiment, therefore signal is defined to include both:



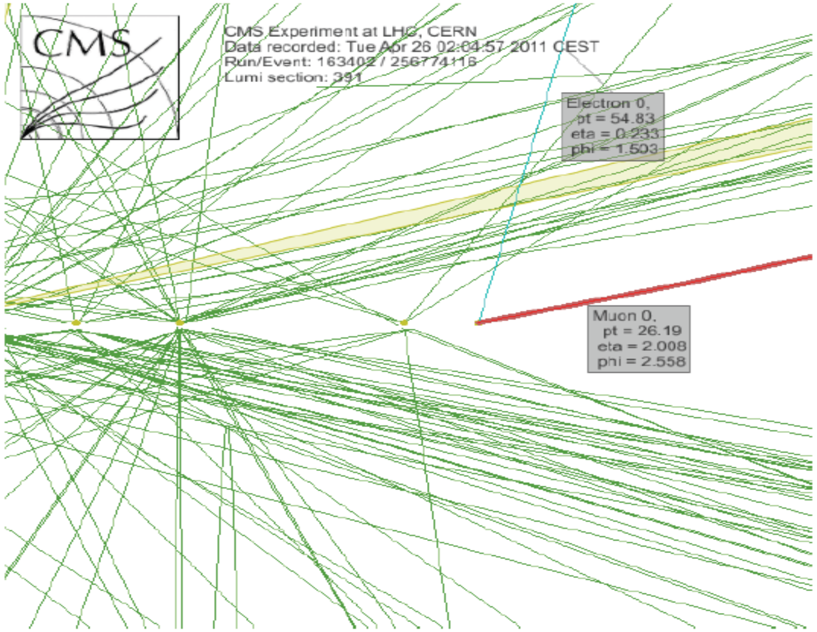
$$pp \to p^{(*)}W^+W^-p^{(*)}$$

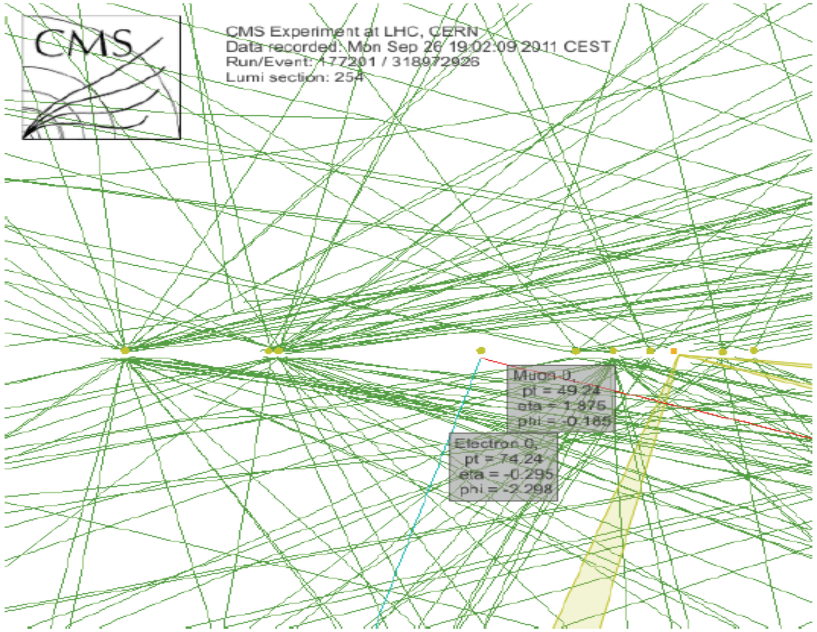
SM signal region (0 extra tracks, pT($e\mu$)>30 GeV)

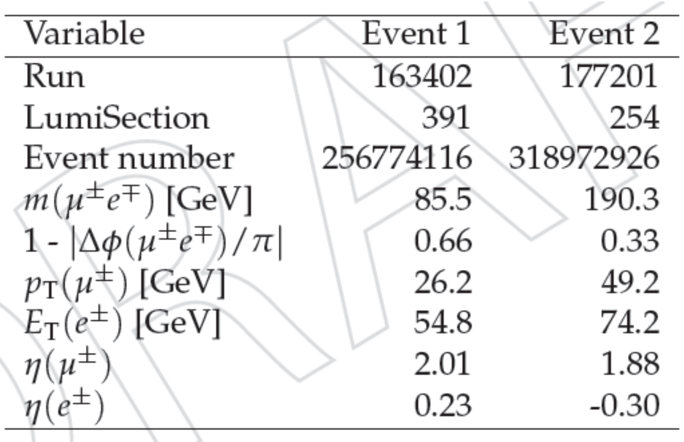


- Expected bkg: 0.8
- Expected signal: 2.4±0.5
- Observed in data: 2 events

SM Signal candidates







Variable	Event 1	Event 2
Run	163402	177201
LumiSection	391	254
Event number	256774116	318972926
$m(\mu^{\pm}e^{\mp})$ [GeV]	85.5	190.3
1 - $\lvert\Delta\phi(\mu^{\pm}e^{\mp})/\pi\rvert$	0.66	0.33
$p_{\mathrm{T}}(\mu^{\pm})$ [GeV]	26.2	49.2
$E_{\mathrm{T}}(e^{\pm})$ [GeV]	54.8	74.2
$\eta(\mu^{\pm})$	2.01	1.88
$\eta(e^{\pm})$	0.23	-0.30

- Event displays and single/double lepton information for the two selected events

Some time later…

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
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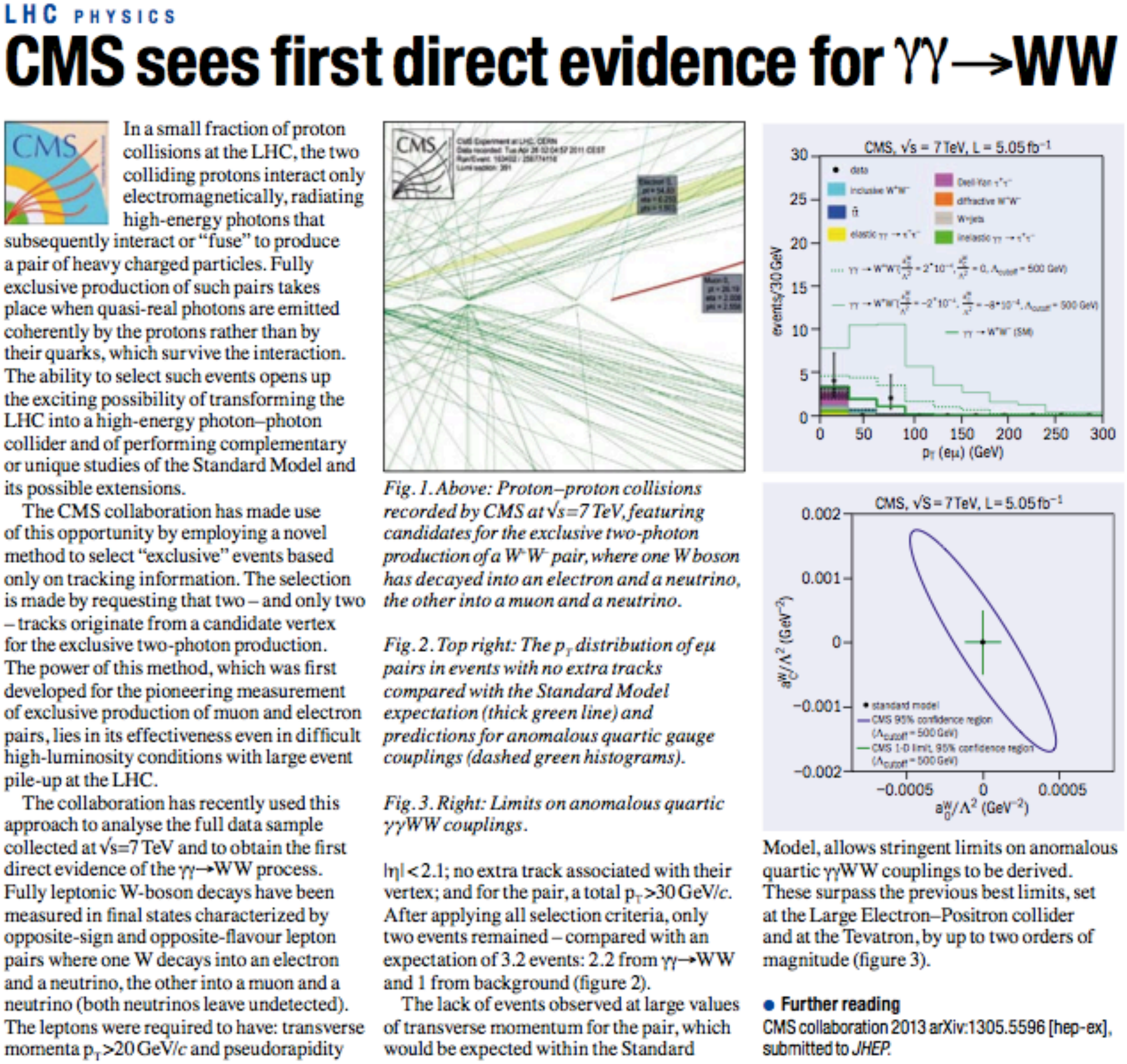


LHC PHYSICS

CMS sees first direct evidence for γγ→WW

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}=7$ TeV and to obtain the first direct evidence of the γγ→WW process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a neutrino (both neutrinos leave undetected). The leptons were required to have: transverse momenta $p_T > 20$ GeV/c and pseudorapidity $|\eta| < 2.1$; no extra track associated with their vertex; and for the pair, a total $p_T > 30$ GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from γγ→WW and 1 from background (figure 2).

The lack of events observed at large values of transverse momentum for the pair, which would be expected within the Standard Model, allows stringent limits on anomalous quartic γγWW couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}=7$ TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

Fig. 2. Top right: The p_T distribution of eμ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

Fig. 3. Right: Limits on anomalous quartic γγWW couplings.

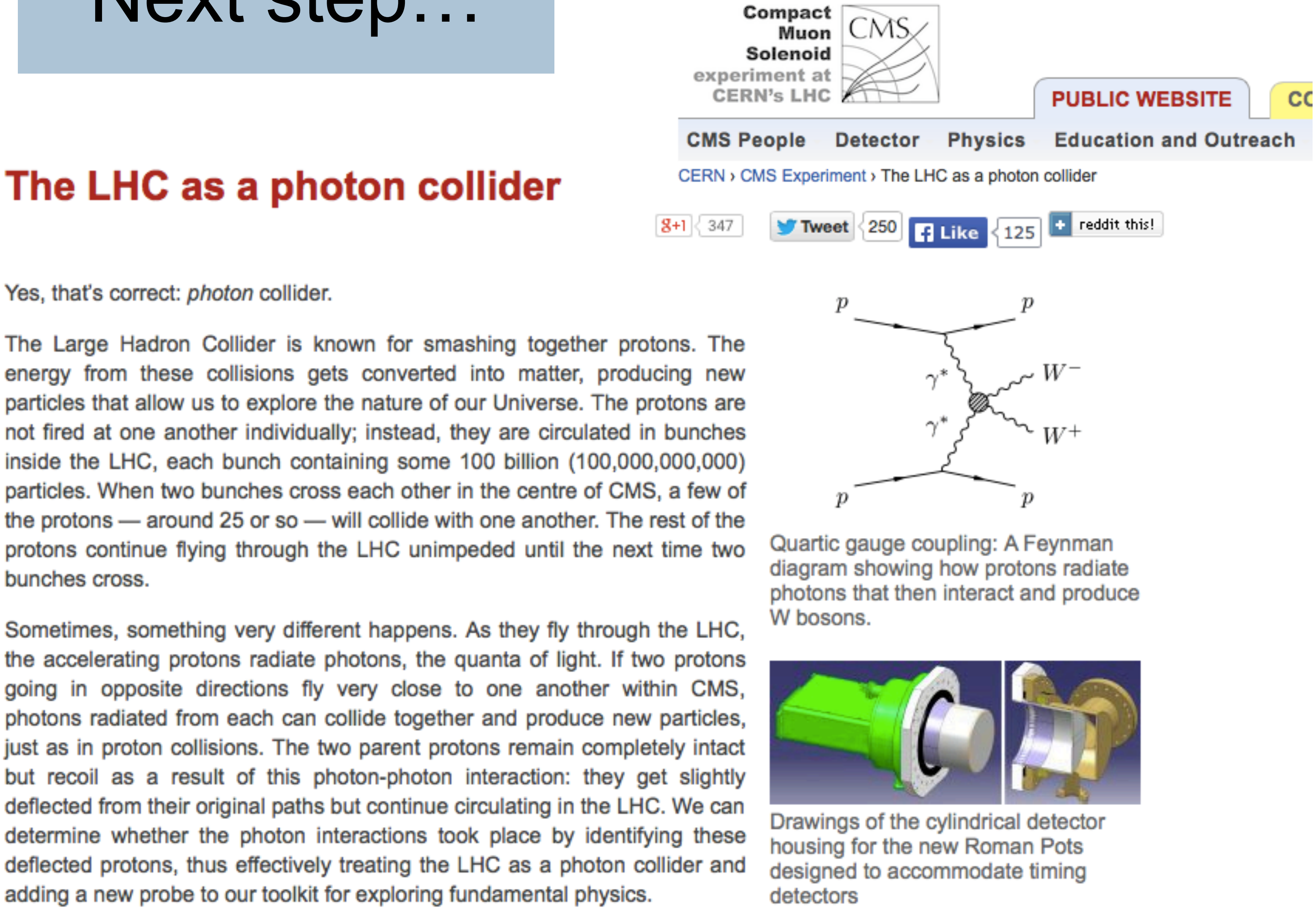
● **Further reading**

CMS collaboration 2013 arXiv:1305.5596 [hep-ex], submitted to *JHEP*.

Part III

What more can be done at the LHC?

Next step…



Compact
Muon
Solenoid
experiment at
CERN's LHC

PUBLIC WEBSITE

CMS People Detector Physics Education and Outreach

CERN › CMS Experiment › The LHC as a photon collider

The LHC as a photon collider

Yes, that's correct: *photon* collider.

The Large Hadron Collider is known for smashing together protons. The energy from these collisions gets converted into matter, producing new particles that allow us to explore the nature of our Universe. The protons are not fired at one another individually; instead, they are circulated in bunches inside the LHC, each bunch containing some 100 billion (100,000,000,000) particles. When two bunches cross each other in the centre of CMS, a few of the protons — around 25 or so — will collide with one another. The rest of the protons continue flying through the LHC unimpeded until the next time two bunches cross.

Sometimes, something very different happens. As they fly through the LHC, the accelerating protons radiate photons, the quanta of light. If two protons going in opposite directions fly very close to one another within CMS, photons radiated from each can collide together and produce new particles, just as in proton collisions. The two parent protons remain completely intact but recoil as a result of this photon-photon interaction: they get slightly deflected from their original paths but continue circulating in the LHC. We can determine whether the photon interactions took place by identifying these deflected protons, thus effectively treating the LHC as a photon collider and adding a new probe to our toolkit for exploring fundamental physics.

Quartic gauge coupling: A Feynman diagram showing how protons radiate photons that then interact and produce W bosons.

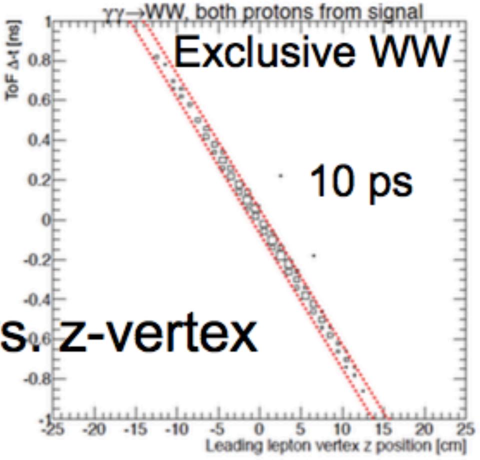
Drawings of the cylindrical detector housing for the new Roman Pots designed to accommodate timing detectors

CT-PPS concept:

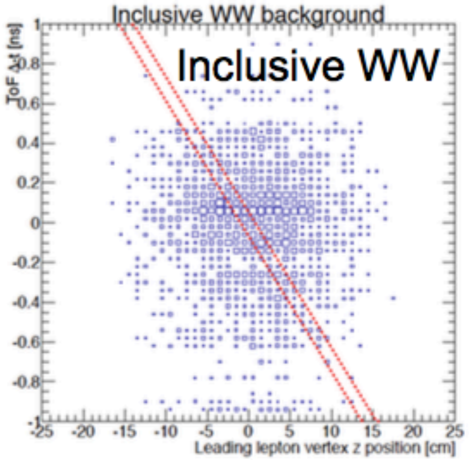
1) Proton spectrometer making use of **machine magnets**
2) Two tracking stations with **3D pixel detectors**
3) One stations with **10 ps timing detectors**

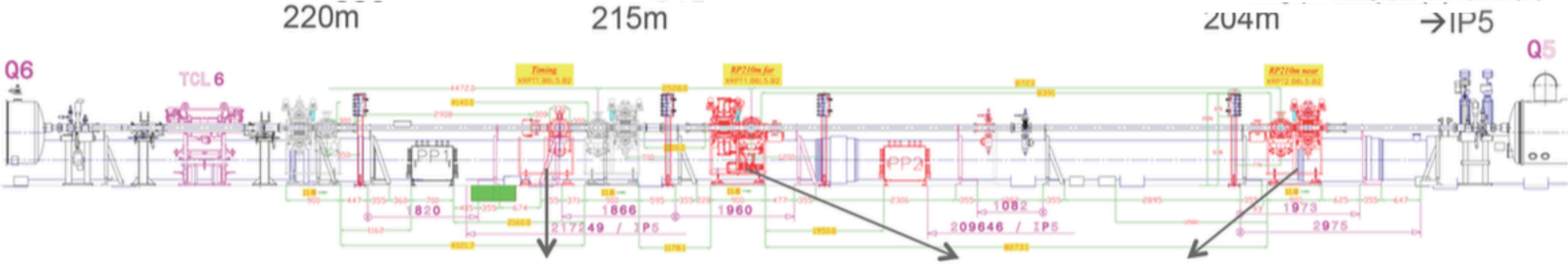
Use timing to reject pileup background

- time difference of two protons is correlated to collision vertex



ToF vs. z-vertex





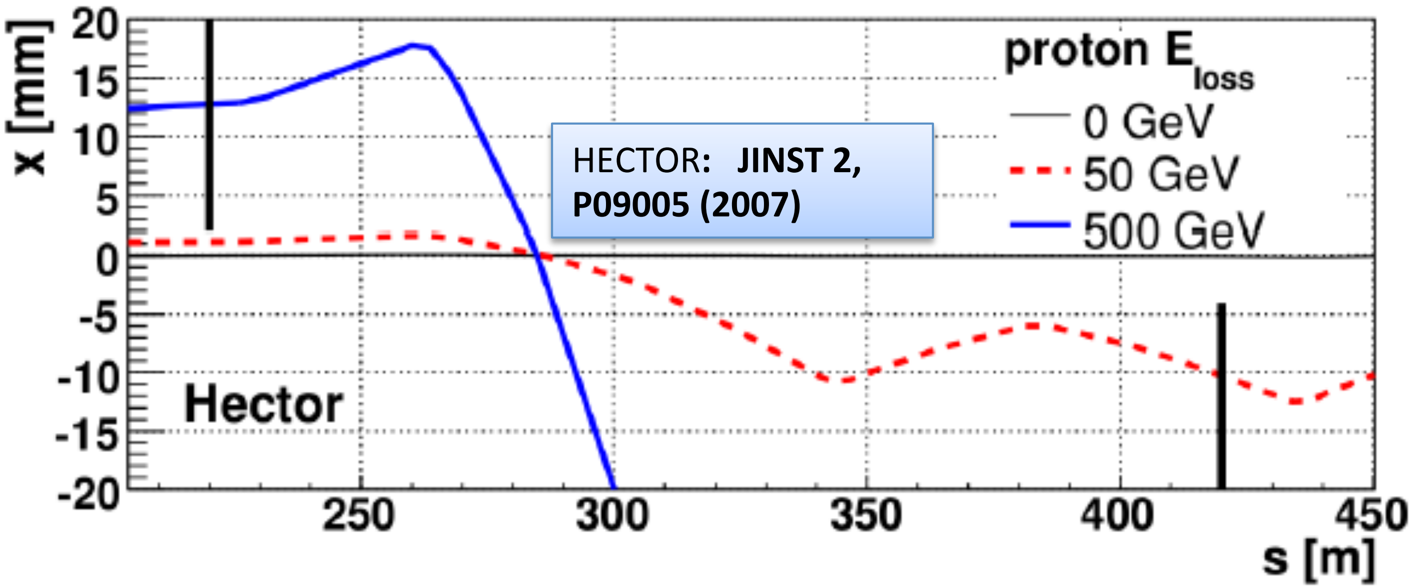
2 new horizontal cylindrical RPs (1 in LS1)

2 horizontal box-shaped RPs

Picosecond ToF detectors @ LHC

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

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

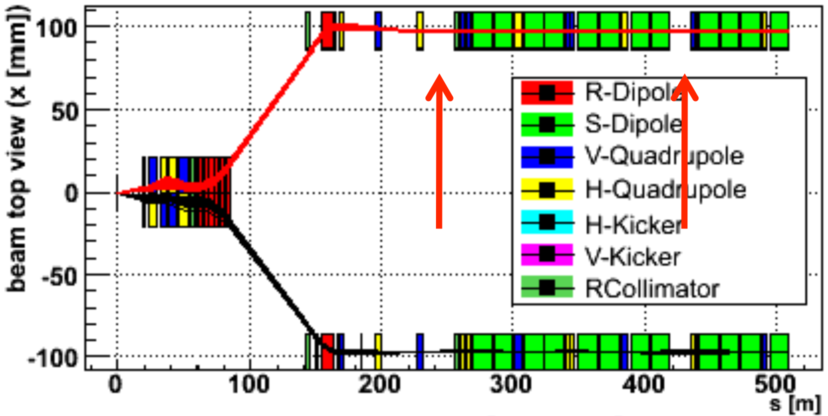


HECTOR: **JINST 2, P09005 (2007)**

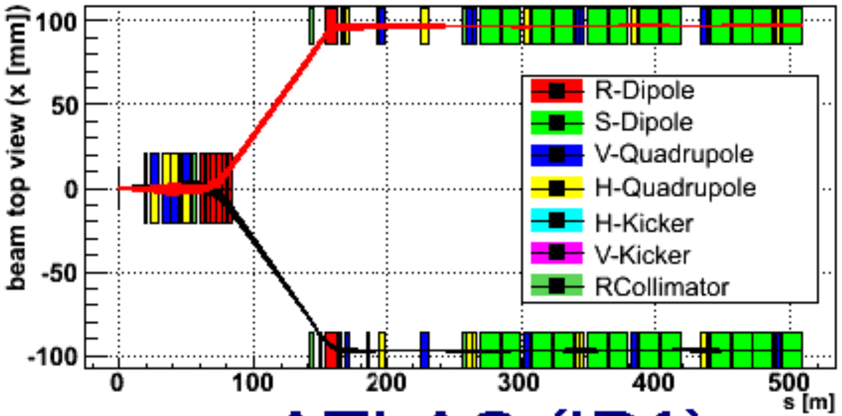
Path length differences are very small for forward protons at LHC, typically << 100 μm corresponding to sub-picosecond time differences.

Ultra fast timing detectors are essential for measuring the exclusive production at LHC, like for the Higgs boson case in pp → pHp, JINST 4 (2009) T10001

Optimal places for tagging Central Exclusive Production (CEP) at LHC: @ 220/240m and 420m from IP

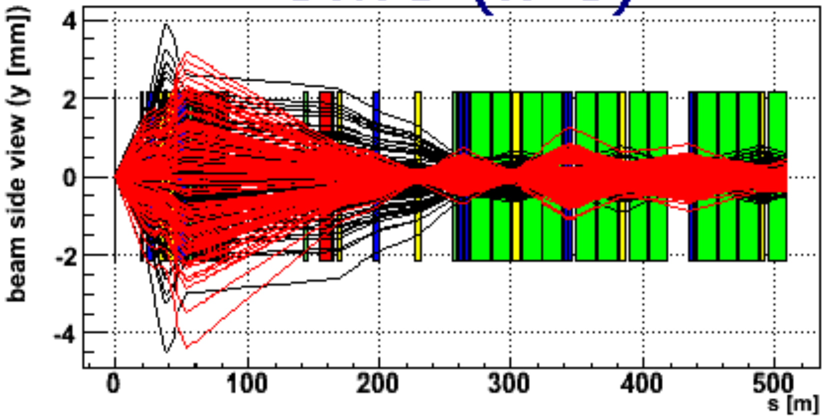


top

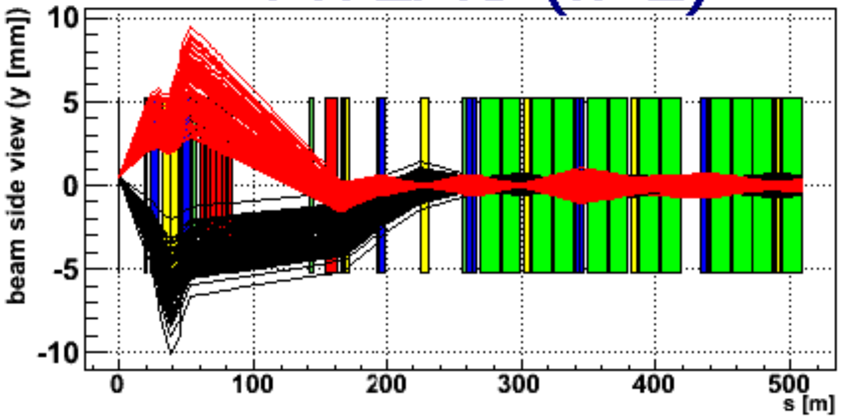


CMS (IP5)

ATLAS (IP1)



side



Horizontal crossing plane

Vertical crossing plane

HECTOR: **JINST 2, P09005 (2007)**
For <u>nominal</u> low-β LHC optics

Measuring (very) forward protons

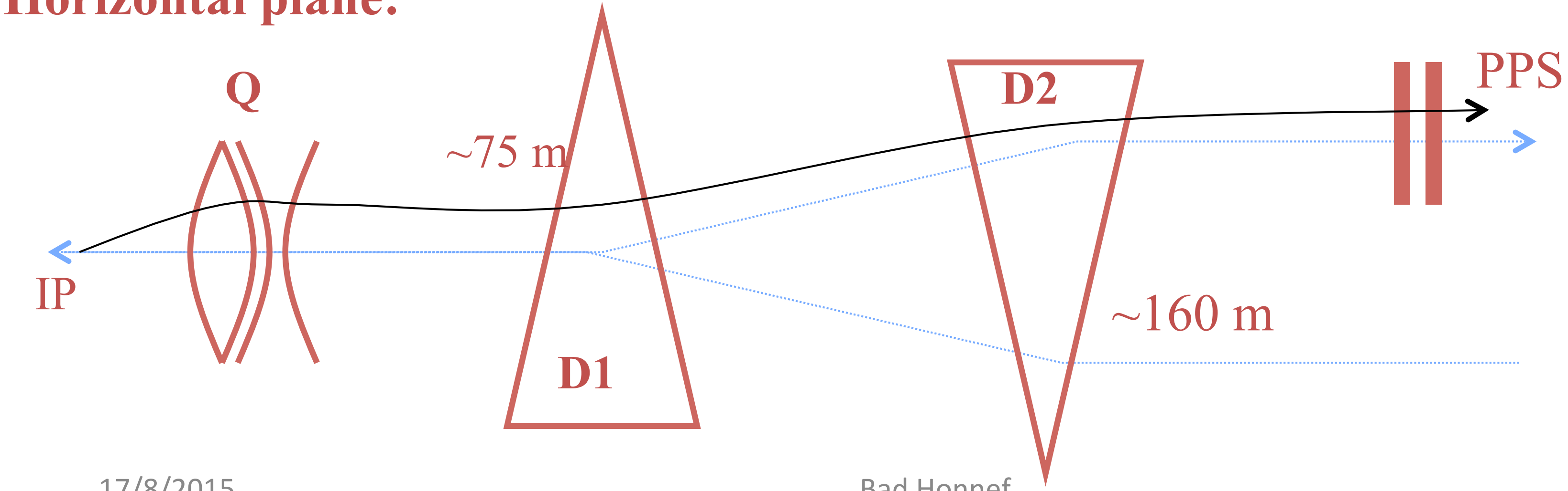
Quick beam-optics course:

- To good approximation beam protons move independently in horizontal and vertical planes
- Particle point-to-point transfer can be computed using transport matrices (**$\mathbf{X}=\mathbf{M}\mathbf{X}_0$**) or, equivalently optics functions β, Φ and *D*

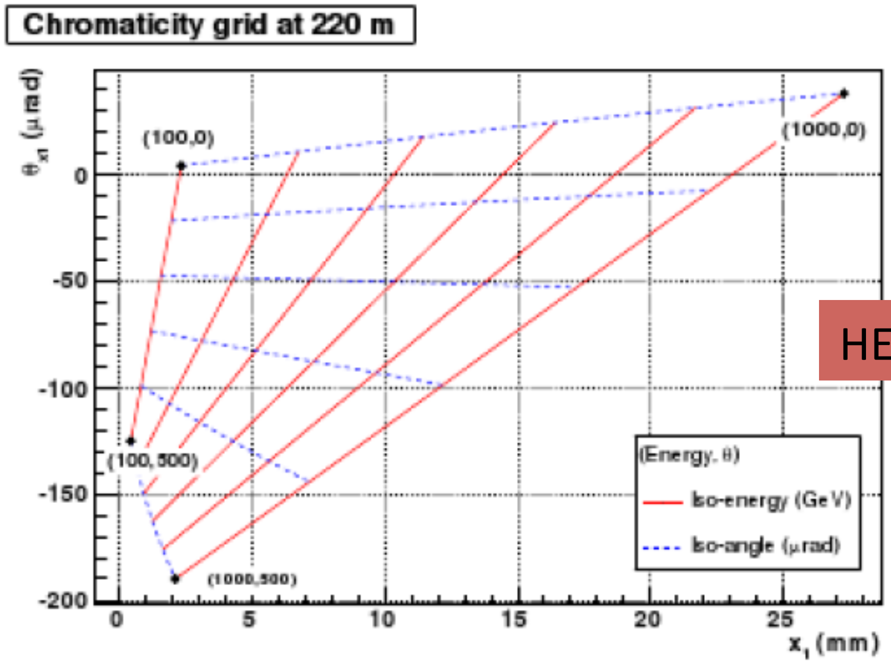
$$x = x^{*}\sqrt{(\beta/\beta^{*})}\sin\Phi + \theta_x^{*}\sqrt{(\beta\beta^{*})}\cos\Phi + D\Delta E/E$$

$= x$

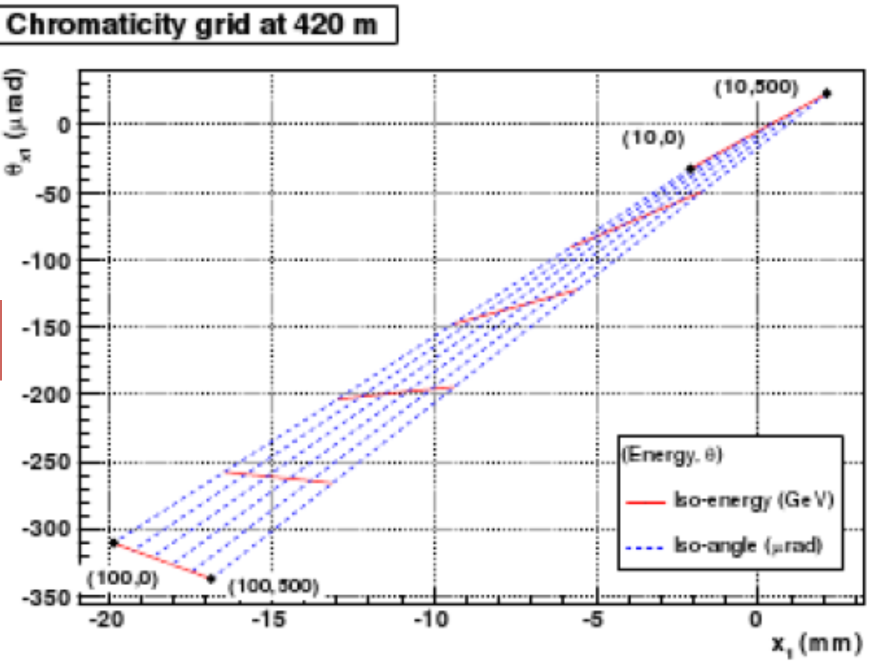
Horizontal plane:

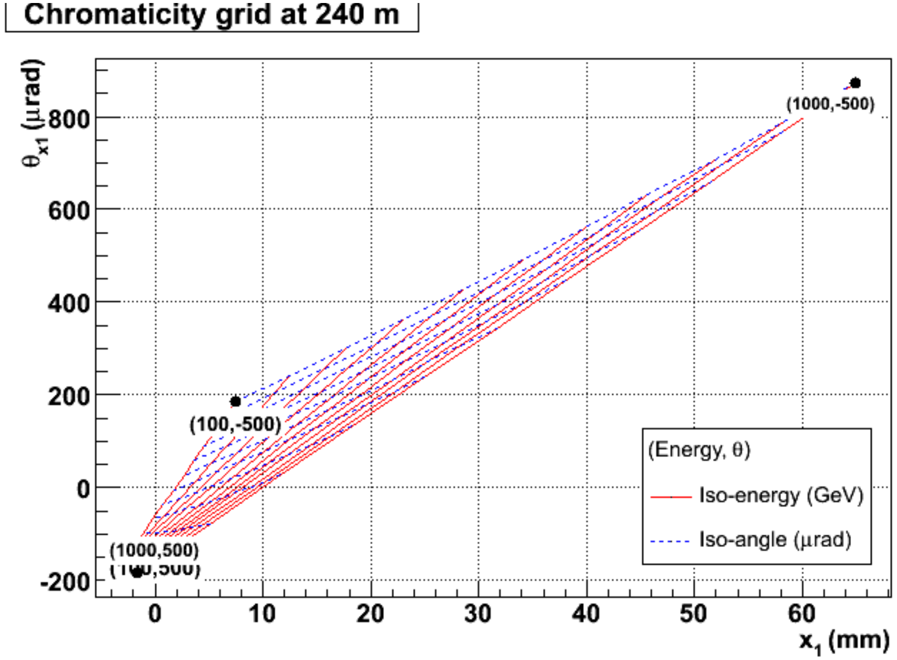


Reconstruction: Chromacity grids


Chromaticity grid at 220 m

HECTOR


Chromaticity grid at 420 m


Chromaticity grid at 240 m

Basic principle:

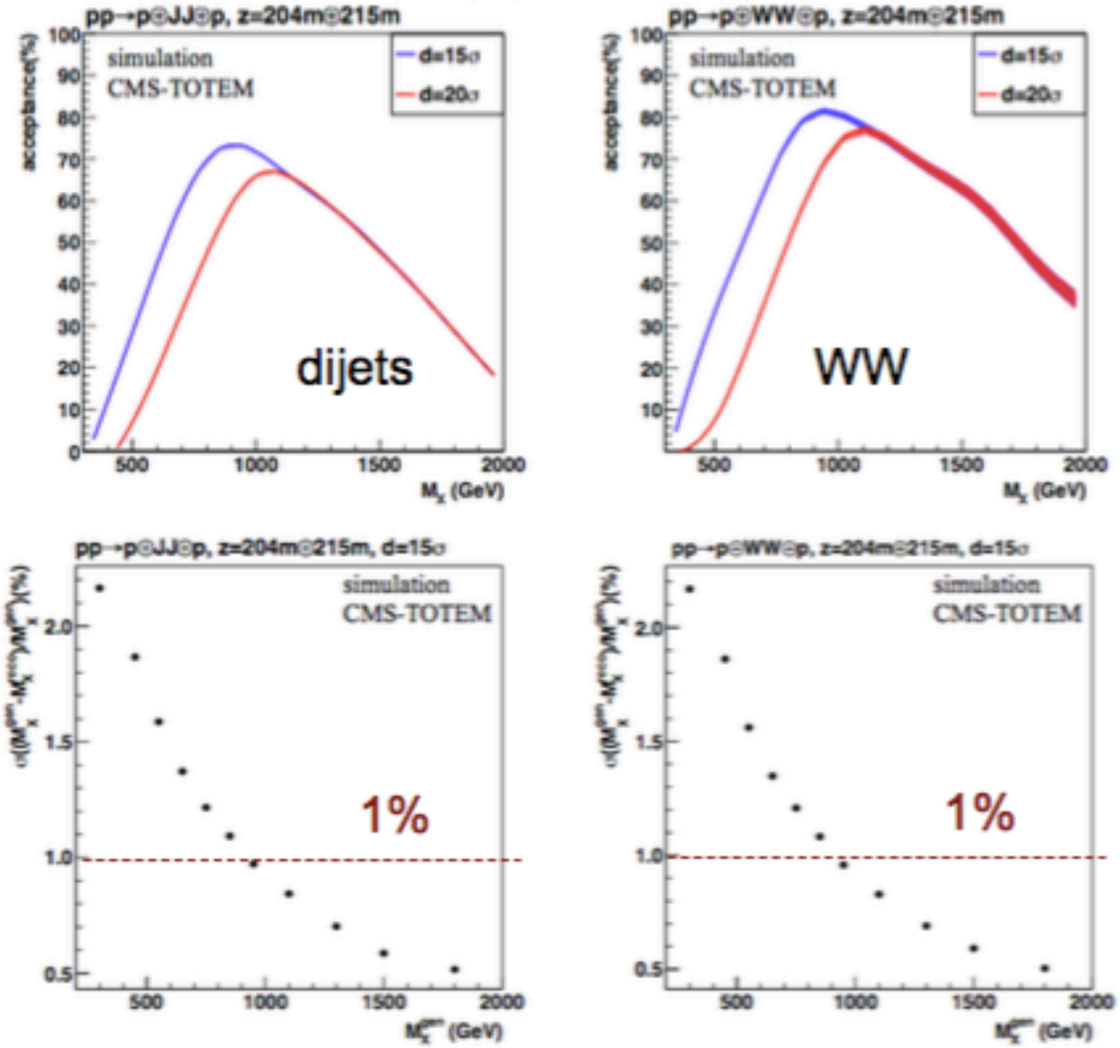
- Three initial variables(position+angle+energy) and two measured (position+angle) → assume nominal vertex position (x=0)
- (Horizontal and vertical planes independent)

In each arm (&plane) position and angle @ PPS give energy loss and scattering angle @ IP

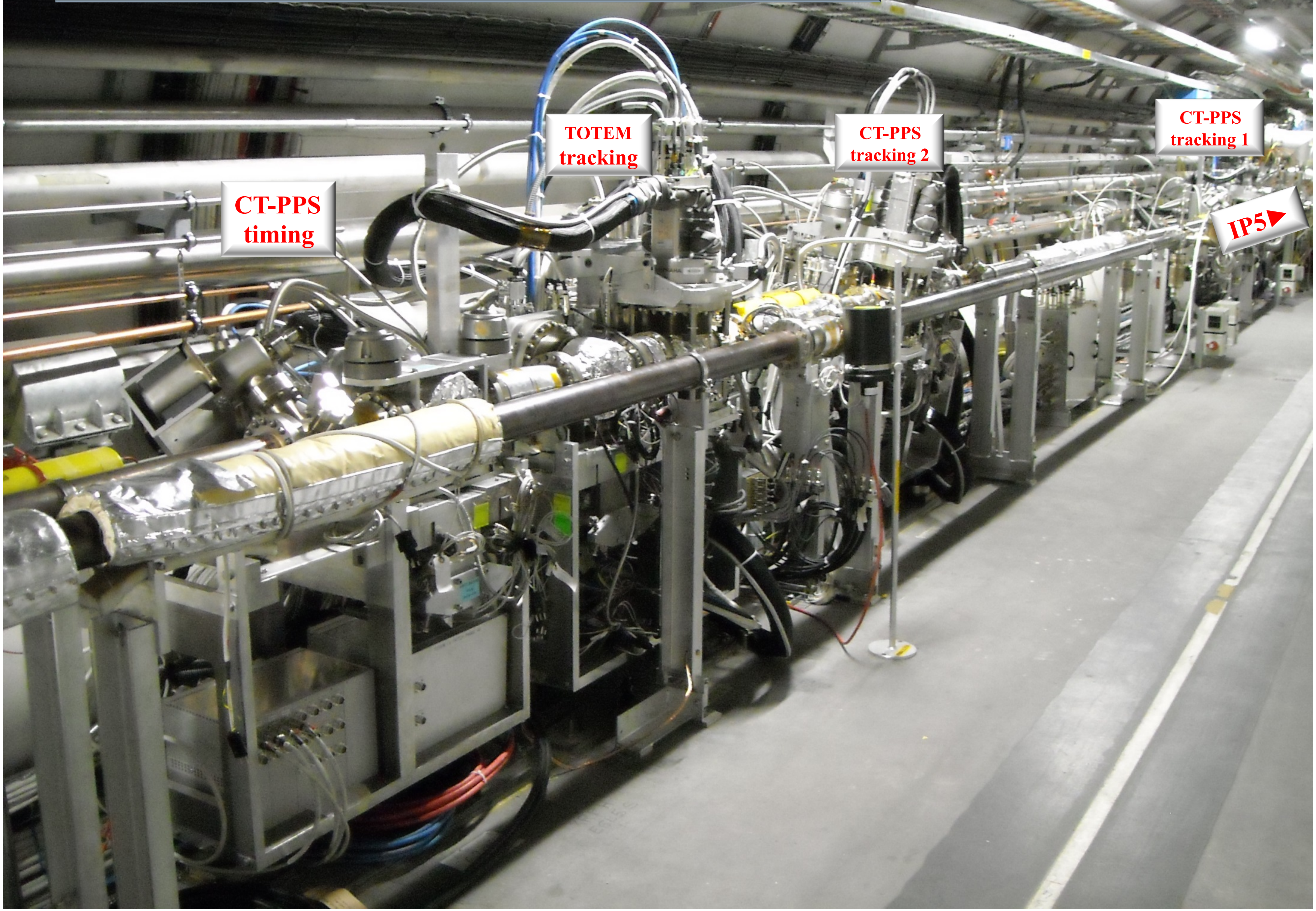
10 μm per point and ~10 m lever arm result in about 2.10^{-4} energy resolution!

Mass acceptance and resolution

- Mass acceptance and resolution vs M_X
- PPS selects exclusive systems in 300-1700 GeV range (ε>5%)
- At 15σ acceptance larger by a factor of two (wrt 20σ) for lower masses
- Mass resolution ~1.5% at 500 GeV



CT-PPS Components for 2016 running



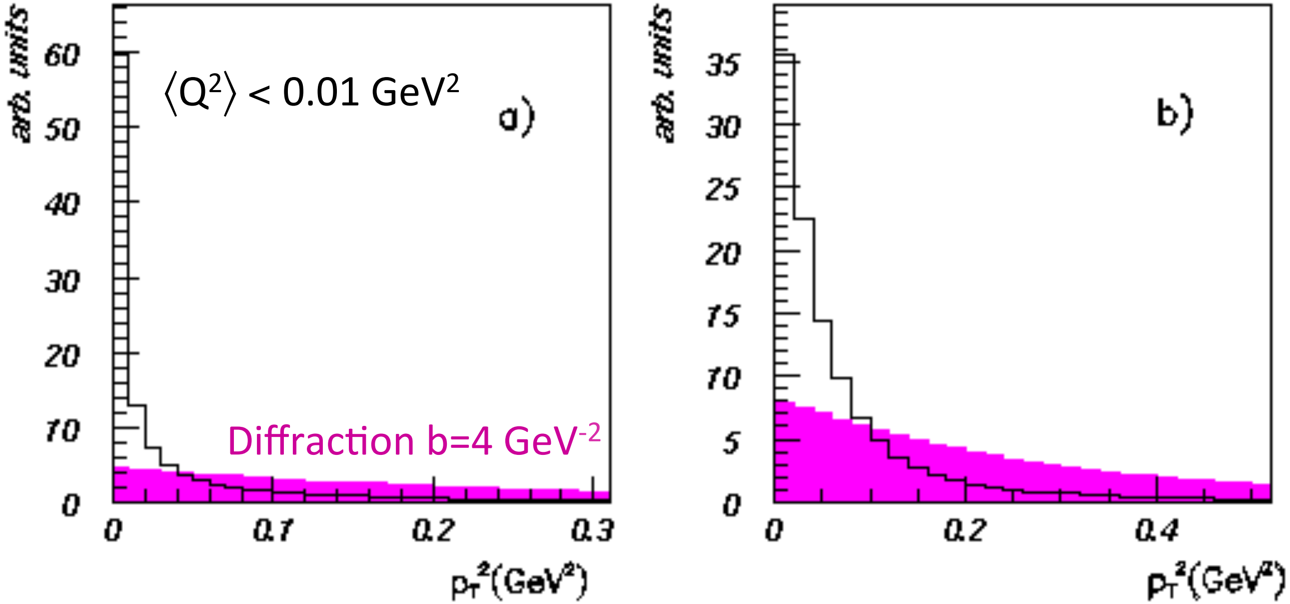
Extra slides

Problem: Same signature (one or two very forward protons) has also *central diffraction* (i.e. *pomeron-pomeron* scattering) in strong interactions

Both processes weakly interfere, and transverse momentum of the scattered protons are on average much softer in two-photon case

Phys. Rev. **D63** (2001) 071502(

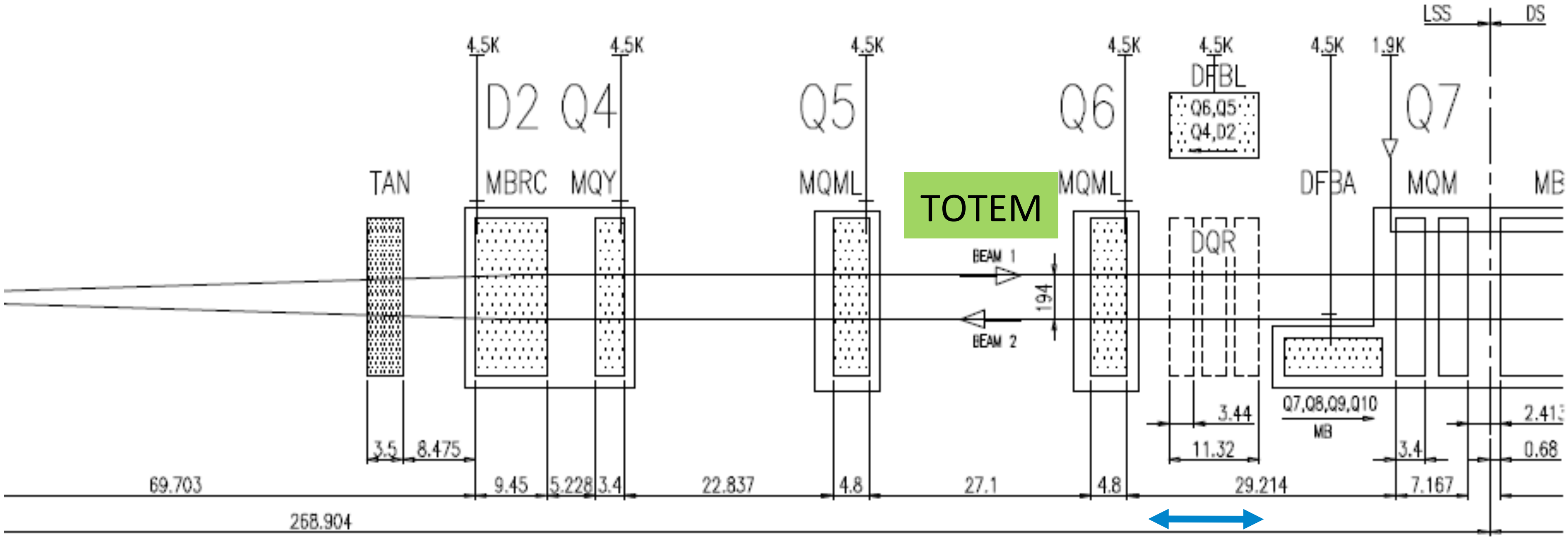
a) `true' distributions; b) distributions smeared due to beam intrinsic p_T; all plots normalized for $p_T^2 < 2\ GeV^2$



p_T gives powerful separation handle provided that size of γγ and pomeron-pomeron cross-sections are not too large…
…unless special high-β running.

Assuming ultimate p_T resolution ≈ 100 MeV; i.e. neglecting detector effects

LHC beam-line close to 240 m



TOTEM

Available space of ~12 m!

From Detlef:

- Space above quench resistors (QRs) is not reserved yet
- Space between QR and beam pipe ~ 25 cm, and space between QRs ~ 50 cm
- No problem of heat load

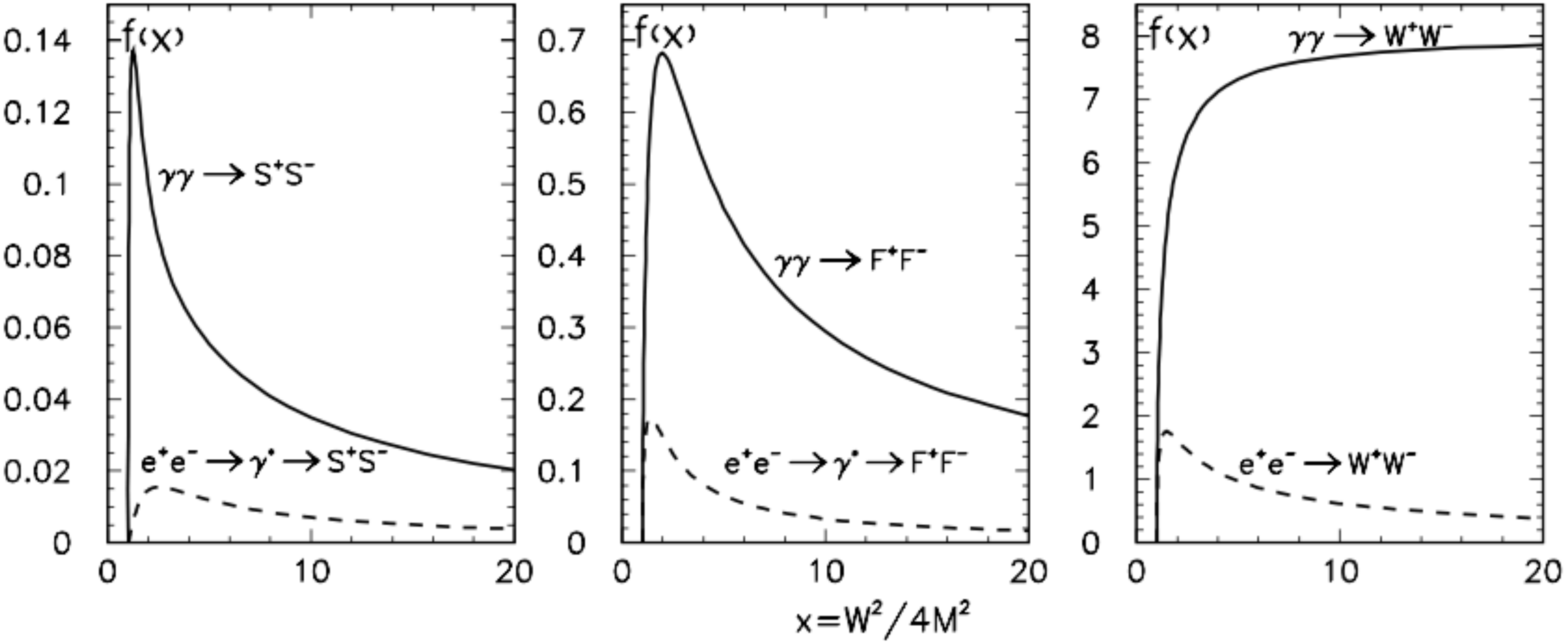


Figure 1.1.3: *Comparison between cross sections for charged pair production in unpolarised* e^+e^- *and* $\gamma\gamma$ *collisions. S (scalars), F (fermions), W (W bosons);* $\sigma = (\pi\alpha^2/M^2)f(x)$, *M is the particle mass, W is the invariant mass (c.m.s. energy of colliding beams),* $f(x)$ *are shown. Contribution of Z boson for production of S and F in* e^+e^- *collisions was not taken into account, it is less than 10%*

AQGCs

- The anomalous couplings in the $\gamma\gamma \rightarrow W^+W^-$, can be introduced with the following effective Lagrangians
- Local $\mathrm{U(1)}_{\mathrm{em}}$ and global $\mathrm{SU(2)}_{\mathrm{c}}$ invariance imposed; these are genuine quartic couplings independent of the gauge ones (a la LEP):

$$L_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W_\alpha^- - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W_\beta^- - W^{-\alpha}W_\beta^+) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

- Where Λ is the scale for new physics, which is set in this analysis to 500 GeV

EPA and absorption corrections

EPA assumes **full** factorization of the long range (-> photon fluxes) and short range (-> $\gamma\gamma$ fusion) physics; values of the impact parameter b are the best check of a regime one works with – they are different for the proton elastic and dissociative cases, though the flux **b** dependence is similar, $dn \propto bdb$.

If one takes the 8 TeV beam and x=0.01 (corresponding to W=160 GeV) than:

Elastic: $b_{max} \approx 20$ fm and $b_{min} \approx 0.6$ fm

Inelastic (dissociative): typ. $b_{max} \approx 0.1$ fm and $b_{min} \approx 0.01$ fm

For two-photon exchange one deals with two impact parameters, so one can approximate $b \approx b_1 + b_2$

EPA and absorption corrections

For two-photon exchange one deals with two impact parameters, hence one can approximate $b \approx b_1 + b_2$

Therefore, relatively small absorption are expected both for fully exclusive (elastic-elastic) as well as single dissociative SD (2x elastic-inelastic) and **BIG** one for DD case (inelastic-inelastic)

Three important comments regarding two-photon lepton pair production:

- Lepton acoplanarity is a good measure of the relevant impact parameters involved; if there is significant absorption it must distort the acoplanarity
- Absorption should increase with increase of W (since b_{max} decreases)
- Fully exclusive pairs die fast with increasing pair pT; so above 1 GeV/c one is left with SD+DD only

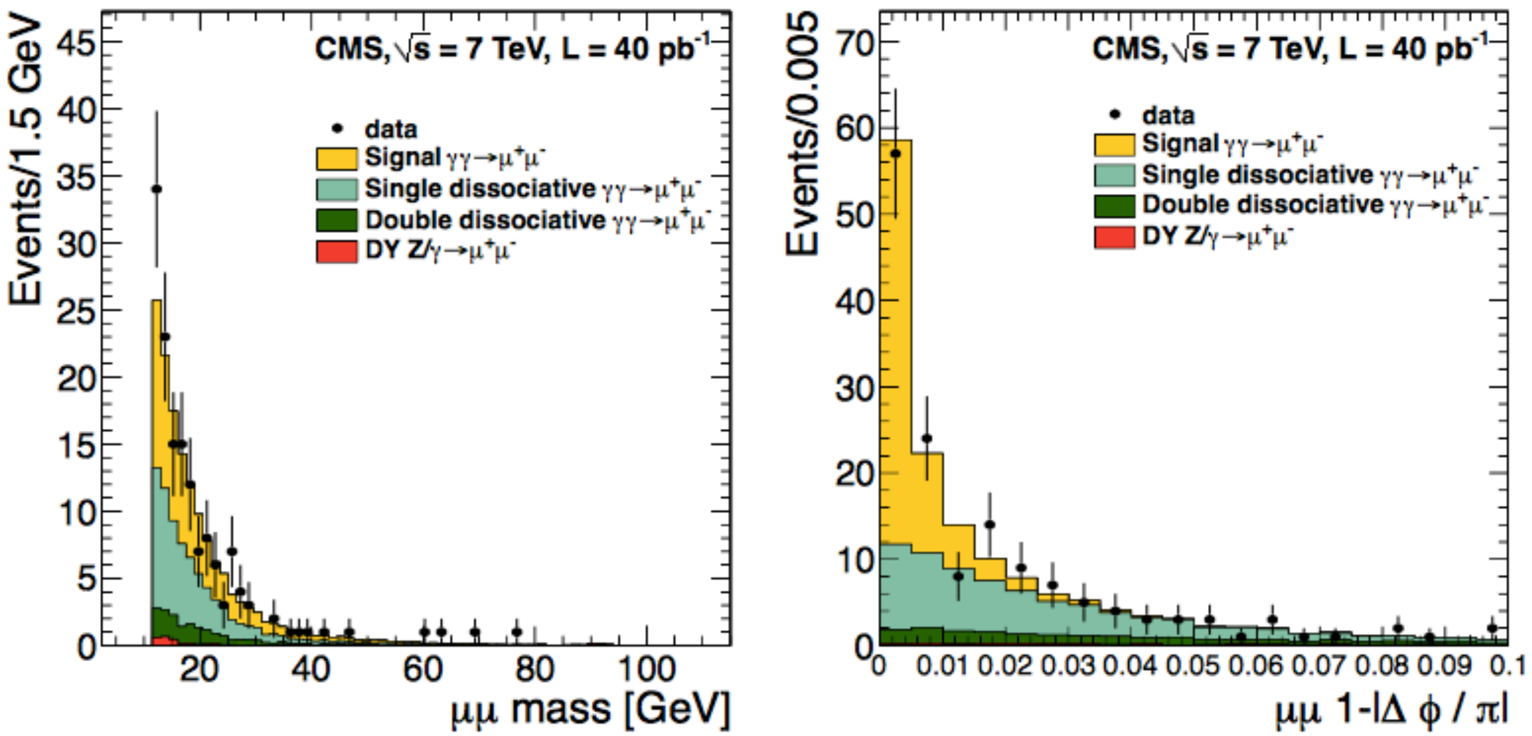


Figure 7: Muon pair invariant mass spectrum (left) and acoplanarity (right), with all selection criteria applied and the simulation normalized to the best-fit value. Data are shown as points with statistical error bars, while the histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red).

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

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

Observe some deficiency but within stat.+syst. errors, without clear hint for absorptive effects in fully exclusive case

EPA and γγ -> WW

Summary for the dilepton (semi-)exclusive production:

No evidence for strong absorption in elastic-elastic production; also above 160 GeV

- LPAIR, which is "mirrored" by EPA calculations, describes well both acoplanarity and invariant mass (W) distributions
- DD seems to be almost completely suppressed! Proper modeling of the DD is essential for further detailed studies of the absorptive corrections.

SOLUTION for getting a proper γγ-> WW from pp –> pWWp(*) as proposed and applied by CMS (and followed recently by ATLAS):

This is a data-driven F factor (in 2011) which "automatically" takes into account the absorptive effects:

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

$$F = 3.23 \pm 0.53.$$

The basic assumption there (backed by the data) is that the absorptive corrections are NOT strongly changing with W

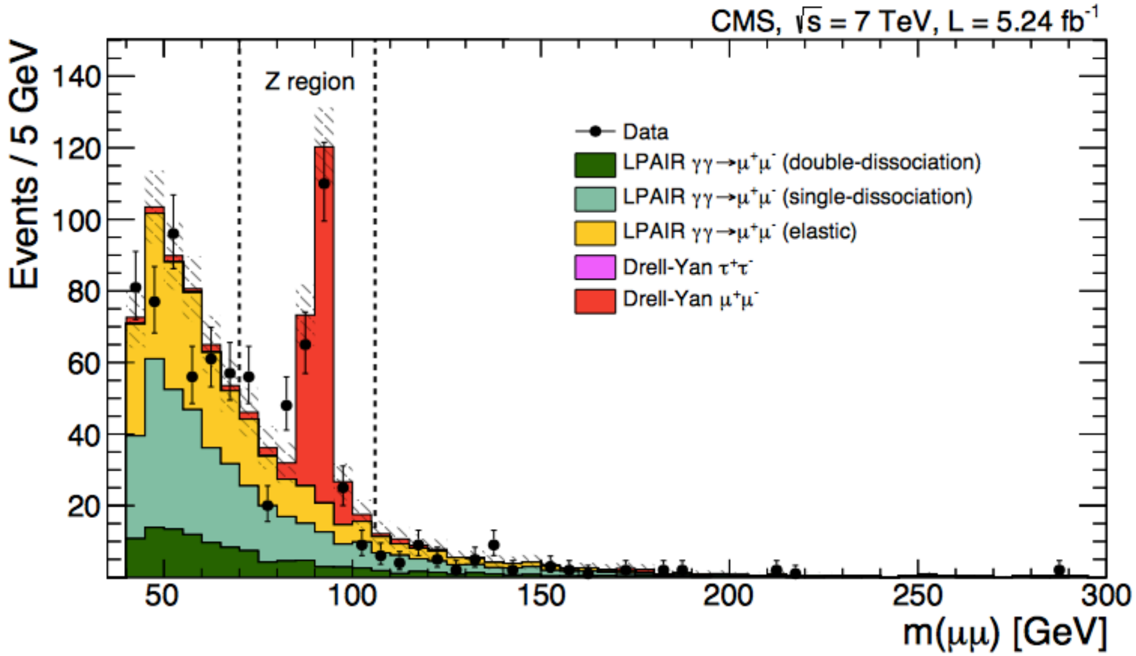


Figure 3: Invariant mass distribution of the muon pairs for the elastic selection with no additional track on the dimuon vertex. The dashed lines indicate the Z-peak region. The hatched bands indicate the statistical uncertainty in the simulation.

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

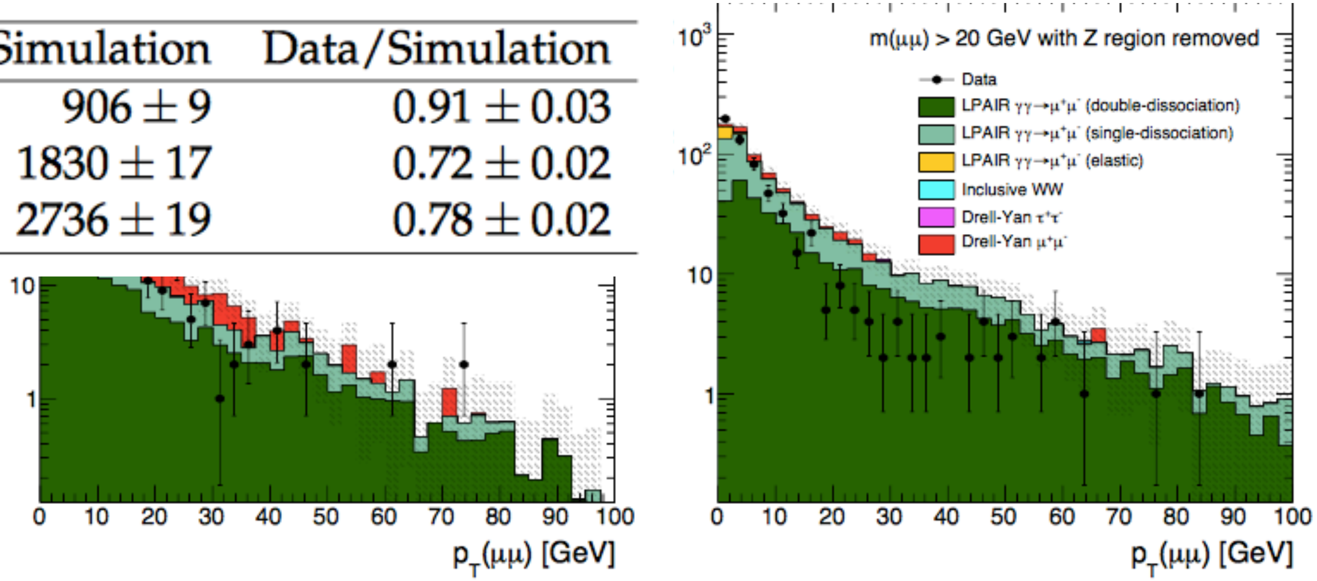


Figure 6: Transverse momentum distribution for $\mu^+\mu^-$ pairs with zero extra tracks passing the dissociation selection, for the Z region only (left), and with the Z region removed (right). The hatched bands

8 TeV update

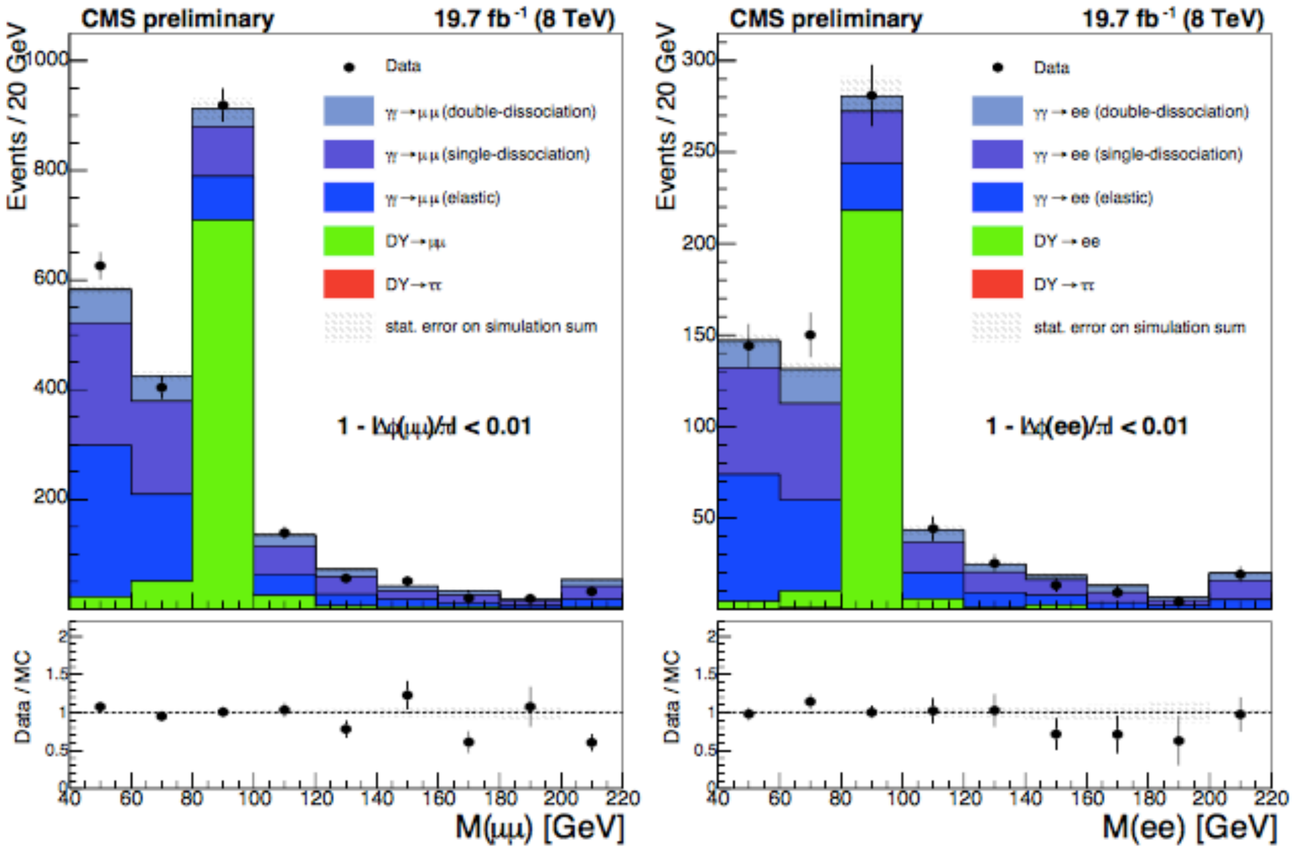


Figure 3: The dilepton invariant mass for the $\mu^+\mu^-$ (left) and e^+e^- (right) final states in the elastic $\gamma\gamma \to \ell^+\ell^-$ control region. The exclusive simulation is scaled to the number of events in data for $m(\ell^+\ell^-) < 70$ GeV or $m(\ell^+\ell^-) > 106$ GeV. The Drell-Yan simulation is scaled to the number of events in data for $m(\ell^+\ell^-) > 70$ GeV or $m(\ell^+\ell^-) < 106$ GeV The last bin in both plots is an overflow bin and includes all events with invariant mass greater than 220 GeV.

8 TeV update

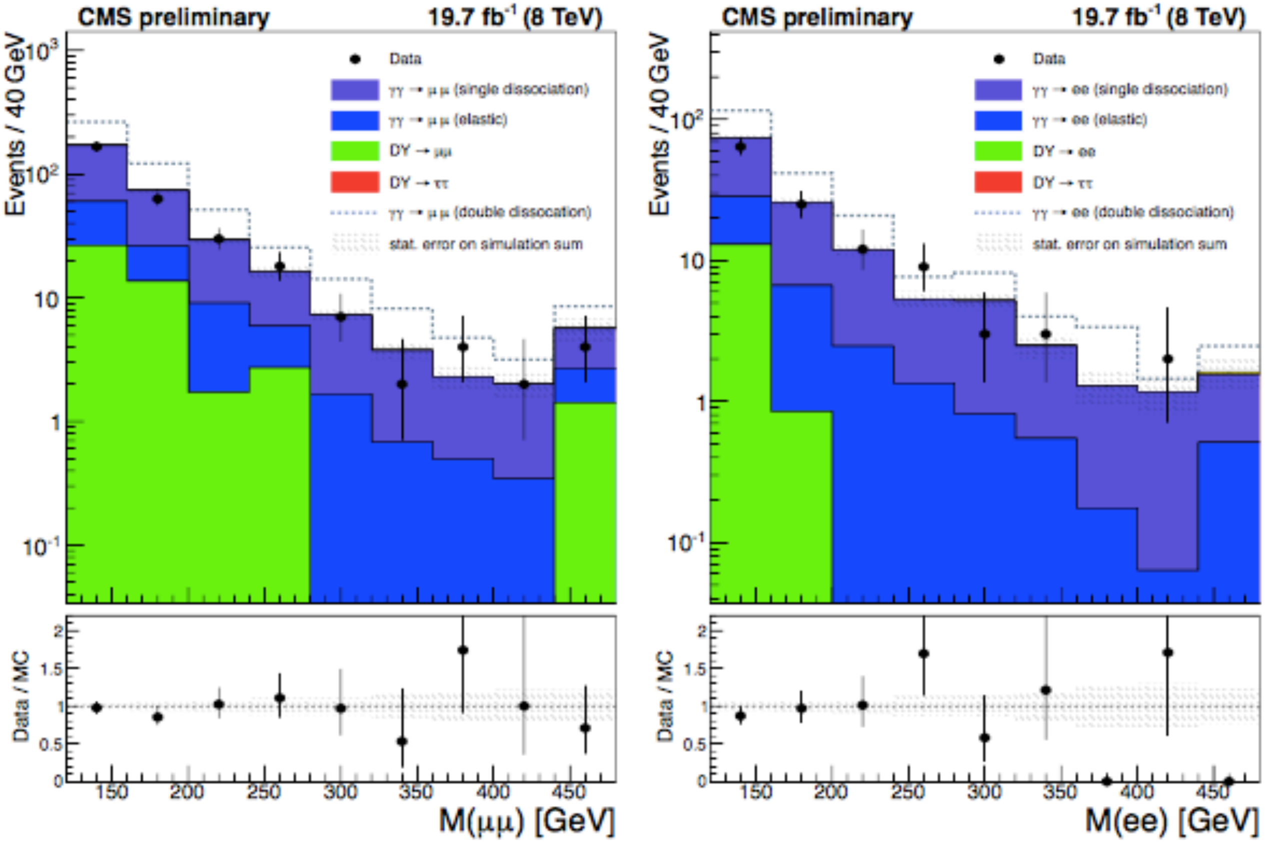


Figure 4: The dilepton invariant mass for the $\mu^+\mu^-$ (left) and e^+e^- (right) final states in the $\gamma\gamma \to \ell^+\ell^-$ proton dissociation control region with 0 additional tracks associated to the dilepton vertex. The efficiency correction has been applied to the exclusive samples. The double-dissociation contribution in the simulation is much too large because of rescattering effects. Therefore, the double-dissociation contribution is not included in the ratio plot and is shown as the blue dotted line on top of the sum of the simulation. The region $m(\ell^+\ell^-) > 160$ GeV is used to obtain the proton dissociation contribution. The last bin is an overflow bin and includes all events above 480 GeV.

EPA and γγ -> WW

The basic assumption there (backed by the data) is that the absorptive effects are NOT changing fast; in practice, it was tested by calculating F factor for increased threshold values, above 160 GeV – up to about 400 GeV we see no clear trend, just (rather small) statistical fluctuations which have been included into systematic errors

BOTTOM LINE:

The γγ -> WW cross-sections measured (correctly) by CMS have no bias due to (not well known) absorption and the corresponding uncertainties of our data-driven procedure of extracting the proper γγ -> WW are included in syst. errors.