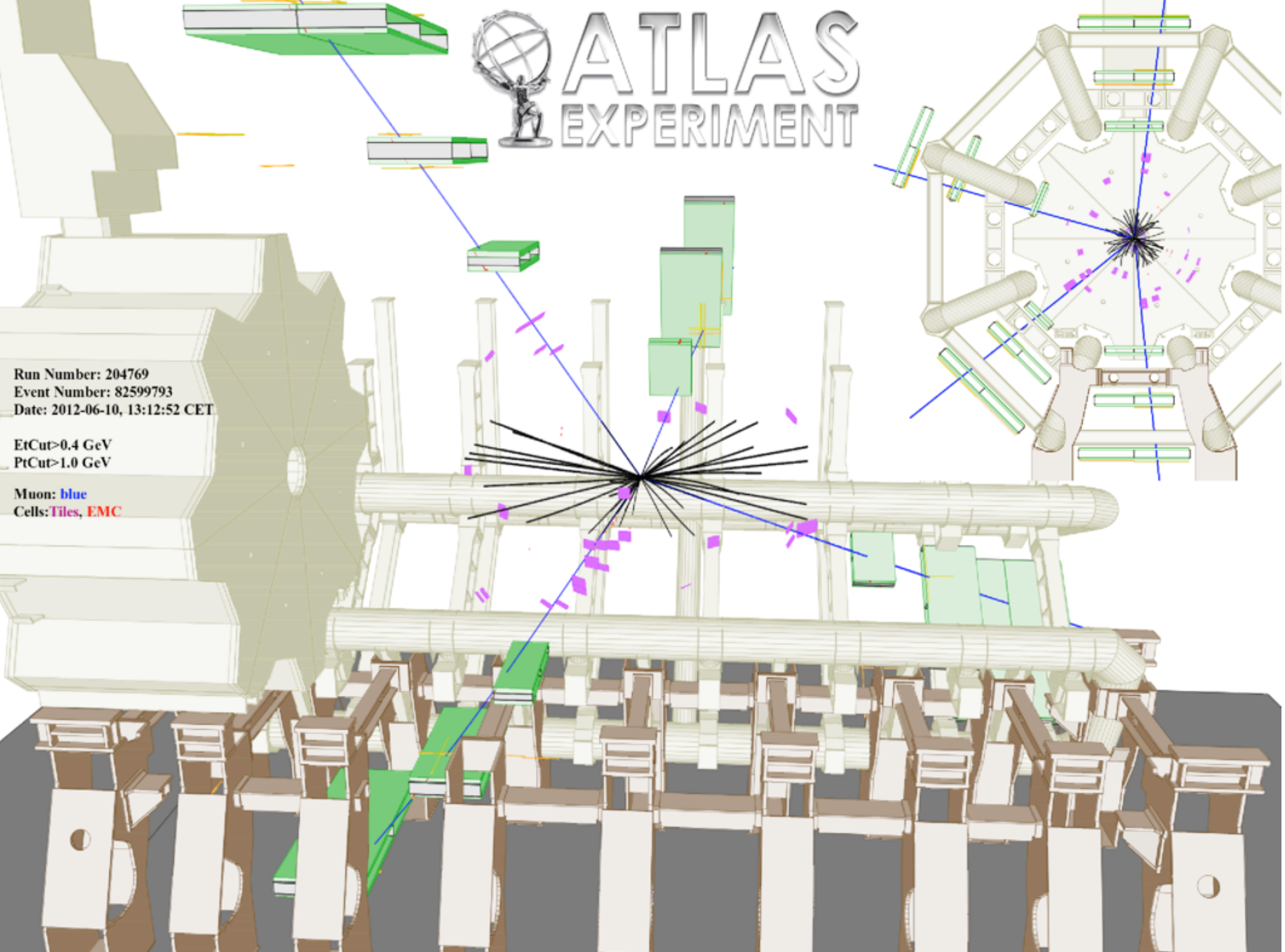

Vector boson scattering from an experimental perspective

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HiggsTools Summer School on Higgs Physics
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Introduction

The non-abelian gauge nature of the standard model predicts the existence of:
- trilinear couplings (TGC)
- quartic couplings (QGC)

Trilinear and quartic couplings can probe different aspects:
- TGC: Non-abelian gauge structure of the SM
- QGC: Mechanism of spontaneous symmetry breaking

[By assuming unitarity combined with the precisely known weak boson coupling to leptons, one is led to the gauge value for TGCs. This does not extend to QGC in massive non-abelian theories.]

The SM Higgs boson is the most economic solution to restore unitarity
We found a Higgs boson: is it fully or partially responsible for EWSB?
Determine EWSB dynamics and look for new physics.

[e.g. heavy scalar singlet interacting strongly with the Higgs sector, may evade the current constraints and still induce a stronger WWWW vertex than in the SM]

In the QGC studies, one tries to constrain “genuine” quartic couplings, i.e. operators that not contribute in TGCs and are thus constrained.

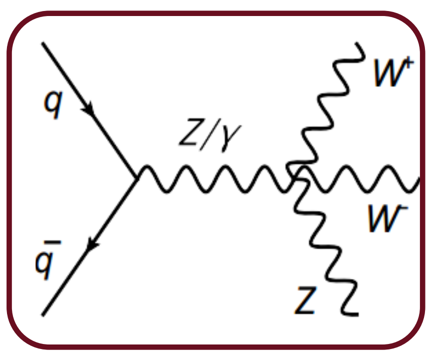
Introduction

QGC process → a process where QGC diagrams contribute
→ No reaction is mediated solely by a QGC vertex
→ Gauge invariant definition of the QGC contribution is not possible

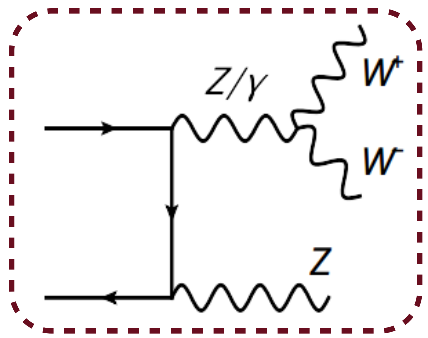
Only makes sense to study the whole electro-weak production!
(including interference)

Two classes of QGC processes are measurable

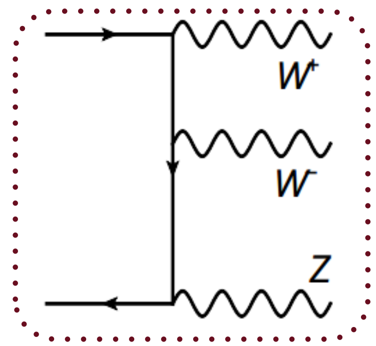
Triple vector boson production



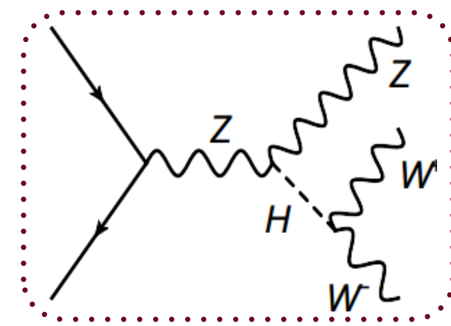
QGC



TGC

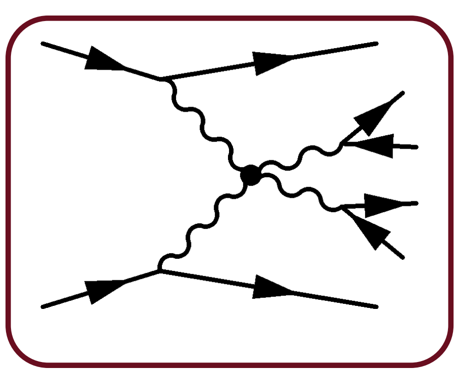


fermion-mediated

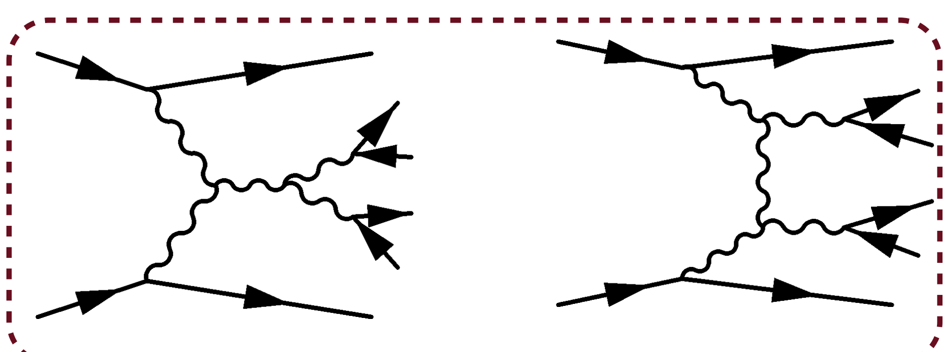


Higgs-mediated

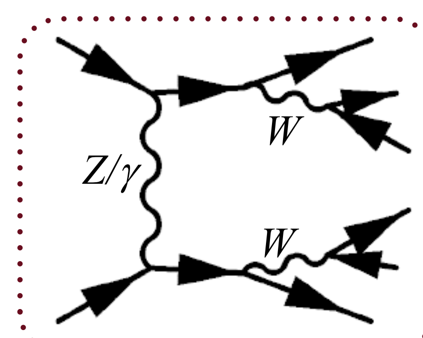
Vector boson scattering/fusion
(VBS/VBF)



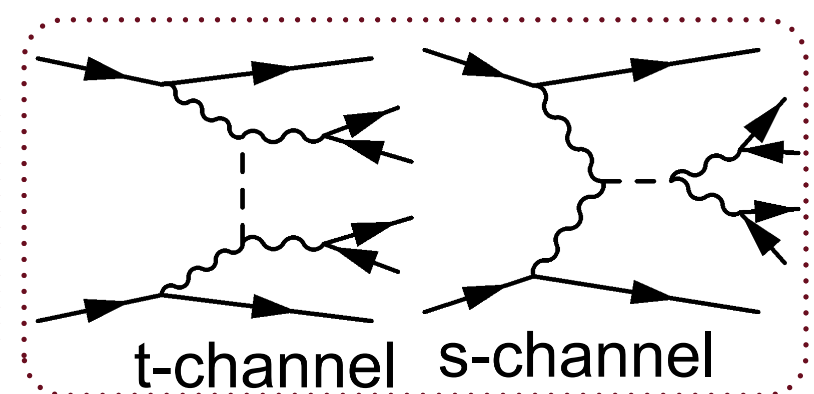
QGC



TGC



fermion-mediated

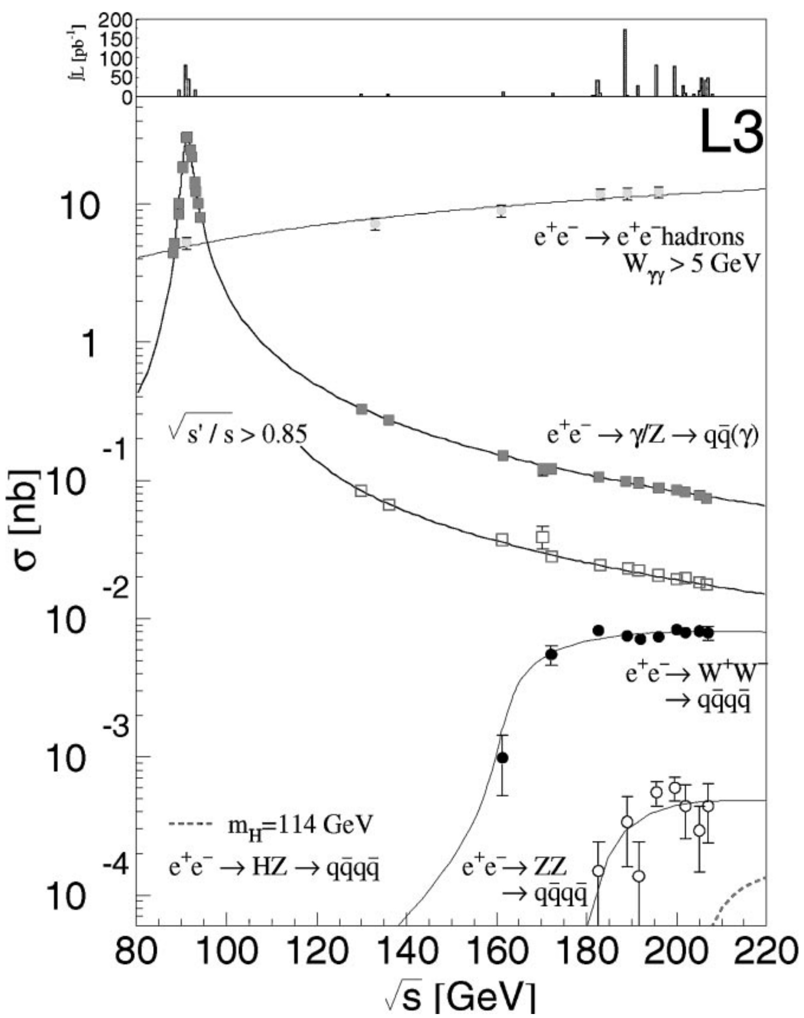


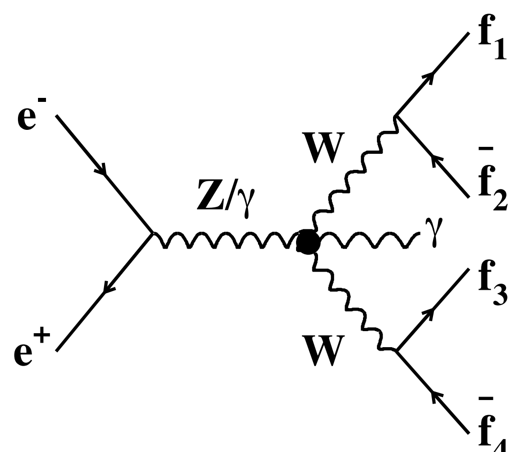
Higgs-mediated

anomalous QGC at LEP

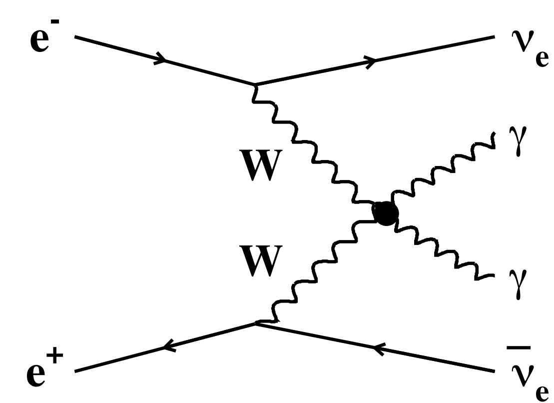
The previous resident of the "LHC" tunnel, hosted:
ALEPH, DELPHI, L3 and OPAL.
Operation 1989-2000
A different experimental environment wrt hadron colliders

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	I_{tot} (mA)	$\mathcal{L}$ 10^{30}cm^{-2}s^{-1}	
1989	1.74	45.6	4	2.6	4.3	LEP 1
1990	8.6	45.6	4	3.6	7	LEP 1
1991	18.9	45.6	4	3.7	10	LEP 1
1992	28.6	45.6	4/8	5.0	11.5	LEP 1
1993	40.0	45.6	8	5.5	19	LEP 1
1994	64.5	45.6	8	5.5	23.1	LEP 1
1995	46.1	45.6	8/12	8.4	34.1	LEP 2
1996	24.7	80.5 - 86	4	4.2	35.6	LEP 2
1997	73.4	90 - 92	4	5.2	47.0	LEP 2
1998	199.7	94.5	4	6.1	100	LEP 2
1999	253	98 - 101	4	6.2	100	LEP 2
2000	233.4	102 - 104	4	5.2	60	LEP 2

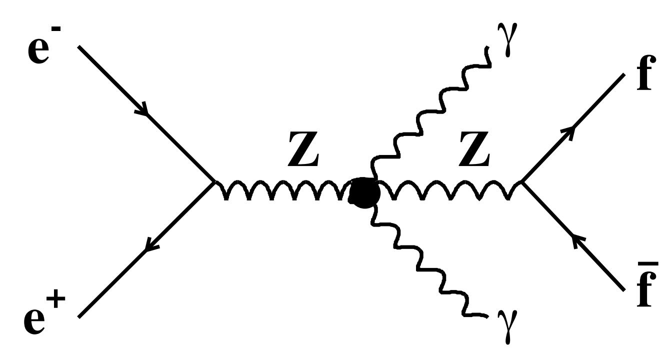




qq(eν,μν,τν)γ/qqqqγ



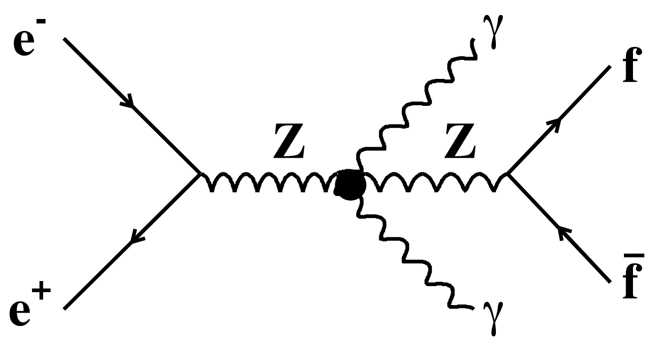
ννγγ



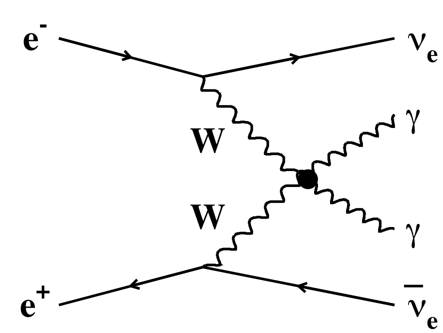
qqγγ

However SM QGC contributions at LEP very small
→ Looking for aQGC

anomalous QGC at LEP

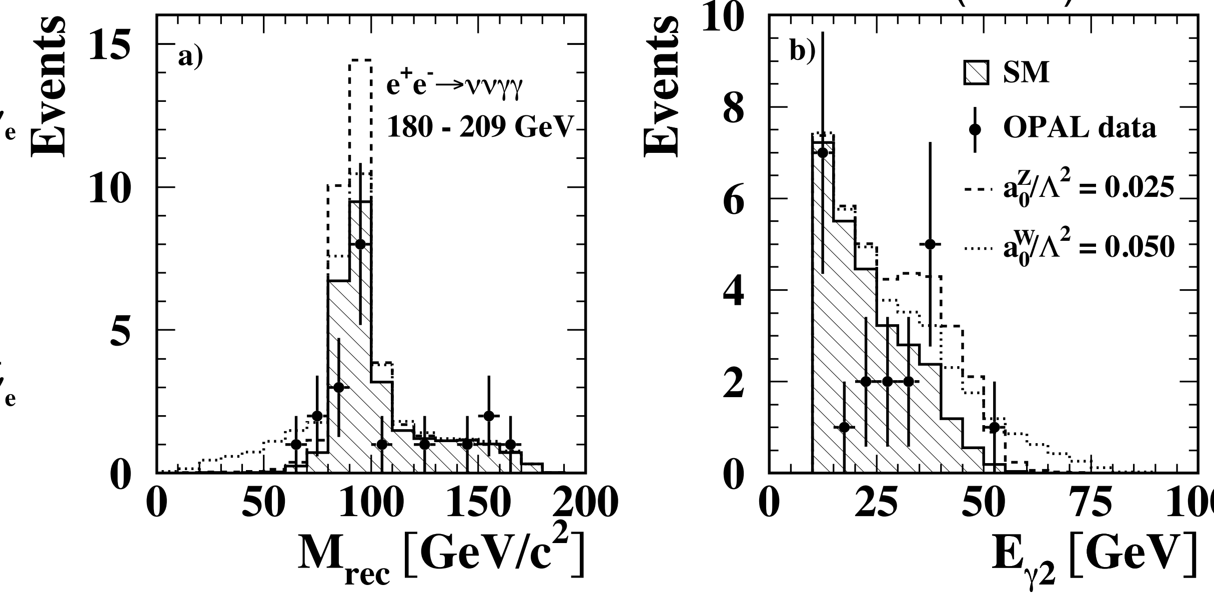


qqγγ

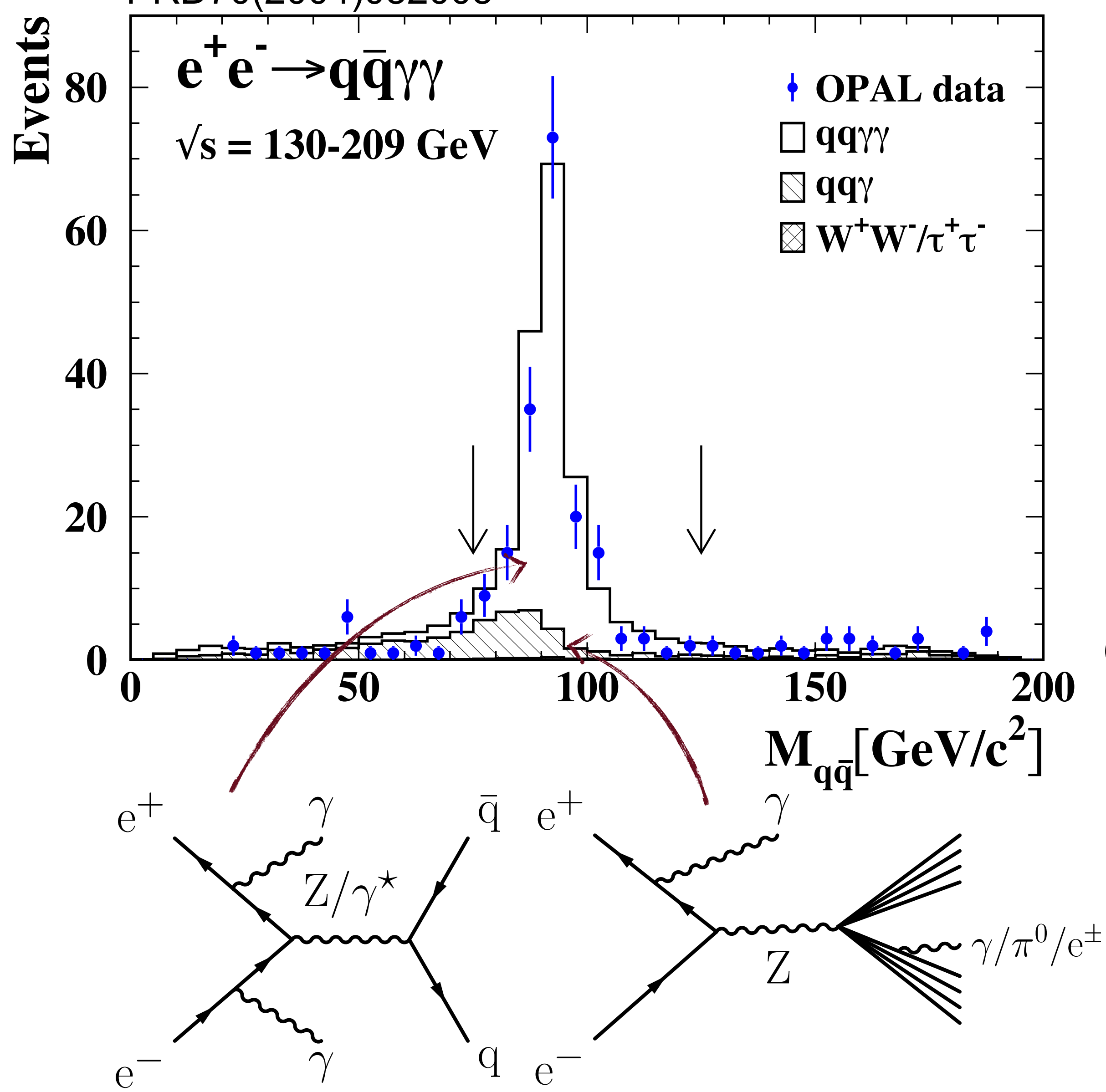


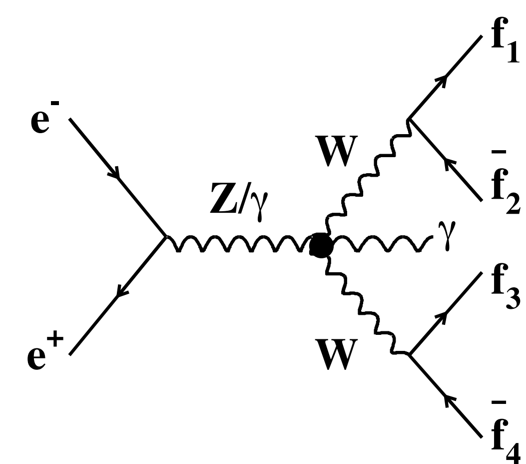
ννγγ

PRD70(2004)032005



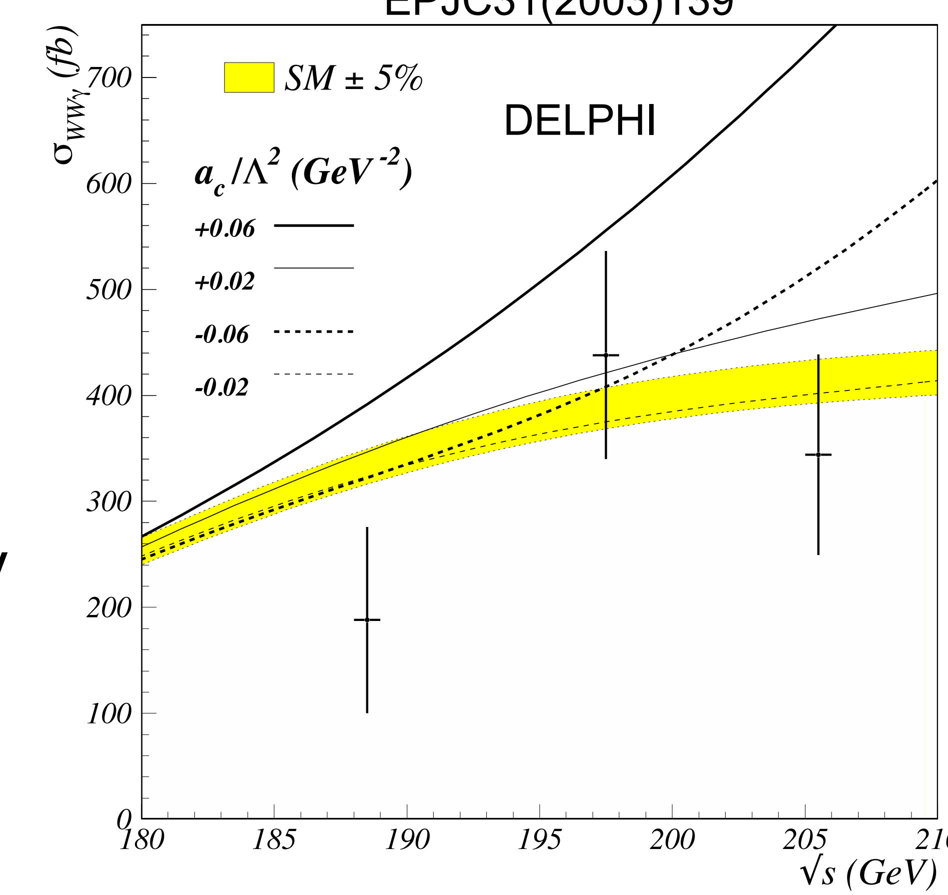
PRD70(2004)032005





qq(eν,μν,τν)γ/qqqqγ

EPJC31(2003)139



Data are found consistent with the SM expectations (contributions from ISR/FSR)

aQGC at LEP

The parametrization of aTGC started by imposing the custodial global SU(2) (to keep ρ-parameter near 1) and $U(1)_{em}$ for the operators involving photons. (symmetry non-linearly realized)

There are two dim-4 operators giving interactions:
- WWWW α_4 parameter (not possible through tri-boson production at e^+e^-)
- WWZZ α_5 parameter (WWZ production - limited by available phase-space at LEP)
- ZZZZ (not present in SM - limited by available phase-space at LEP)

The following dim-6 operators involving at least one photon:

$$\mathcal{L}_0 = -\frac{e^2}{16\Lambda^2} a_0 \, F^{\mu\nu} F_{\mu\nu} \overline{\mathbf{W}}_\alpha \overline{\mathbf{W}}^\alpha,$$

C and P-conserving
[can parametrize exchange of heavy neutral scalar]

$$\mathcal{L}_c = -\frac{e^2}{16\Lambda^2} a_c \, F^{\mu\alpha} F_{\mu\beta} \overline{\mathbf{W}}^\beta \overline{\mathbf{W}}_\alpha,$$

C and P-conserving

$$\mathcal{L}_n = -\frac{e^2}{16\Lambda^2} a_n \, \varepsilon_{ijk} F^{\mu\nu} \overline{W}^i_{\mu\alpha} \overline{W}^j_\nu \overline{W}^{k,\alpha},$$

P-conserving

$$\tilde{\mathcal{L}}_0 = -\frac{e^2}{16\Lambda^2} \tilde{a}_0 \, F^{\mu\nu} \tilde{F}_{\mu\nu} \overline{\mathbf{W}}_\alpha \overline{\mathbf{W}}^\alpha,$$

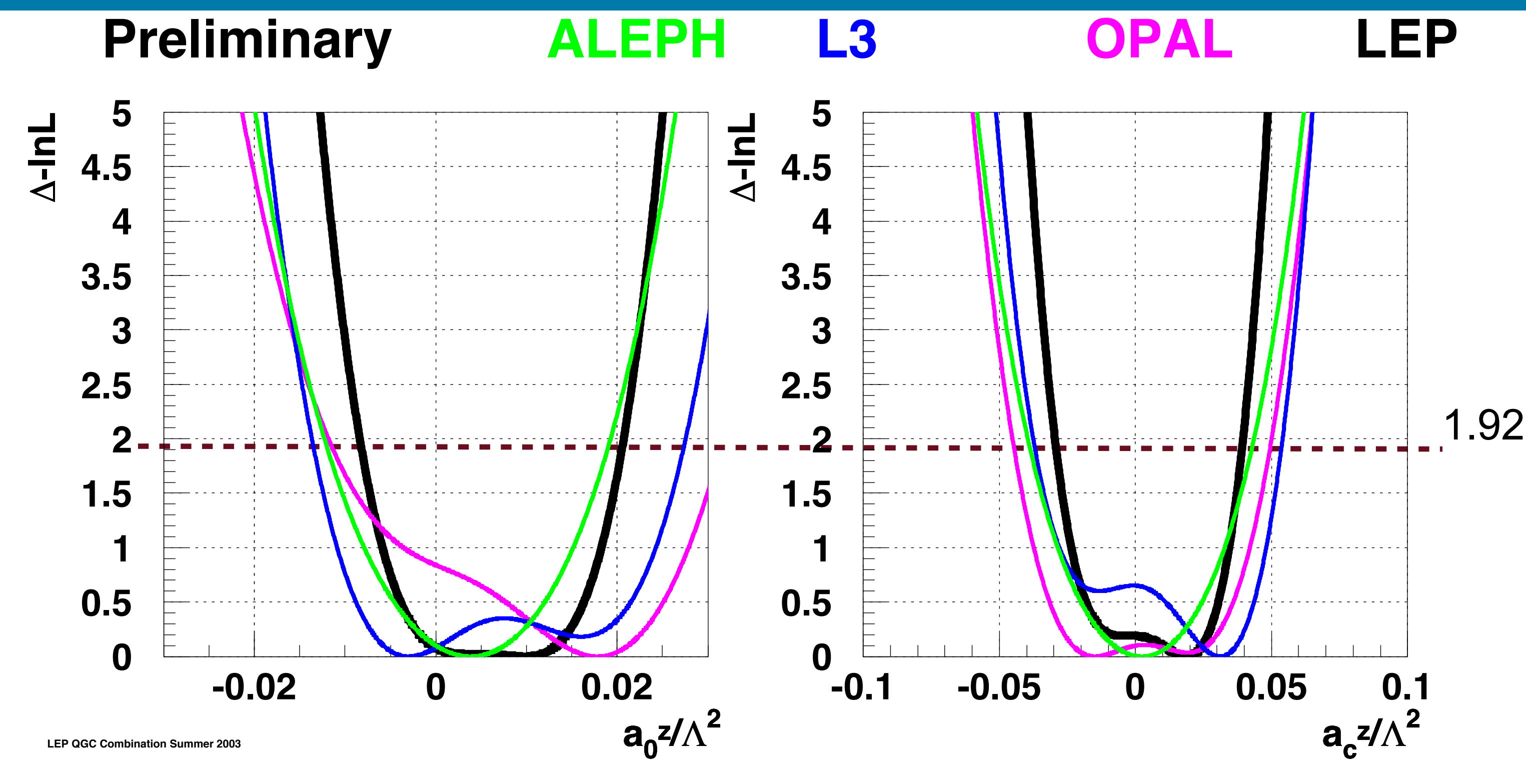
C-conserving

$$\tilde{\mathcal{L}}_n = -\frac{e^2}{16\Lambda^2} \tilde{a}_n \, \varepsilon_{ijk} \tilde{F}^{\mu\nu} \overline{W}^i_{\mu\alpha} \overline{W}^j_\nu \overline{W}^{k,\alpha},$$

CP-conserving but violates both C and P

Scale of New Physics

aQGC at LEP



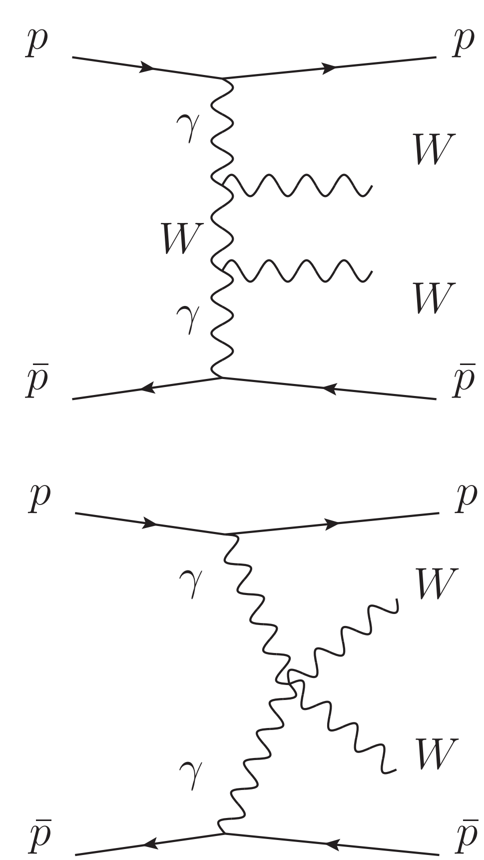
In the combination, couplings associated to WWγγ and ZZγγ vertices are assumed to be different.
Only results for ZZγγ were combined (ννγγ and Zγγ final states)

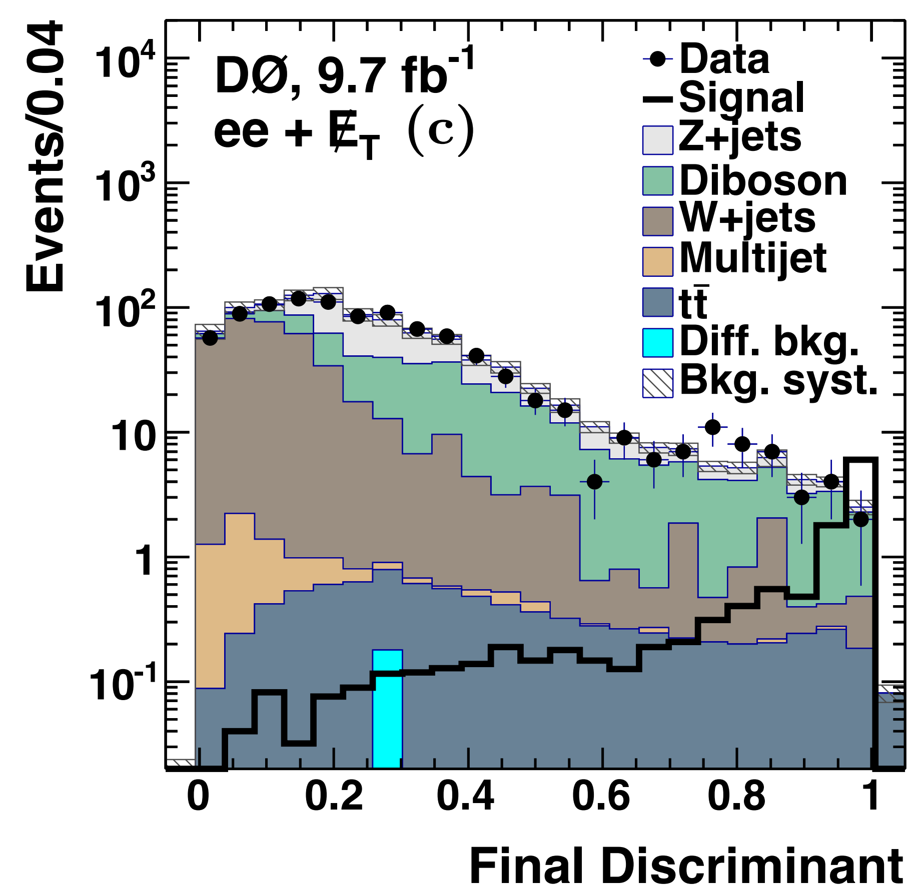
@Tevatron
D0 search for exclusive γγ→WW
To dump cross-section explosion at high-energies;
a form factor is added

$$a_i^W \to \frac{a_i^W}{(1 + M_{\gamma\gamma}^2/\Lambda_{\text{cutoff}}^2)^2},$$

with Λ=500 GeV

$$|a_0^W/\Lambda^2| < 0.0025 \text{ GeV}^{-2} \text{ and } |a_C^W/\Lambda^2| < 0.0092 \text{ GeV}^{-2}$$

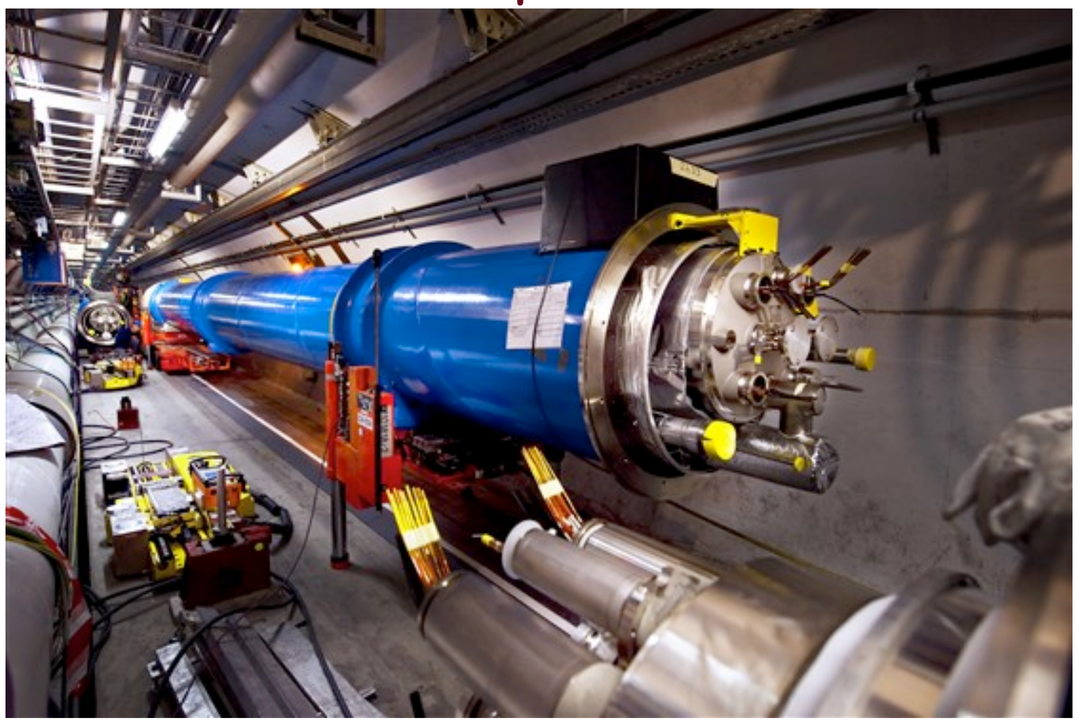




PRD88(2013)012005

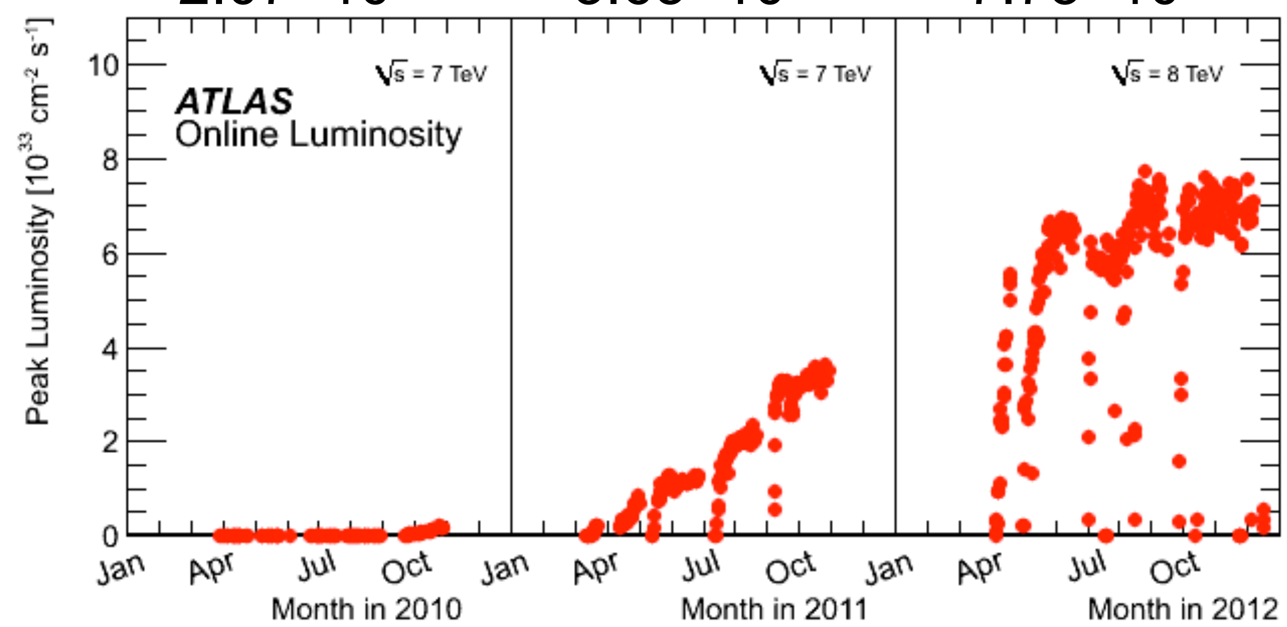
Large Hadron Collider Run I

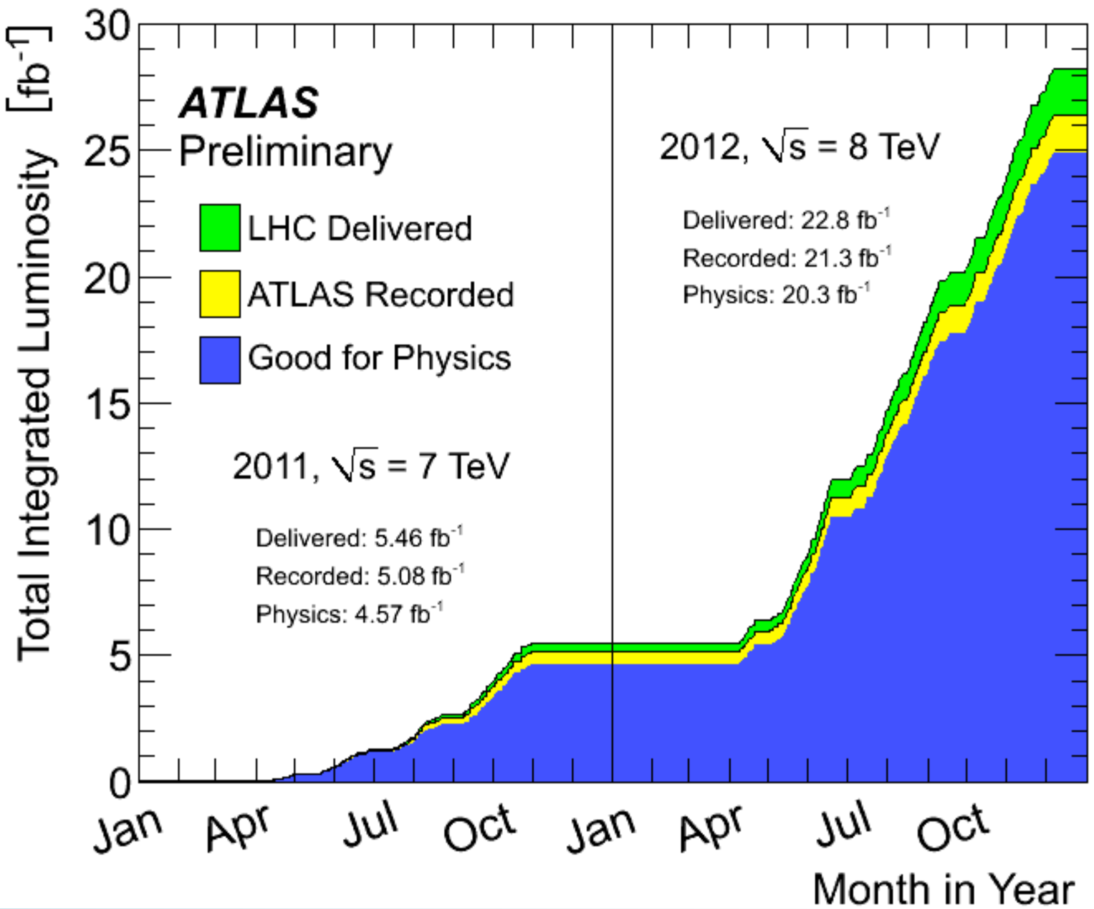
1232 superconducting dipoles with B field of (up to) 8.3T
1.9K → the coolest place in the universe!

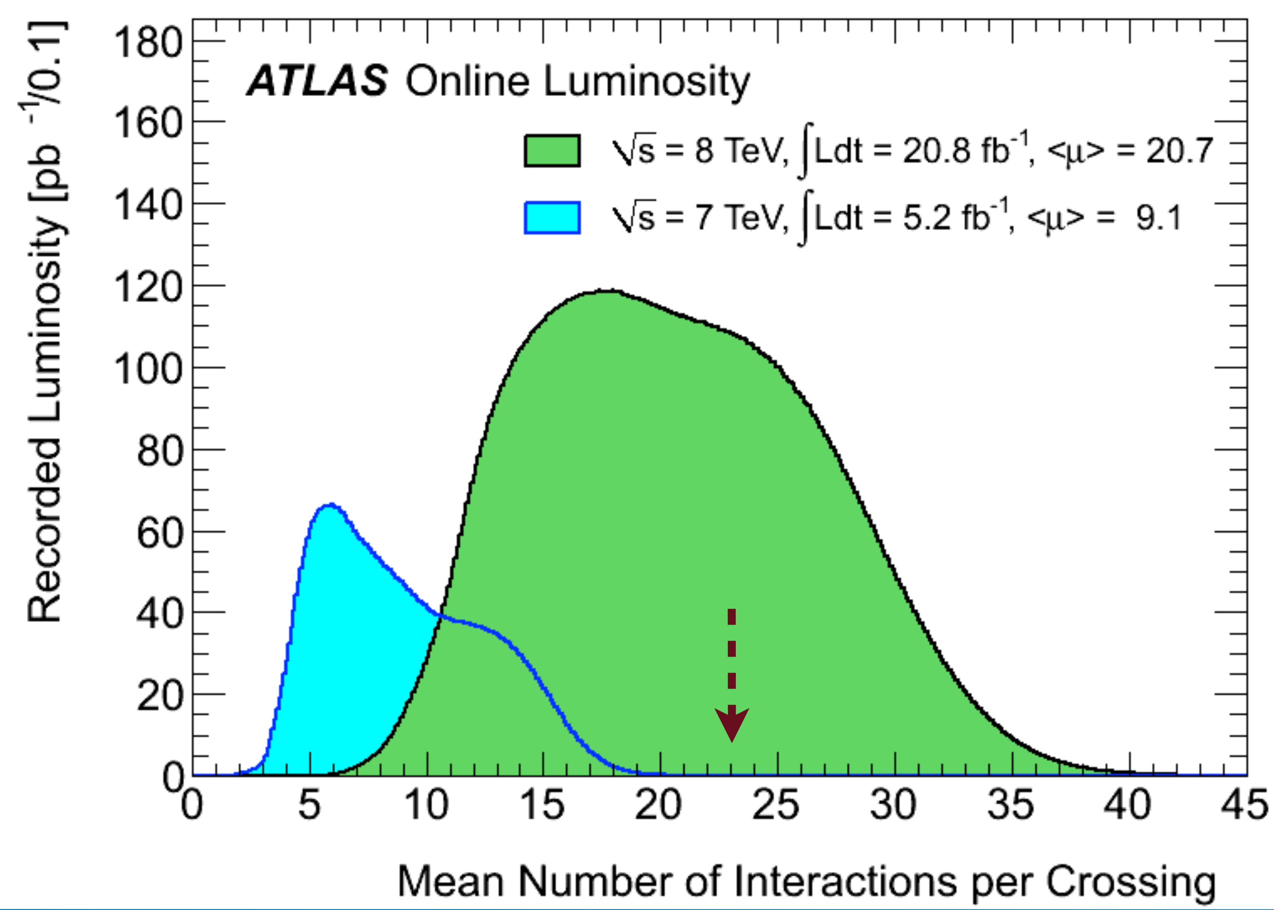


Peak Luminosity [$cm^{-2}s^{-1}$]

2.07×10^{32} 3.65×10^{33} 7.73×10^{33}

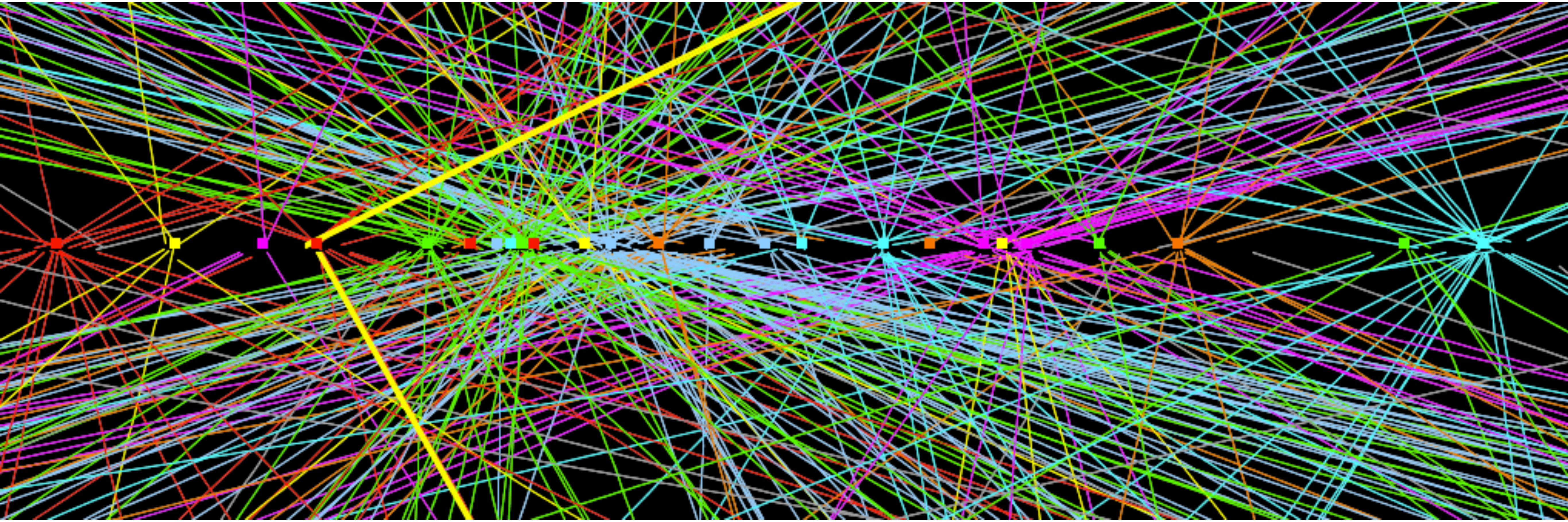






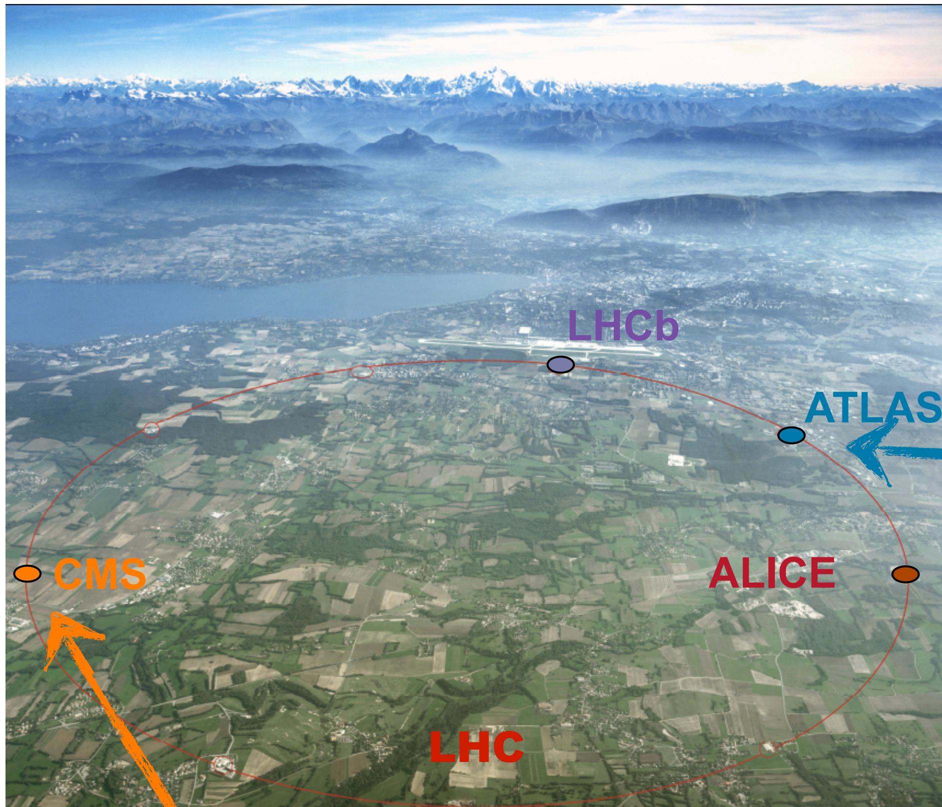
Pile-up

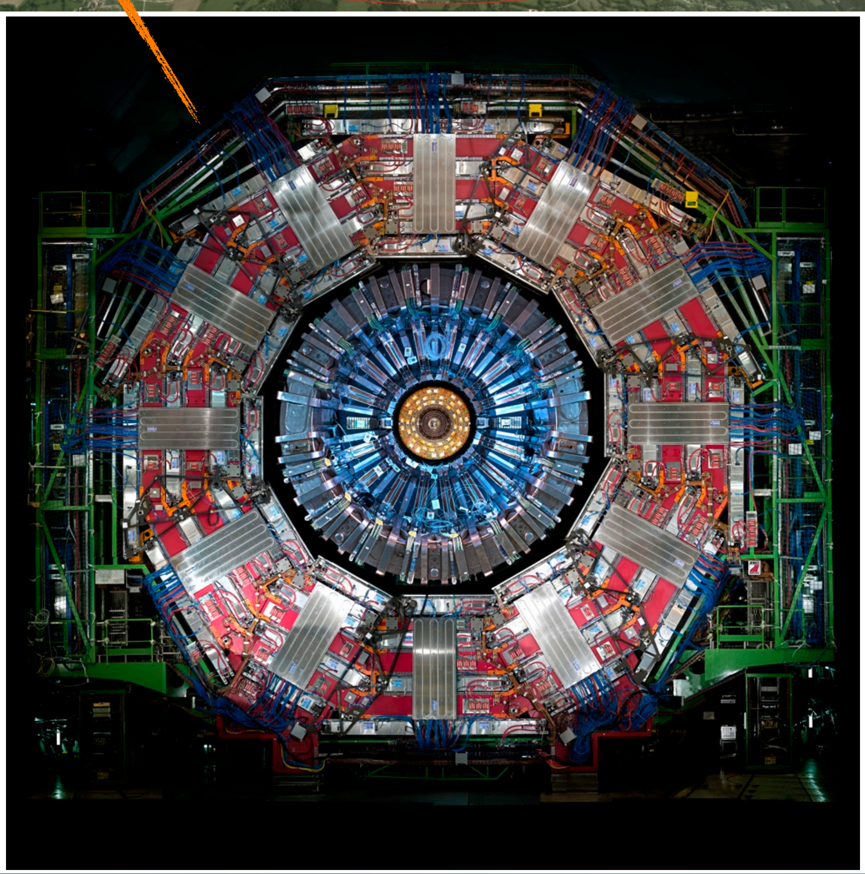
Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown

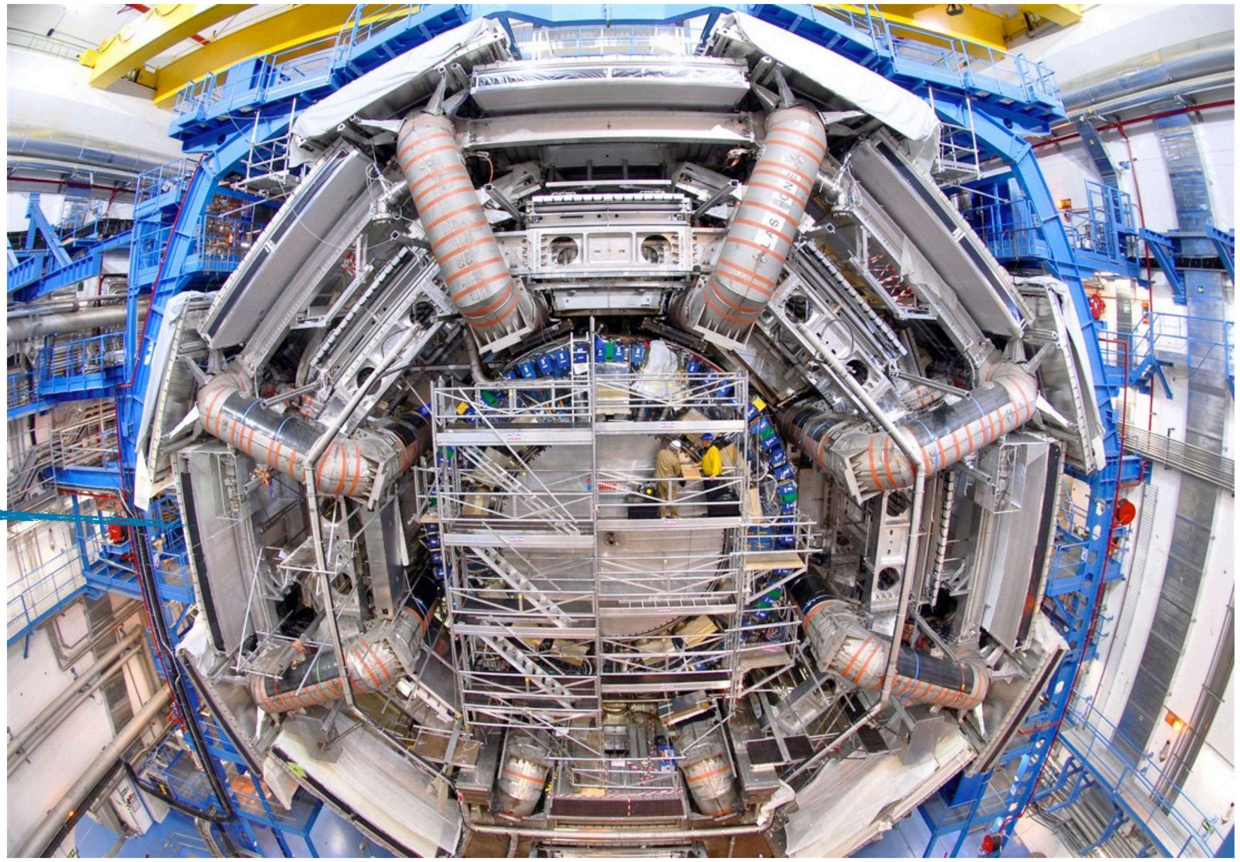


This is just the "in-time" pile-up
Need to account also for the "out-of-time" pile-up
[due to interaction in earlier and later bunch-crossings]

The LHC experiments

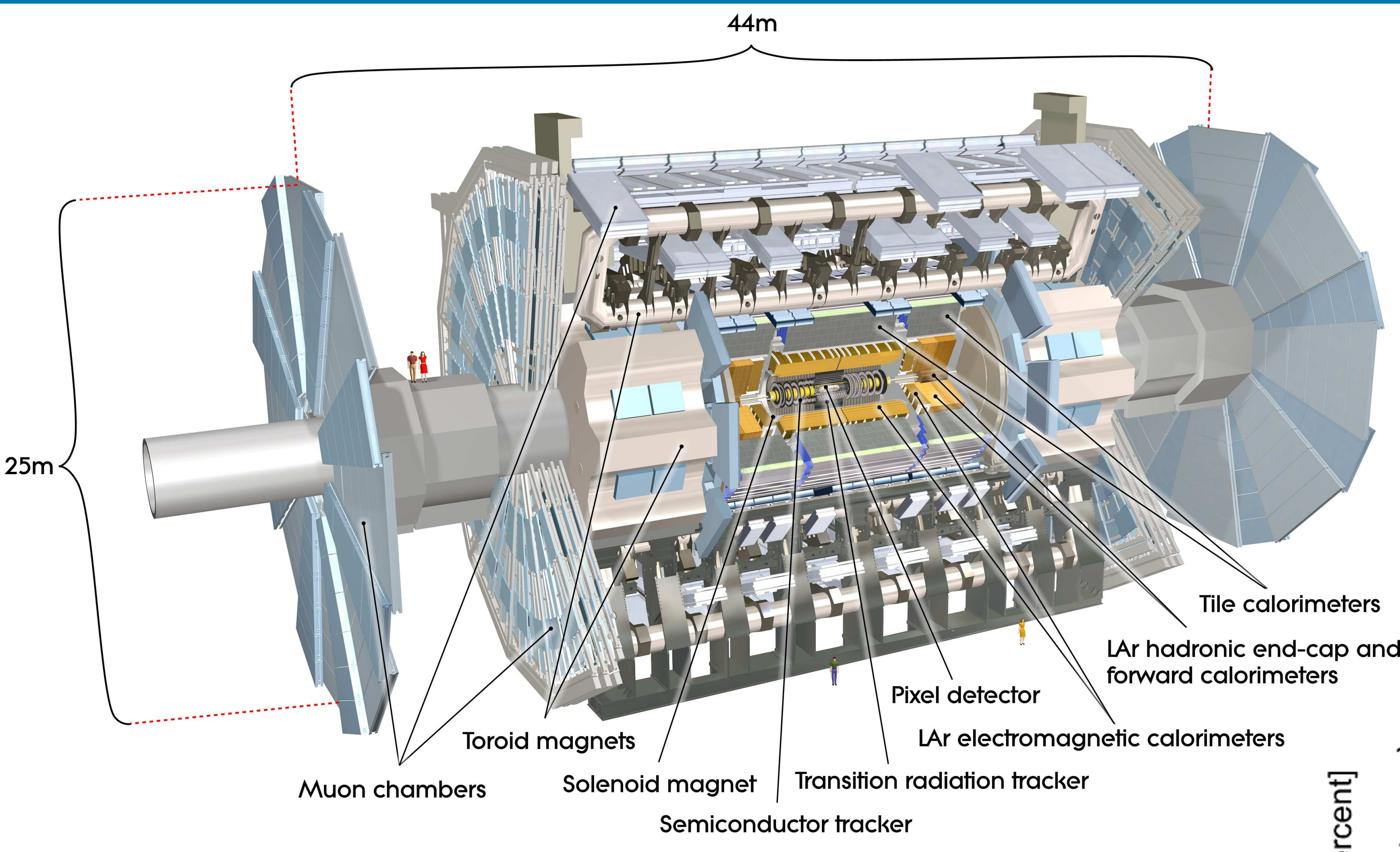






ATLAS Collaboration: 38 countries, 177 institutions, ~2900 scientific authors

A Toroidal LHC ApparatuS



	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

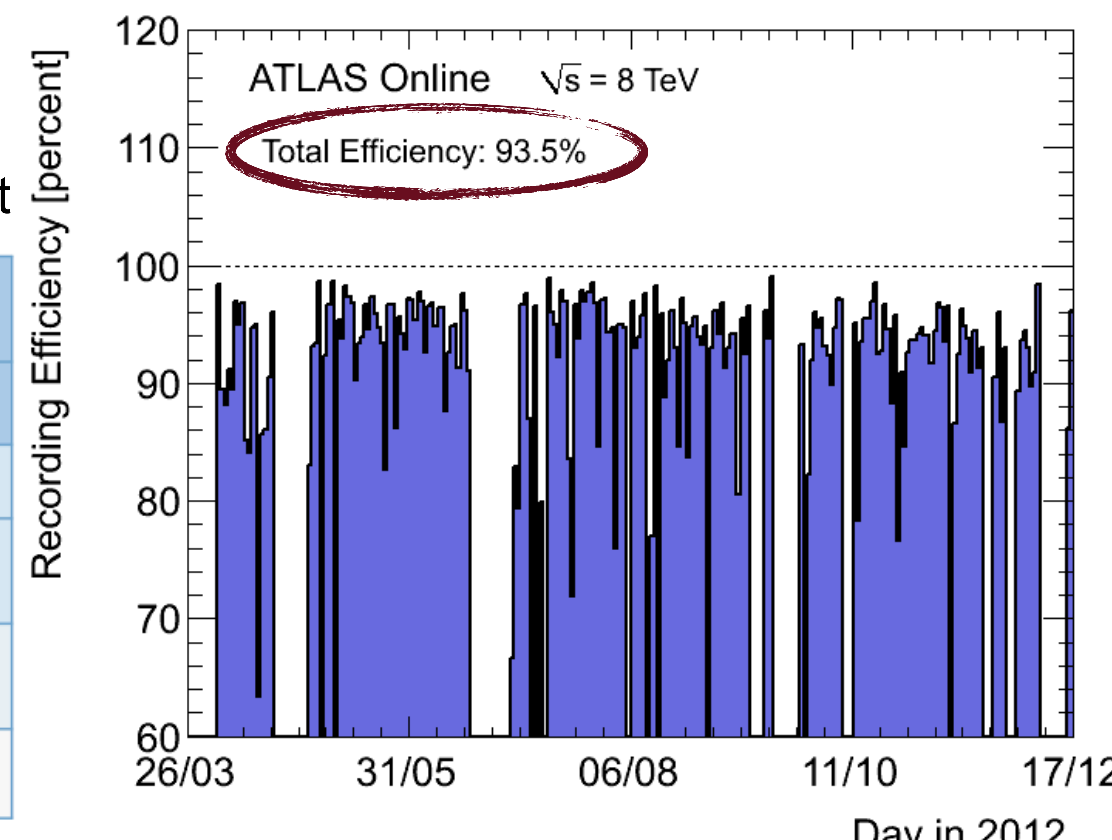
⇒ General purpose detector designed for the harsh LHC environment

ATLAS p-p run: April-December 2012

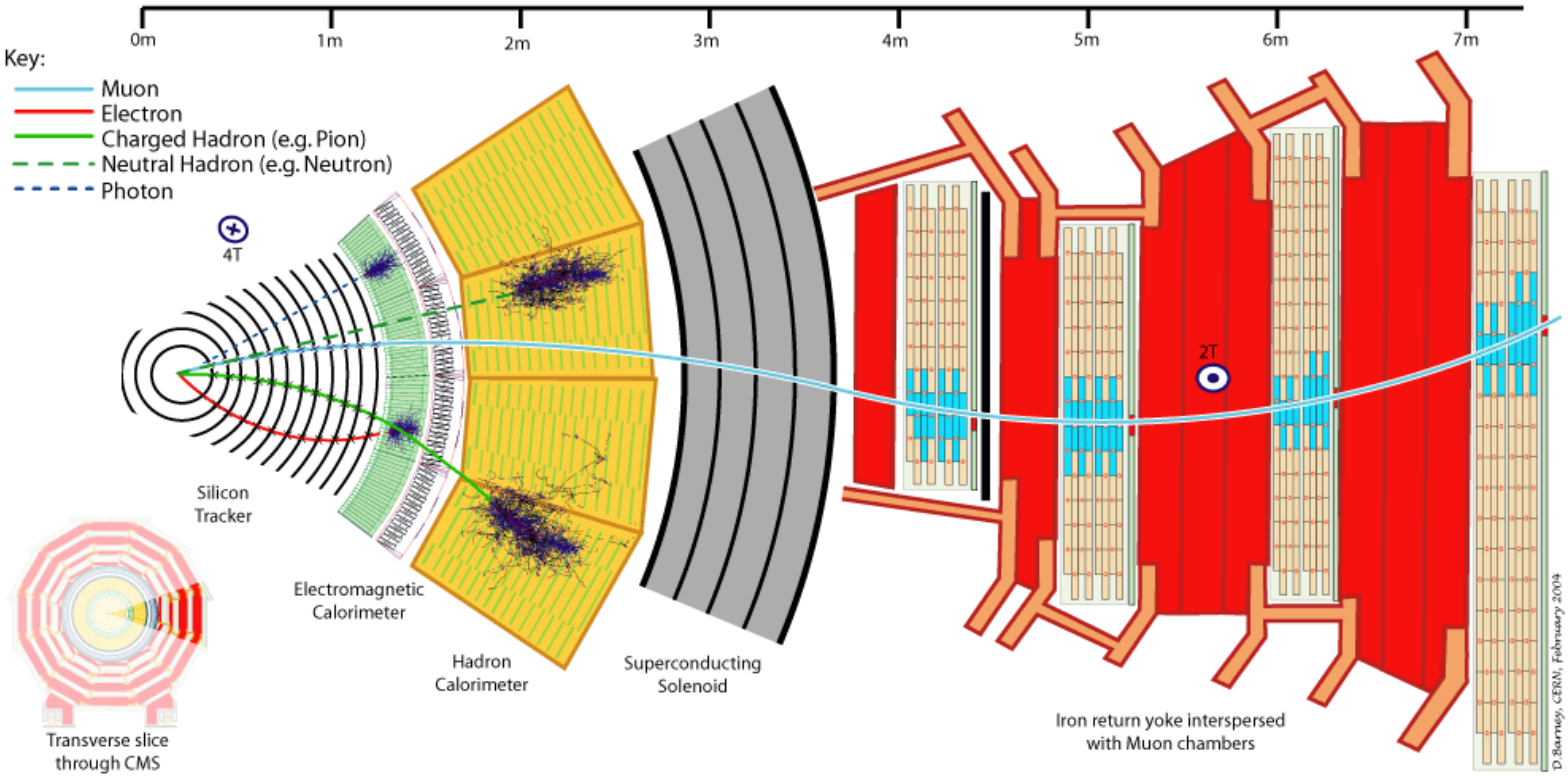
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

All good for physics: 95.8%

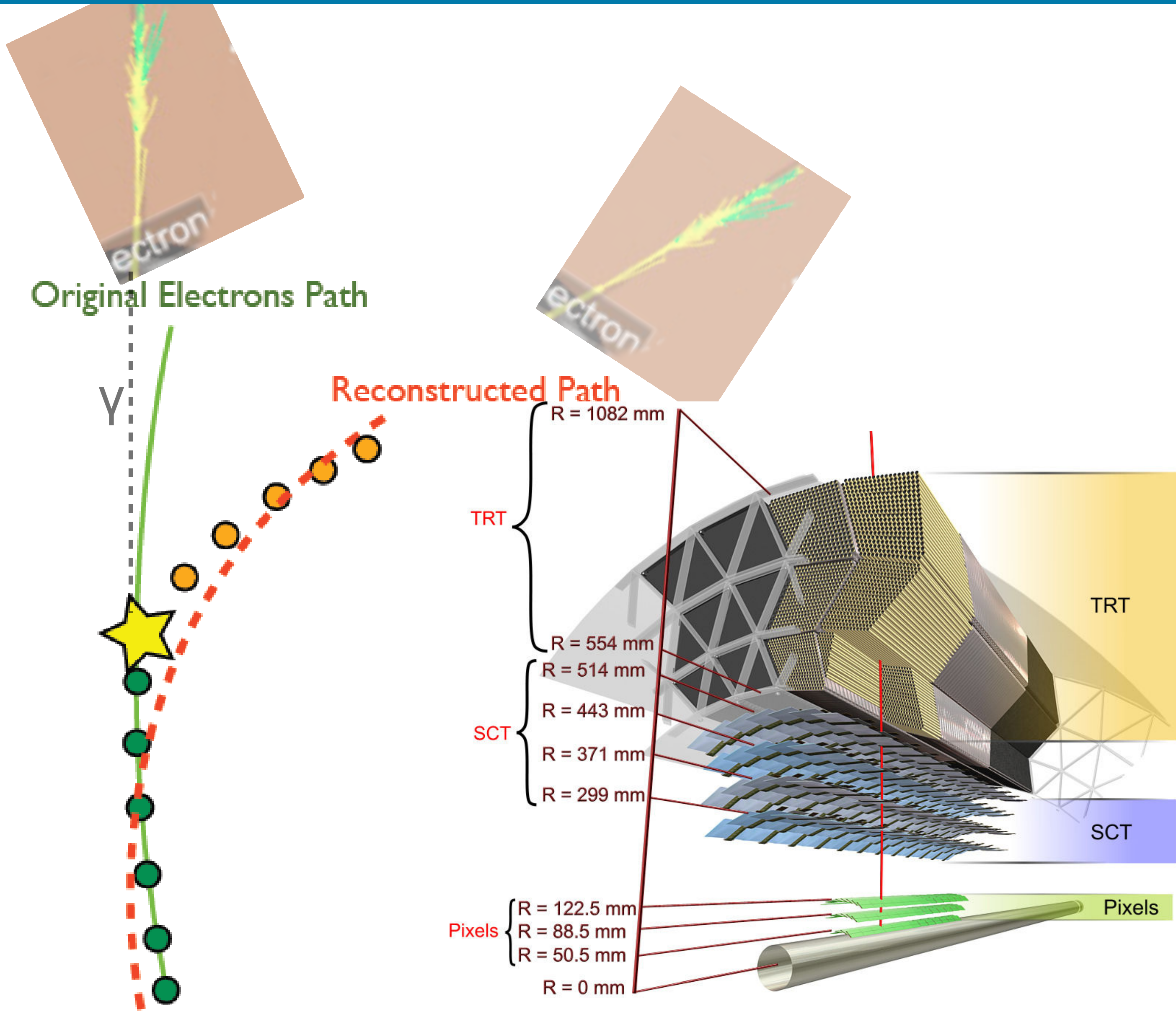
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

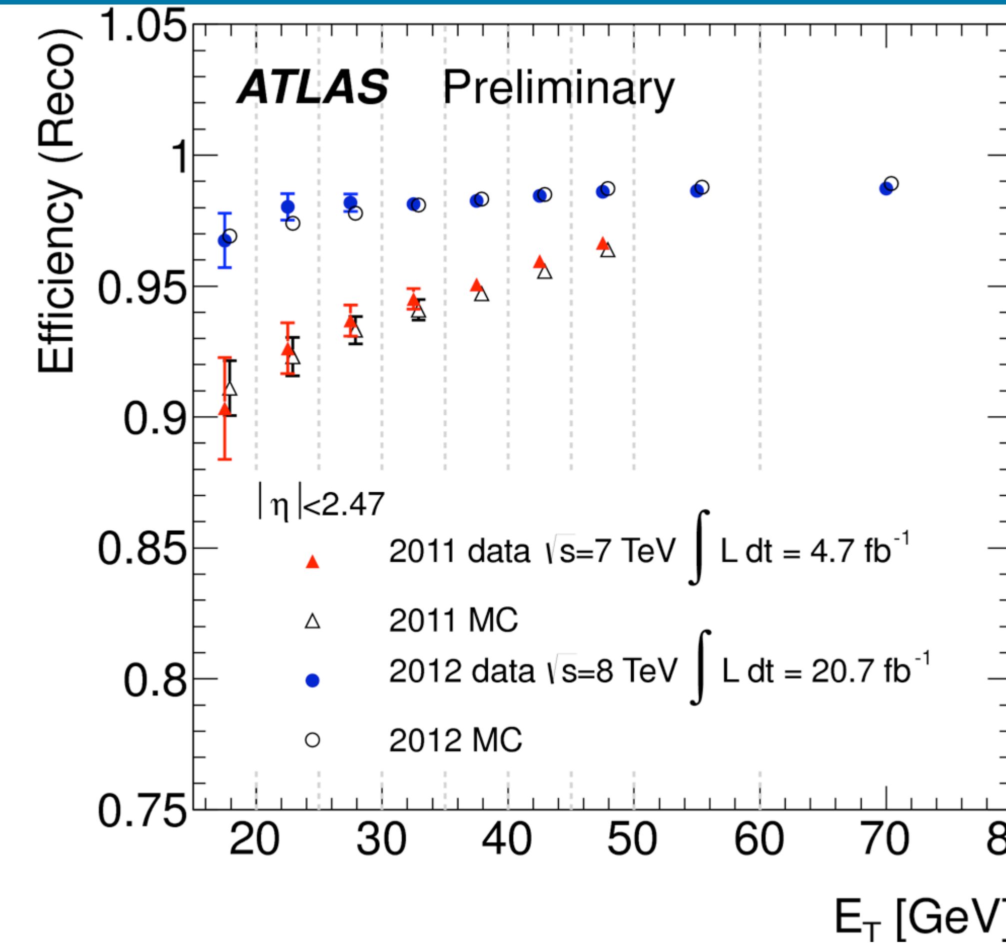


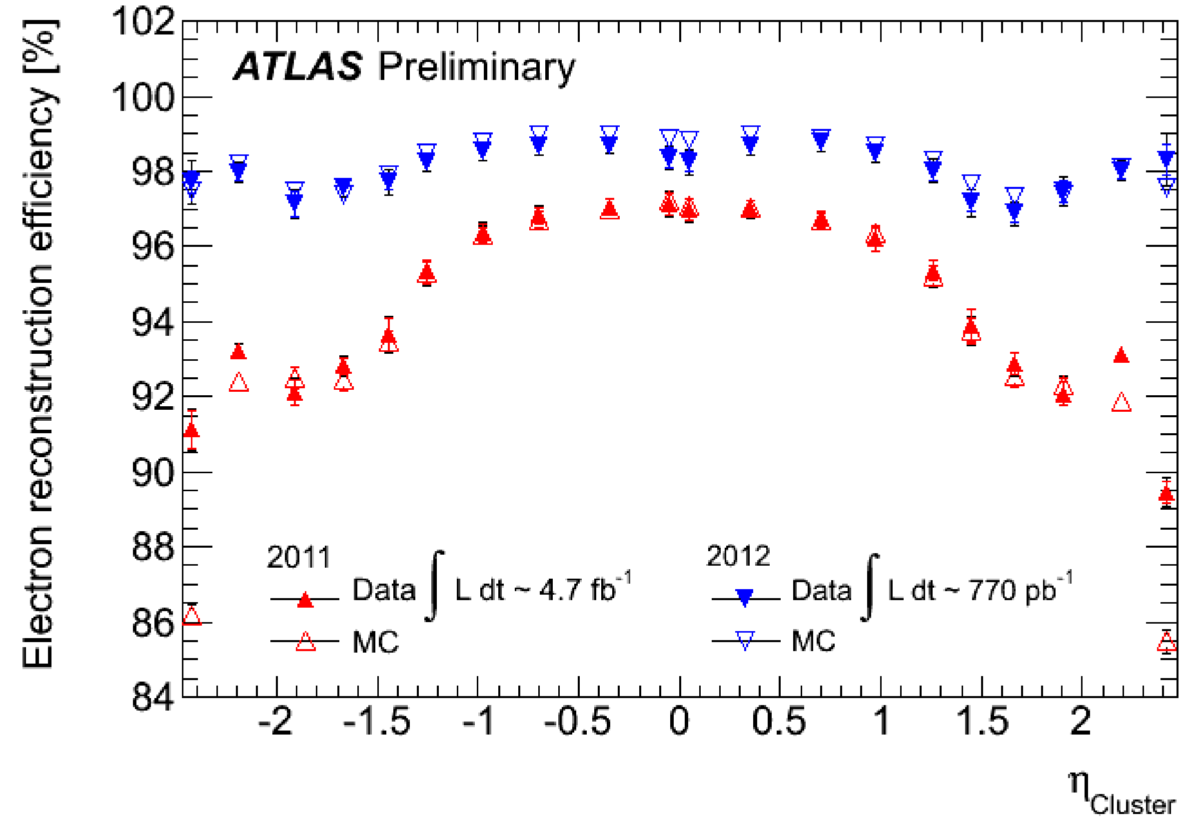
"Physics Objects"



Electron Reconstruction

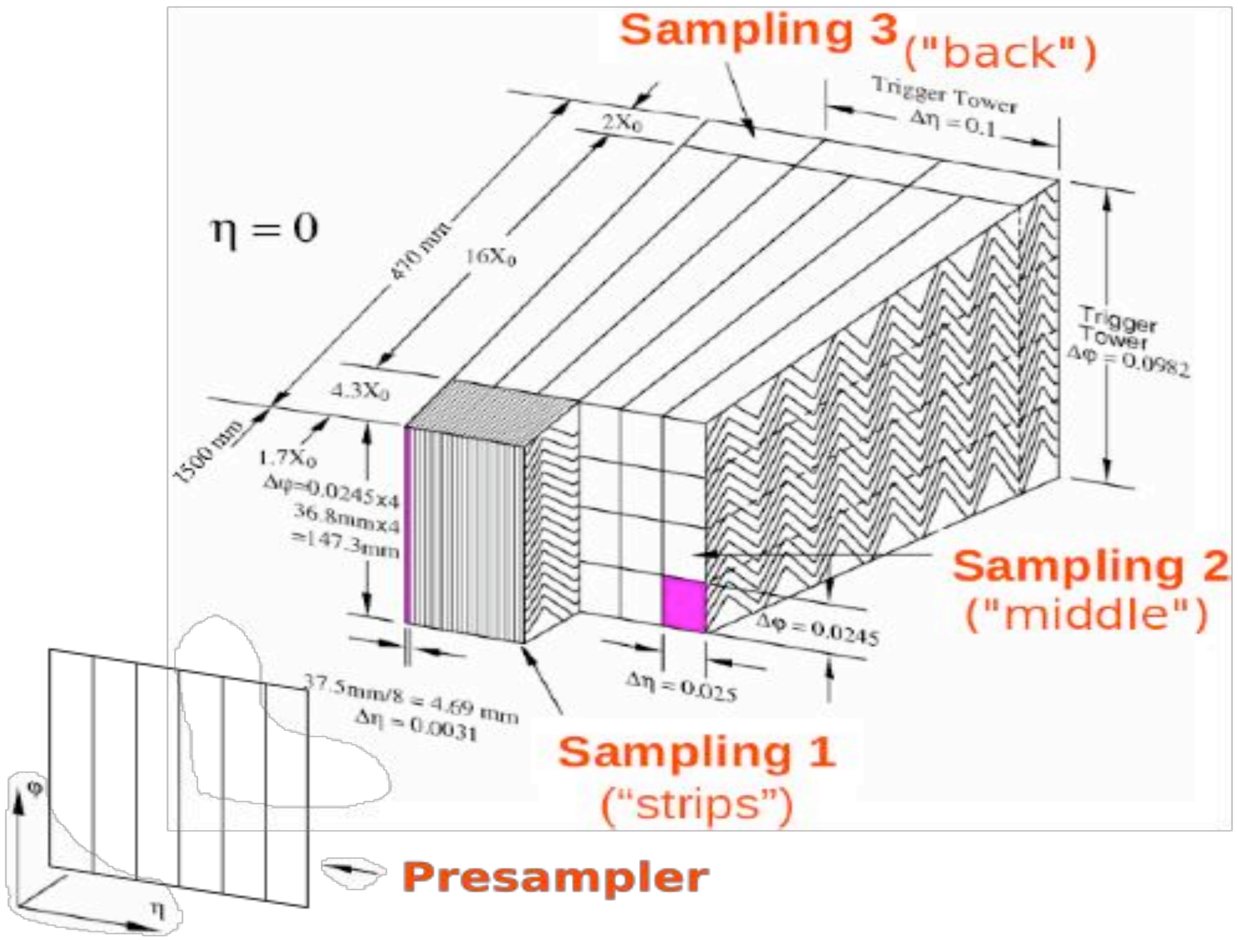


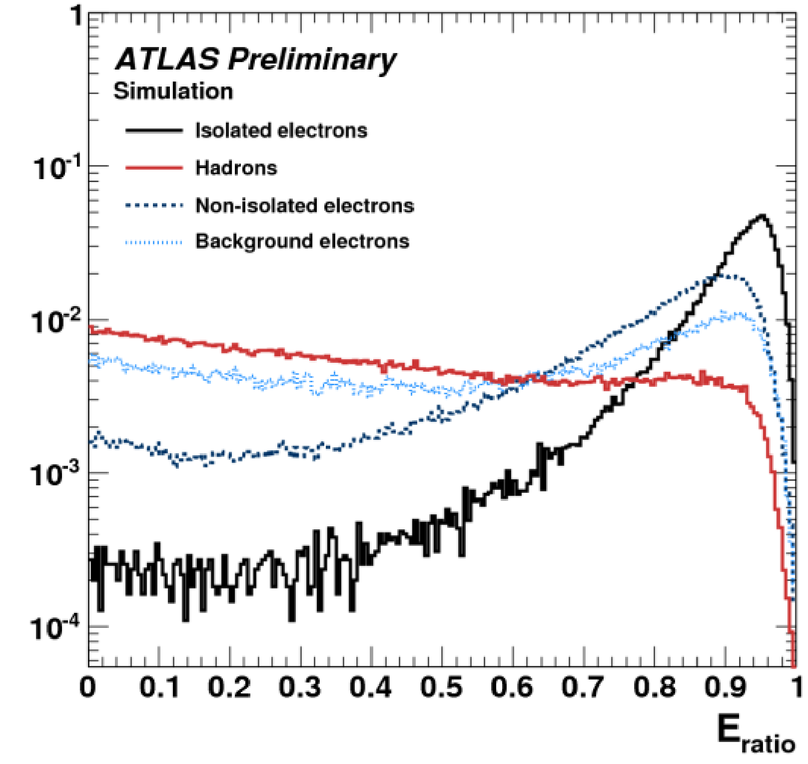


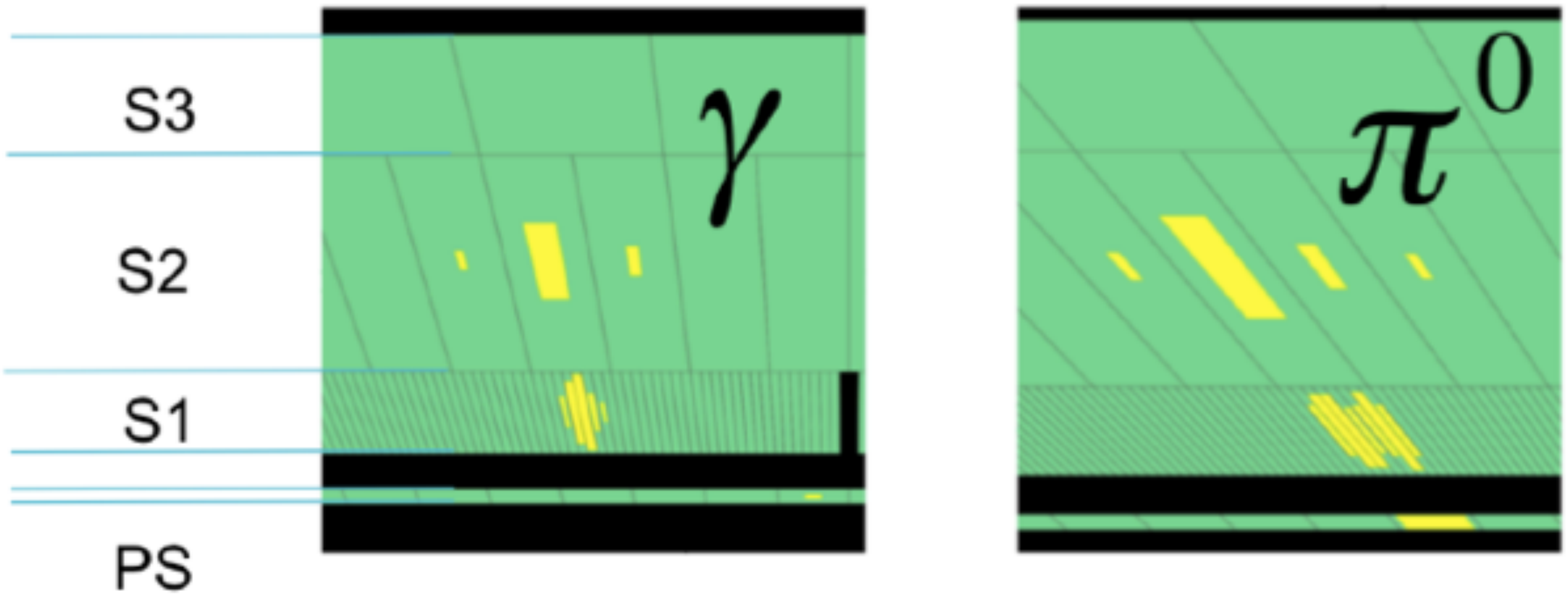


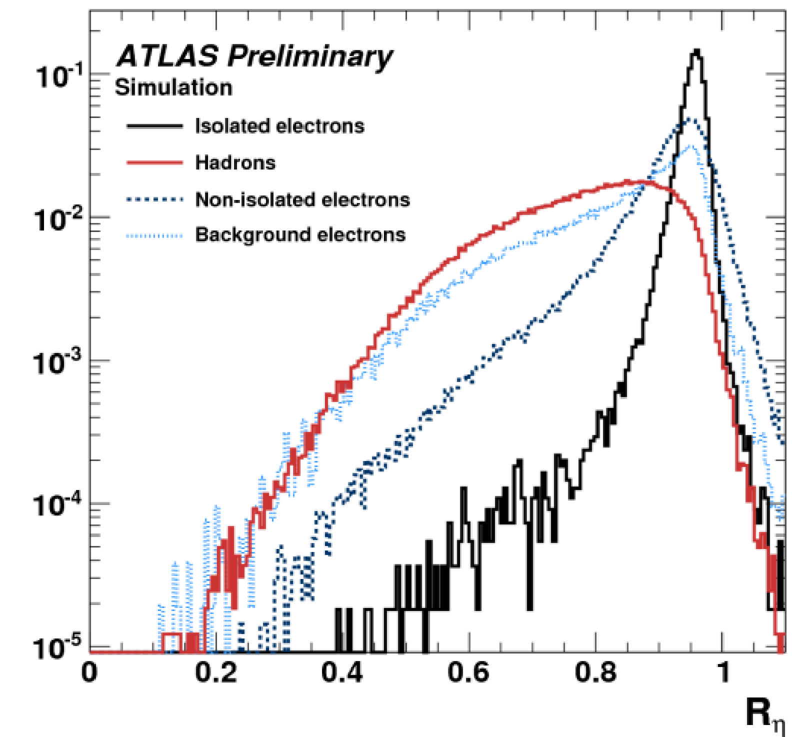
Electrons suffer bremsstrahlung, complicating reconstruction
→ Pattern recognition and track-fitting algorithms need to account for this
e.g. track reconstruction using GaussianSumFilter

Electron/Photon Identification

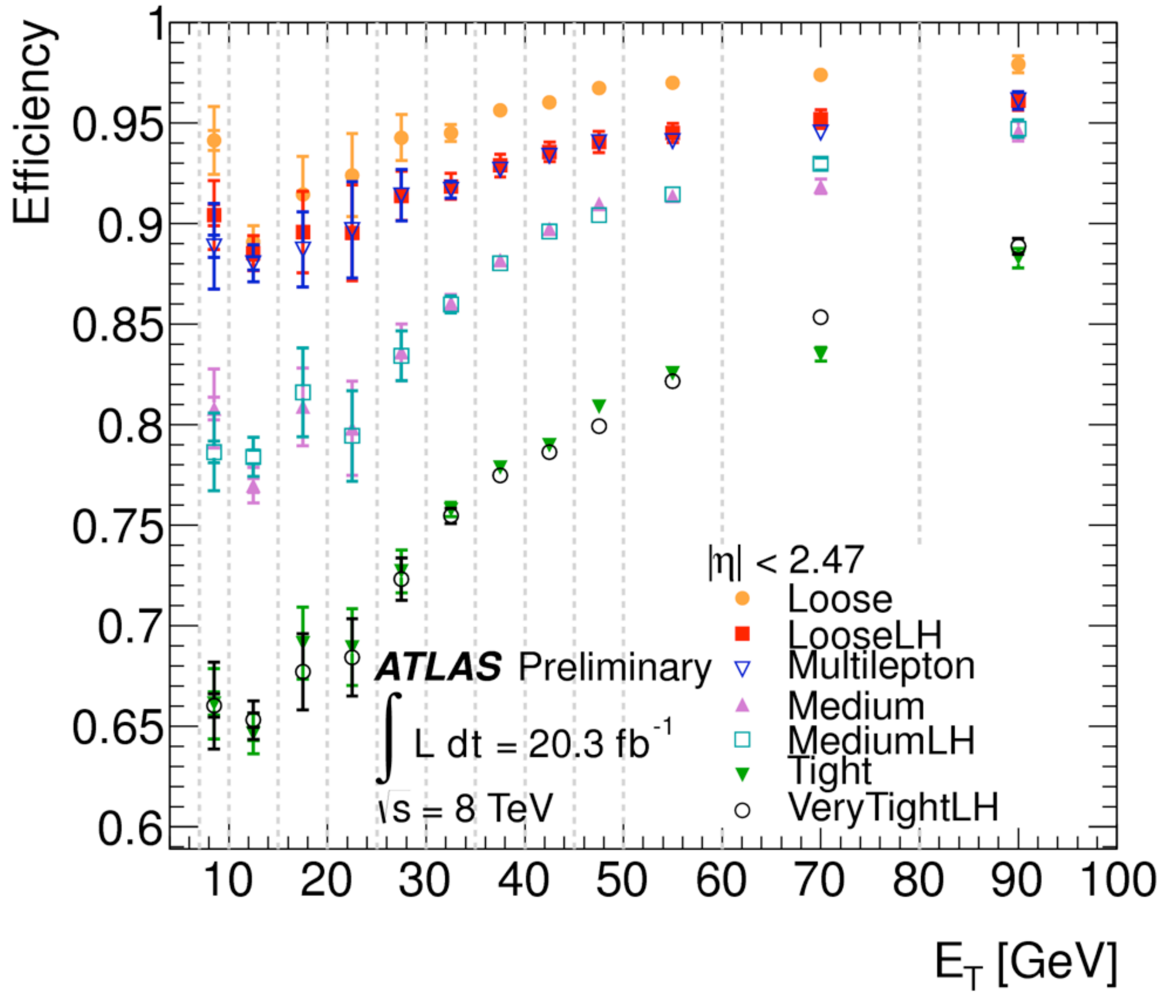


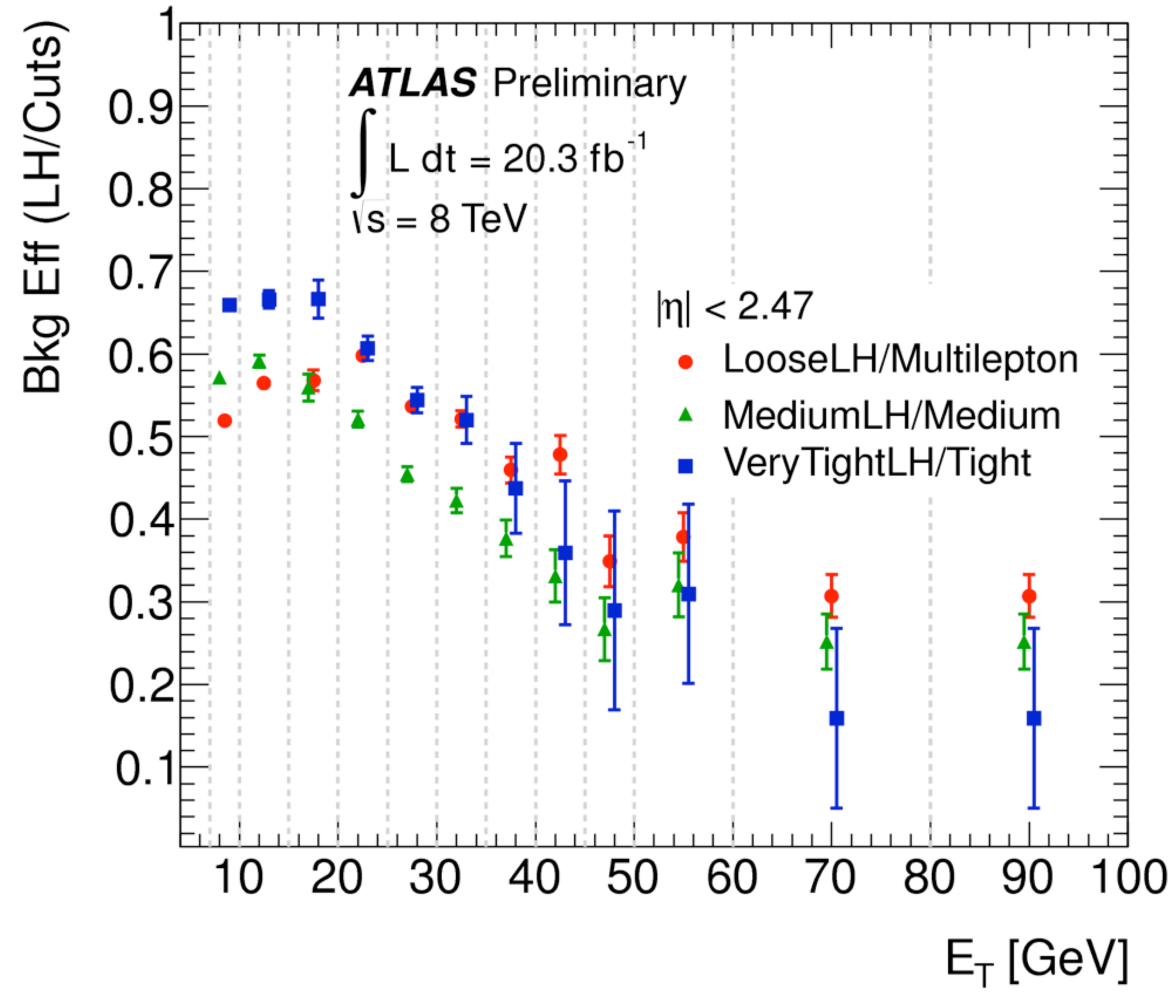






Electron/Photon Identification

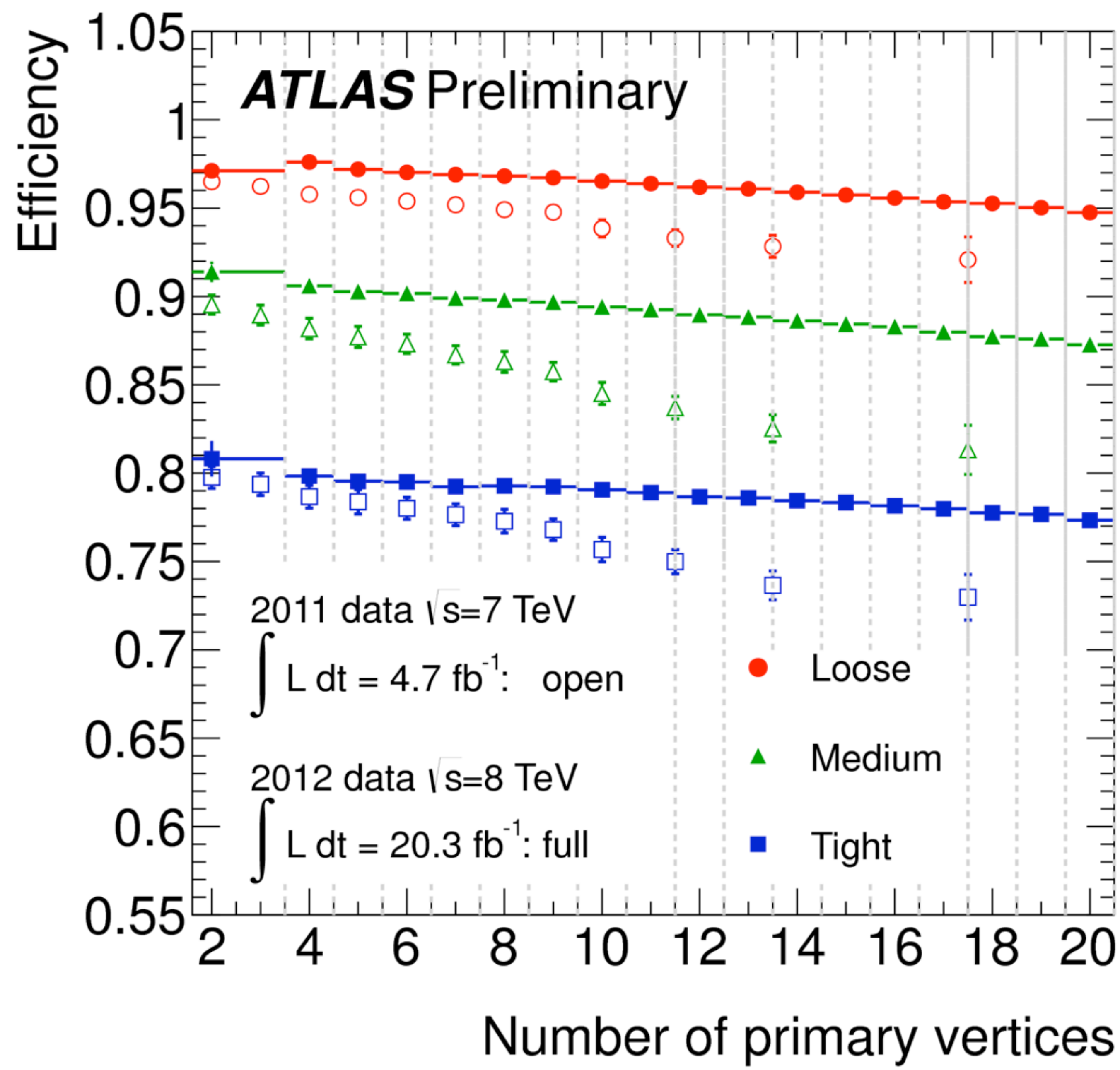




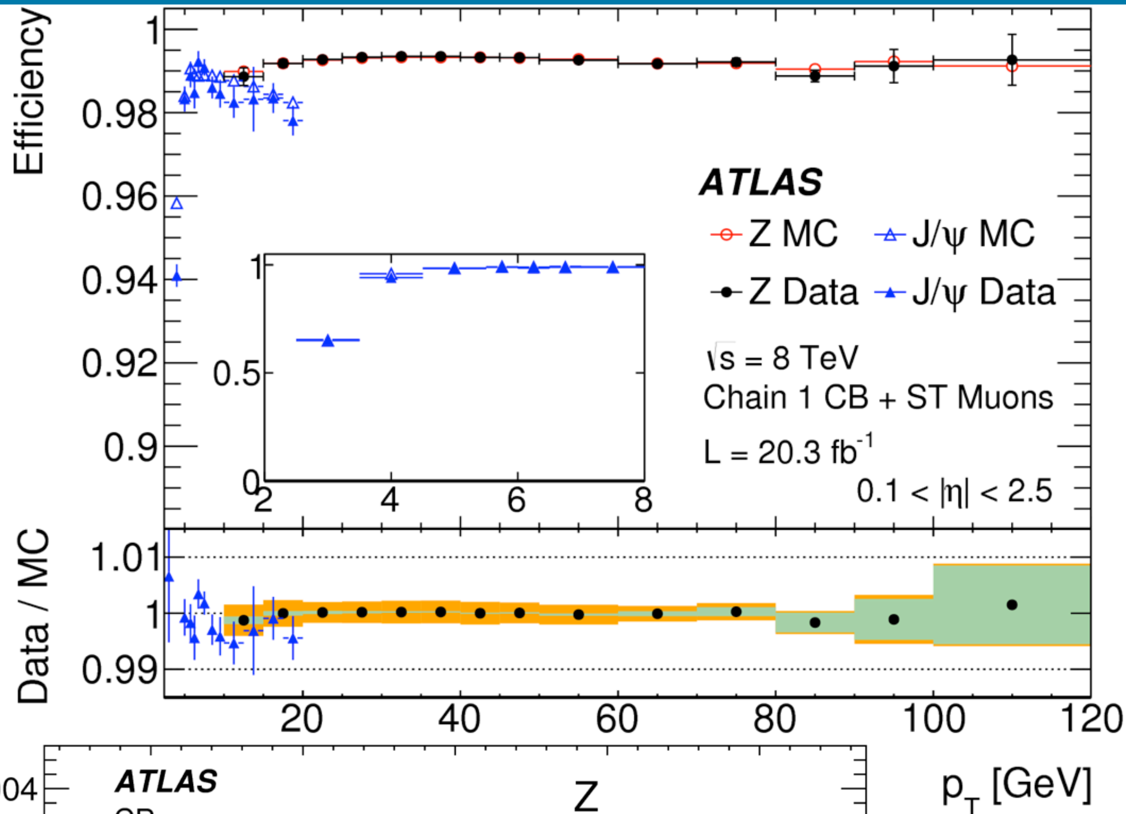
The detector provides us with several pieces of information
(shower shapes, tracking, cluster-tracking matching)
Need to decide:
→ how to best exploit the info (simple "rectangular" selections, MVAs, ...)
→ what is the optimal trade-off between efficiency and "fake"-rate for the given analysis

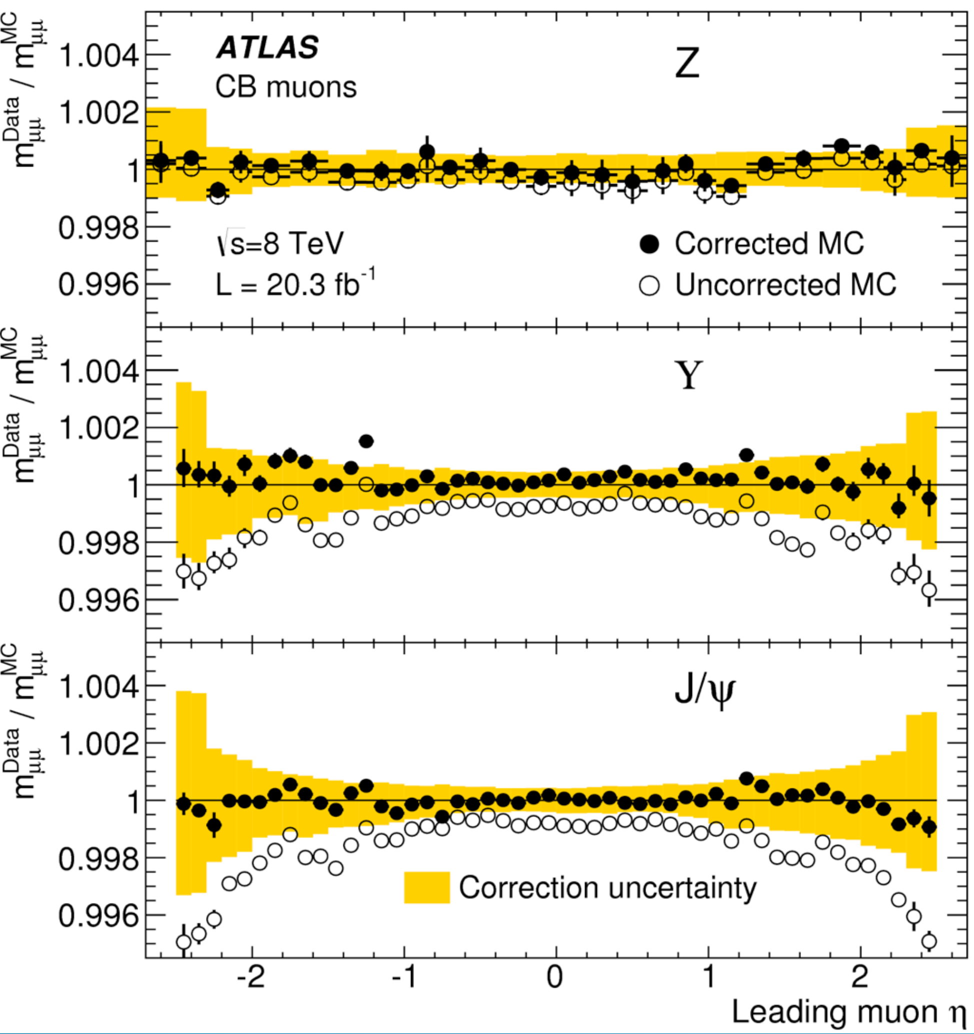
Electron/Photon Identification: Pile-up... again

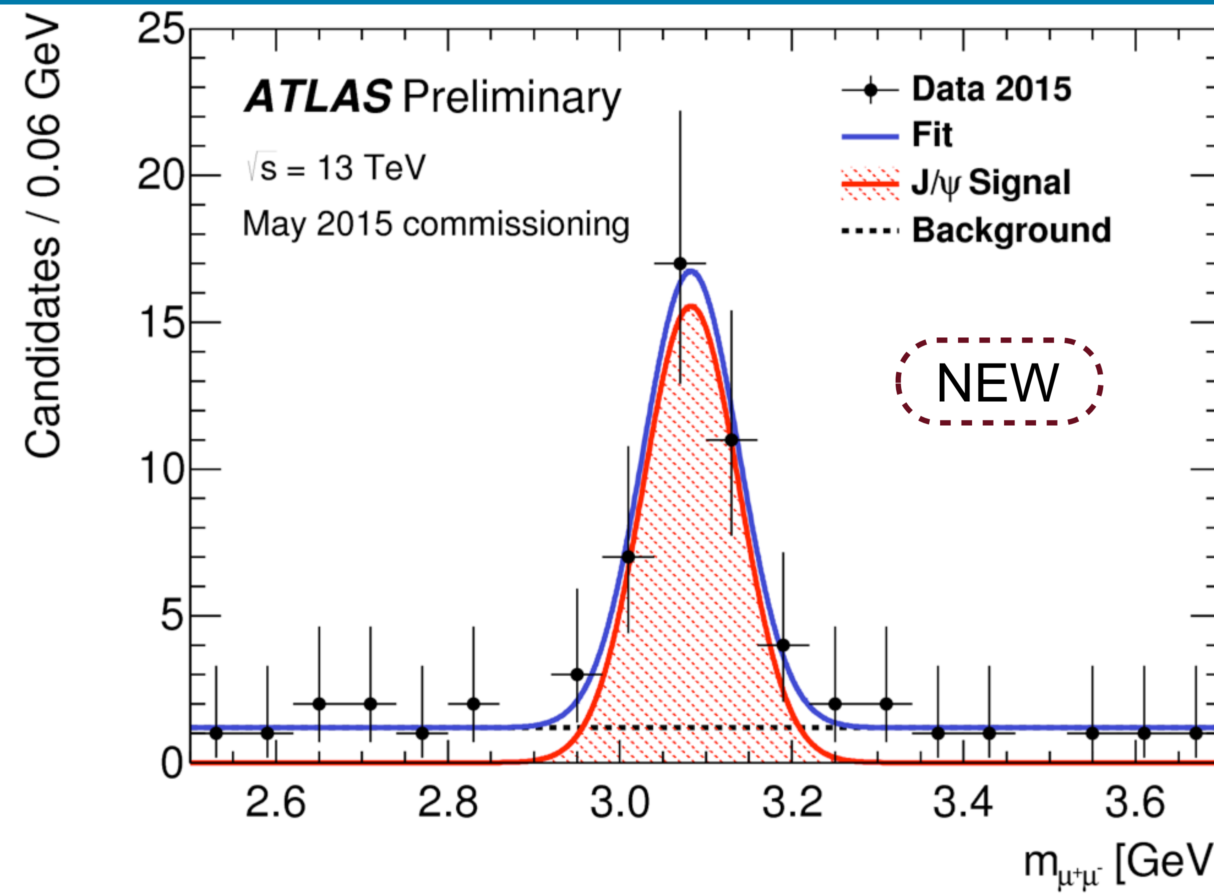
For electron identification algorithms, a lot of attention needs to go in the choice/handling of input variables and their dependence on pile-up
[e.g. R_η is sensitive to pile-up]

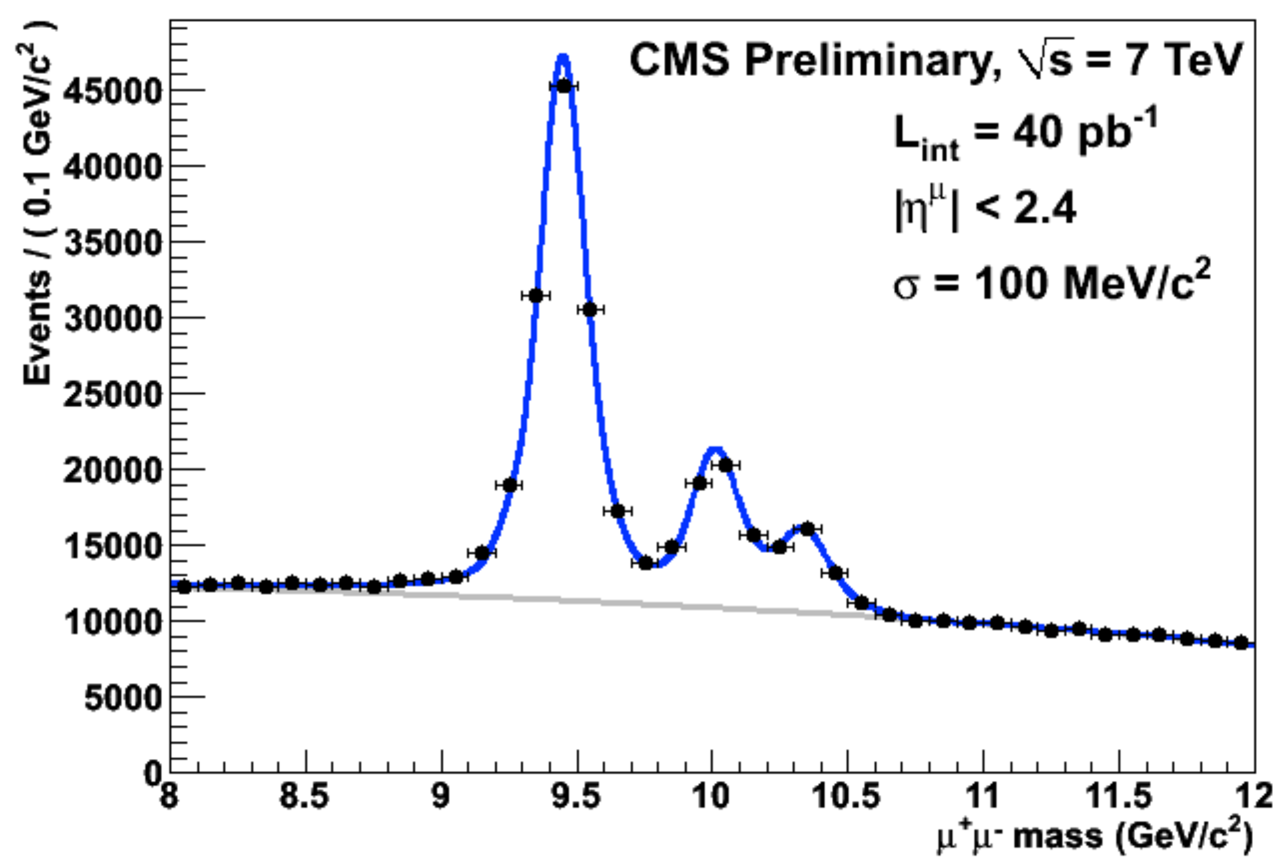


Muon Reconstruction/Identification



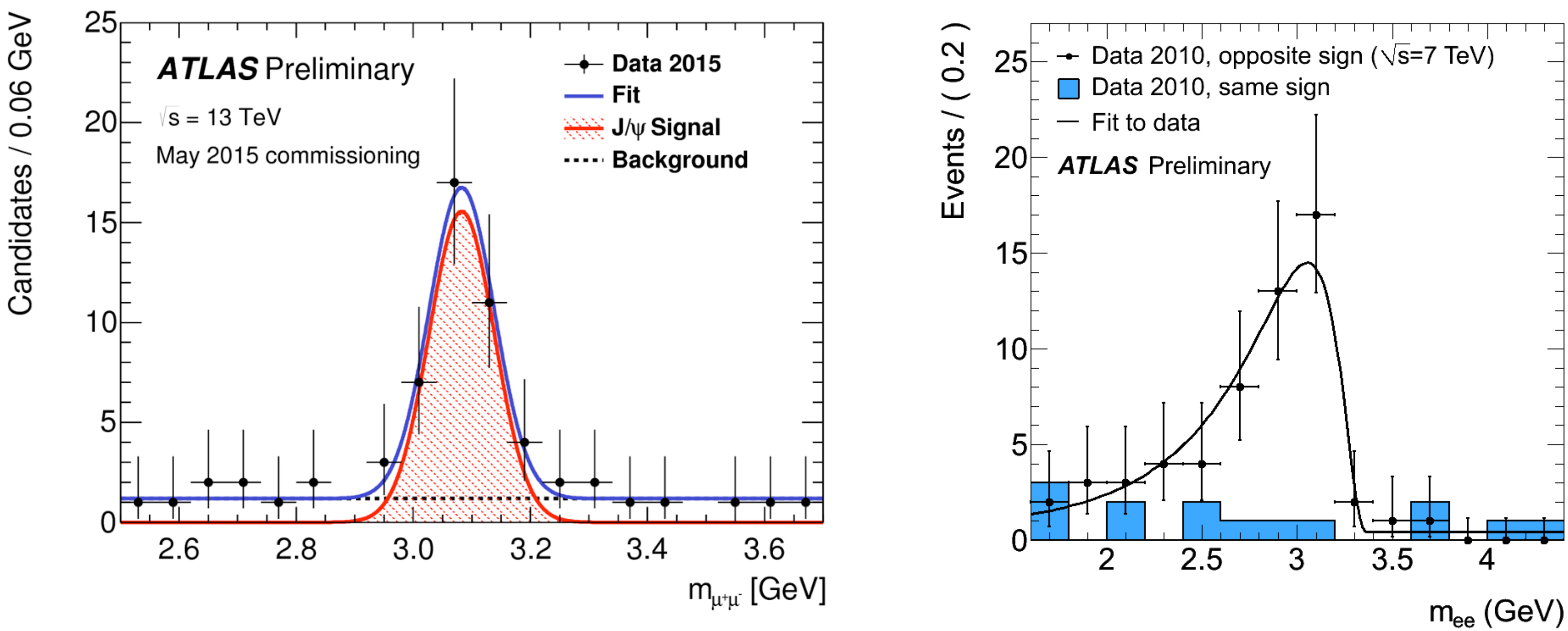






An unfair comparison

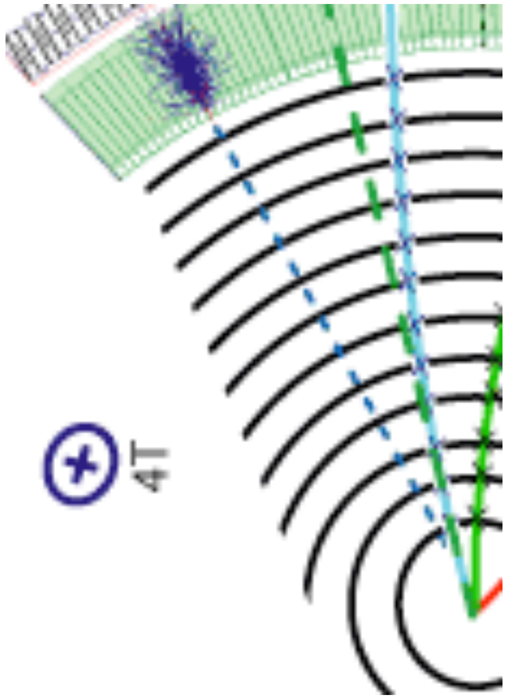
This comparison is completely "unfair";
made in the region where the muons have the absolute advantage
[and not the latest reconstruction is used - but this is 2nd order effect]



One cannot assume that in the detector
electrons and muons are the same
(let alone tau-leptons)
For each object dedicated work to make the most out
of the detector capabilities is required

Photons

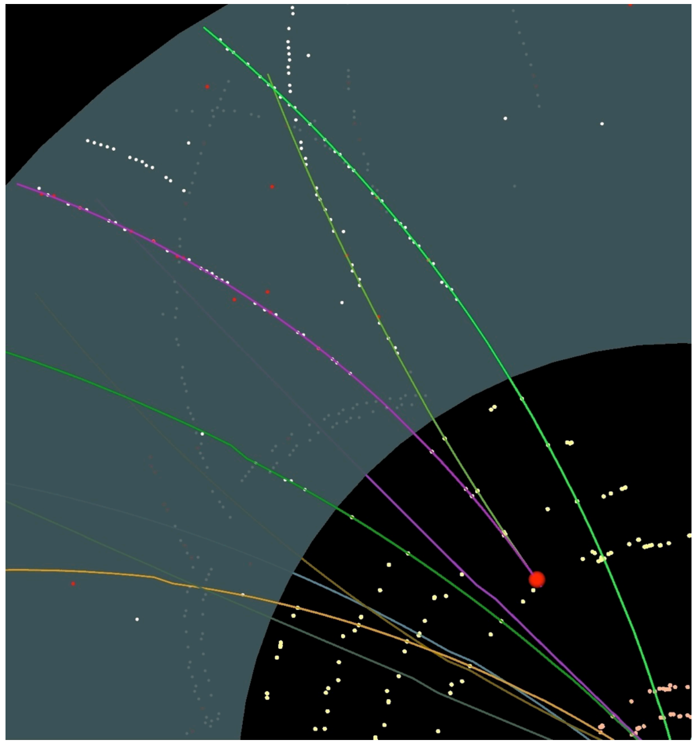
Unconverted Photon

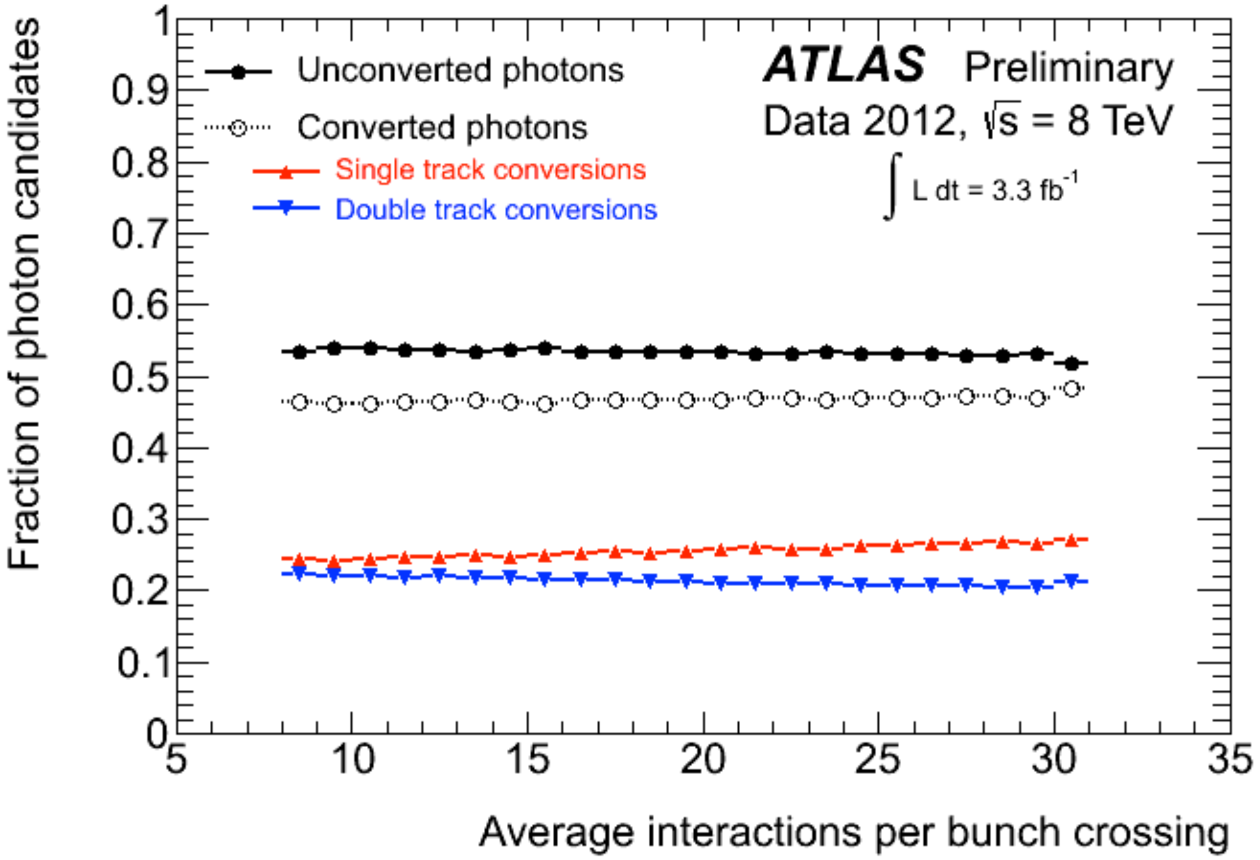


Ideally, the photon in the detector is:
a cluster of electromagnetic energy without any associated track

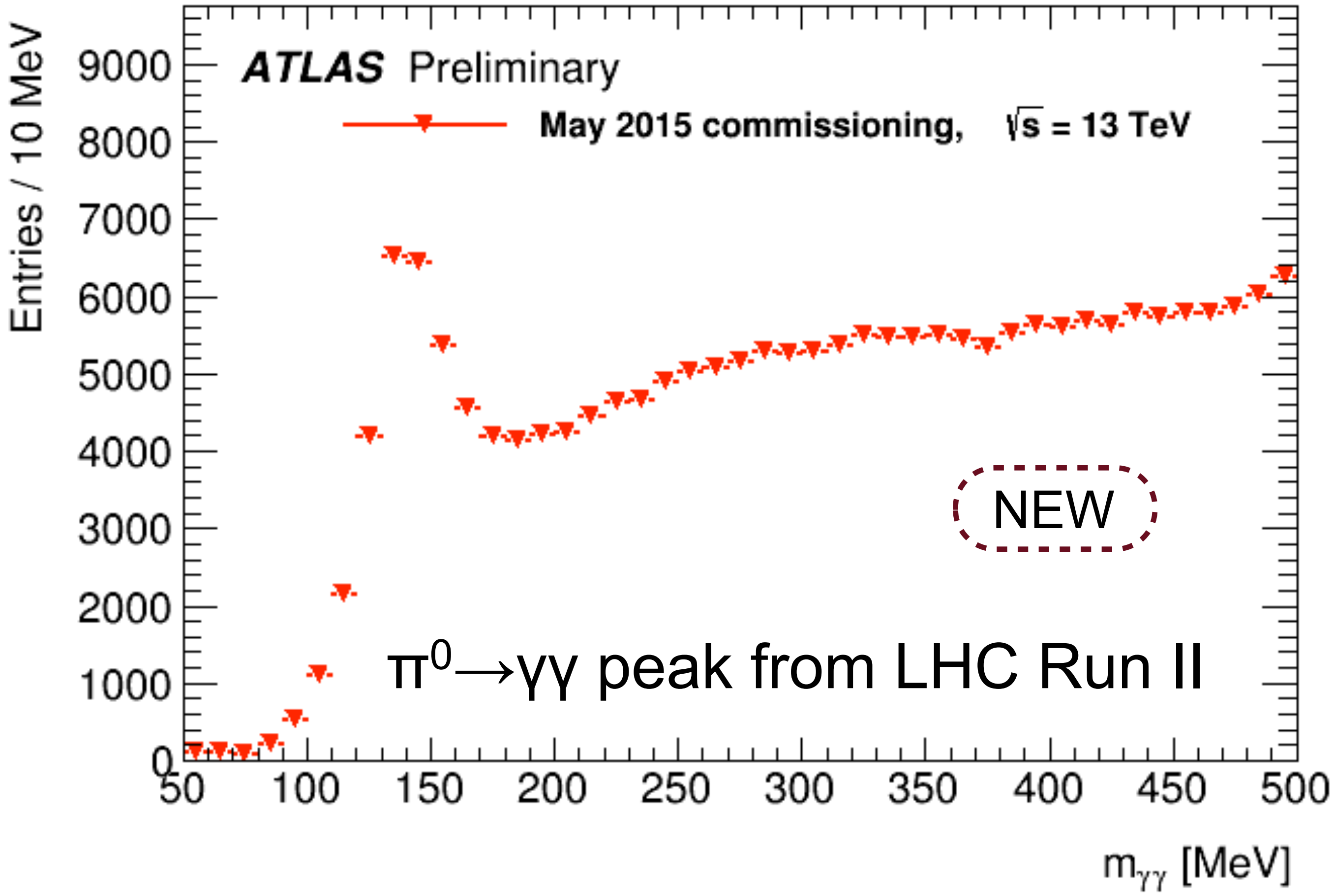
Reality is richer!
Photons may convert to e^+e^- pair in the detector material

Converted Photon



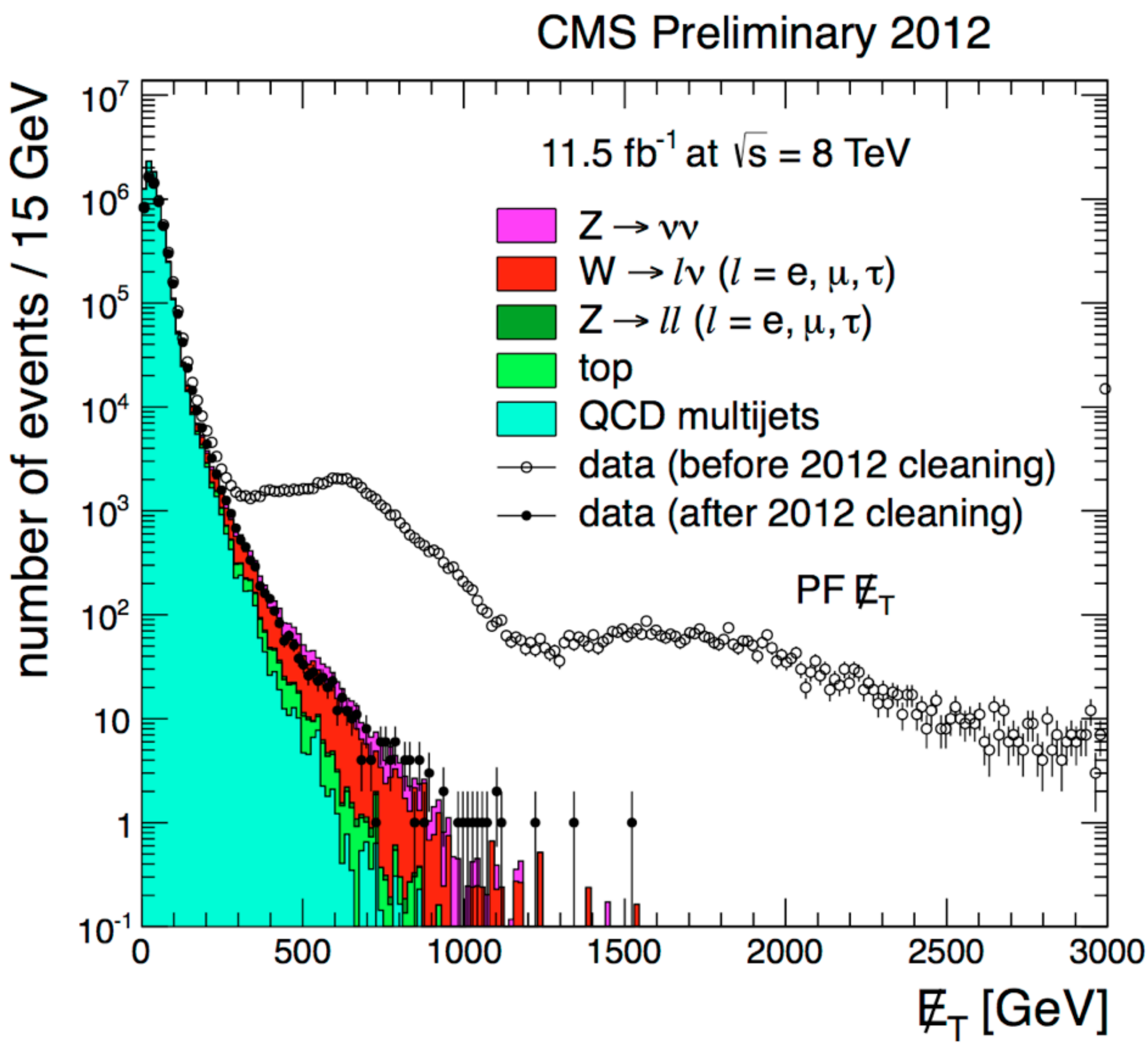


Stable photon reconstruction vs pile-up (within 1%)



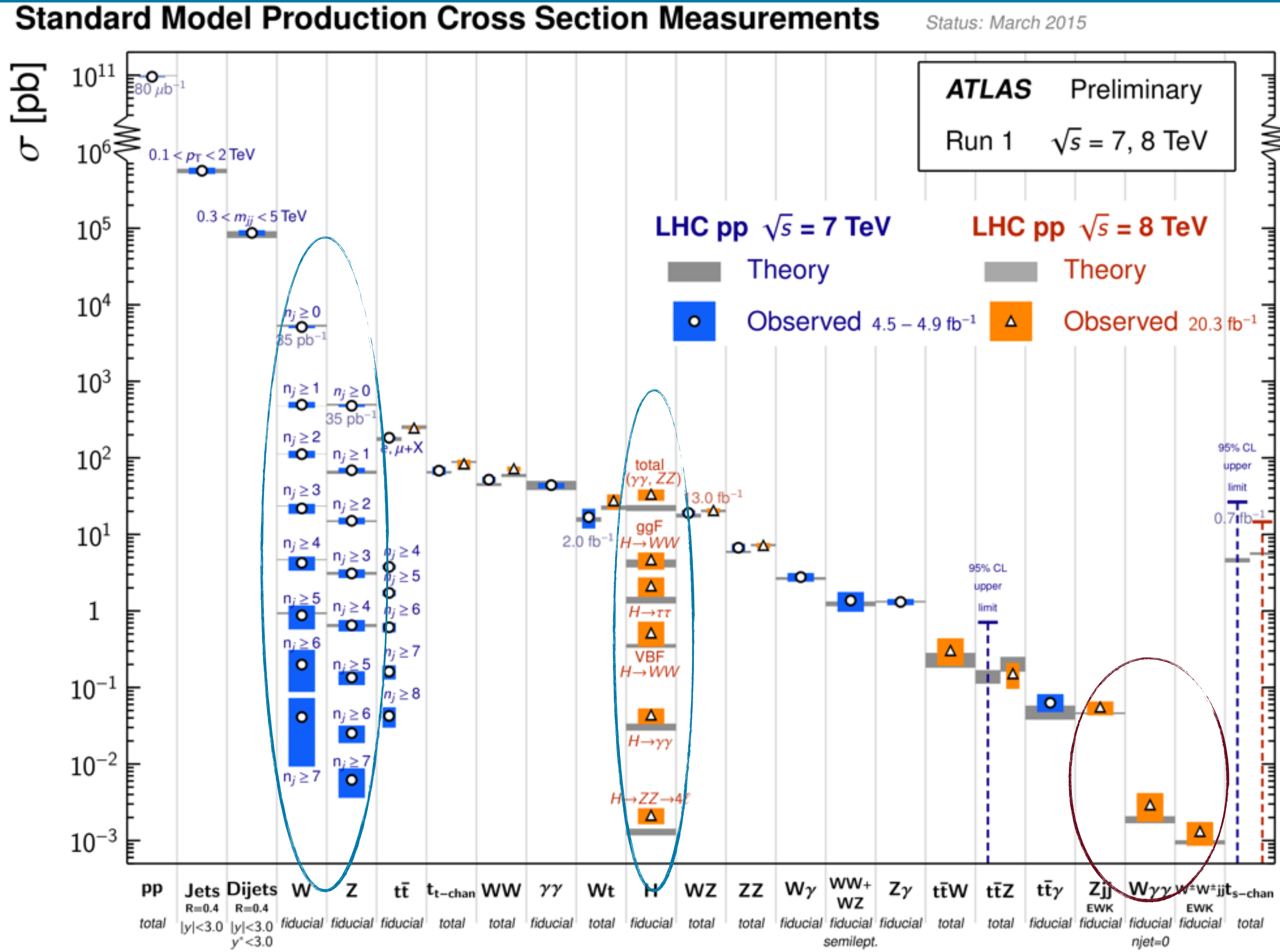
Missing transverse momentum

CMS-PAS-JME-12-002

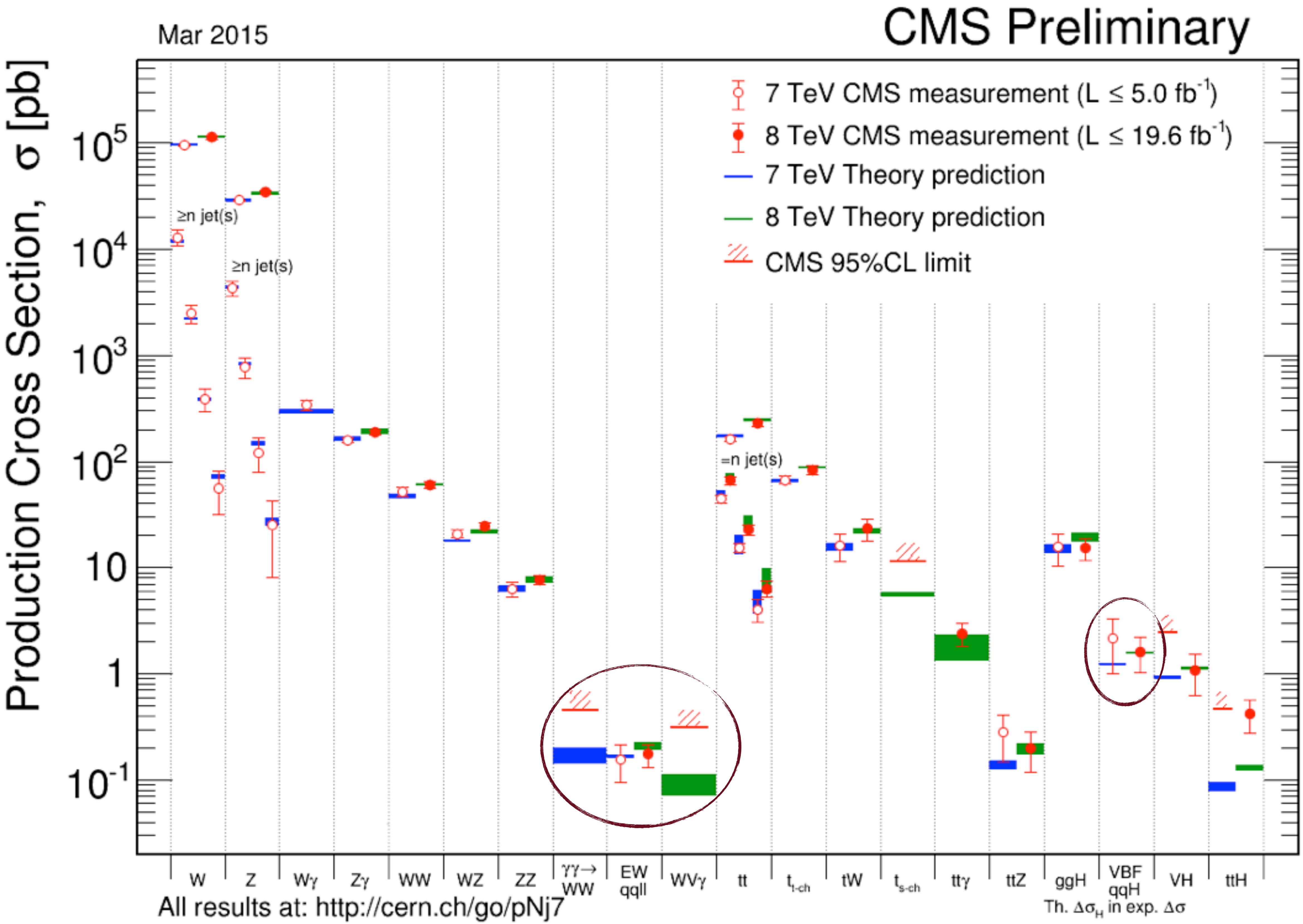


Detector operation conditions should be constantly monitored

Snapshot of cross section measurements

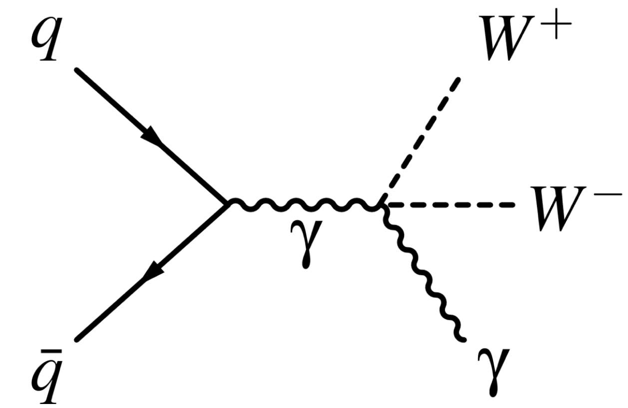


Snapshot of cross section measurements

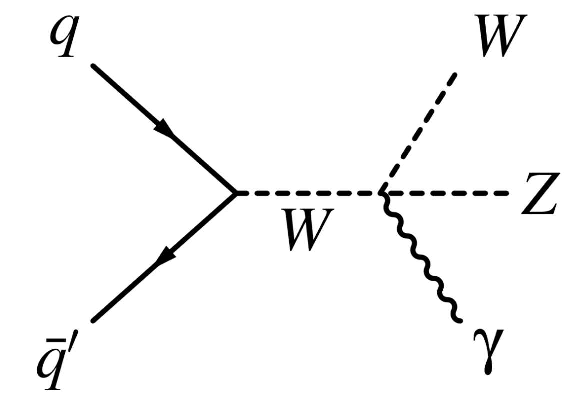


Search for WWγ/WZγ→lν(qq)γ

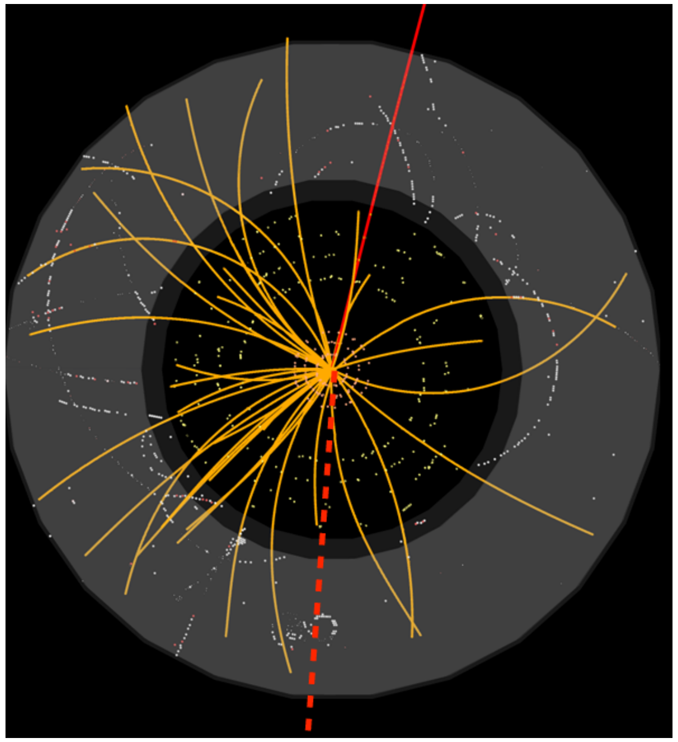
Search for triboson production WVγ
CMS: ~19.3 fb^{-1} of 8 TeV data, published as PRD90, 032008 (2014)



Signature: W(V)γ→lν(qq)γ, WWγ and WZγ treated together
Main background Wγ+jets, then WV+jets

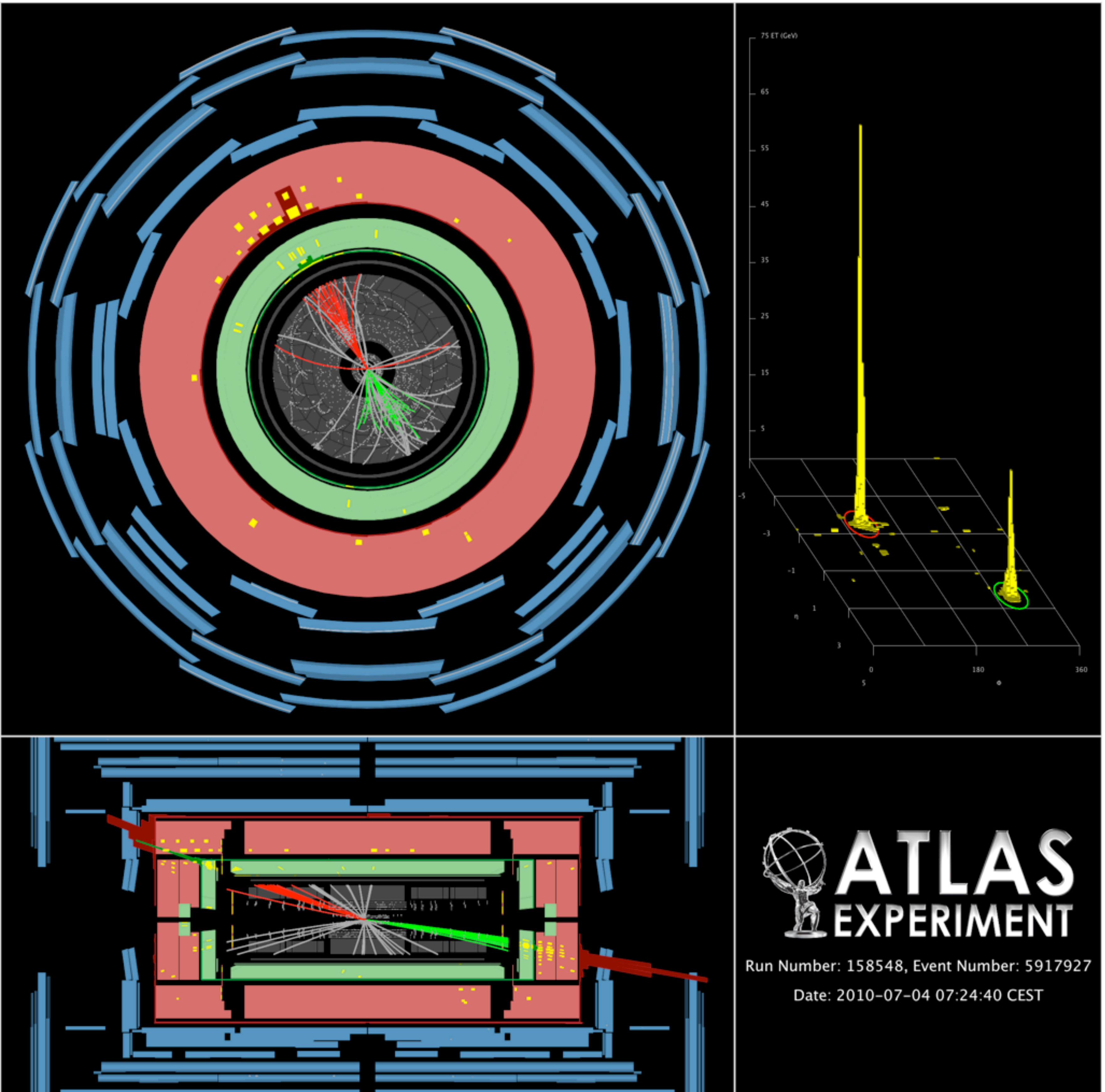


Selection:
- Trigger: muon p_T>24 GeV, electron p_T>27 GeV
- Lepton selection
  - one isolated muon p_T>25 GeV, |η|<2.1, or
  - one isolated electron p_T>30 GeV, |η|<2.5 (excluding 1.44-1.57)
- Veto events with additional muons (electrons) p_T>10 (20) GeV
- MET>35 GeV
- $m_T = \sqrt{p_\ell^T \; \not{E}_T \, [\Delta\phi_{\ell,\not{E}_T}]}$ >30 GeV
- Photon E_T>30 GeV and |η|<1.44
- ≥ 2 jets anti-kT R=0.4 p_T>30 GeV and |η|<2.4
  - Two highest p_T are forming the V→qq candidate
- Δφ(highest p_T jet, MET)>0.4
- 70 < m_{jj} <100 GeV, $|\Delta\eta_{jj}|$<1.4
- b-tag veto veto
- Z veto $|m_Z - m_{e\gamma}|$>10 GeV



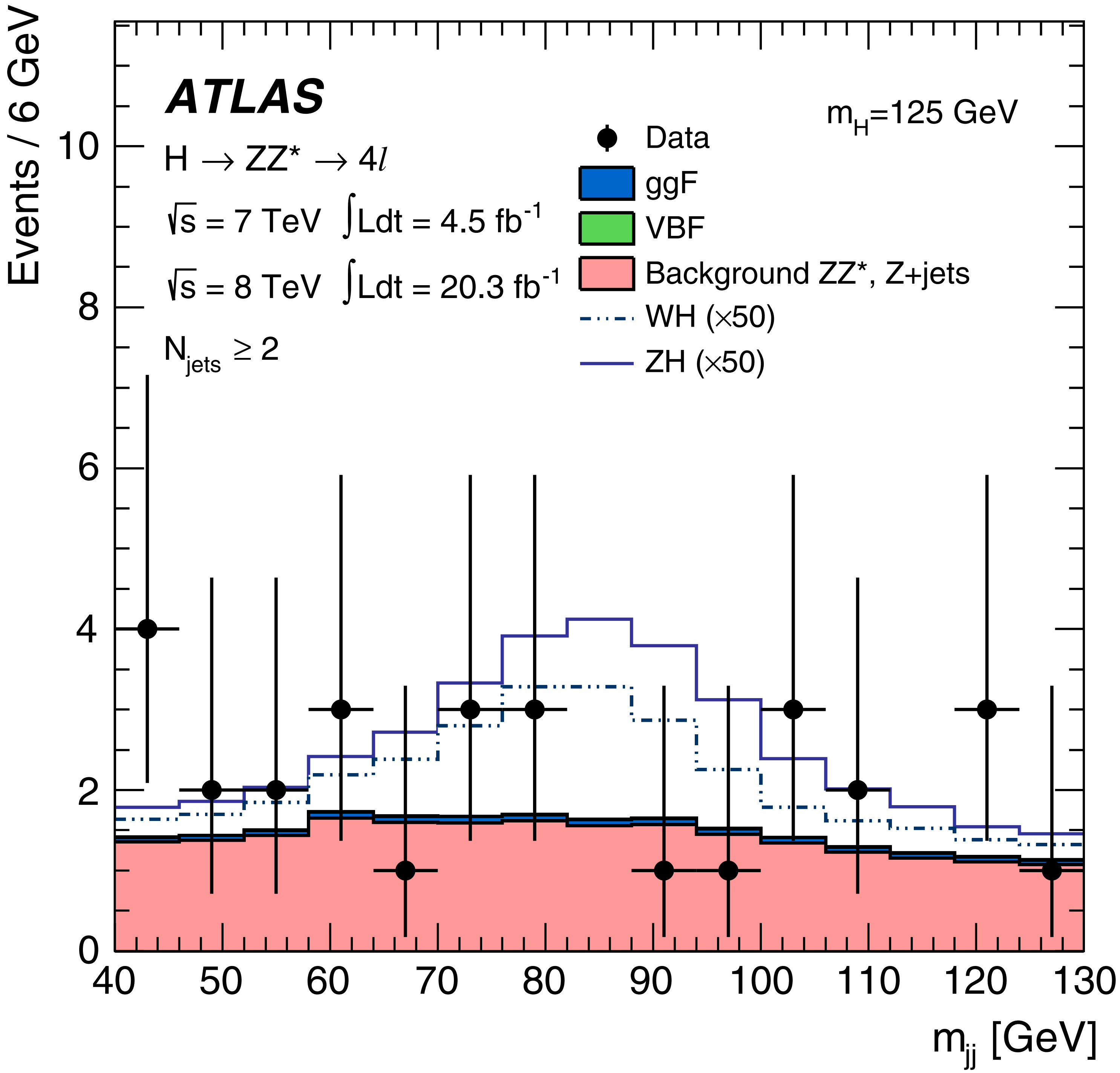
W→μν candidate

Δφ(highest pT jet, MET)>0.4



m_{jj}=2.55 TeV.
pT,eta1: 420 GeV,-1.51,
pT,eta2: 320 GeV,2.32
No other jets with pT>20 GeV. Event collected on 4 July 2010

m_{jj} resolution



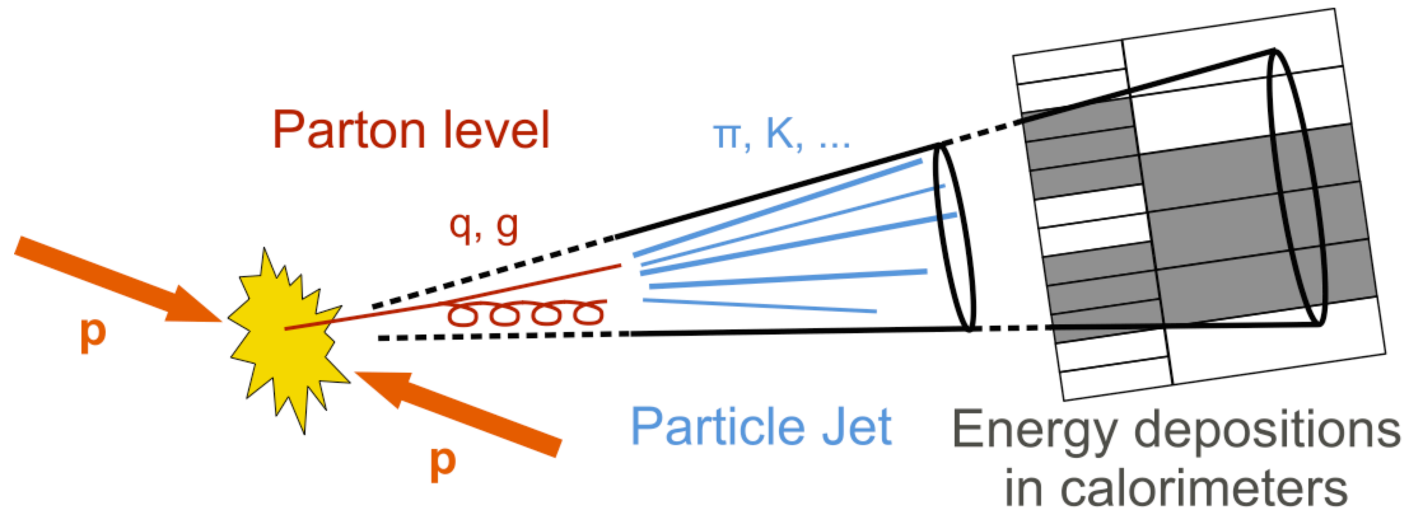
Jet energy, E, resolution scales $\propto A/\sqrt{E}$

Typical values of A~50-100%

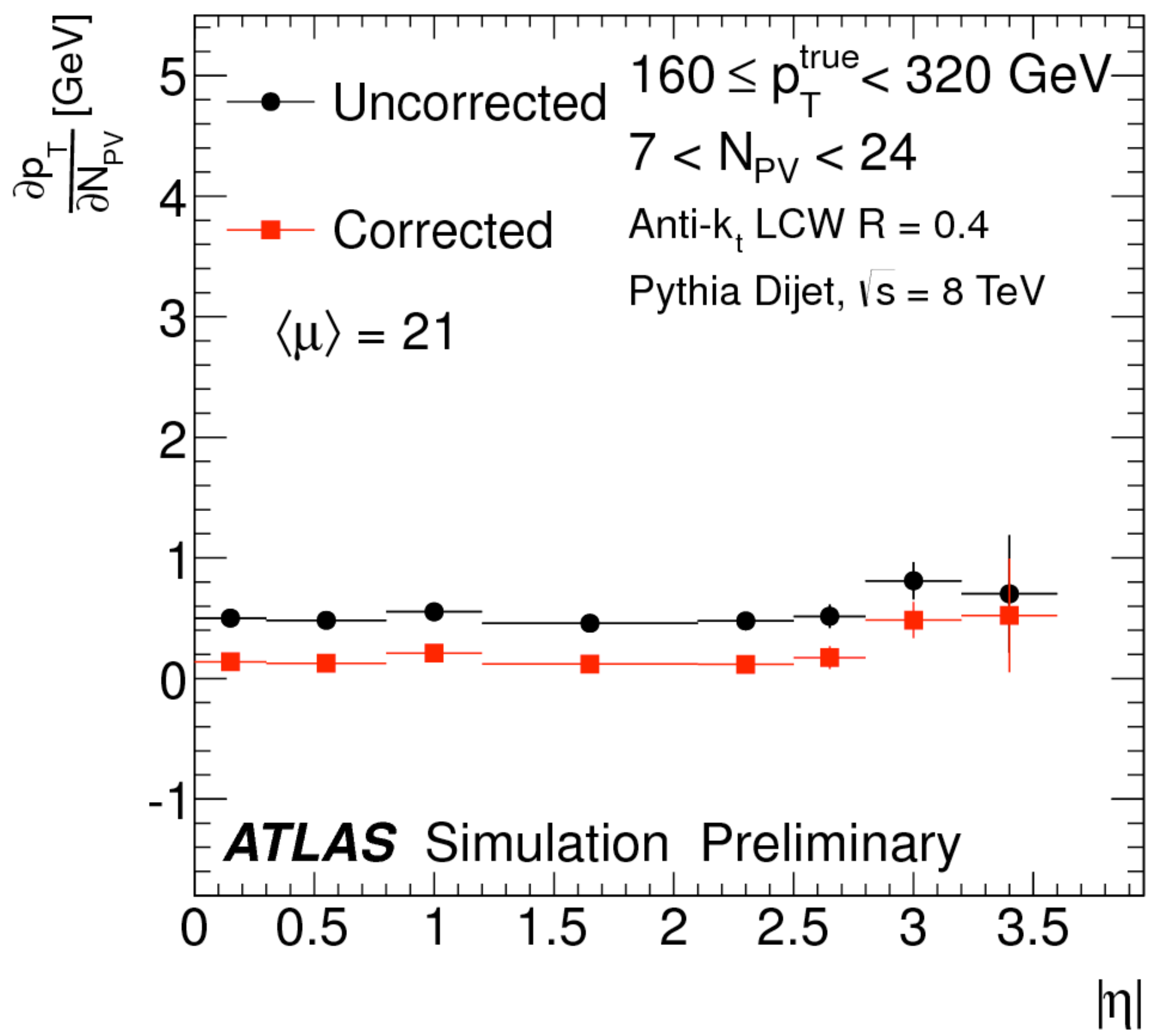
For energies relevant for this search typical $\delta m_{jj}/m_{jj}$ ~ 10%

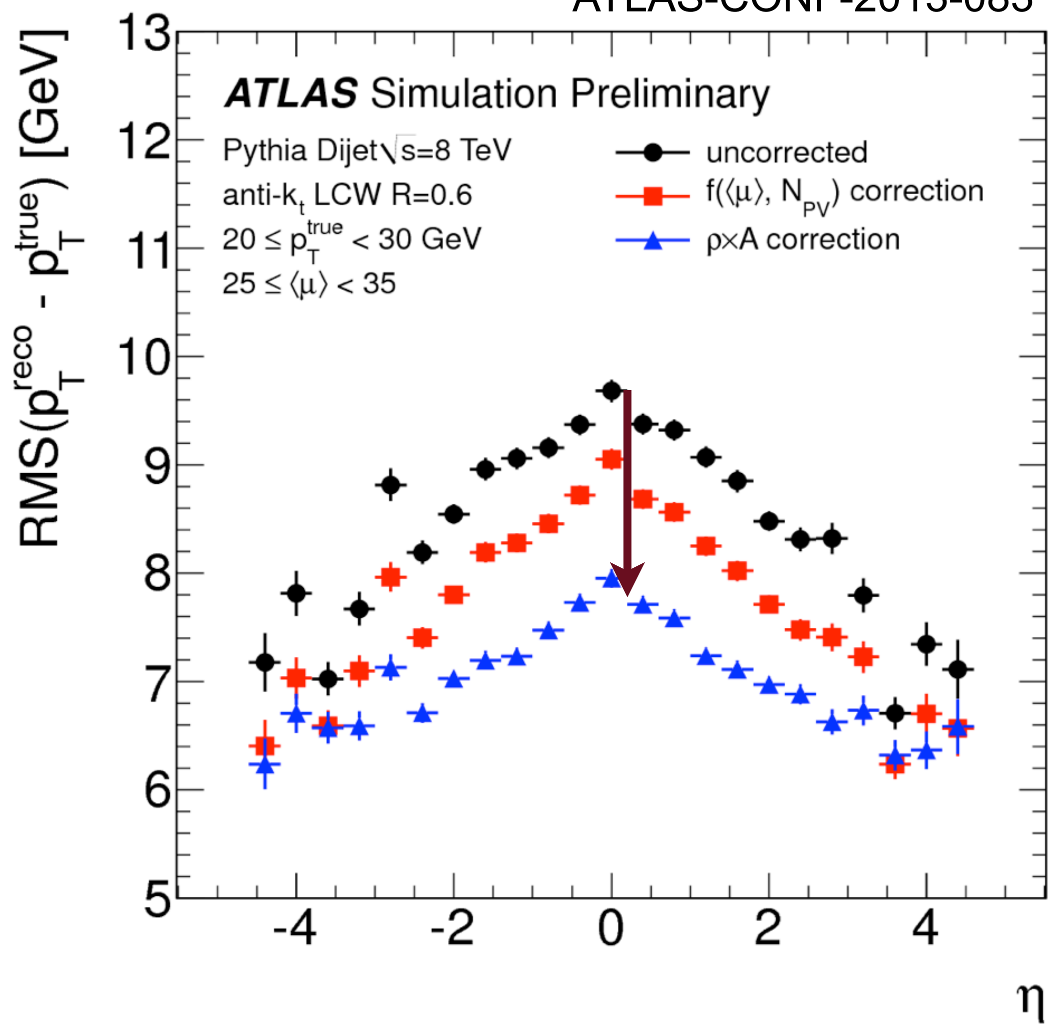
Caveat: expected m_{jj} resolution for another analysis in another experiment, for illustration only

jets in pile-p



ATLAS-CONF-2013-083





Pile-up contributes to energy of reconstructed jets ~0.5 GeV/interaction

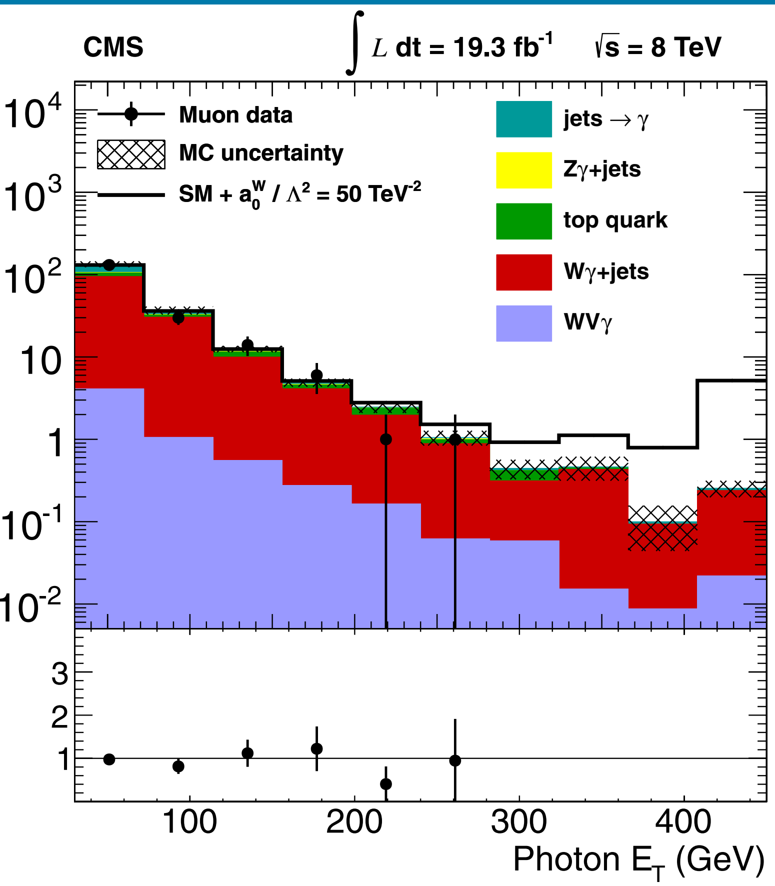
Search for WWγ/WZγ→lν(qq)γ

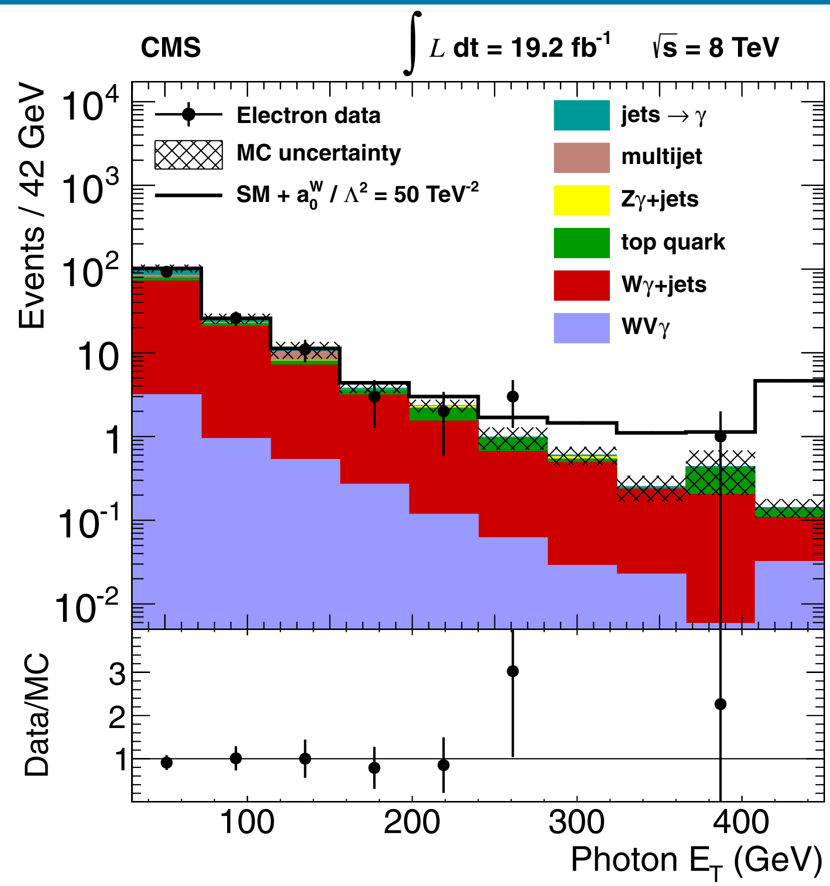
Process	Muon channel number of events	Electron channel number of events
SM $WW\gamma$	6.6 ± 1.5	5.0 ± 1.1
SM $WZ\gamma$	0.6 ± 0.1	0.5 ± 0.1
$W\gamma$ + jets	136.9 ± 10.5	101.6 ± 8.5
WV + jets, jet $\to \gamma$	33.1 ± 4.8	21.3 ± 3.3
MC $t\bar{t}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC $Z\gamma$ + jets	1.7 ± 0.1	1.5 ± 0.1
Multijets	...	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139
Total Background Prediction	~187	~142

95% CL upper limit σ(WVγ):
3.4×SM (4.4×SM expected)

→ WVγ is "Signal",
all other processes are "Background".
→ Counting experiment
total observed events lower than expected ("downward" fluctuation) thus limit tighter than expected

Search for WWγ/WZγ→lν(qq)γ





aTGC search uses photon E_T as discriminant

Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20$ TeV^{-2}	$-24 < a_0^W/\Lambda^2 < 23$ TeV^{-2}
$-34 < a_C^W/\Lambda^2 < 32$ TeV^{-2}	$-37 < a_C^W/\Lambda^2 < 34$ TeV^{-2}
$-25 < f_{T,0}/\Lambda^4 < 24$ TeV^{-4}	$-27 < f_{T,0}/\Lambda^4 < 27$ TeV^{-4}
$-12 < \kappa_0^W/\Lambda^2 < 10$ TeV^{-2}	$-12 < \kappa_0^W/\Lambda^2 < 12$ TeV^{-2}
$-18 < \kappa_C^W/\Lambda^2 < 17$ TeV^{-2}	$-19 < \kappa_C^W/\Lambda^2 < 18$ TeV^{-2}

The LEP aTGC results in terms of dim-6 operators, with non-linear realisation of SU(2)×U(1) in effective Lagrangian

Post-Higgs boson discovery: linear realization a la SM more appropriate, quartic couplings involving photons appear as dim-8 operators.

For some operators similar Lorentz structure between the two realization - can be expressed in terms of each other - whereas others cannot.

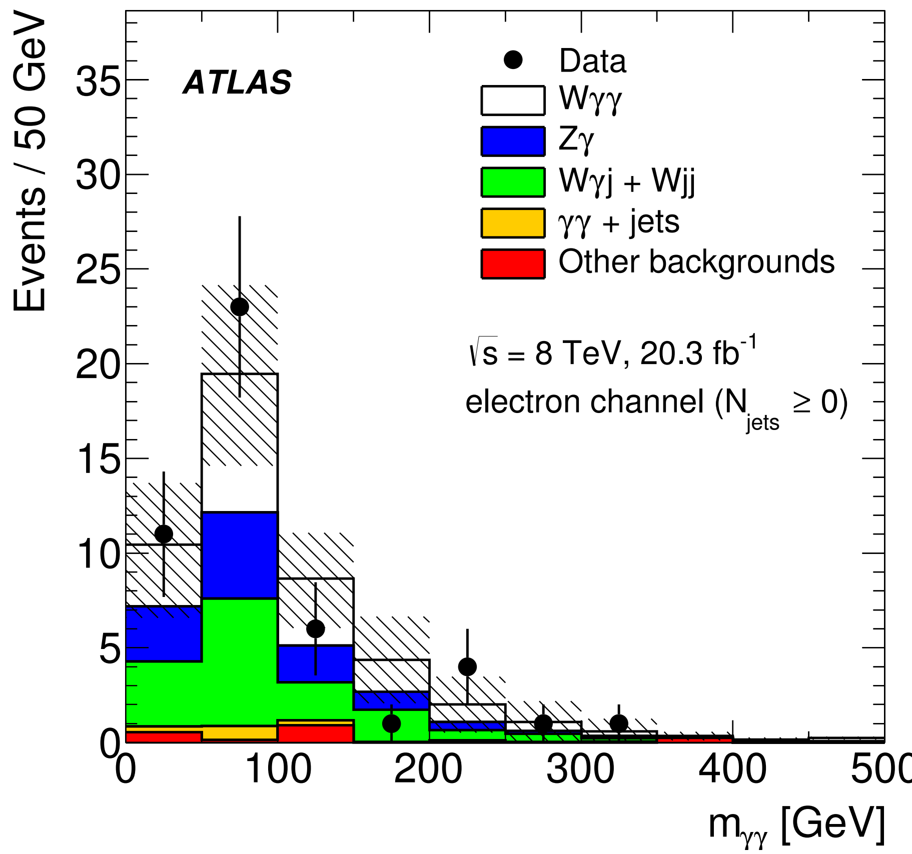
4 parameters with analogues between the two realizations, as well as one which is unique to the linear realization, presented. Also at the same time the form factor was dropped.

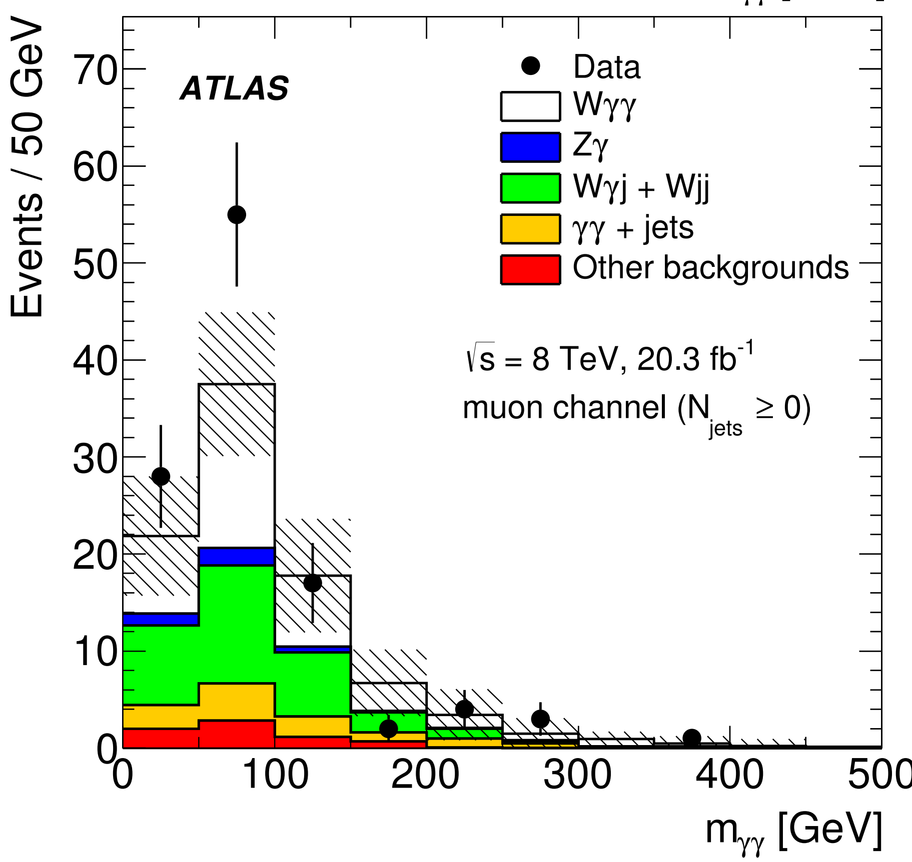
Search for Wγγ→lνγγ

Search for triboson production Wγγ
ATLAS: ~20.3 fb^{-1} of 8 TeV data, published as arXiv:1503.03243

Signature: Wγγ→lνγγ
Main background Wγ+jets, then Wjj, Zγ, γγ+jets

Selection criteria	$e\nu\gamma\gamma$	$\mu\nu\gamma\gamma$
Lepton p_T	$p_T^e > 20\,GeV$	$p_T^\mu > 20\,GeV$
Lepton η	$\lvert\eta_e\rvert < 2.47$ excl. $1.37 < \lvert\eta_e\rvert < 1.52$	$\lvert\eta_\mu\rvert < 2.4$
W transverse mass	$m_T > 40\,GeV$	
Missing E_T	$> 25\,GeV$	
Lepton track isolation	$p_T^{iso}(\Delta R = 0.2) < 0.15\,p_T^{lepton}$	
Lepton calo isolation	$E_T^{iso}(\Delta R = 0.2) < 0.20\,p_T^{lepton}$	–
Lepton $\lvert d_0\rvert/\sigma(d_0)$	< 6	< 3
Lepton $\lvert z_0 \cdot \sin\theta\rvert$	< 0.5 mm	
Photons	$E_T^\gamma > 20\,GeV$ $\lvert\eta_\gamma\rvert < 2.37$ (excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$) $\Delta R(l,\gamma) > 0.7$ $\Delta R(\gamma,\gamma) > 0.4$ $E_T^{iso}(\Delta R = 0.4) < 4\,GeV$	
Z rejection cuts	$m(e\gamma\gamma) - m(Z) < -10\,GeV$ or $> 5\,GeV$	–
	$m(e\gamma_1) - m(Z) < -10\,GeV$ or $> 3\,GeV$	–
	$m(e\gamma_2) - m(Z) < -5\,GeV$ or $> 3\,GeV$	–
	$p_T(e\gamma\gamma) > 30\,GeV$	–
	inclusive: $N_{jet} > 0$; exclusive: $N_{jet} = 0$	
Jet	anti-k_t with R=0.4 $p_{T^{jet}} > 30\,GeV$, $\lvert\eta^{jet}\rvert < 4.4$ $\Delta R(\text{lepton}/\gamma, \text{jet}) > 0.3$ jet vertex fraction > 0.5 for jets with $p_T < 50\,GeV$ and $\lvert\eta\rvert < 2.4$	





Search for Wγγ→lνγγ

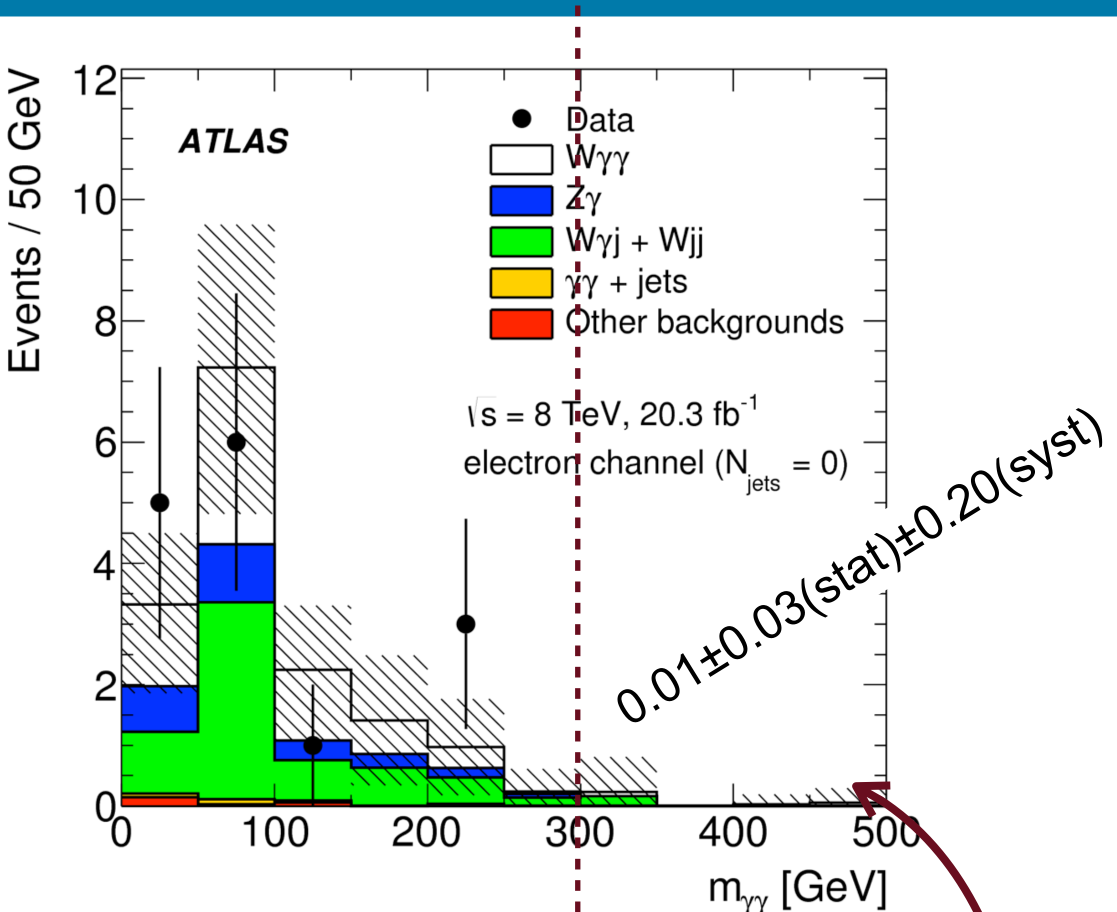
Definition of the fiducial region
$p_T^\ell > 20\,GeV$, $p_T^\nu > 25\,GeV$, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40\,GeV$
$E_T^\gamma > 20\,GeV$, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^P < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma,\text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{\text{jet}} > 30\,GeV$, $\lvert\eta^{\text{jet}}\rvert < 4.4$

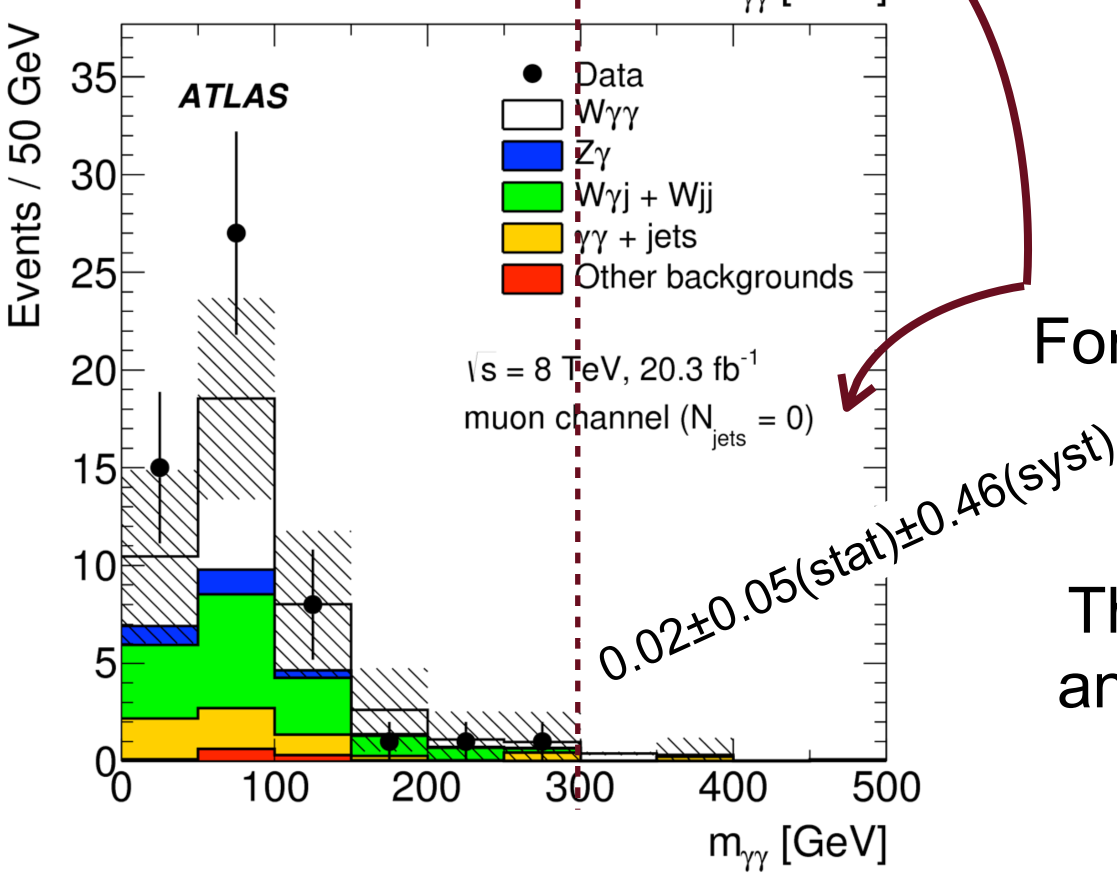
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

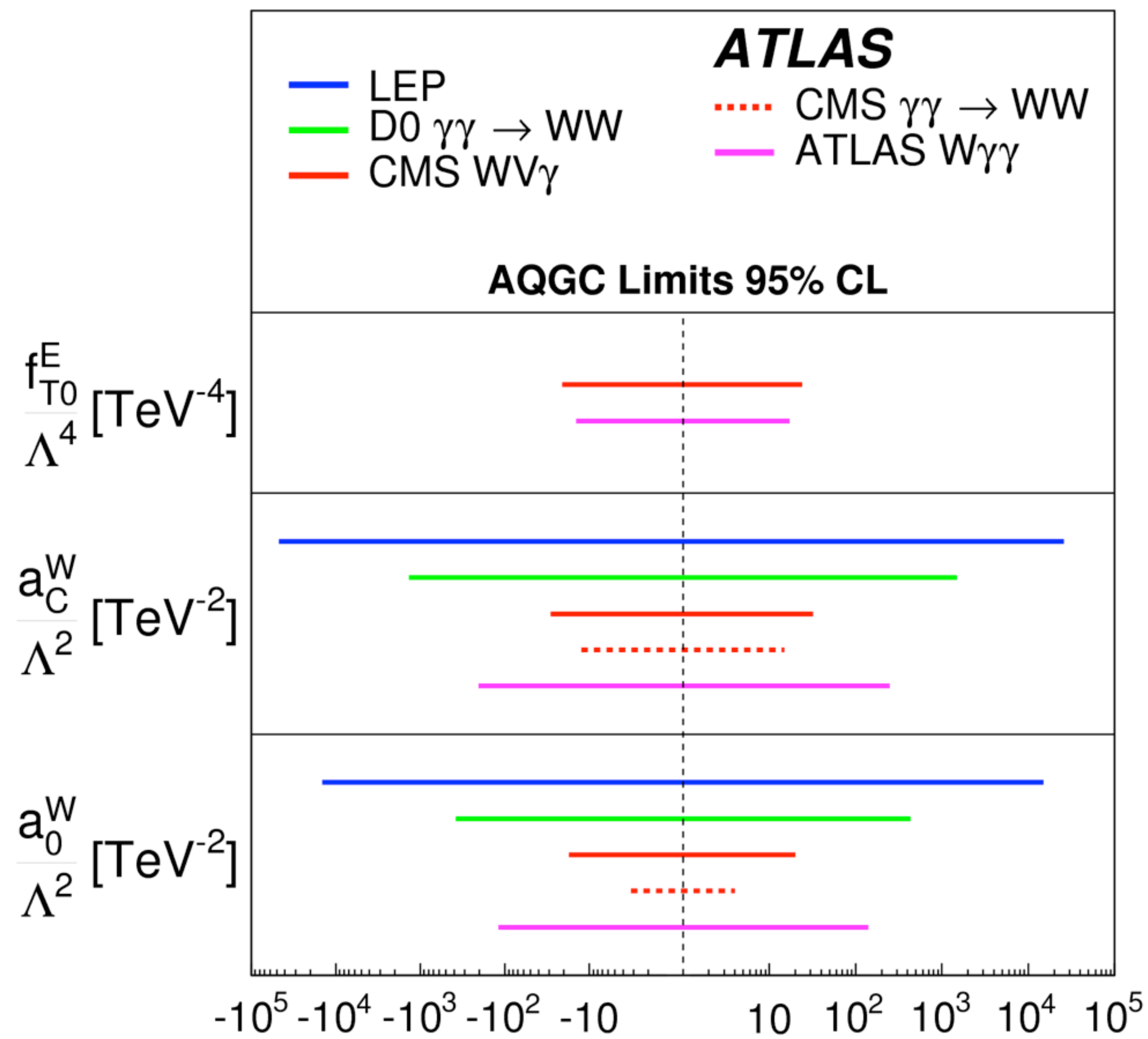
Significance in inclusive production cross-section >3σ

First evidence for triple-gauge boson production

Search for Wγγ→lνγγ: aQGC







(no form factor)

For aQGC require additional selection $m_{\gamma\gamma}$>300GeV on top of the exclusive selection

Three dim-8 operators (linear realisation) are constrained, and translated to match definitions used by LEP and CMS. Results with and without form factor given

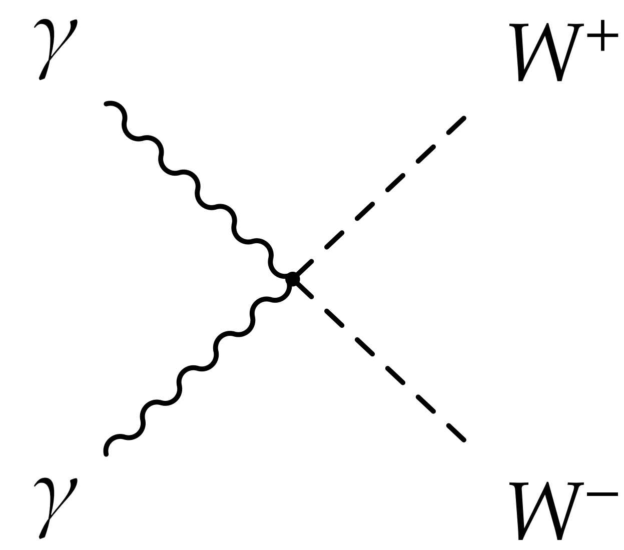
Exclusive VBS at LHC: γγ→WW

First VV→VV analysis at the LHC : γγ→WW
CMS using 5.2 fb^{-1} of 7 TeV data, published as JHEP 07 (2013) 216

Signature is exclusive or quasi-exclusive W^+W^- production:

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

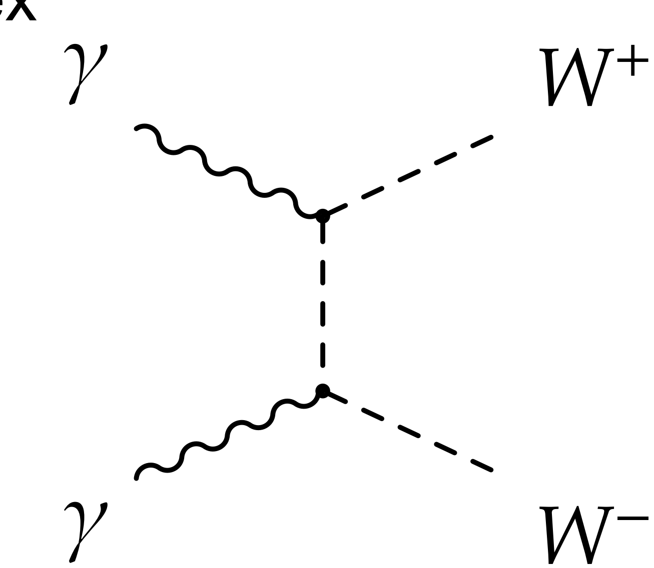
both very-forward scattered protons escape detection



QGC

Distinct signature: In the interaction only $e^\pm\mu^\mp$ produced, nothing else
Main backgrounds: γγ/DY→ττ, diffractive WW and W+jets

Selection:
- Leptons with p_T>20 GeV and |η|<2.4
- e-μ pair with opposite charge and compatible with a common vertex
- m_{ll}>20 GeV
- zero additional tracks in vertex
  → Underlying Event for non-exclusive pp interactions
- $p_T(e\mu)$ > 30 GeV
  → suppress γγ/DY→ττ
- veto events passing $\mu^\pm\mu^\mp$ selection
  → suppress DY events with μ mis-identified as e, due to brem
- for aQGC studies $p_T(e\mu)$ > 100 GeV



TGC

γγ→WW

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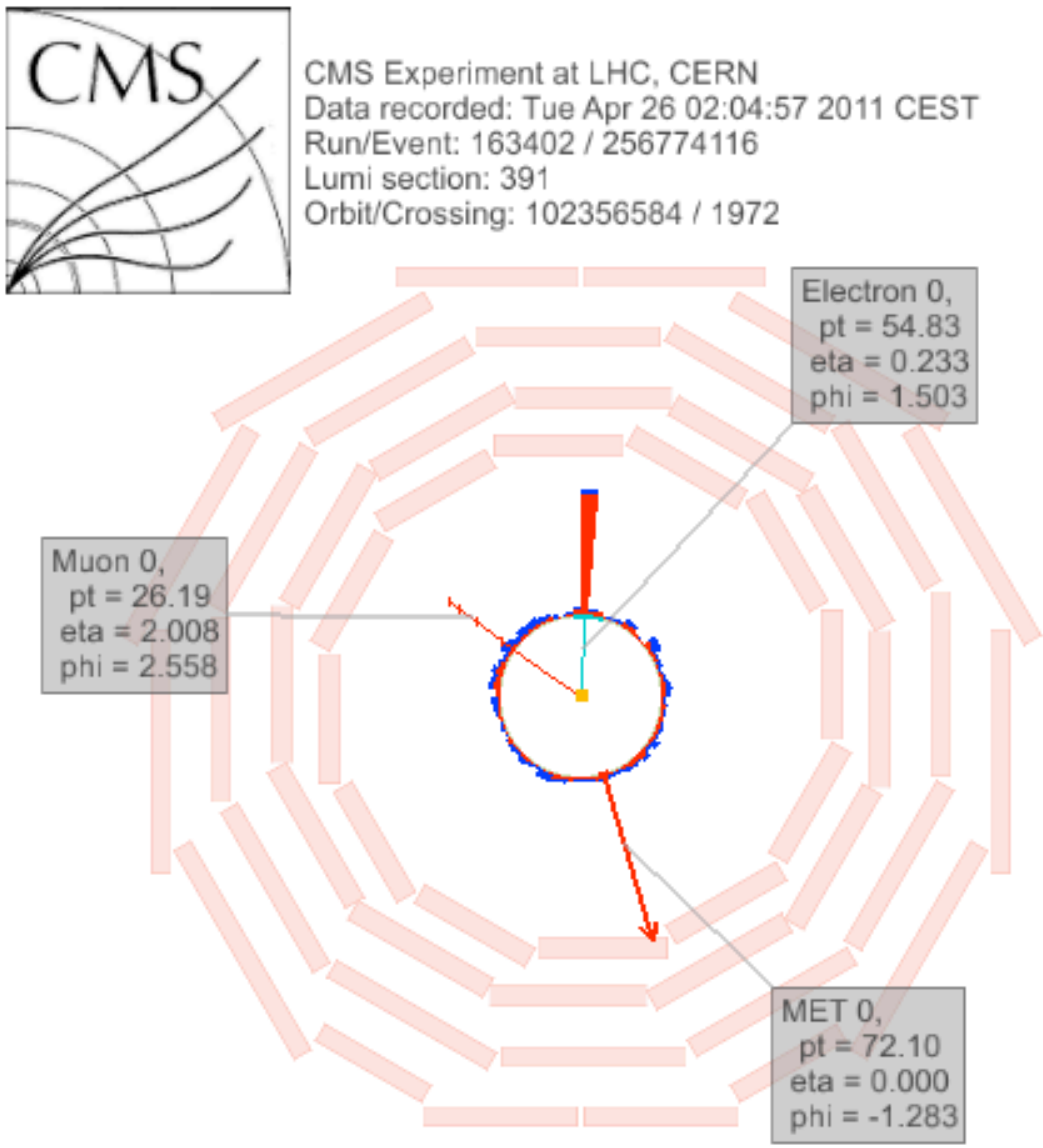

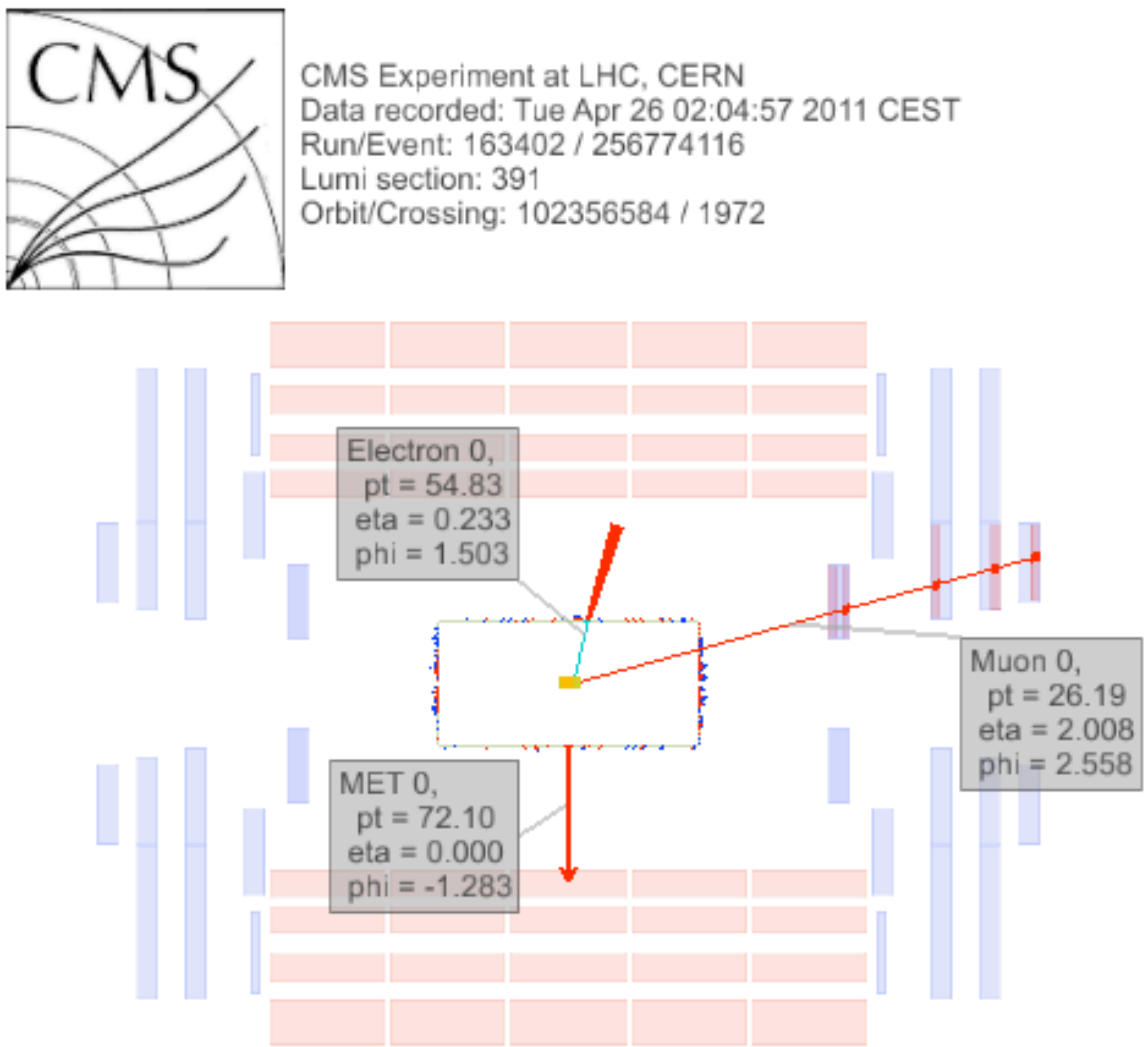

This is the kind of events we look for!

γγ→WW

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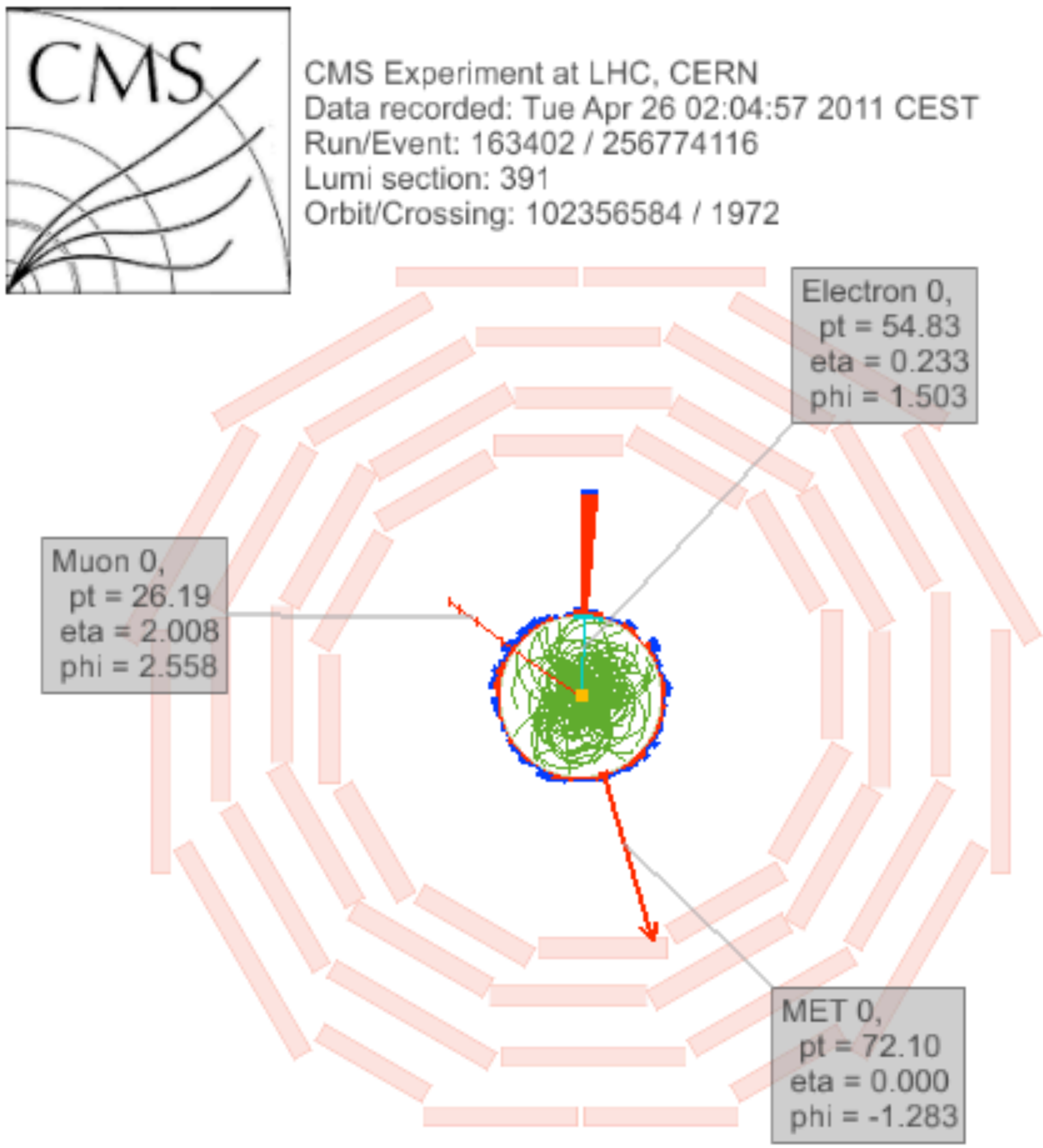
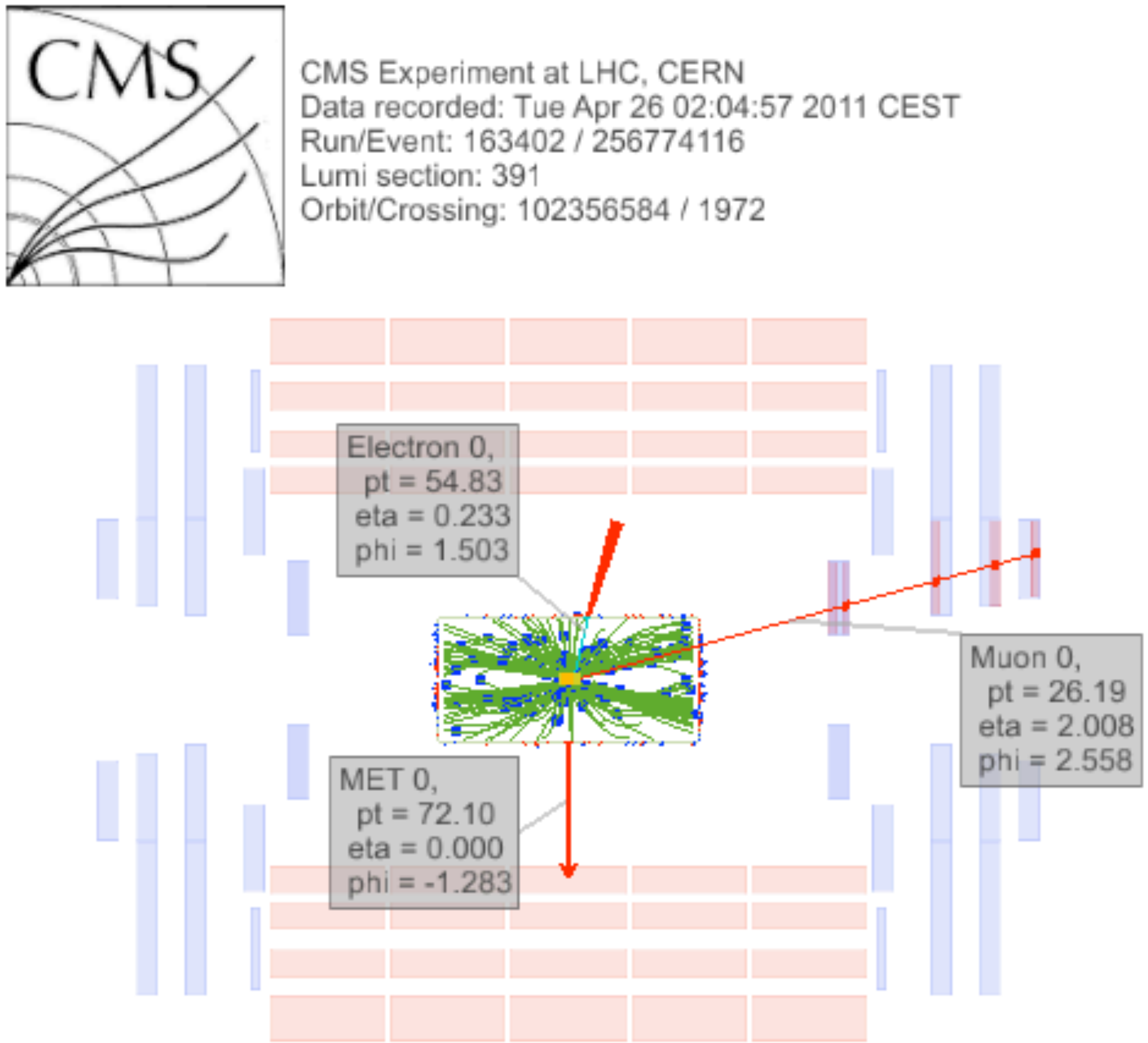
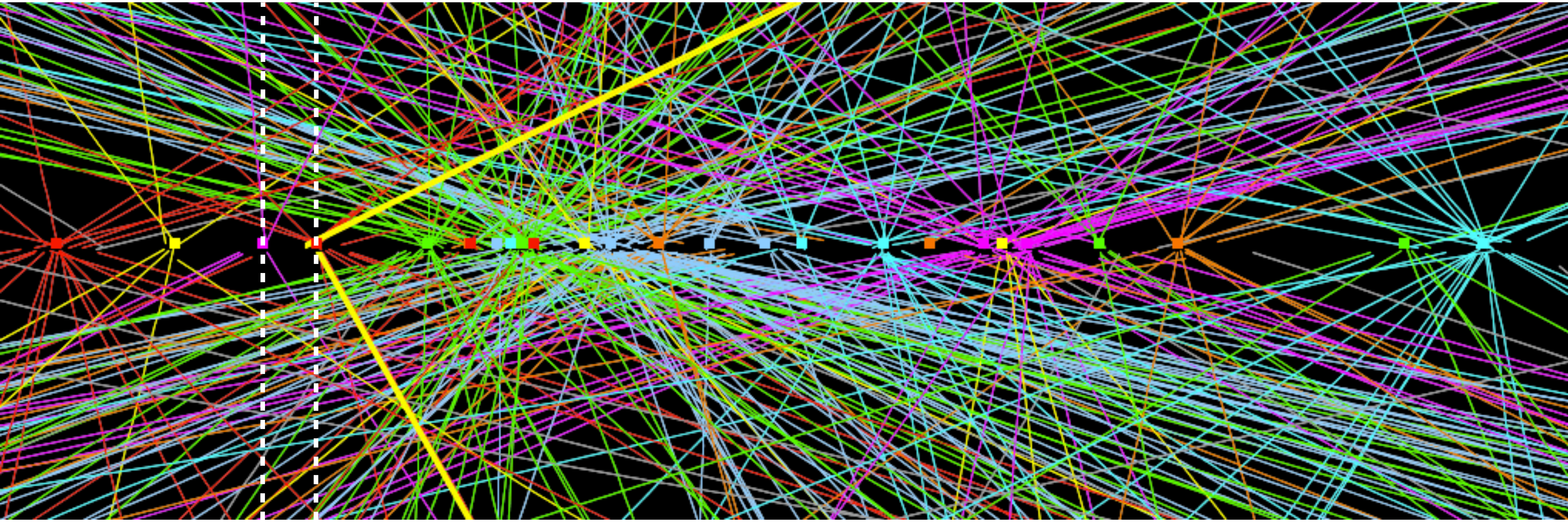




This is the kind of events we see...
striking difference in the activity in the detector

Pile-up (again)



Δz

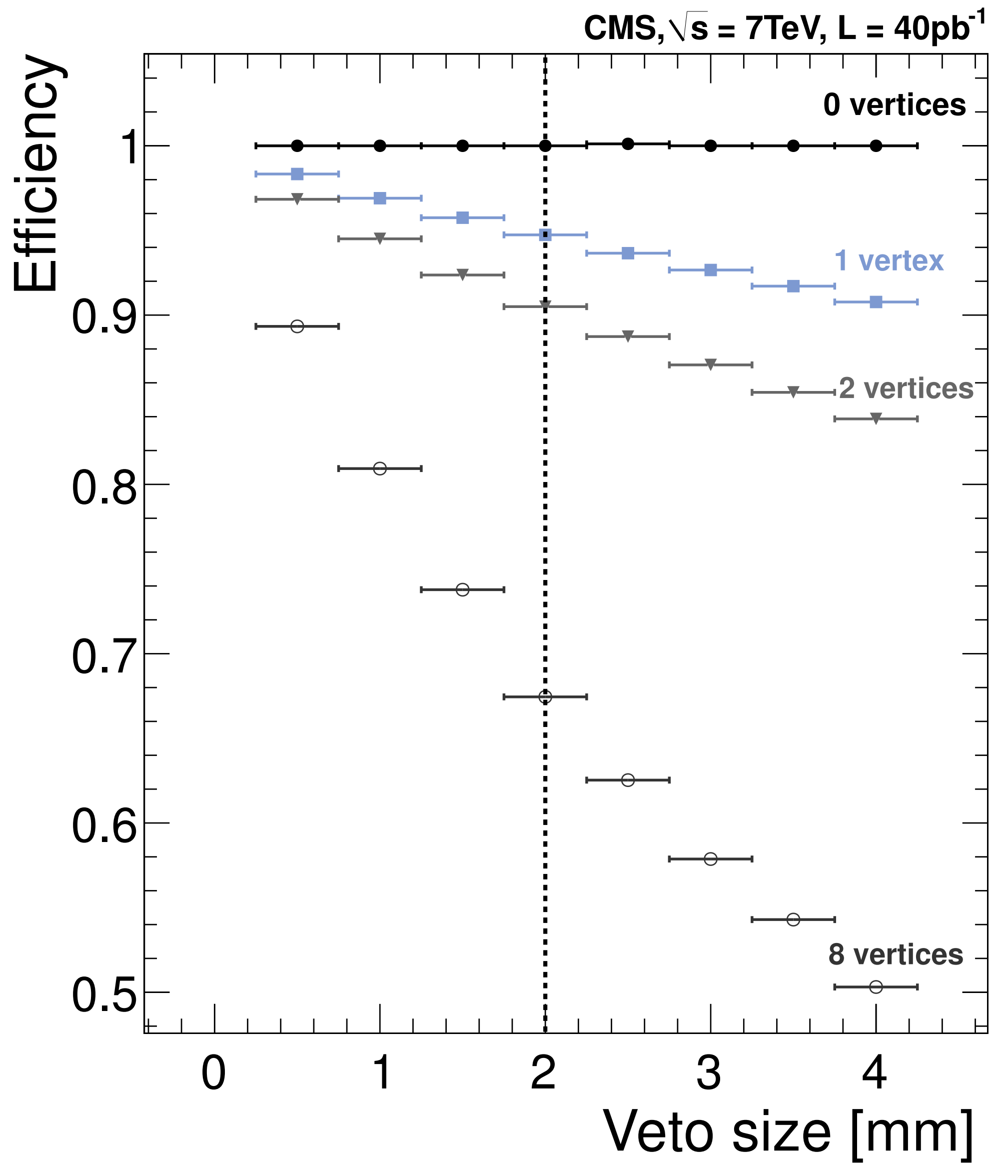
Our handle to separate different pp interactions within the same bunch crossing

Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown

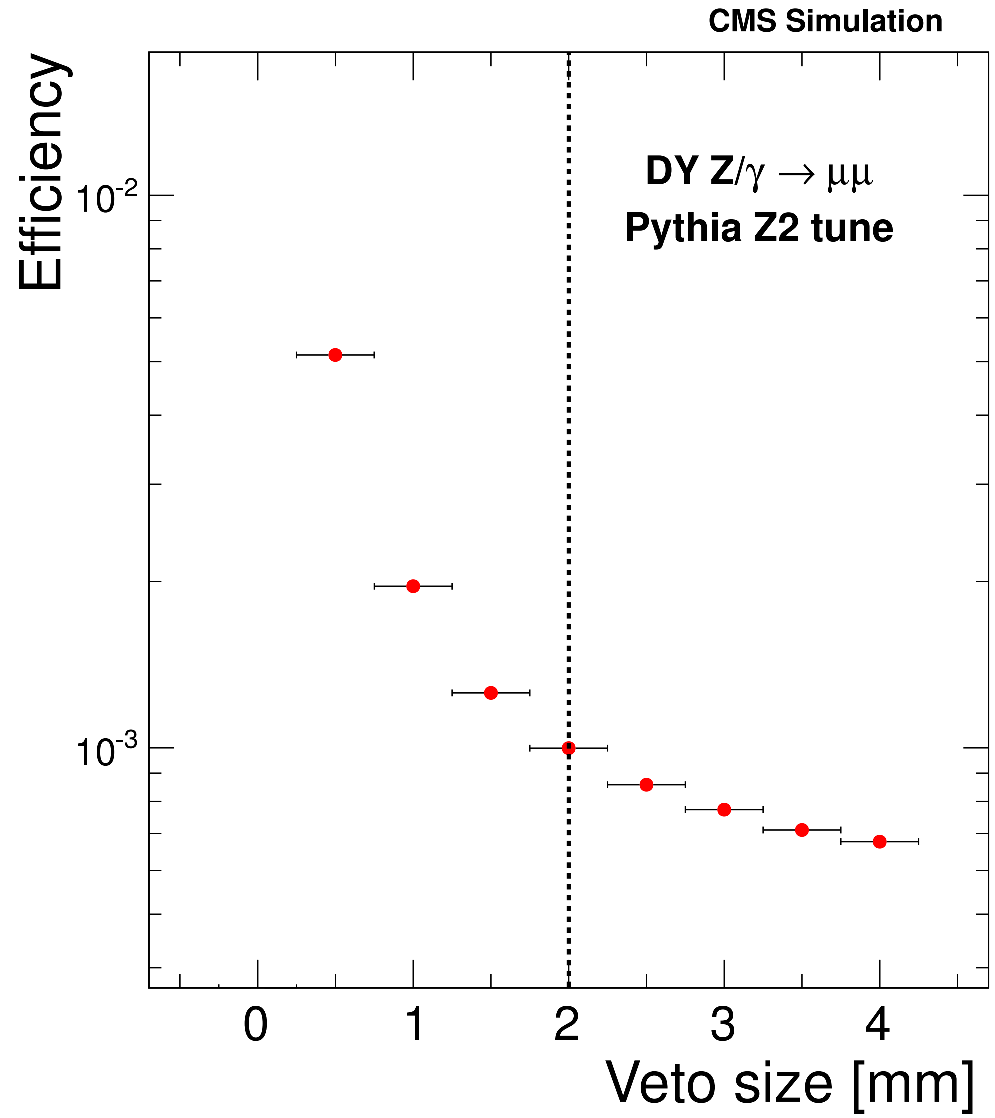
Δz requirement

JHEP 01 (2012) 052

Veto eμ reconstructed vertices which have another track within 2mm
Trade-off between signal efficiency and background rejection:
wide Δz to "capture" tracks accompanying DY events, but narrow enough to suppress pile-up



"zero-bias" events, triggered only by presence of colliding bunches. Artificial dimuon vertex added in each event as proxy for an exclusive dimuon interaction.



Signal efficiency deteriorates rapidly when μ increases → challenging analysis for 8 TeV data?
7 TeV datasample <μ>=9 interactions/bc → 40% signal inefficiency

Vertex Track Multiplicity

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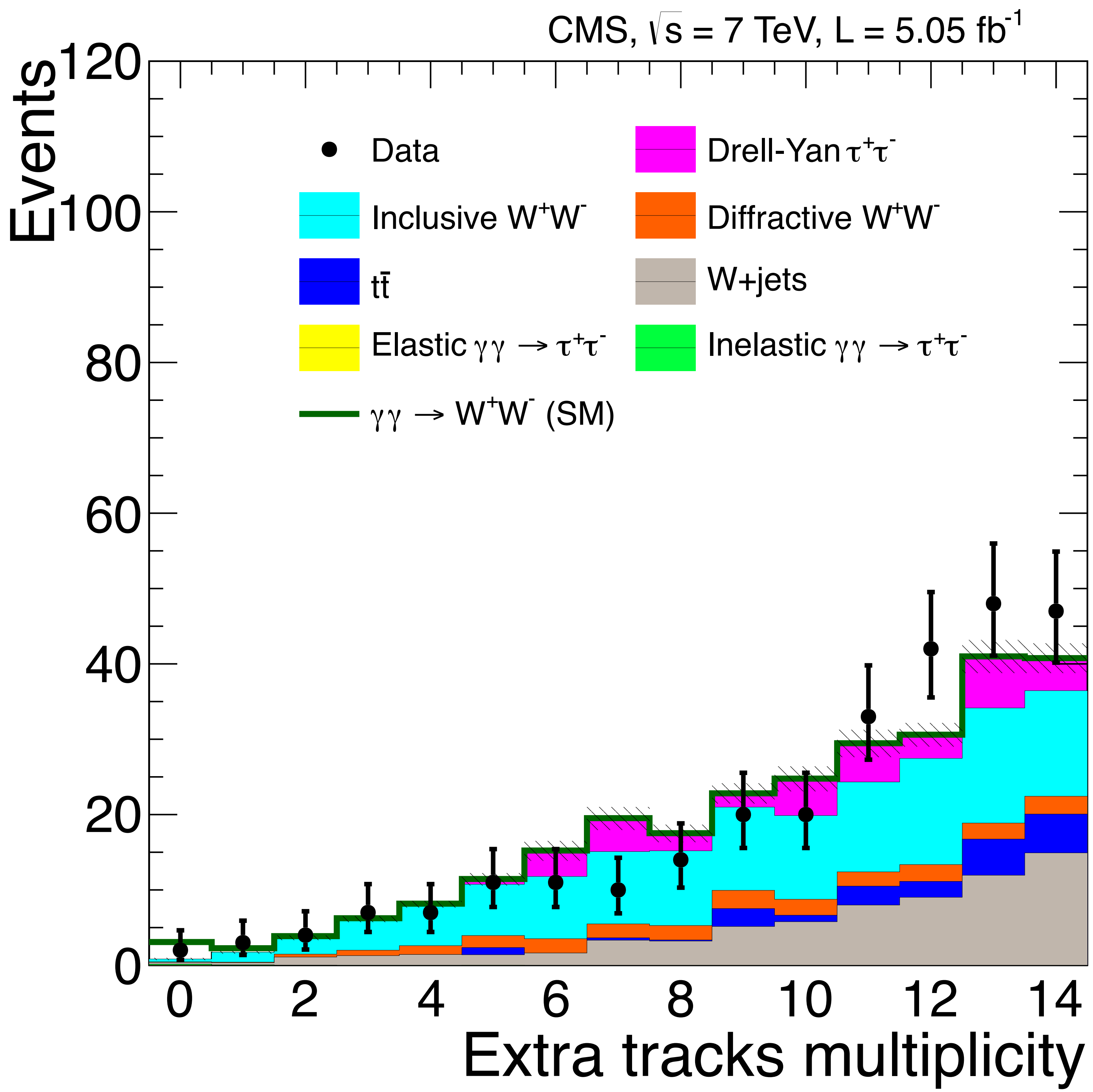
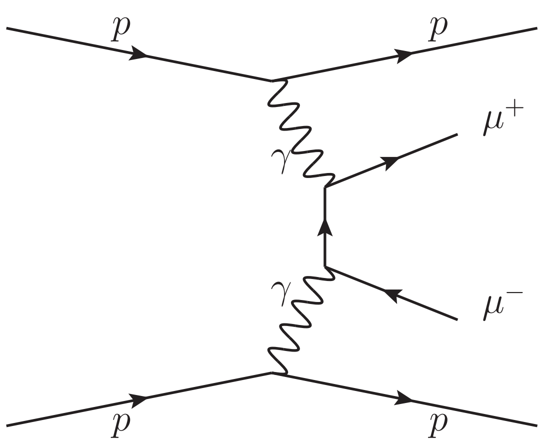
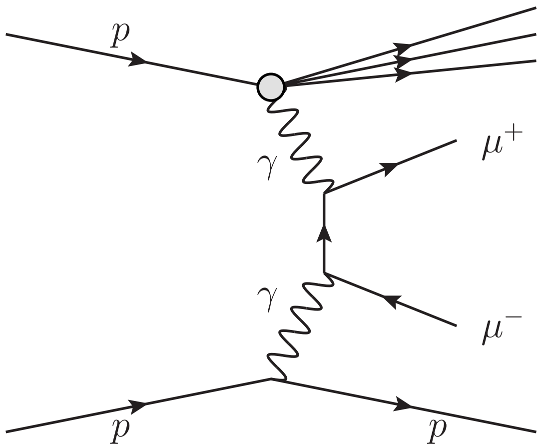
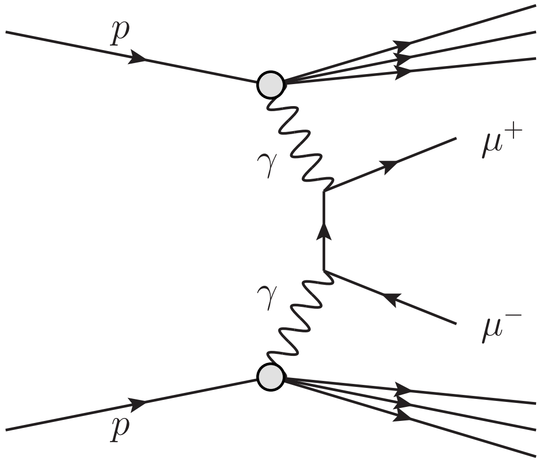


Estimating the SM expectation







exclusive/elastic

inelastic/
proton dissociative

inelastic/
proton dissociative

γγ→WW produced in:

- "elastic" pp collisions
- "inelastic" pp collisions → one or both protons are breaking up

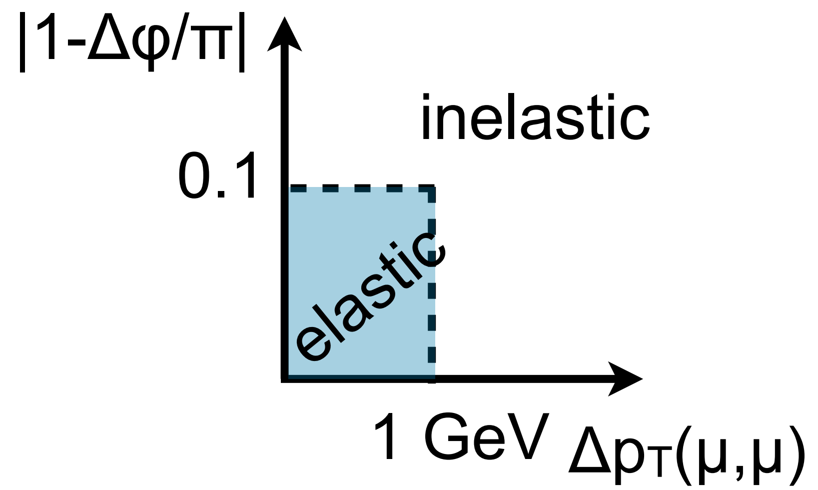
Proton dissociative processes difficult to estimate from "first principles" → soft-QCD

Absorption effects caused by strong interactions between the protons usually result in smaller dissociative contribution

Employ a data-driven estimate using the clean "$\gamma\gamma \to \mu^+\mu^-$" process,
also can be used to check the pile-up rejection (track veto) requirement

the γγ→μμ control region

Divide the sample in two regions based on p_T balance and acoplanarity

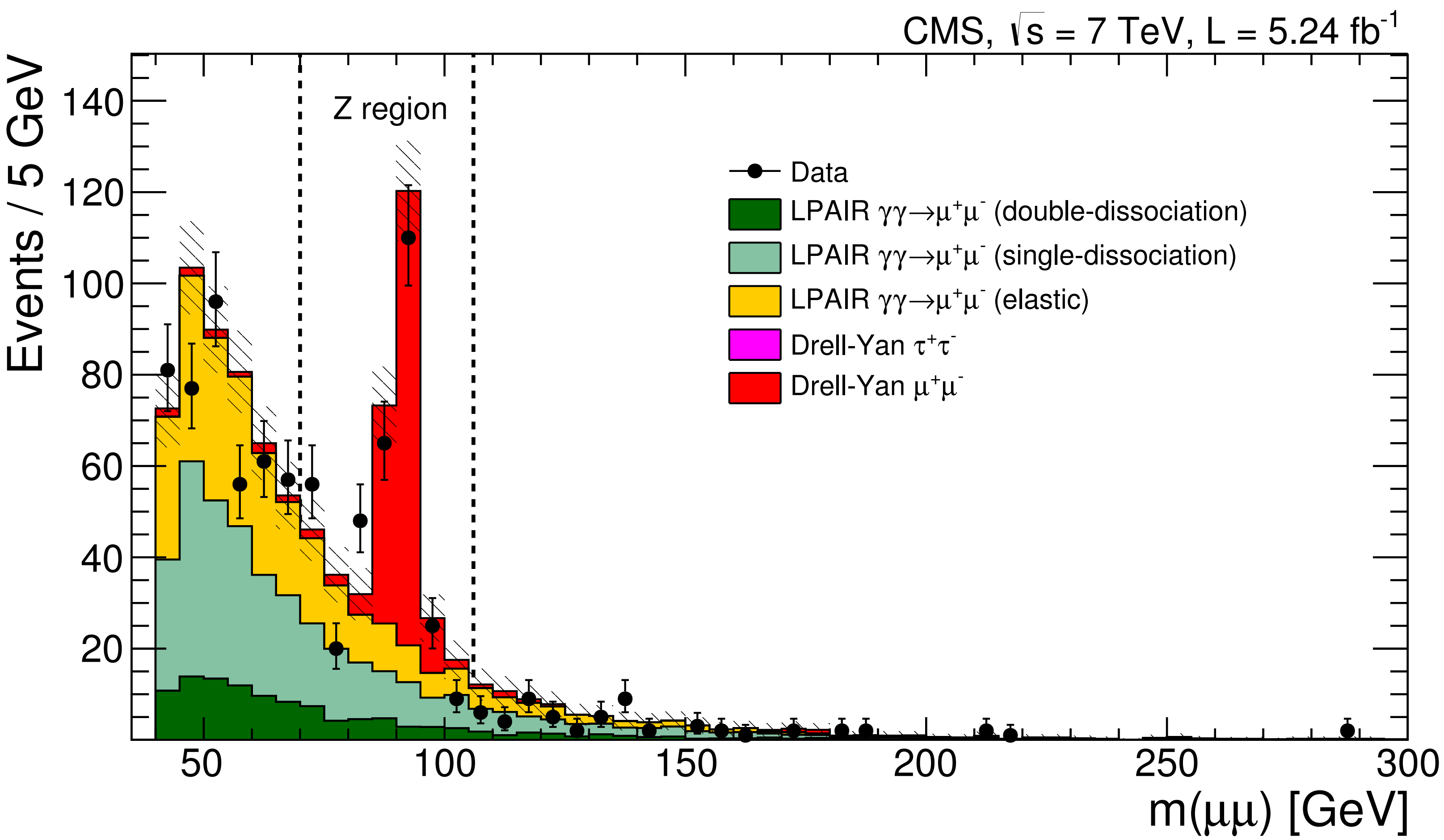


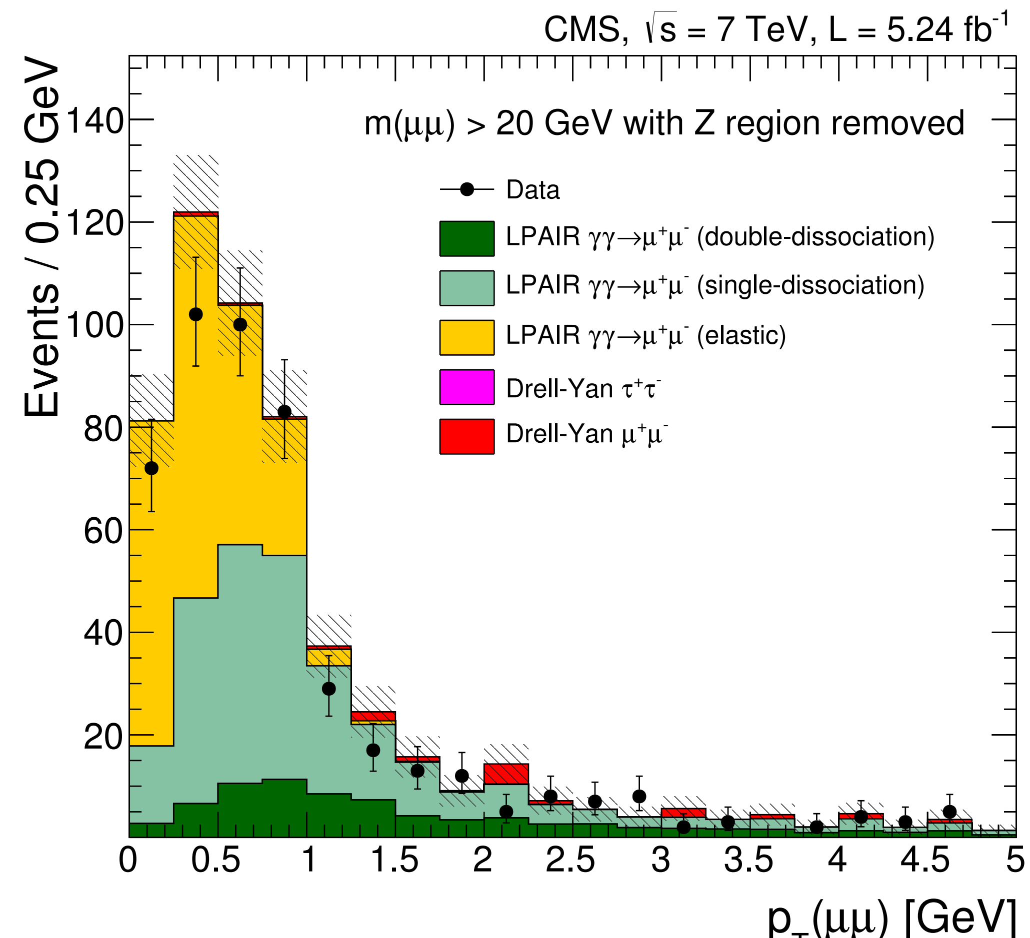
Region	Data	Simulation	Data/Simulation
Elastic	820	906 ± 9	0.91 ± 0.03
Dissociation	1312	1830 ± 17	0.72 ± 0.02
Total	2132	2736 ± 19	0.78 ± 0.02

(statistical uncertainties only)

Observed events compared to total expected events in the two control regions, after trigger and preselection criteria.

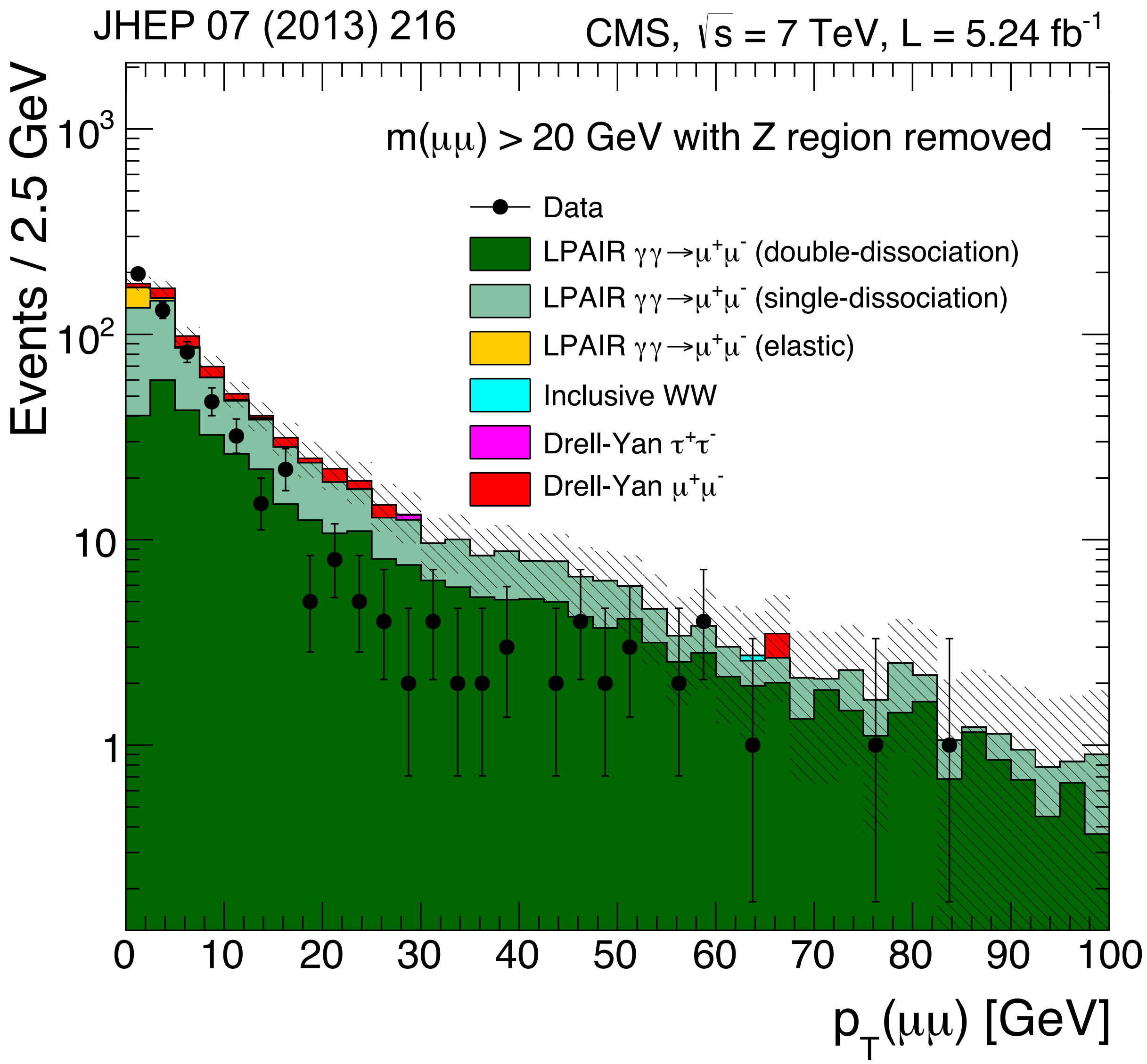
the γγ→μμ control region: elastic-region

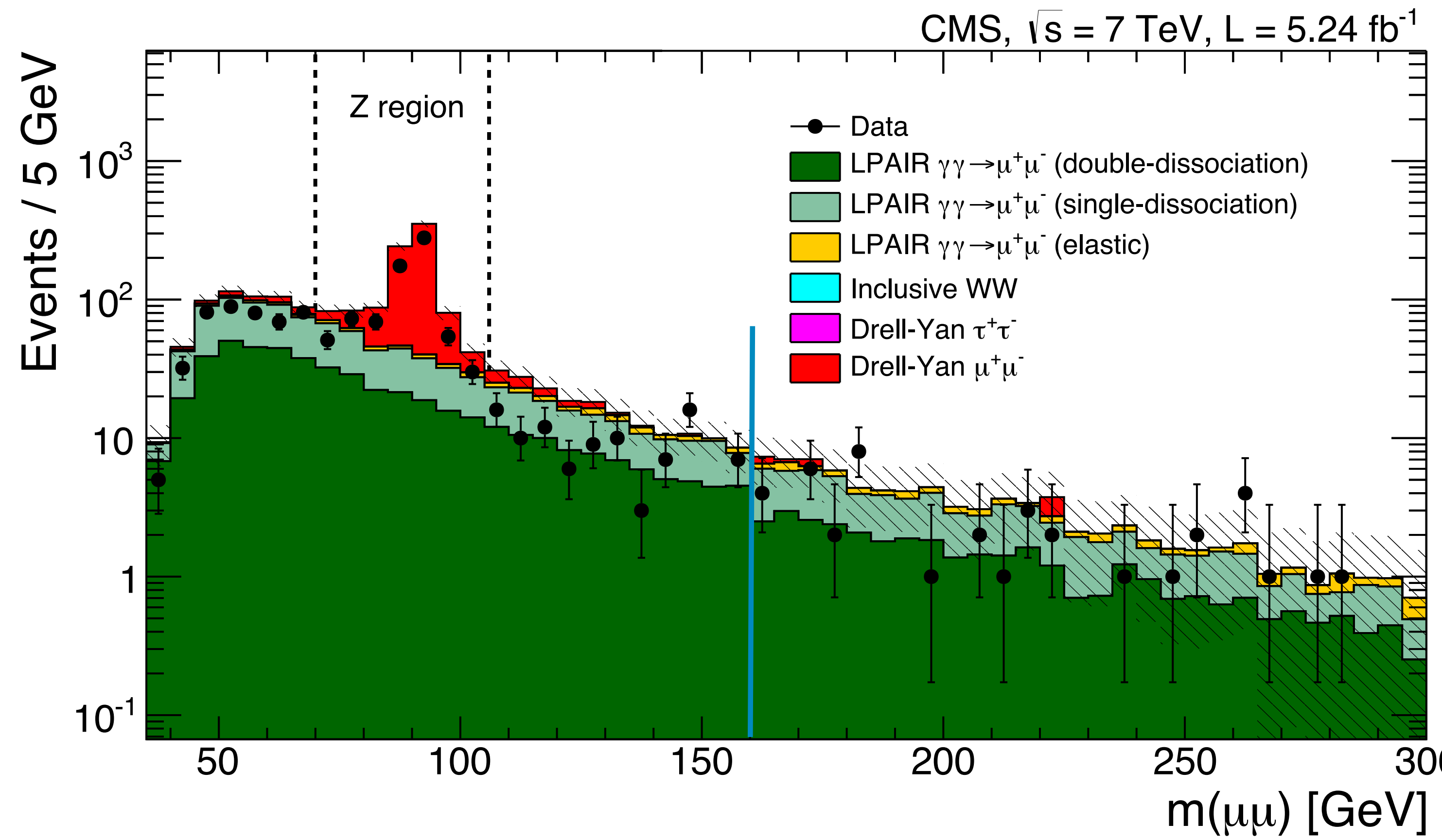




This is the region we have the better understanding of, and can use the Z peak to cross-check the Drell-Yan contributions

the γγ→μμ control region: inelastic-region

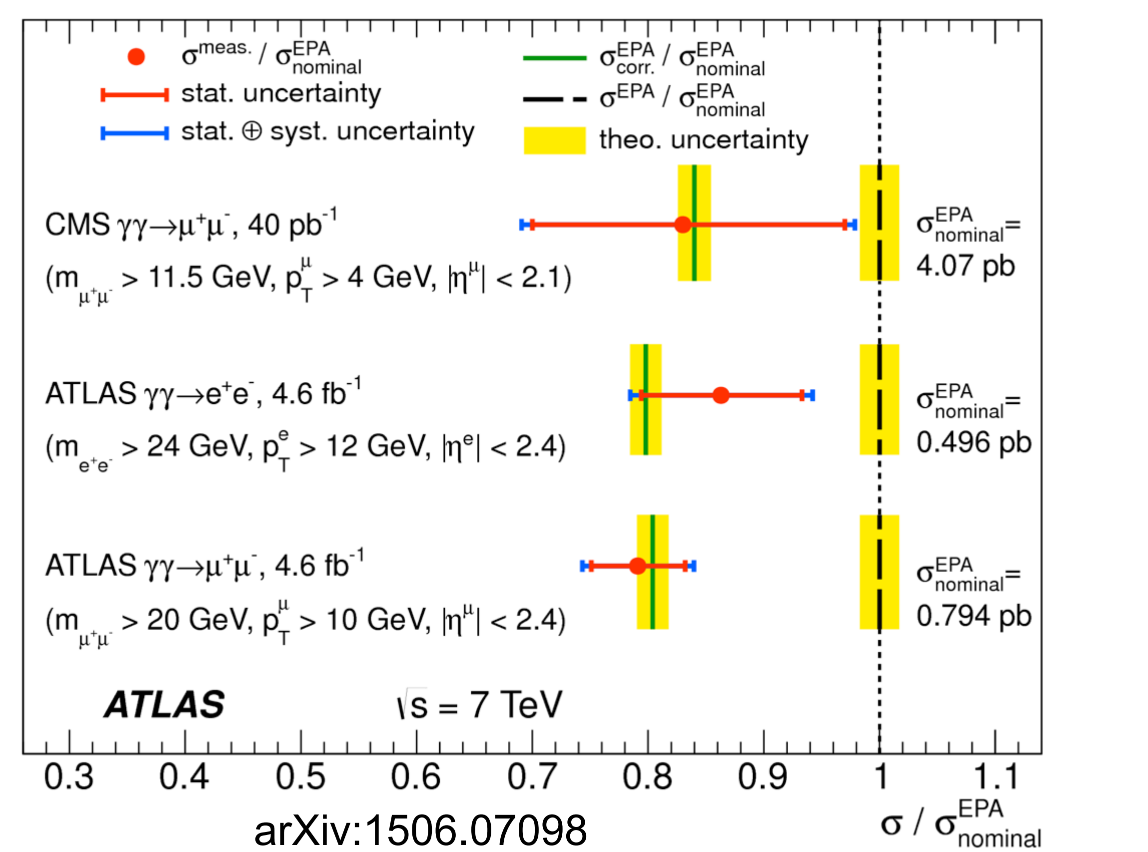




Scale Factor F estimated for quasi-exclusive production with respect to the “fully exclusive” elastic production of the LPAIR MC

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

$$F = 3.23 \pm 0.53.$$



γγ→WW: Control Regions

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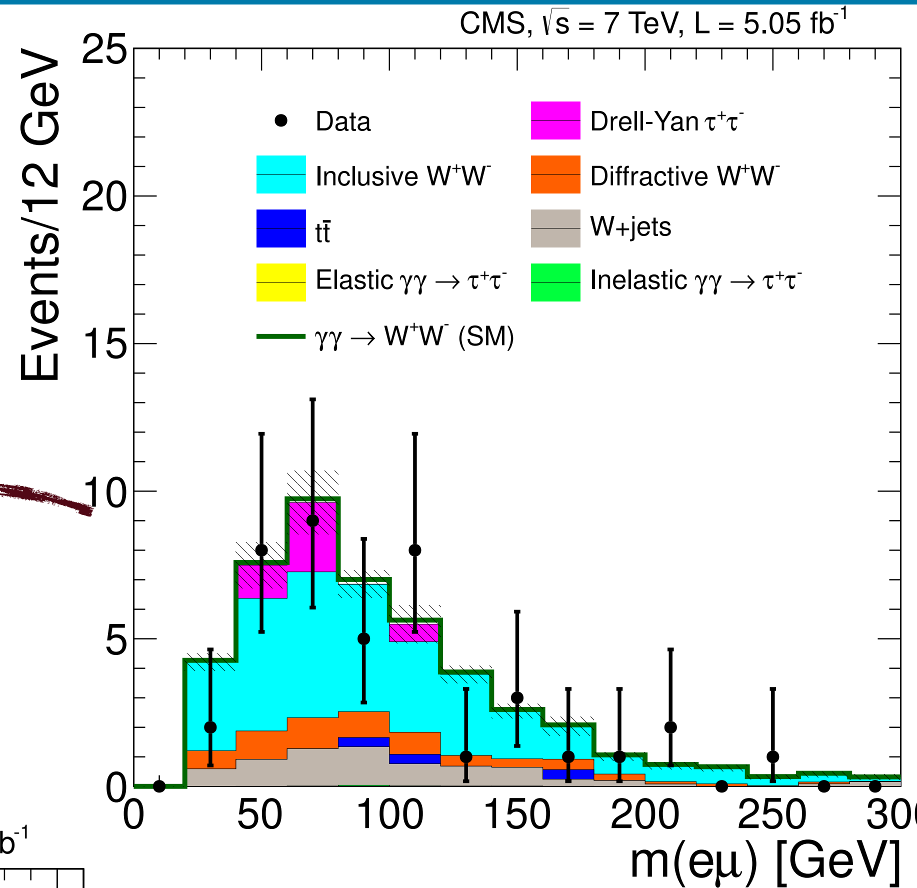
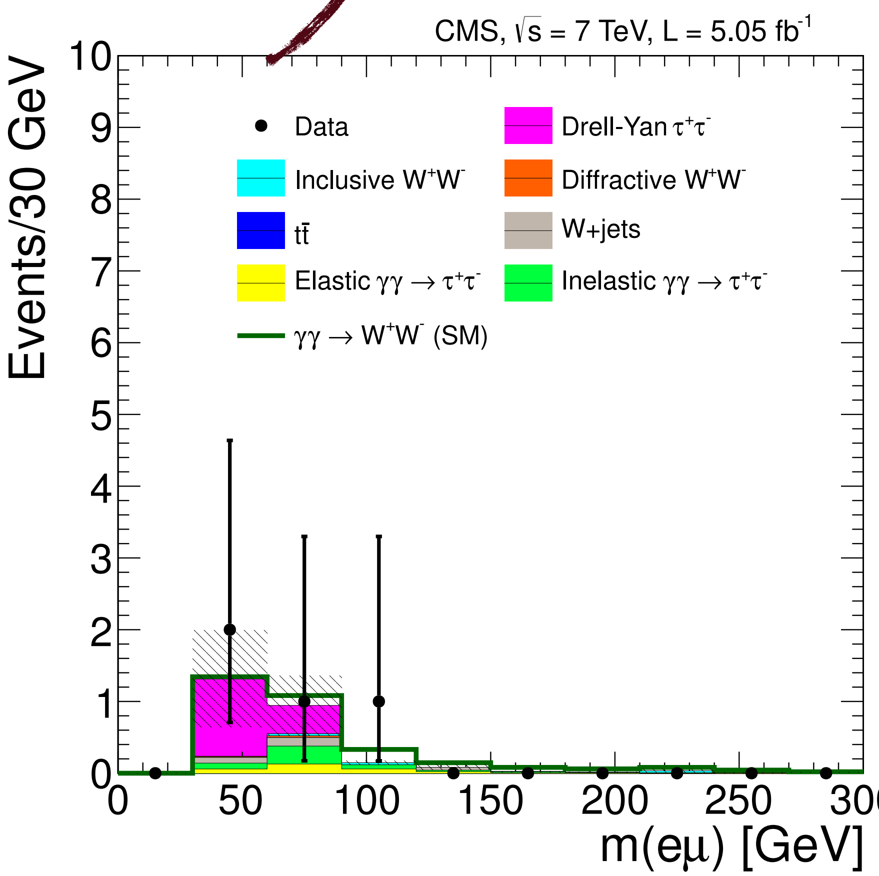
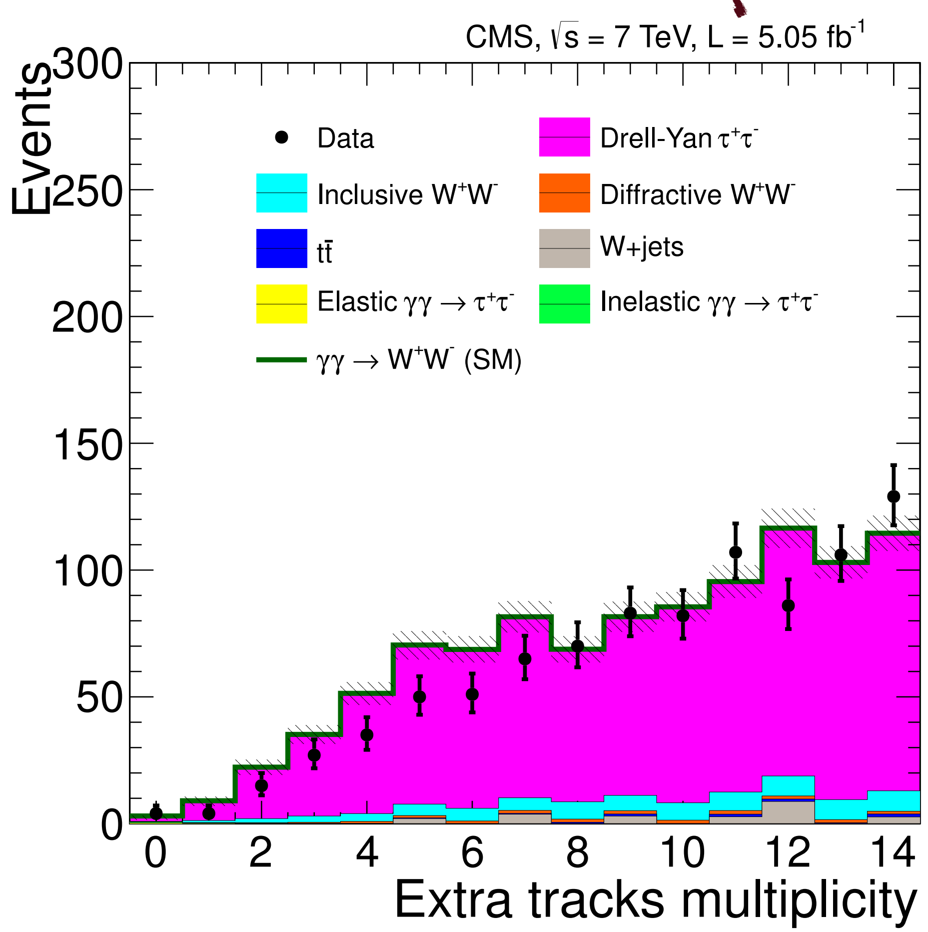
Region	Background process	$N_{\text{extra tracks}}$	$p_T(\mu^\pm e^\mp)$
1	Inclusive W^+W^-	$1 \le N_{\text{extra tracks}} \le 6$	>30 GeV
2	Inclusive Drell-Yan $\tau^+\tau^-$	$1 \le N_{\text{extra tracks}} \le 6$	<30 GeV
3	$\gamma\gamma \to \tau^+\tau^-$	$N_{\text{extra tracks}} = 0$	<30 GeV

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







γγ→WW: Results

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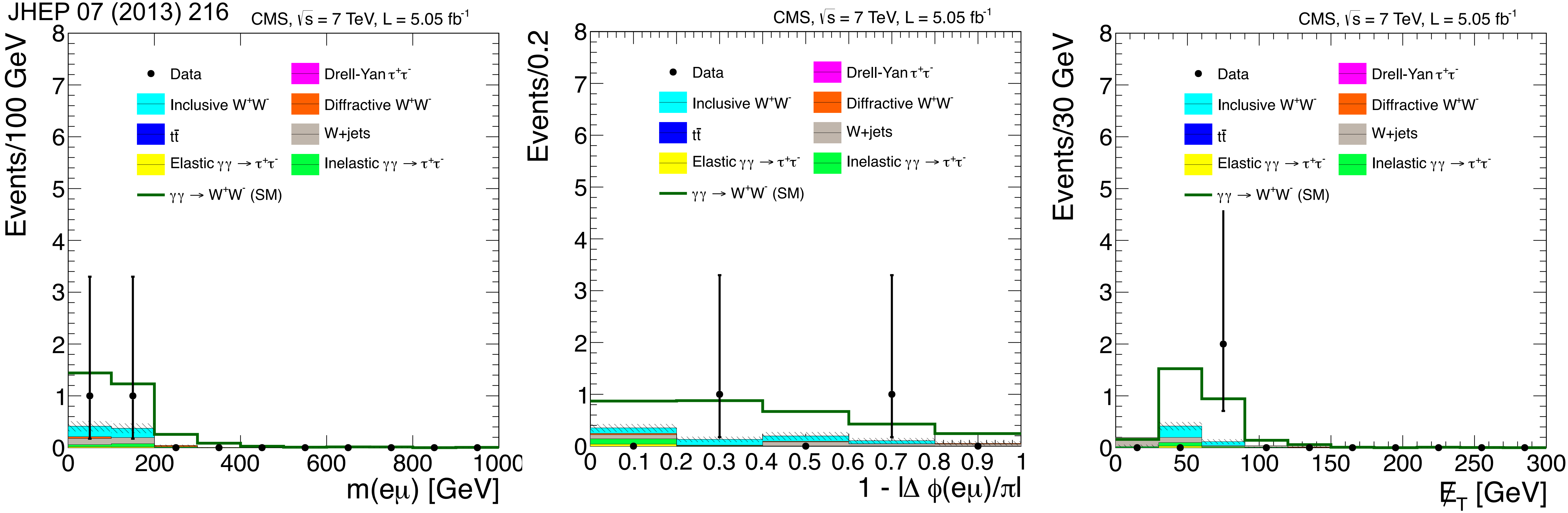

After applying the full selection, 2 events are observed
Expected background: 0.84 ± 0.15 events
Significance : ~1σ
Cross-section × Branching ratio:

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

In terms of 95% CL upper limit: $2.6(1.0^{+0.5}_{-0.6}) \times$ SM
95% CL upper limit: $\sigma(\mathrm{pp} \to \mathrm{p}^{(*)}\mathrm{W}^+\mathrm{W}^-\mathrm{p}^{(*)} \to \mathrm{p}^{(*)}\mu^\pm\mathrm{e}^\mp\mathrm{p}^{(*)}) < 10.6\,\mathrm{fb}.$

Cross section predicted 4.0 ± 0.7 fb

γγ→WW: Results

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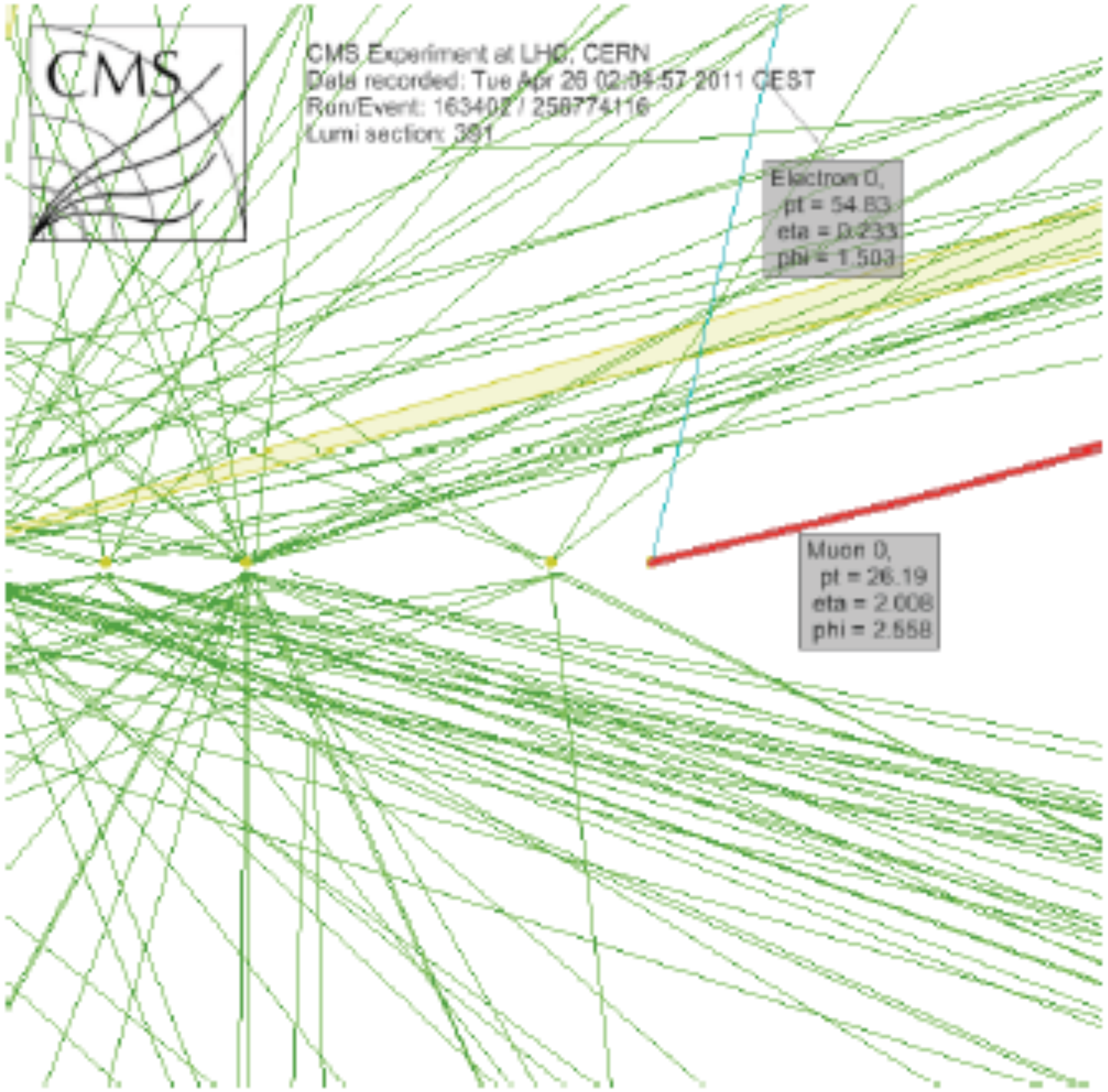

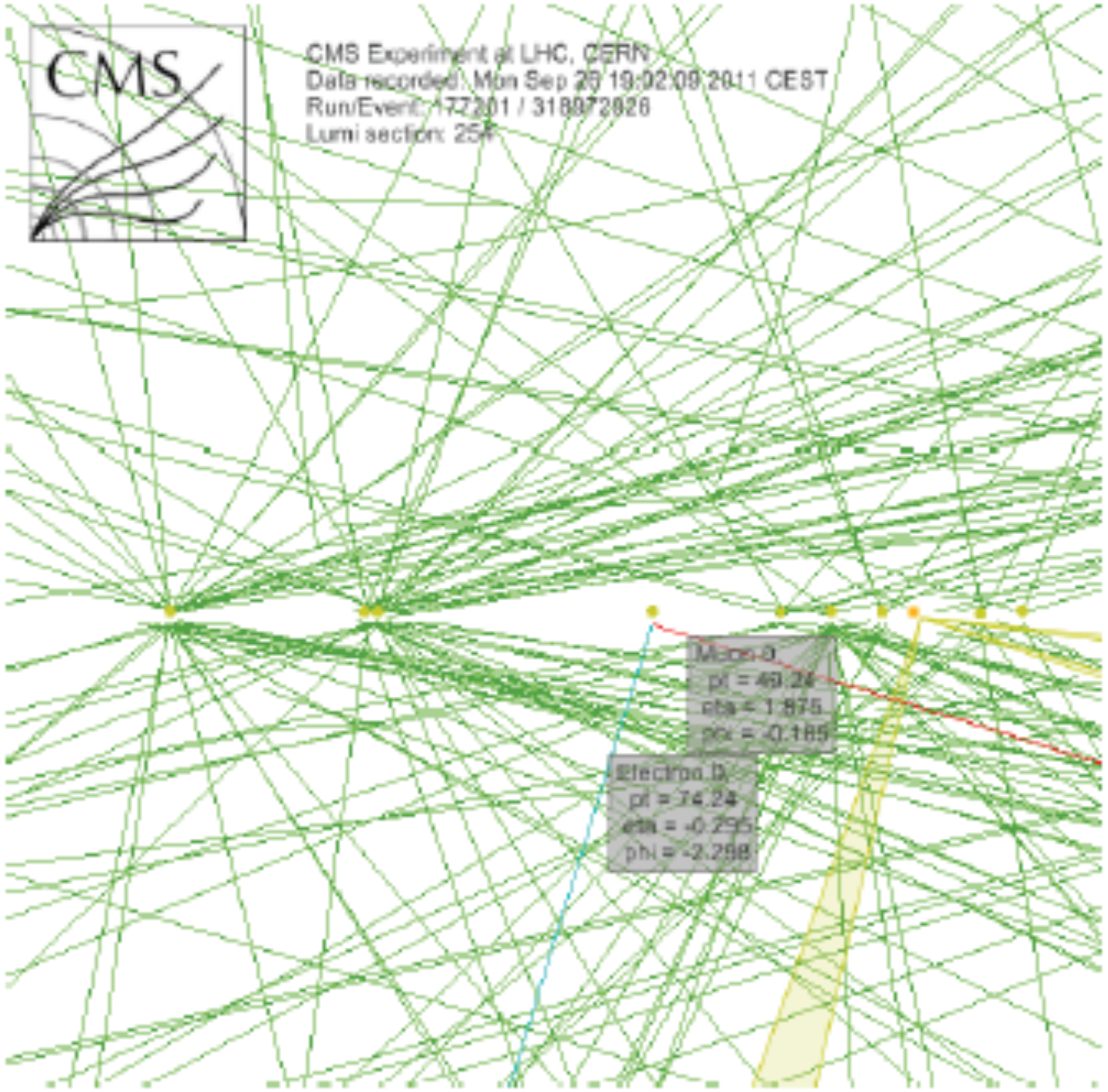

γγ→WW: aTGCs

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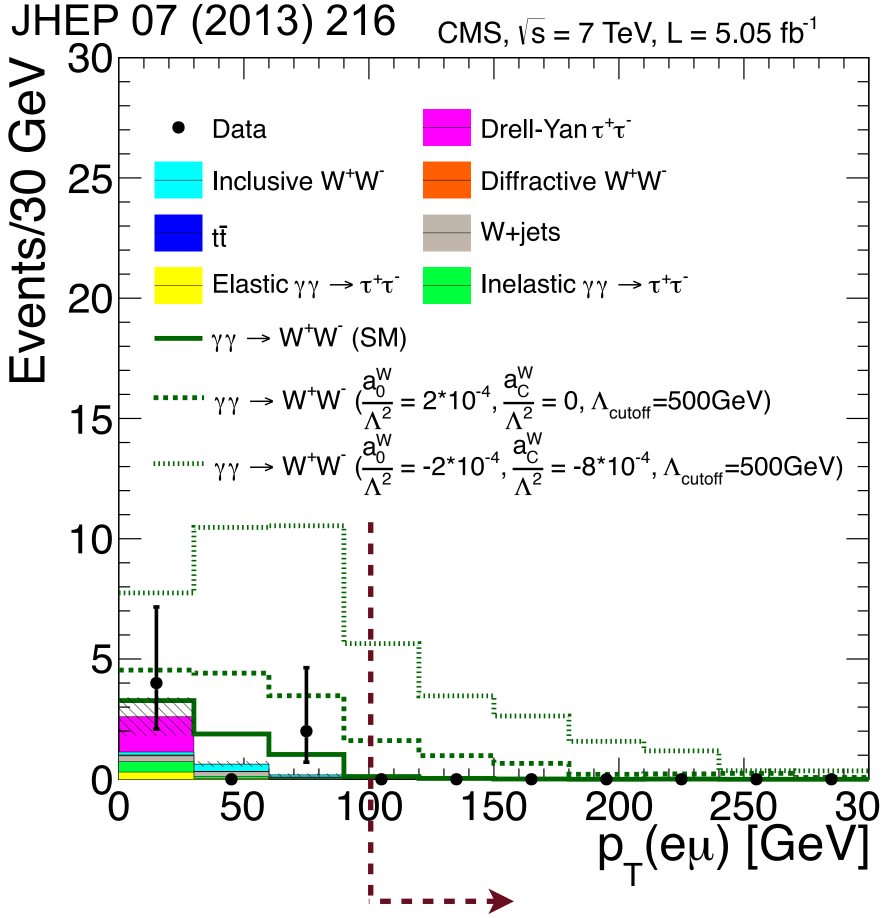
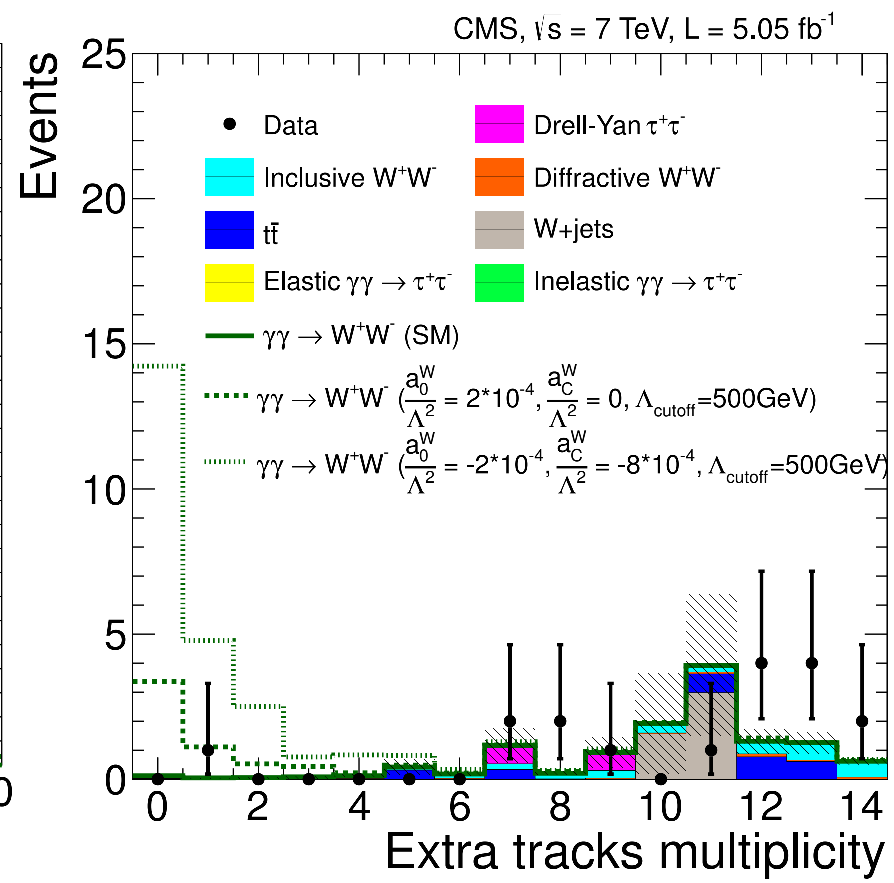
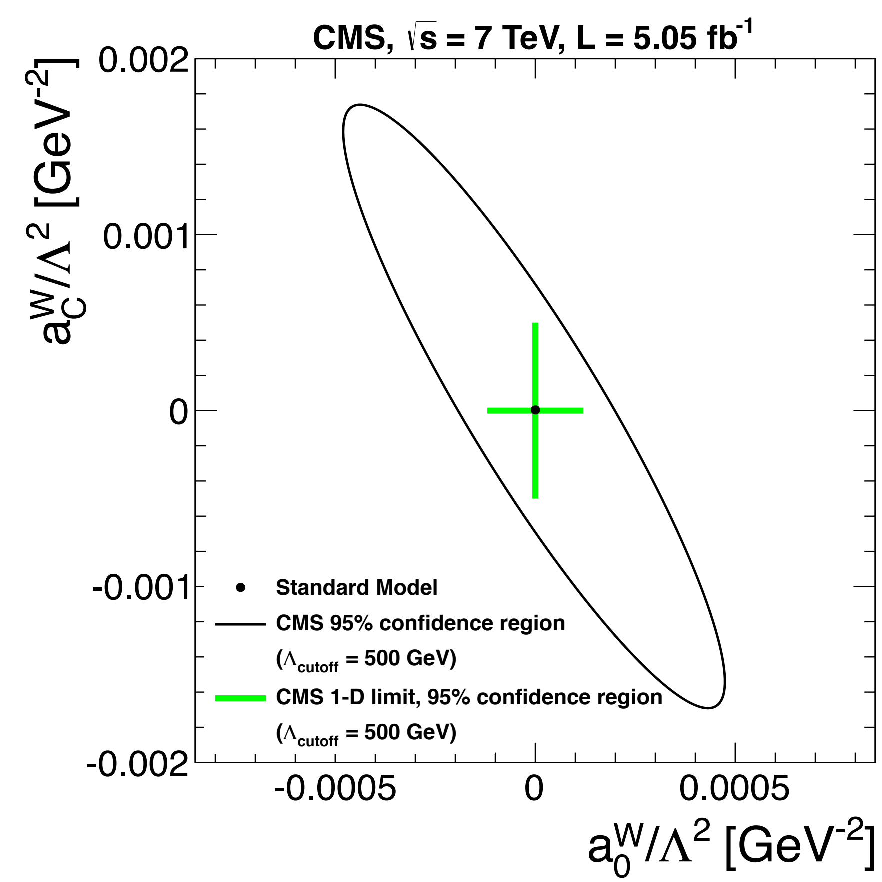




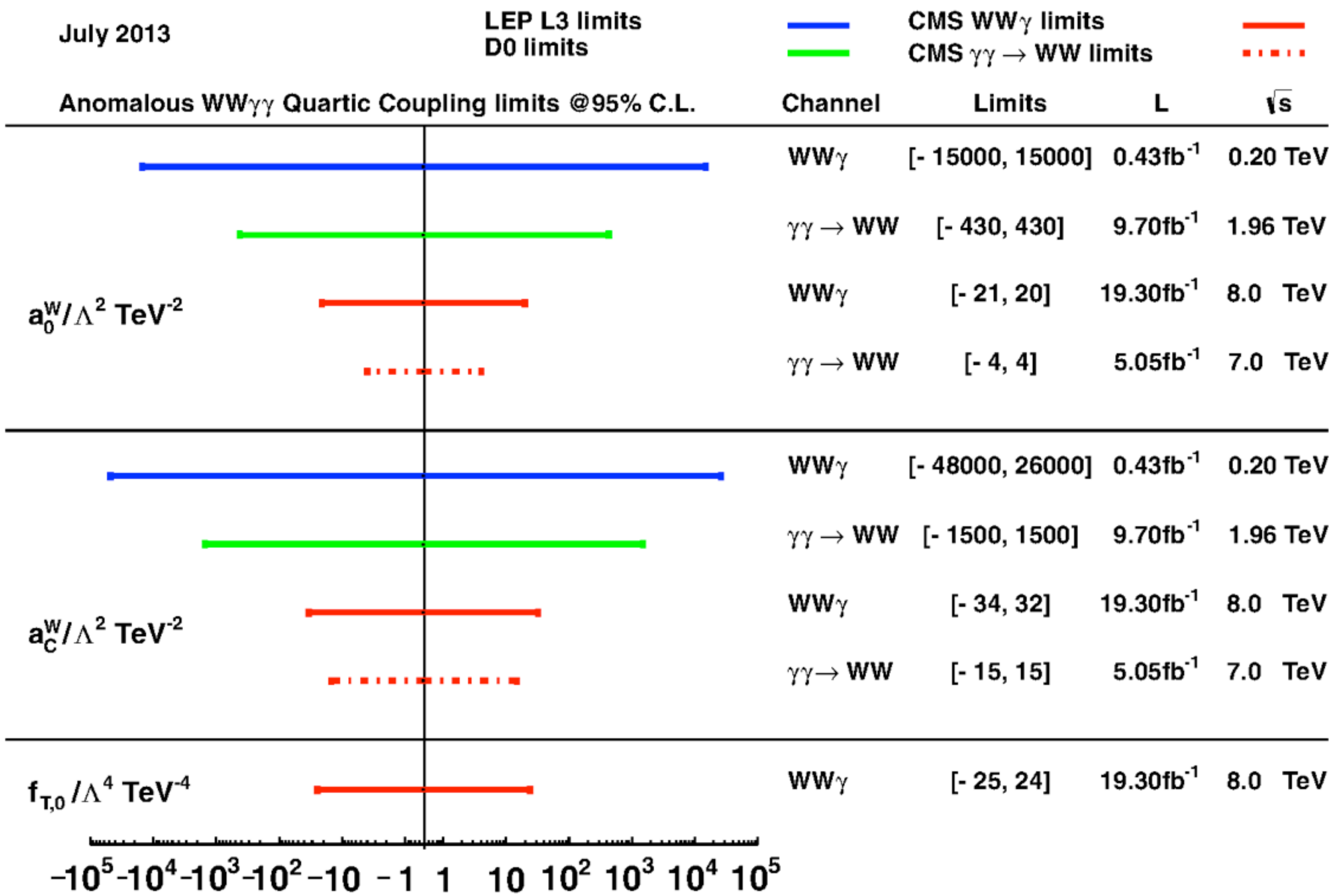
Anomalous QGC would result in a harder $p_T(e\mu)$ spectrum
aQGC region is defined as $p_T(e\mu)$>100GeV

No events observed,
0.14±0.02 expected

Limits on aQGC reported both with and without form factors



γγ→WW: aTGCs



Currently in a transient state, moving from the "old" formalism of chiral Lagrangians (non-linear realisation of the symmetries) to a la SM effective Lagrangians (linear realisation of the symmetry)

Also the form factor approach is slowly being abandoned

PRD90, 0032008 (2014)

Additional Slides