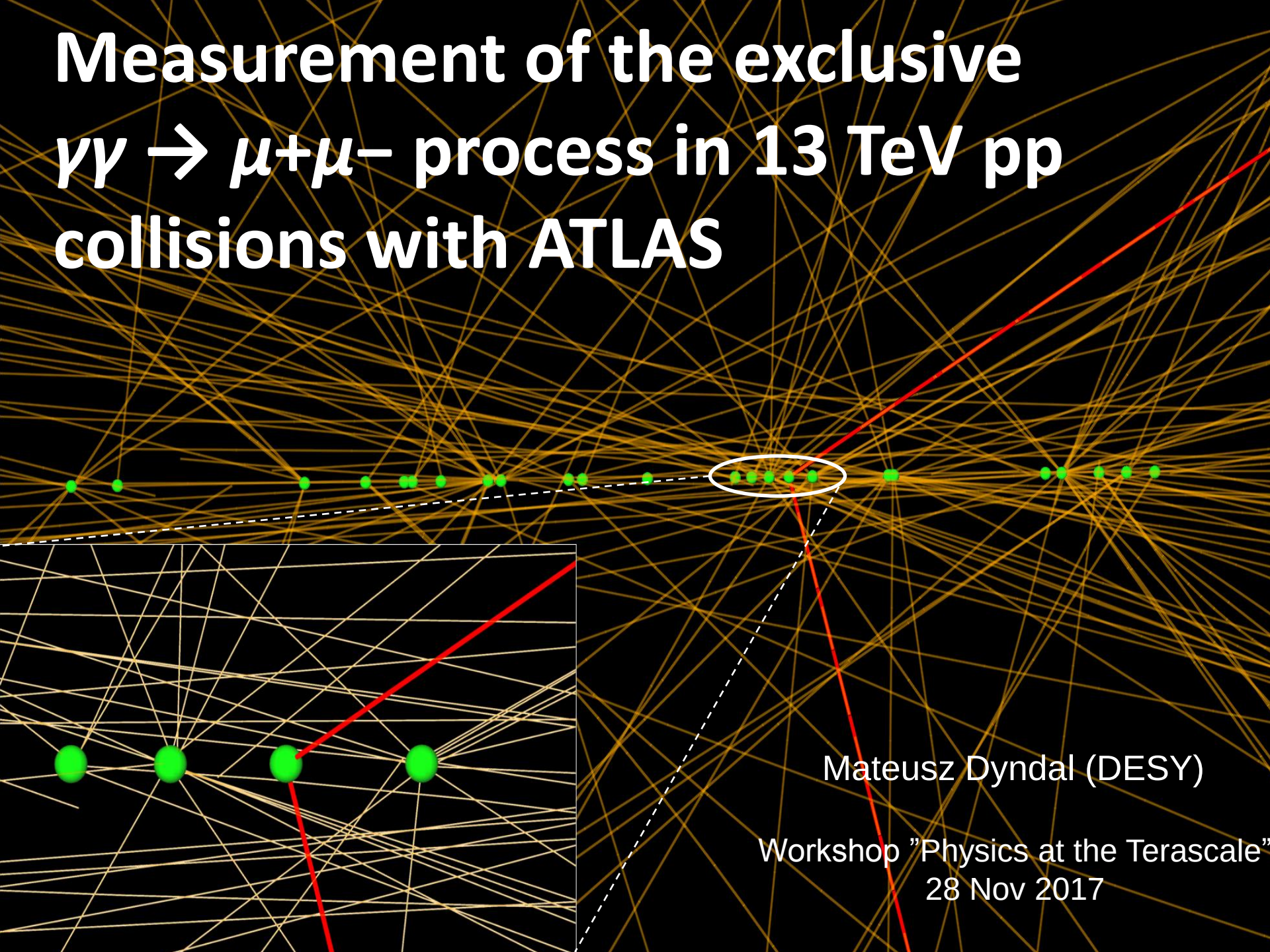
Measurement of the exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ process in 13 TeV pp collisions with ATLAS

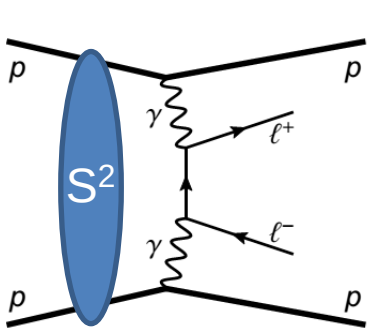


Mateusz Dyndal (DESY)

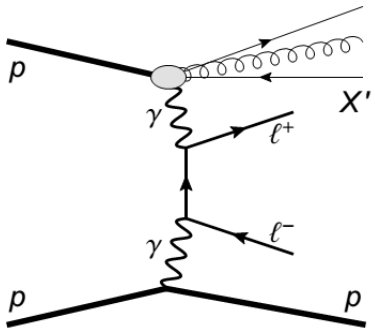
Workshop ”Physics at the Terascale”
28 Nov 2017

Motivation: exclusive $\gamma\gamma \rightarrow l^+ l^-$ production

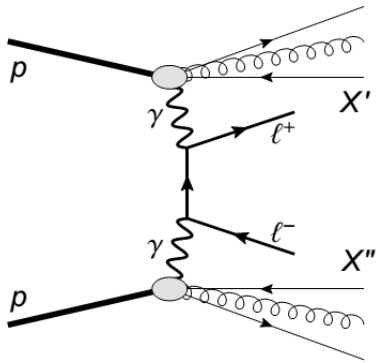
- Standard candle for photon-induced physics
- Good benchmark to test the effect of absorptive corrections
- In pp (togeter with S-diss+D-diss): non-negligible background in Drell-Yan like measurements
- Good process to calibrate / control $\boldsymbol{\gamma\gamma \rightarrow W^+ W^-}$ ($\rightarrow e\mu$) reaction



Exclusive

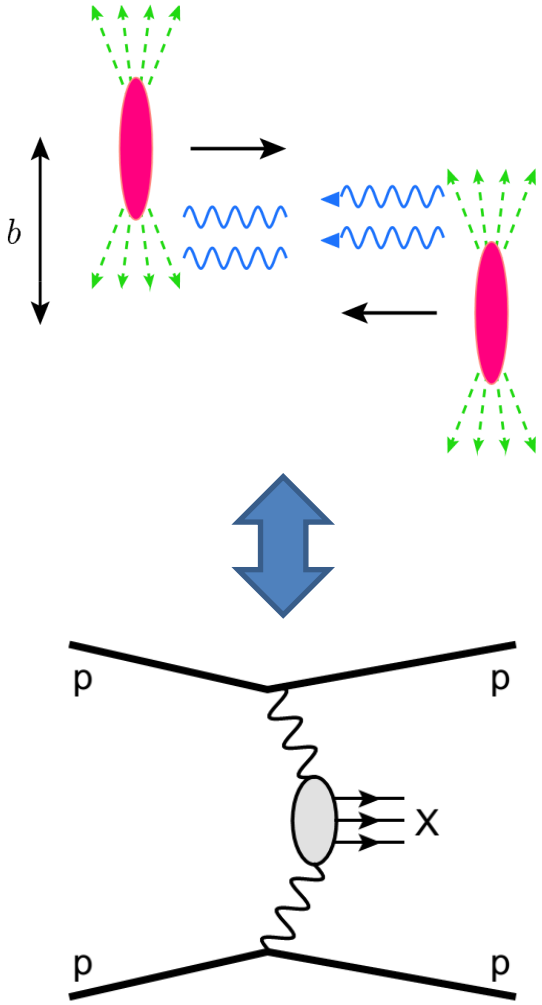


Single-dissociation



Double-dissociation

pp ($\gamma\gamma$) $\rightarrow$ pp X process modeling



[Chen et al., PRD 7 (1973) 3485-3502]
[Budnev et al., NPB 63 (1973) 519-541]

The cross-section for this process can be calculated:

(1) Using the number of equivalent photons (EPA) by integration over the whole virtuality range:

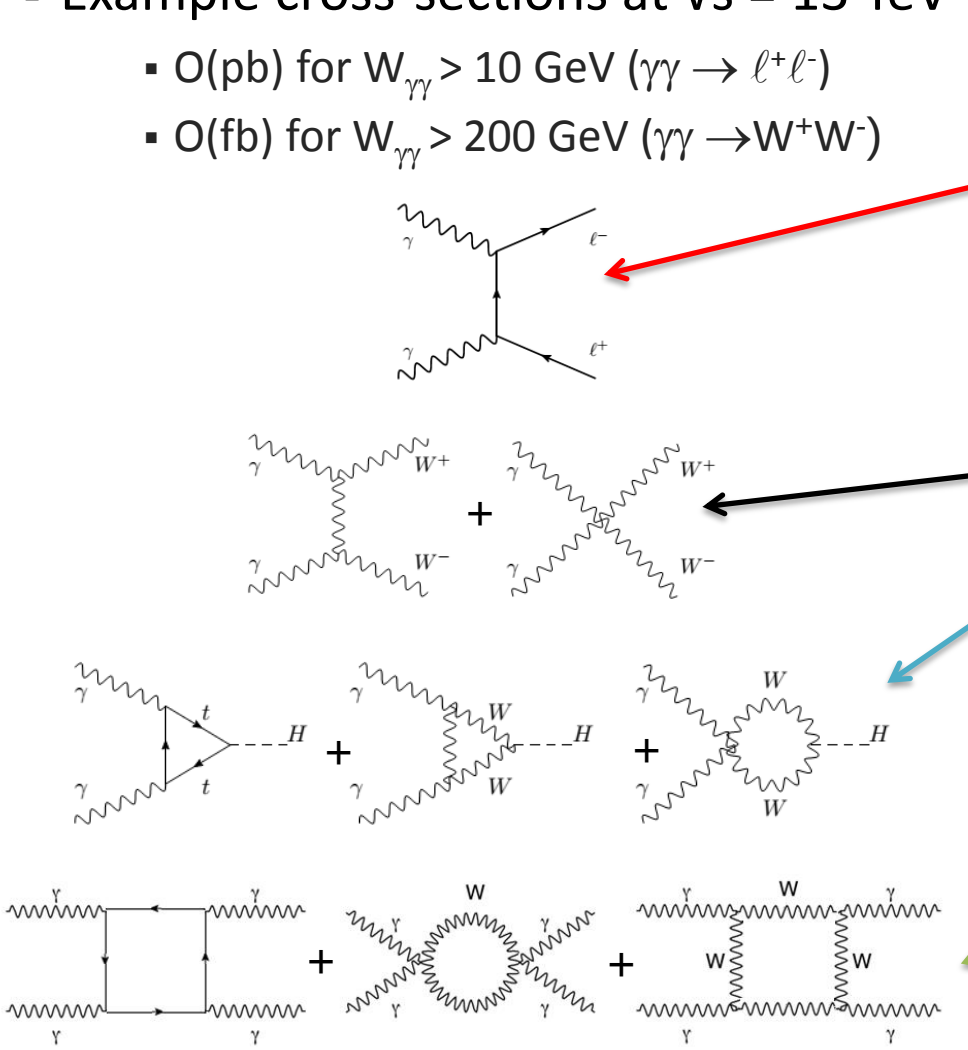
$$dN = \frac{\alpha}{\pi}\frac{dQ^2}{Q^2}\frac{dx}{x}\left[(1-x)\left(1-\frac{Q^2_{min}}{Q^2}F_E(Q^2)\right)+\frac{x^2}{2}F_M(Q^2)\right]$$

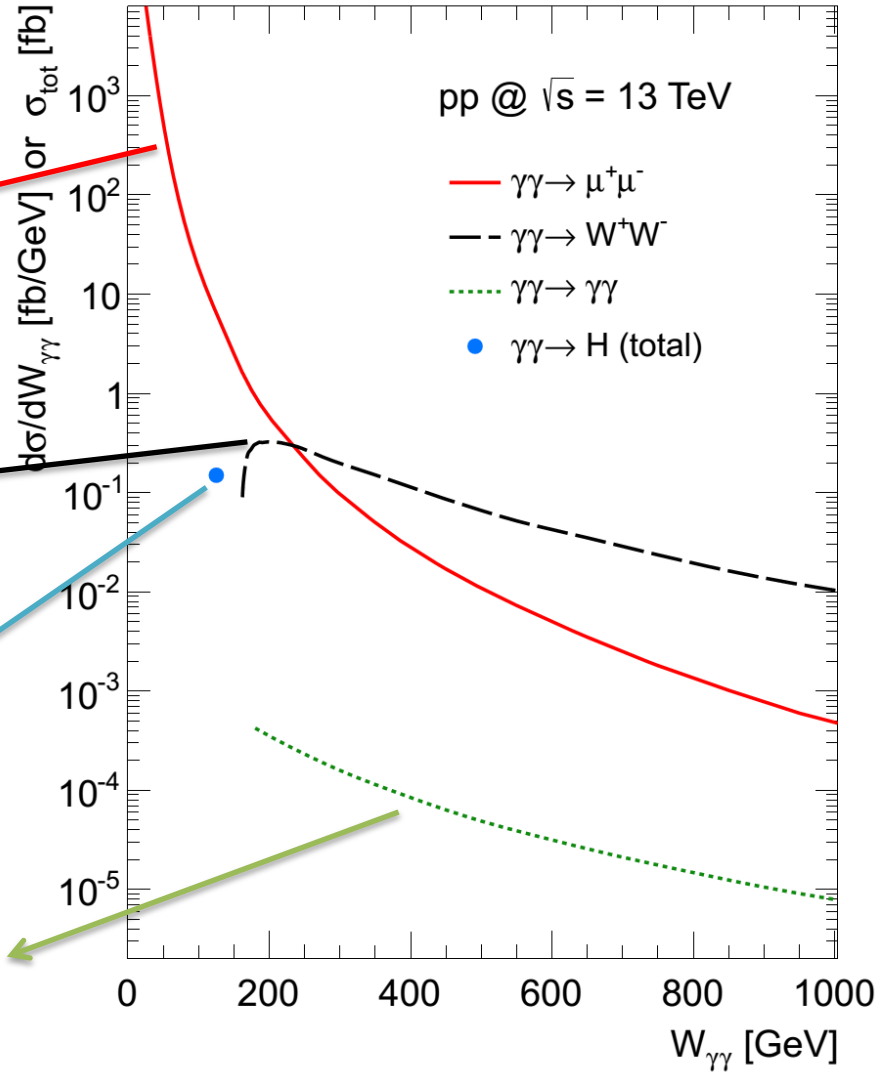
$$Q^2_{min} \simeq m_p^2\frac{x^2}{1-x} \qquad Q^2_{max} = 2\ \mathrm{GeV}^2$$

(2) EW $\gamma\gamma \rightarrow$ **X** cross-section.

pp ($\gamma\gamma$) $\rightarrow$ pp X process modeling

- Example cross-sections at $\sqrt{s}$ = 13 TeV
  - O(pb) for $W_{\gamma\gamma} > 10$ GeV ($\gamma\gamma \rightarrow \ell^+\ell^-$)
  - O(fb) for $W_{\gamma\gamma} > 200$ GeV ($\gamma\gamma \rightarrow W^+W^-$)

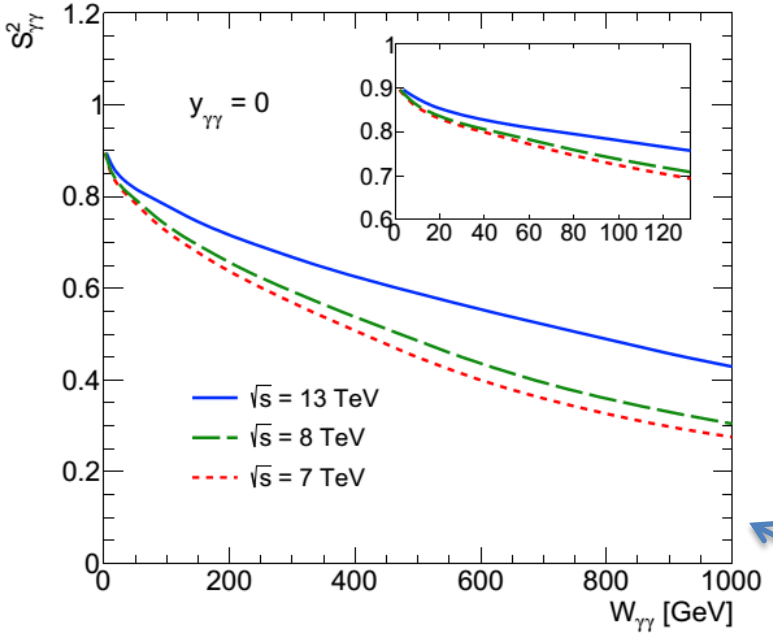


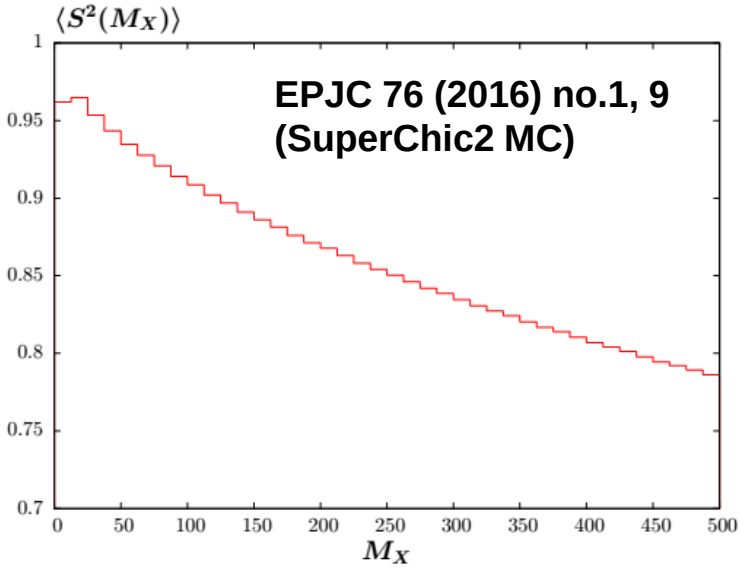


Absorptive corrections

- Various models predict the evolution of survival factor (calculated wrt **bare QED** calculations)
  - Survival factor **increases** with **increasing** pp sqrt(s)
  - Survival factor **increases** when we **decrease** dilepton invariant mass

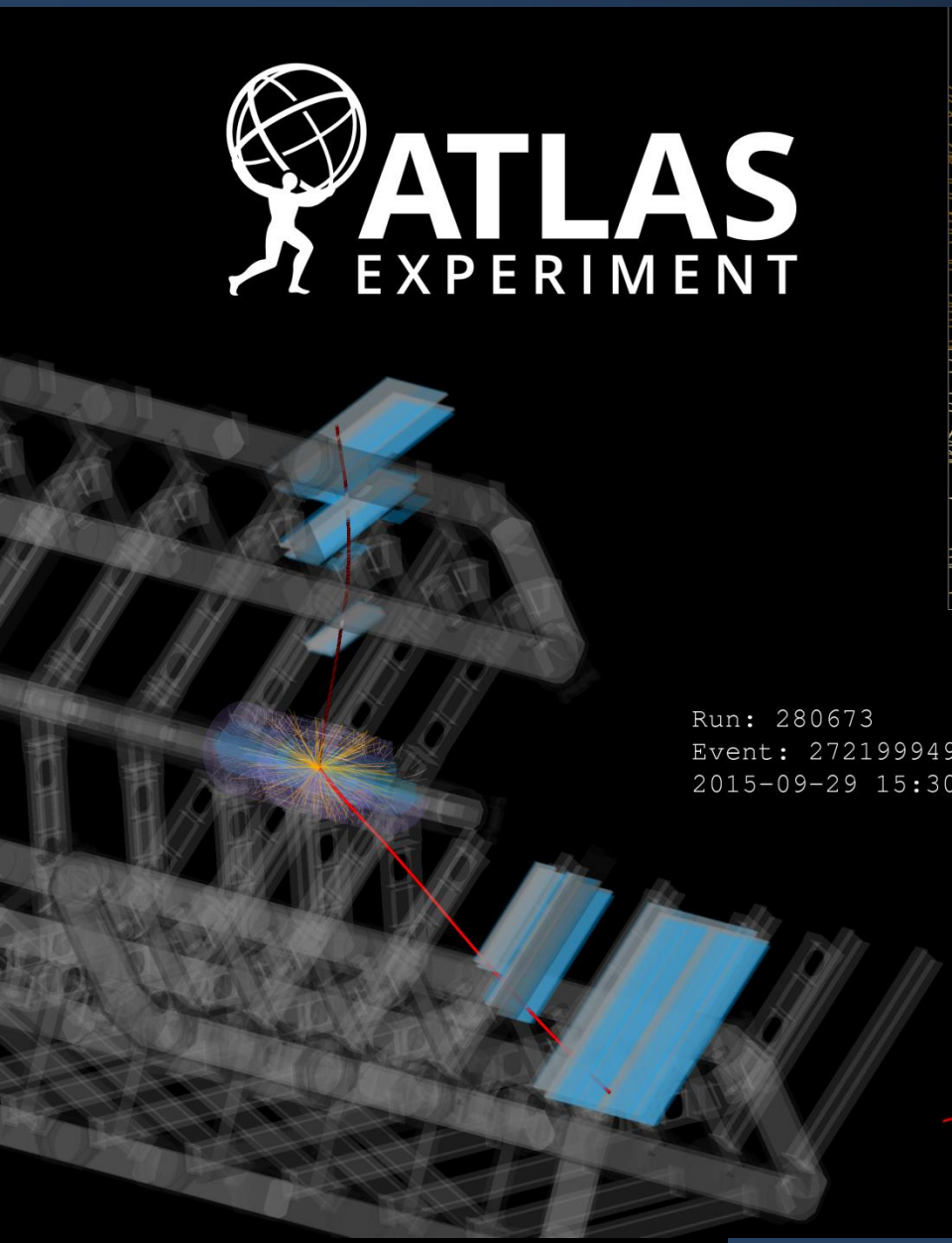
PLB 741 (2015) 66-70
(finite-size effects)

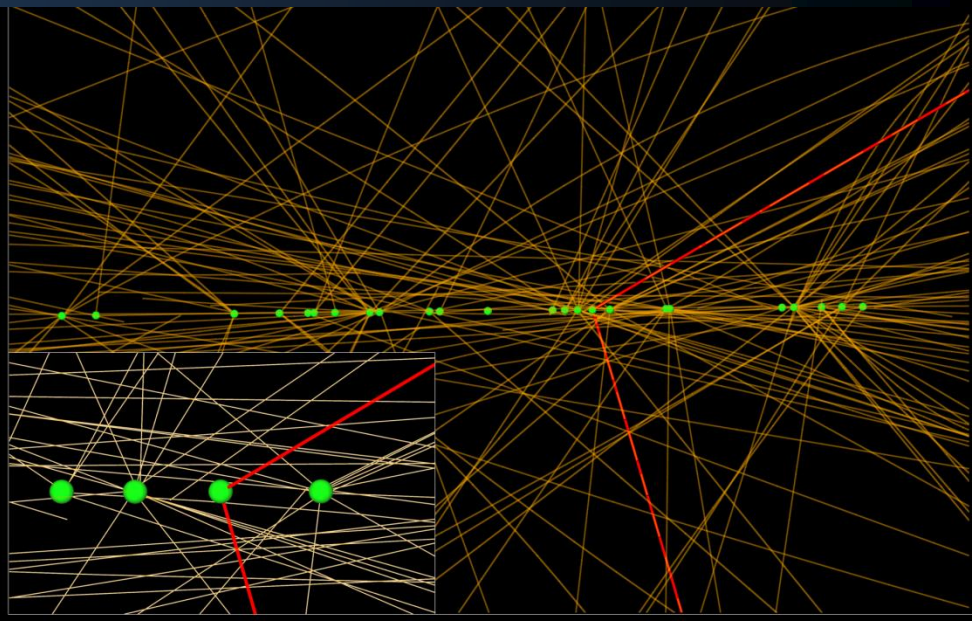




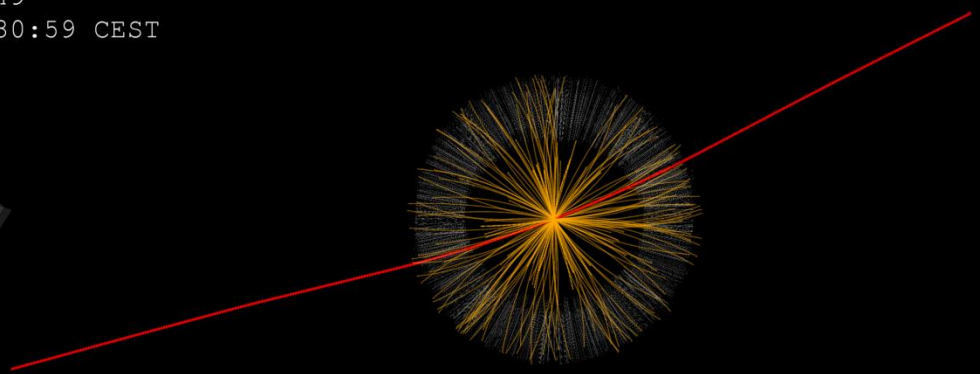
$$S^2_{\gamma\gamma} = \frac{\int_{b_1>r_p}\int_{b_2>r_p} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1 d^2\vec{b}_2}{\int_{b_1>0}\int_{b_2>0} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)d^2\vec{b}_1 d^2\vec{b}_2}$$

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





Run: 280673
Event: 272199949
2015-09-29 15:30:59 CEST



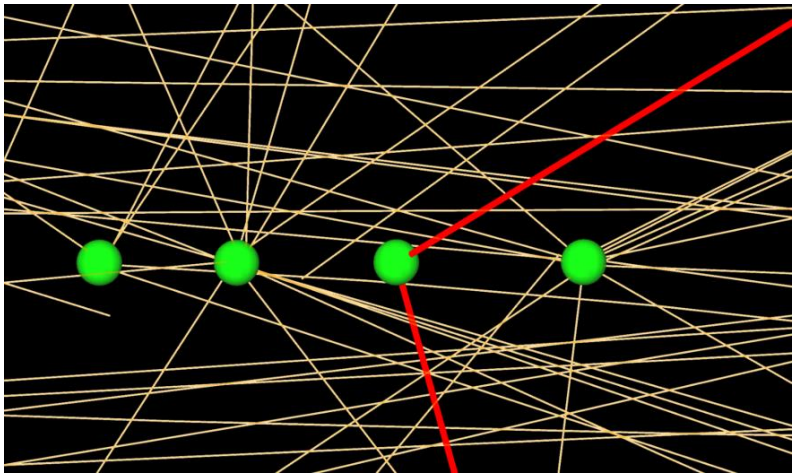
Event selection

- Dataset: 2015 data is used (3.2 fb^{-1})

- Muons:
  - **$p_T^{\mu} > 6$ GeV, 12 GeV < $m_{\mu+\mu-}$< 30 GeV -> topological dimuon trigger**
  - $p_T^{\mu} > 10$ GeV, $m_{\mu+\mu-} > 30$ GeV **(w. extra $p_T^{\mu\mu}$ requirement)**
  - $|\eta_{\mu}|<2.4$

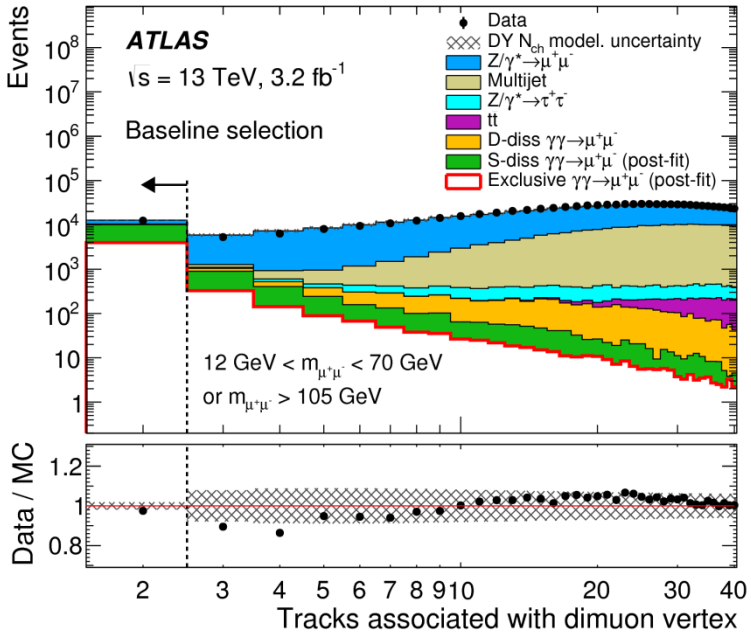
- Charged-particle tracks: $p_T > 400$ MeV, $|\eta| < 2.5$ -> define reaction exclusivity

- Exclusive selection:
  - **1 mm** dilepton-vertex longitudinal isolation
  - **$m_{\mu+\mu-}$ < 70 GeV** -> to suppress DY
  - Dimuon system p_T **< 1.5 GeV**

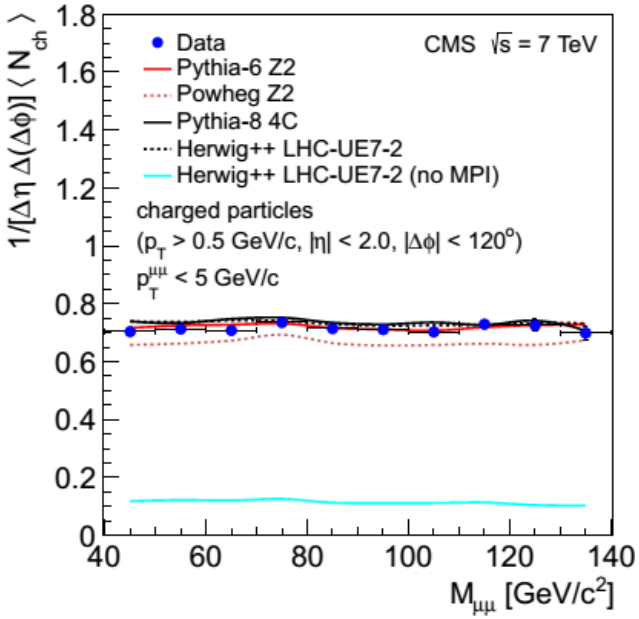


Drell-Yan N_{ch} correction

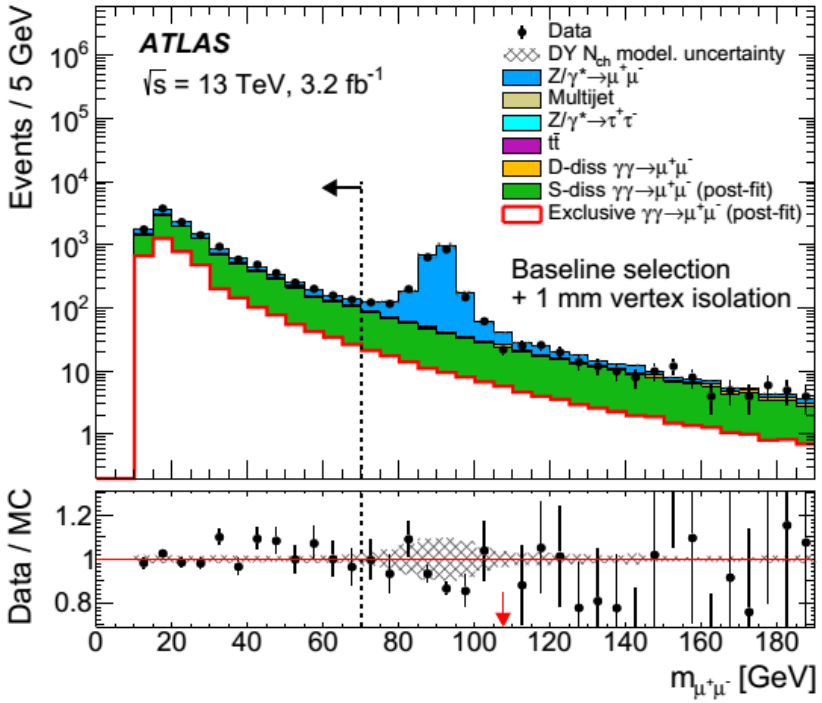
- Mismodeling of charged-particle multiplicity in DY MC [Powheg+Pythia8+AZNLO] -> up to **50% at low-N_{ch}**
- Correction to N_{ch} in DY MC is applied
  - Weights extracted in DY-enriched region (70 GeV < $m_{\mu+\mu}$ < 105 GeV)
  - Extrapolation to SR ($m_{\mu+\mu}$ < 70 GeV)

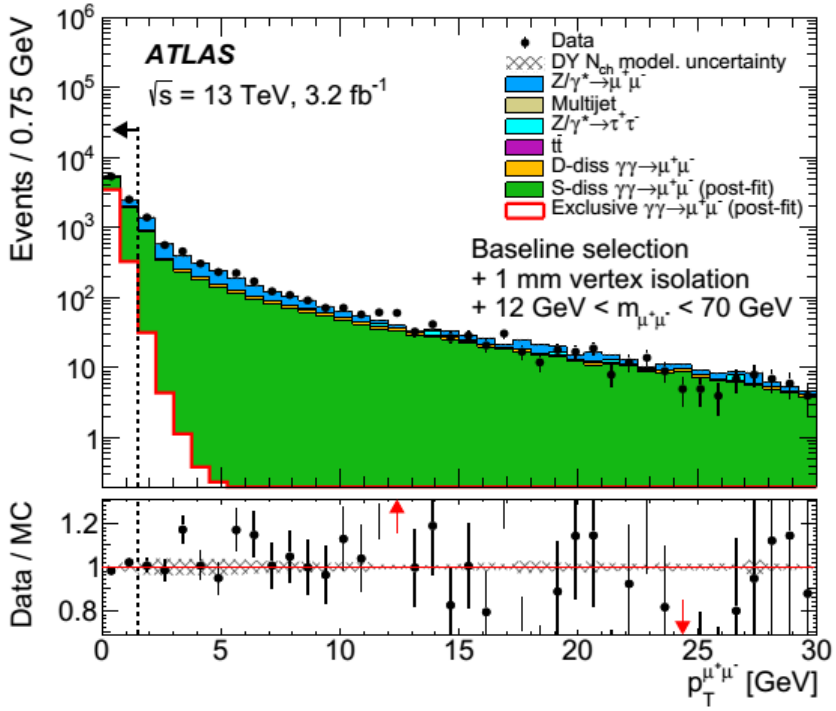


[EPJC 72 (2012) 2080]



Event selection (summary)

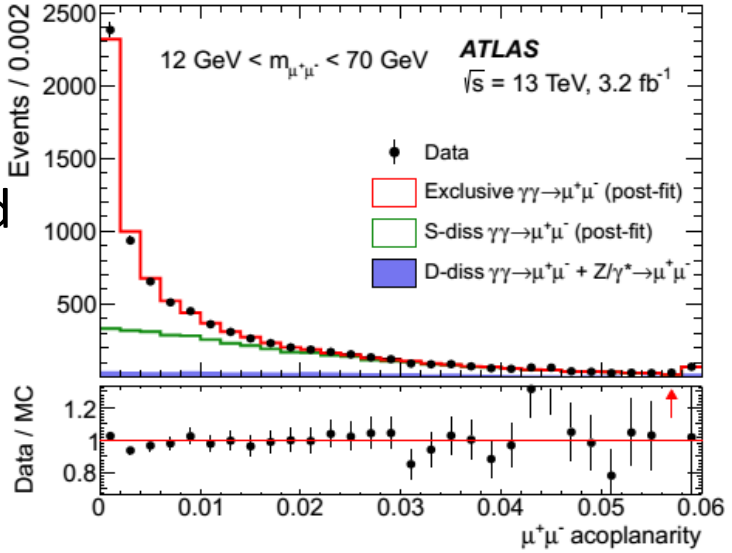




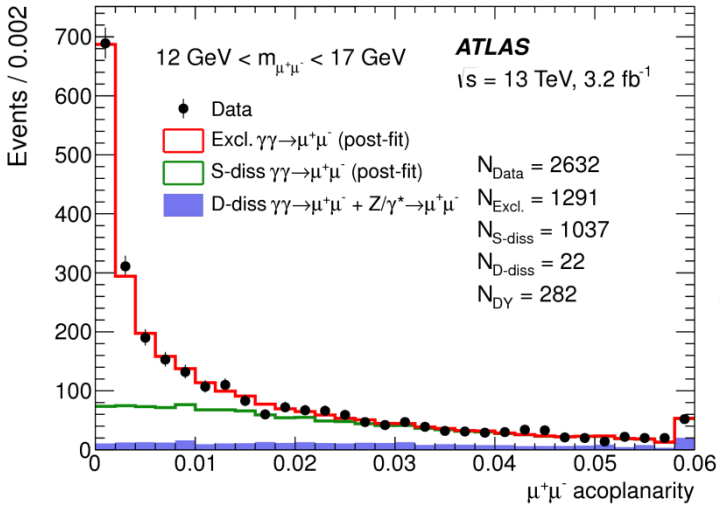
	Data	Signal	Total background	S-diss	D-diss	$Z/\gamma^* \to \mu^+\mu^-$	$Z/\gamma^* \to \tau^+\tau^-$	Multijet	$t\bar{t}$
Baseline selection	2 933 384	5740	2 897 000	8640	8000	2 268 000	10 900	590 000	12 200
1 mm vertex isolation	14 759	4560	11 100	6840	300	3900	30	50	0
$m_{\mu^+\mu^-} < 70$ GeV	12 395	4420	8800	6420	300	2000	30	50	0
$p_{\mathrm{T}}^{\mu^+\mu^-} < 1.5$ GeV	7952	4370	4300	3550	60	670	7	10	0

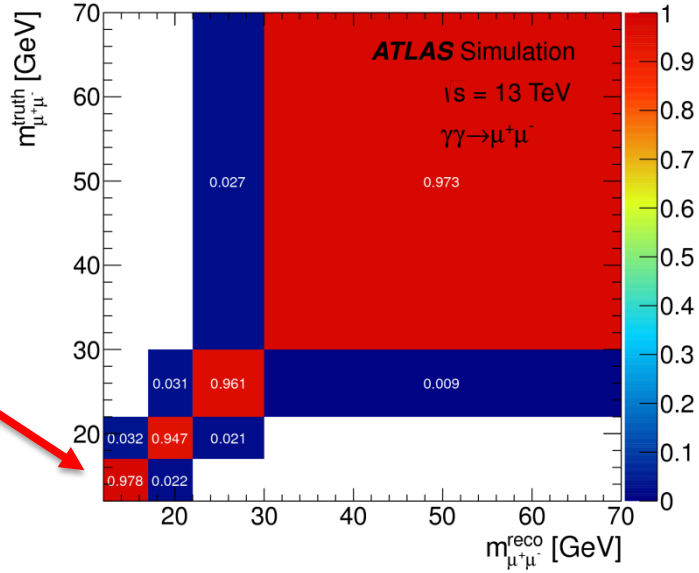
Signal extraction

- Binned max-likelihood fit to the measured dilepton acoplanarity distribution
- Allow **exclusive signal** and **S-diss** background to float



- Studying the cross-section also in **4 bins of $m_{\mu+\mu-}$**



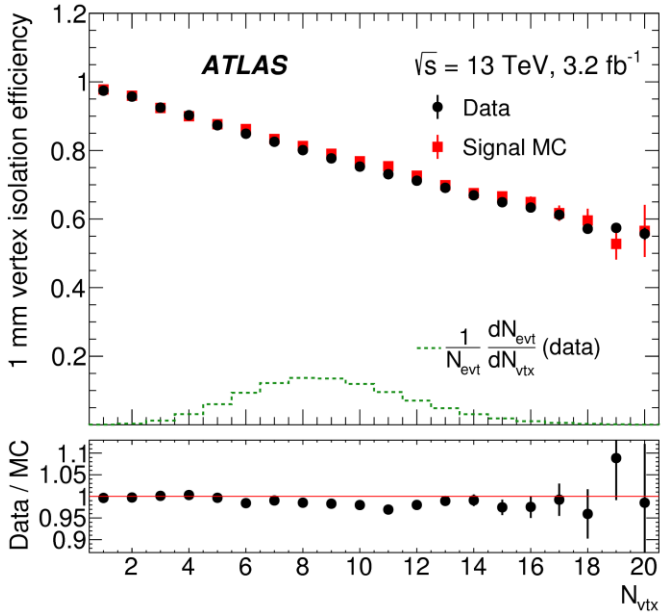


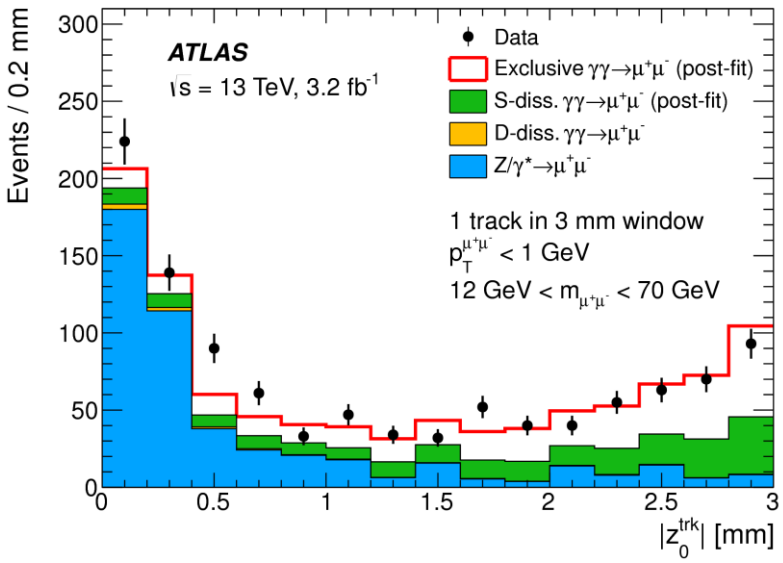
Systematic uncertainties & checks

- Dominated by shapes and L_{int} uncertainties

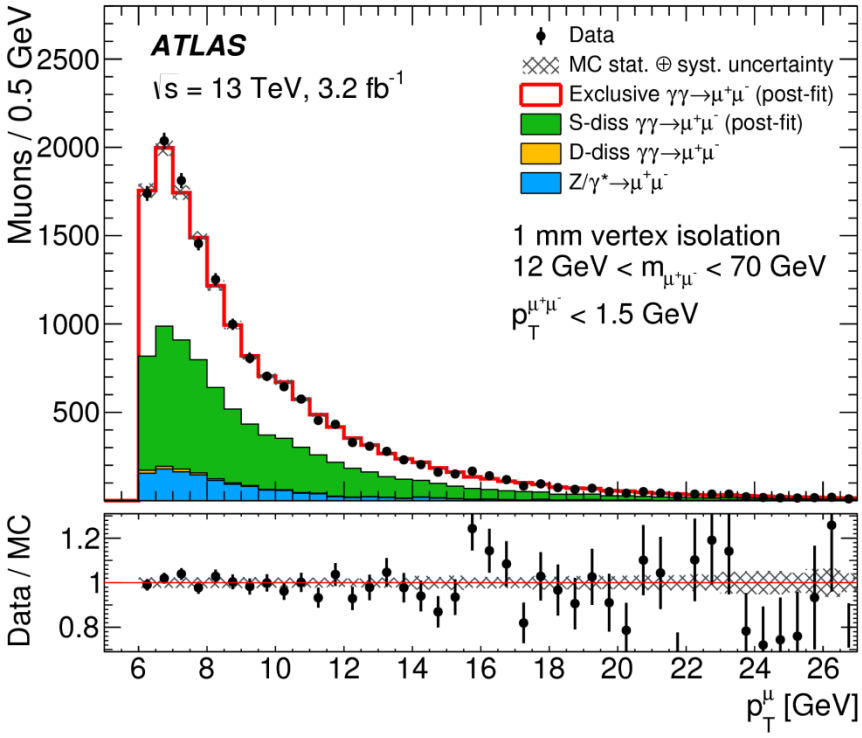
	Uncorrelated		Correlated							
$m_{\mu^+\mu^-}$ [GeV]	$\delta^{trig.}_{stat.}$ [%]	$\delta^{reco.}_{stat.}$ [%]	$\delta^{trig.}_{syst.}$ [%]	$\delta^{reco.}_{syst.}$ [%]	$\delta^{sc./res.}$ [%]	δ^{veto} [%]	δ^{PU} [%]	$\delta^{bkg.}$ [%]	δ^{shapes} [%]	$\delta^{lumi.}$ [%]
12–17	0.3	0.1	0.9	0.9	-0.4	-1.2	-0.5	0.8	3.0	2.1
17–22	0.3	0.1	0.9	1.0	-0.4	-1.2	-0.5	0.8	3.3	2.1
22–30	0.2	0.1	0.9	1.0	-0.2	-1.2	-0.5	0.6	3.5	2.1
30–70	0.3	0.1	1.0	1.1	-0.3	-1.2	-0.5	0.4	4.0	2.1
12–70	0.3	0.1	0.9	1.0	-0.3	-1.2	-0.5	0.8	3.3	2.1

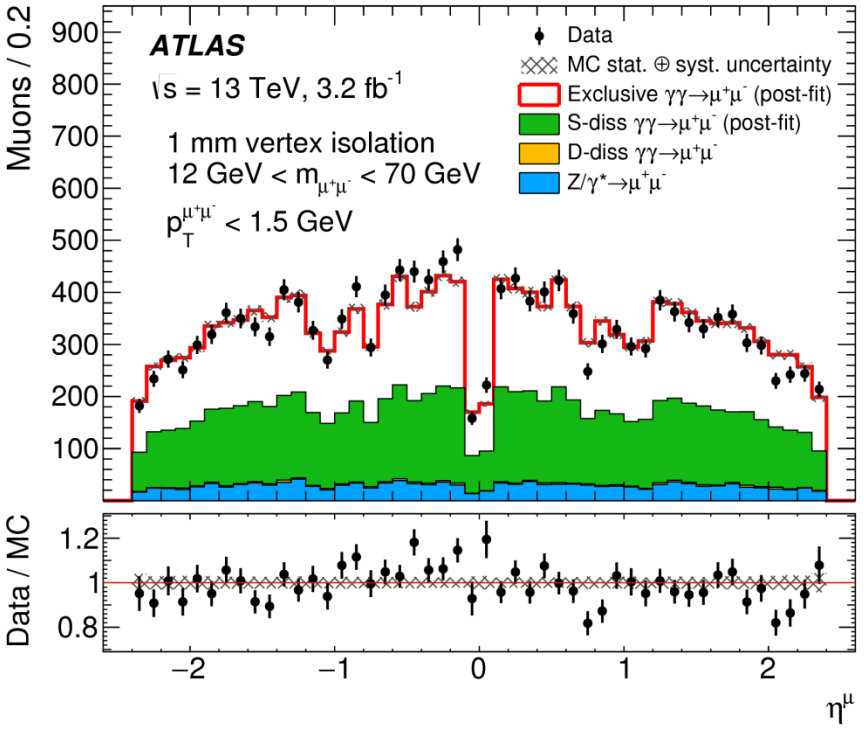
- Extra cross-checks for pile-up modeling in MC



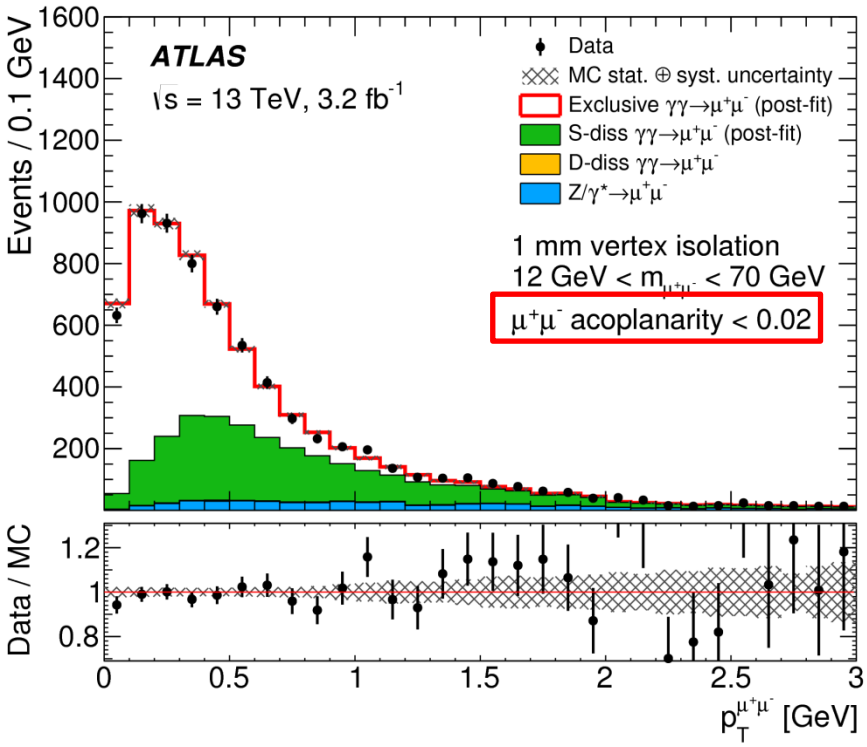


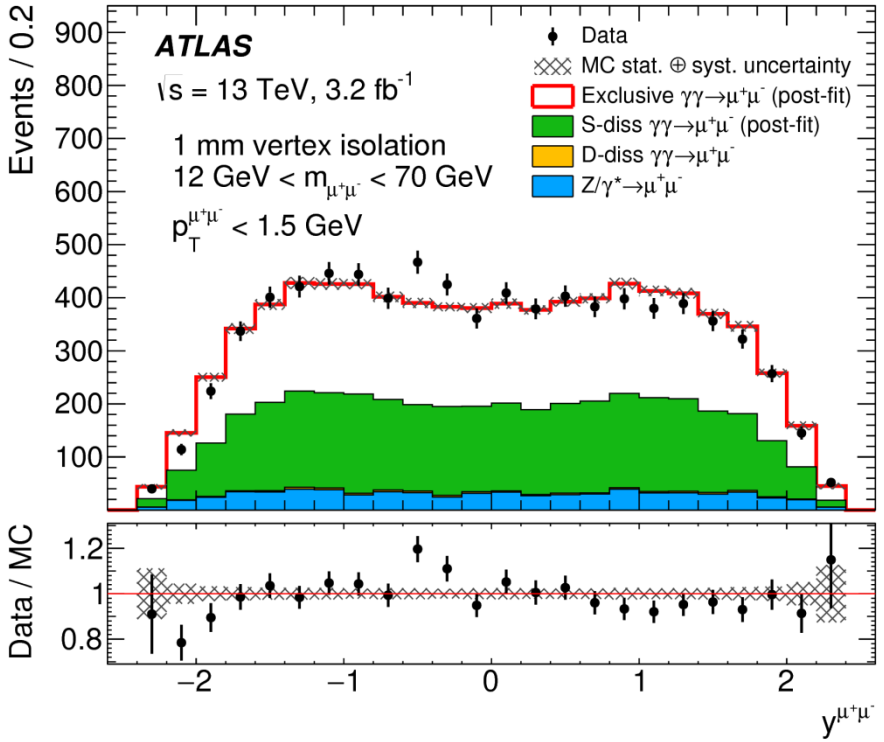
Control distributions





Control distributions





Fiducial cross section extraction

- Fiducial region definition ->

Invariant mass range	p_T^μ requirement	$\lvert\eta^\mu\rvert$ requirement
$12\ \text{GeV} < m_{\mu^+\mu^-} < 30\ \text{GeV}$	> 6 GeV	< 2.4
$m_{\mu^+\mu^-} > 30\ \text{GeV}$	> 10 GeV	< 2.4

- Fiducial cross section definition

$$\sigma^{\text{excl. fid.}}_{\gamma\gamma\to\mu^+\mu^-} = \frac{N_{\text{excl.}}}{L_{\text{int}} \times C}$$

from best-fit

data-driven estimate

- Measurement: **σ^{fid} = 3.12 ± 0.07 (stat.) ± 0.14 (syst.) pb**

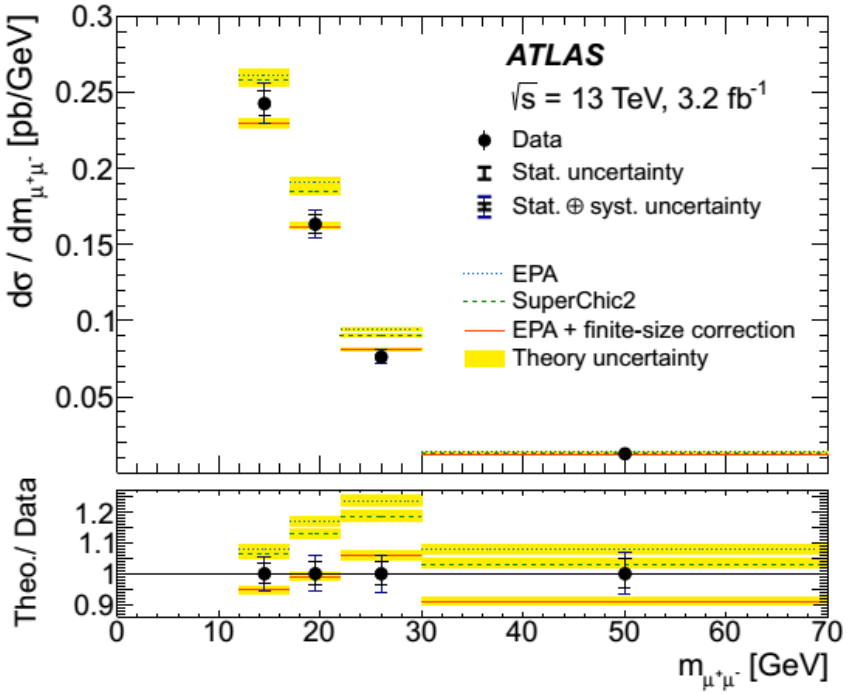
- Predictions:
  - **$\sigma^{\text{EPA,corr.}}$ = 3.06 ± 0.05 pb**
  - **$\sigma^{\text{SuperChic2}}$ = 3.45 ± 0.05 pb**

Differential cross section extraction

- Small migrations: bin-by-bin unfolding is used
  - Cross-checked with Bayesian unfolding

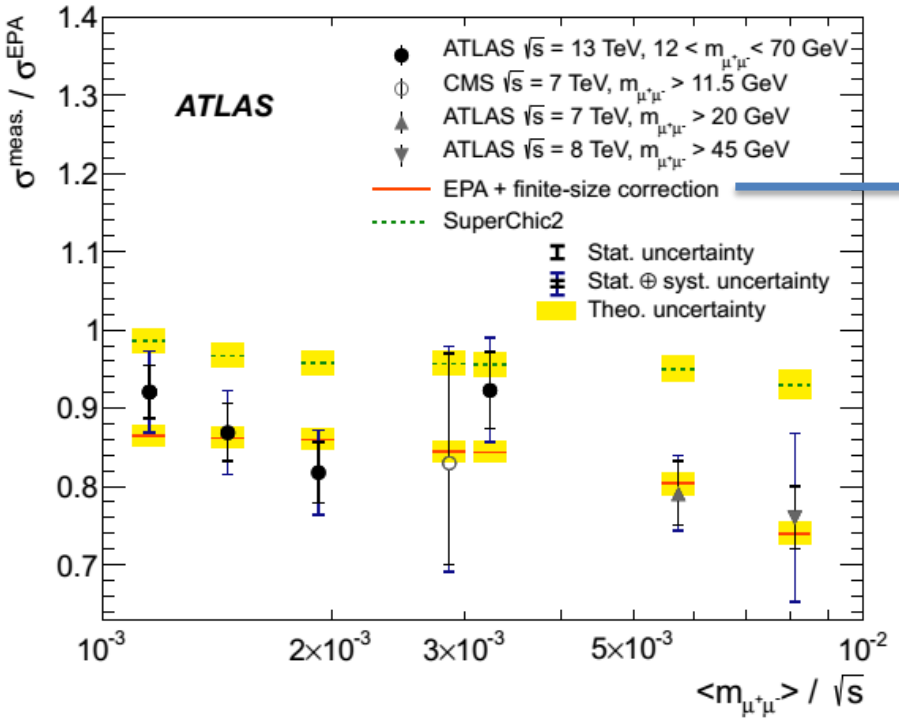
$$\left(\frac{d\sigma^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-}}{dm_{\mu^+\mu^-}}\right)_i = \frac{N^i_{\text{excl.}}}{L_{\text{int}} \times C_i \times (\Delta m)_i}$$

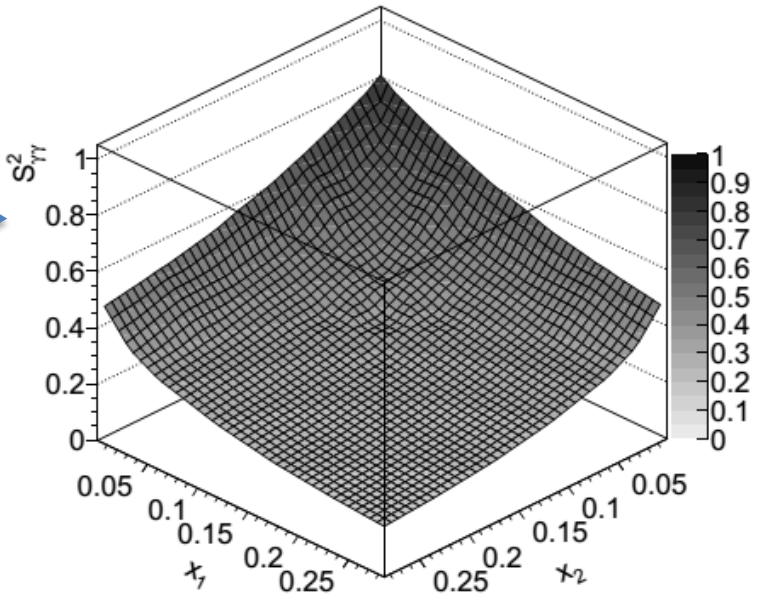
$m_{\mu^+\mu^-}$ [GeV]	$N^i_{\text{excl.}}$	C_i	$d\sigma/dm_{\mu^+\mu^-}$ [pb/GeV]	$\delta^{\text{stat.}}$ [%]	$\delta^{\text{syst.}}$ [%]
12–17	1290± 60	0.333±0.007	0.243 ± 0.013	3.4	4.3
17–22	1040± 50	0.398±0.008	0.164 ± 0.010	3.7	4.5
22–30	830± 40	0.428±0.009	0.076 ± 0.005	3.9	4.6
30–70	690± 40	0.416±0.008	0.013 ± 0.001	4.9	4.9



Results interpretation

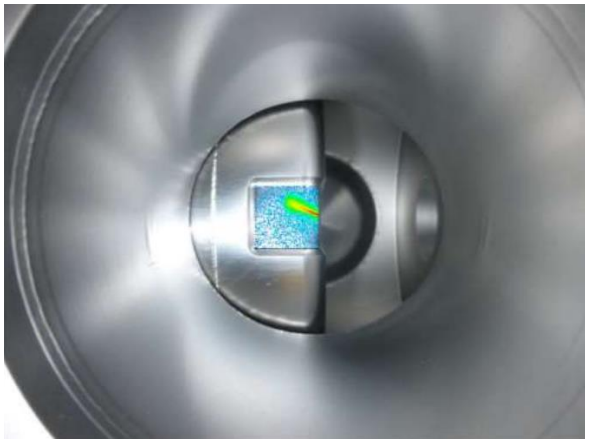
- $\langle m_{\mu^+\mu^-} \rangle / \sqrt{s} \approx \langle x \rangle$ → average energy fraction of proton taken by the quasi-real photon
- x-scaling of survival factor is visible
  - lowest-x region is probed at 13 TeV



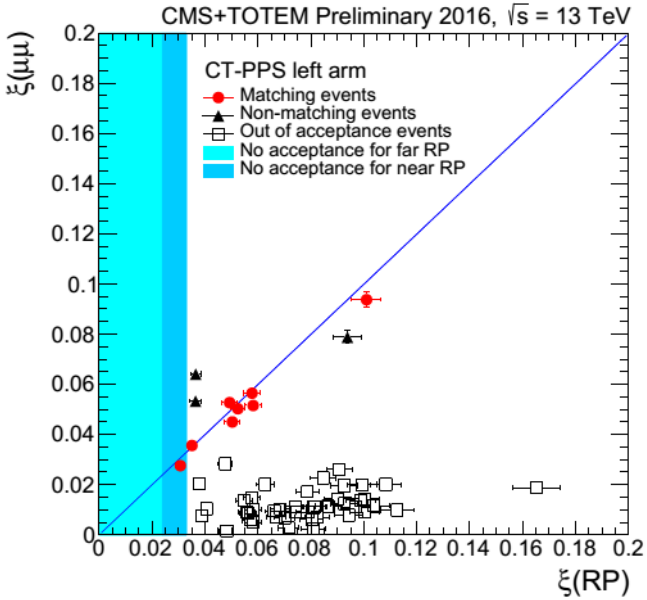


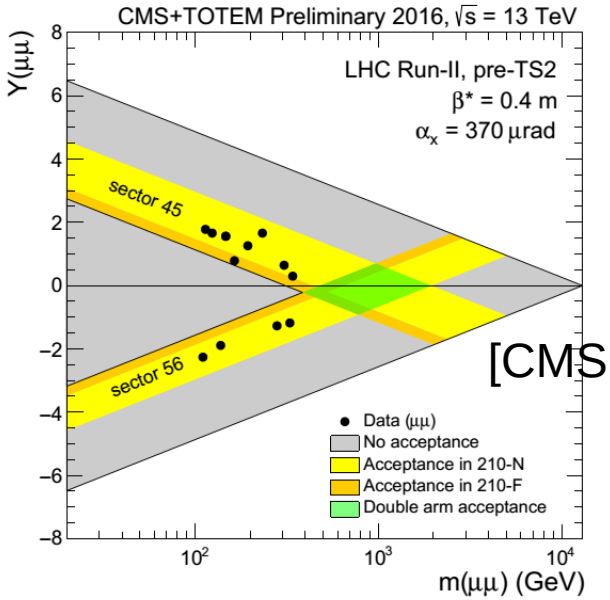
A look ”forward”

- To reduce systematic uncertainties
  -> Forward proton tagging
  -> But: acceptance only at high-mass
  (two-arm acceptance >~ 200 GeV…)



- ’Full’ observation of pp(γγ) -> μμ pp(*) with single p-tag by CT-PPS





[CMS PAS PPS-17-001]

Summary

- Exclusive dimuon production has been measured in 13 TeV pp data
  - Focus on low-mass region (12 GeV < $m_{\mu+\mu}$ < 70 GeV)
  - Topological μμ trigger is employed
- Fiducial and differential cross sections in agreement with model predictions
- Evolution of absorptive effects with reaction kinematics is visible
- Full info at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-13/

Backup

Theory uncertainties

- Theory uncertainties
  - Proton elastic form-factors uncertainty: estimated by comparing between standard dipole parameterization (used in H++) with state-of-the-art parameterizations fitted to elastic e-p data
    -> maximum difference (deviation) is 1.5%
  - Higher-order EWK effects: 0.7% (since they are not included in the simulation) -> estimated in http://arxiv.org/abs/hep-ph/9812411
  - Total theory uncertainty: **~1.6%**