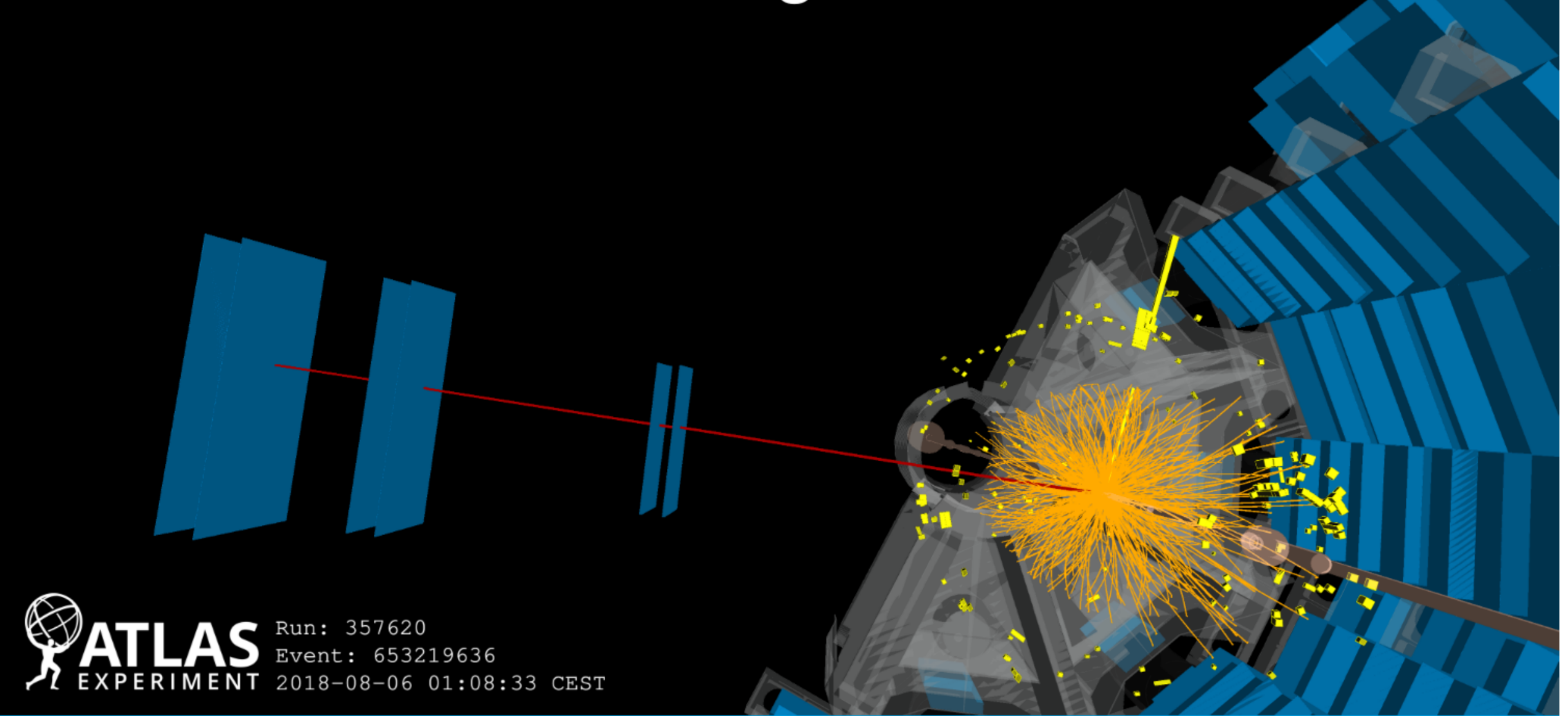
A window to new physics measurements: **Photon scattering at the LHC**



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University of Sheffield

Seminar, University of Birmingham, March 17th 2021

The Standard Model: A success story

Fermions:
Matter particles

Quarks

u c t

d s b

Leptons

ν_e ν_μ ν_τ

e μ τ

Bosons:
Force carriers

g — Strong force

γ — Electro-magentic force

Z, W — Weak force

Higgs Boson:
Found at last

H

describes fundamental forces and particles

complete and self-consistent theory

The Standard Model: Free parameters

Parameters of the Standard Model			[hide]
Symbol	**Description**	**Renormalization scheme (point)**	**Value**
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		125.36±0.41 GeV (tentative)

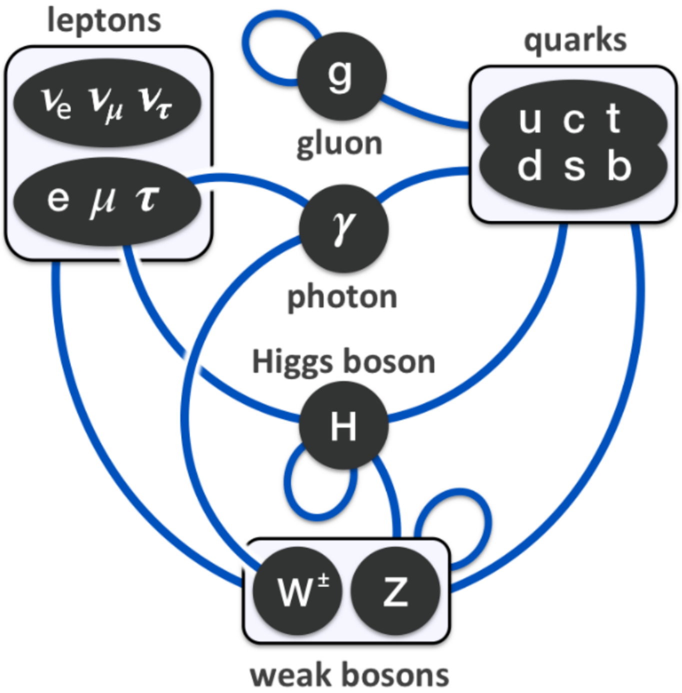
19 free parameters

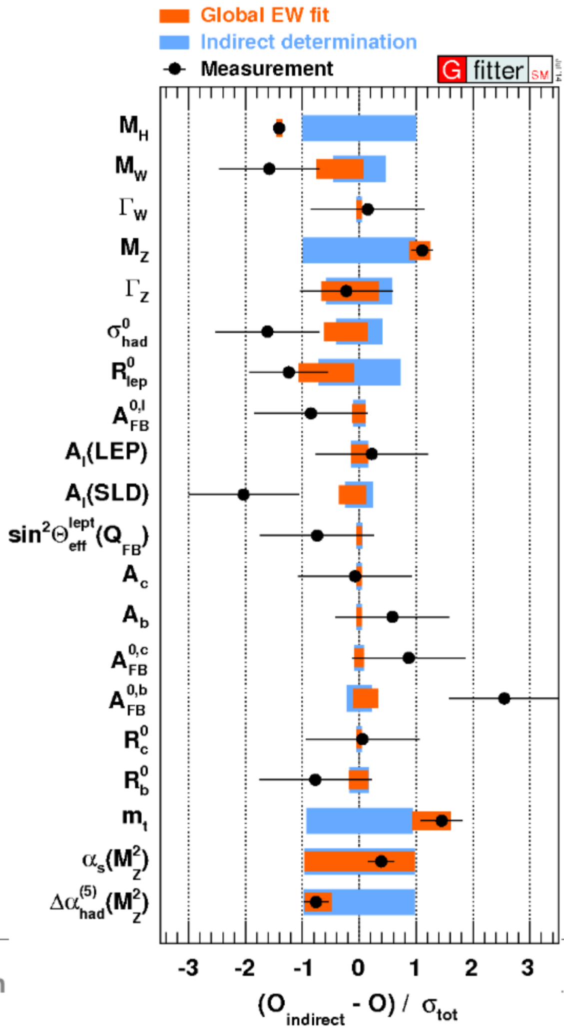
- particle masses
- CKM mixing angle (mass and electroweak eigenstates of quarks)
- Gauge couplings (strength of forces)
- Symmetry properties of QCD
- Parameters of electroweak symmetry breaking (Higgs mass and vaccum expection value)

The Standard Model: Extremely predictive

Once parameters are known, everything else is “fixed”

Extremely precise predictions allow for consistency tests of the SM





The Standard Model's biggest triumph

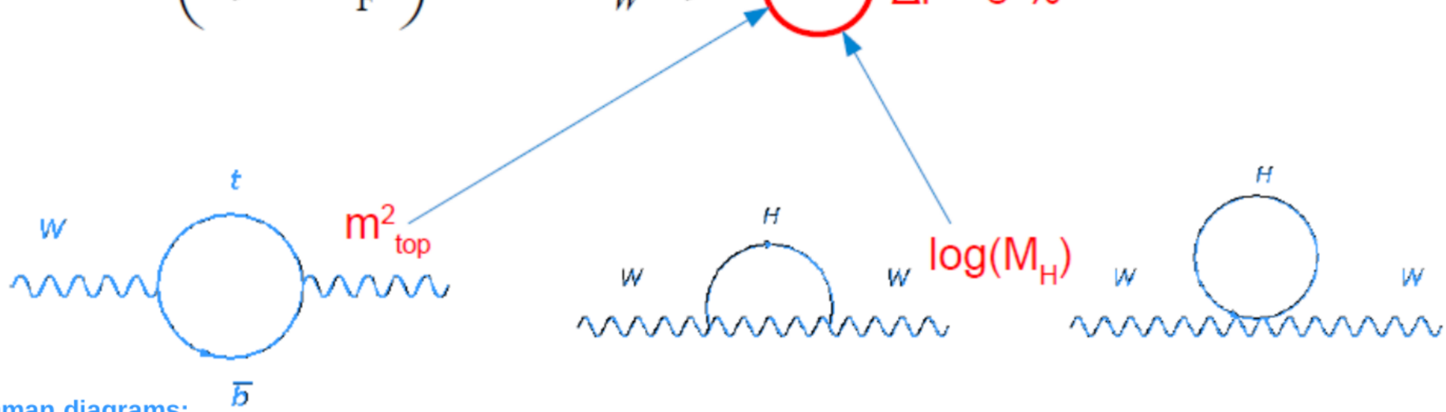
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

- Even before the direct discovery, indirect constraints on Higgs mass through connections with W and top

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

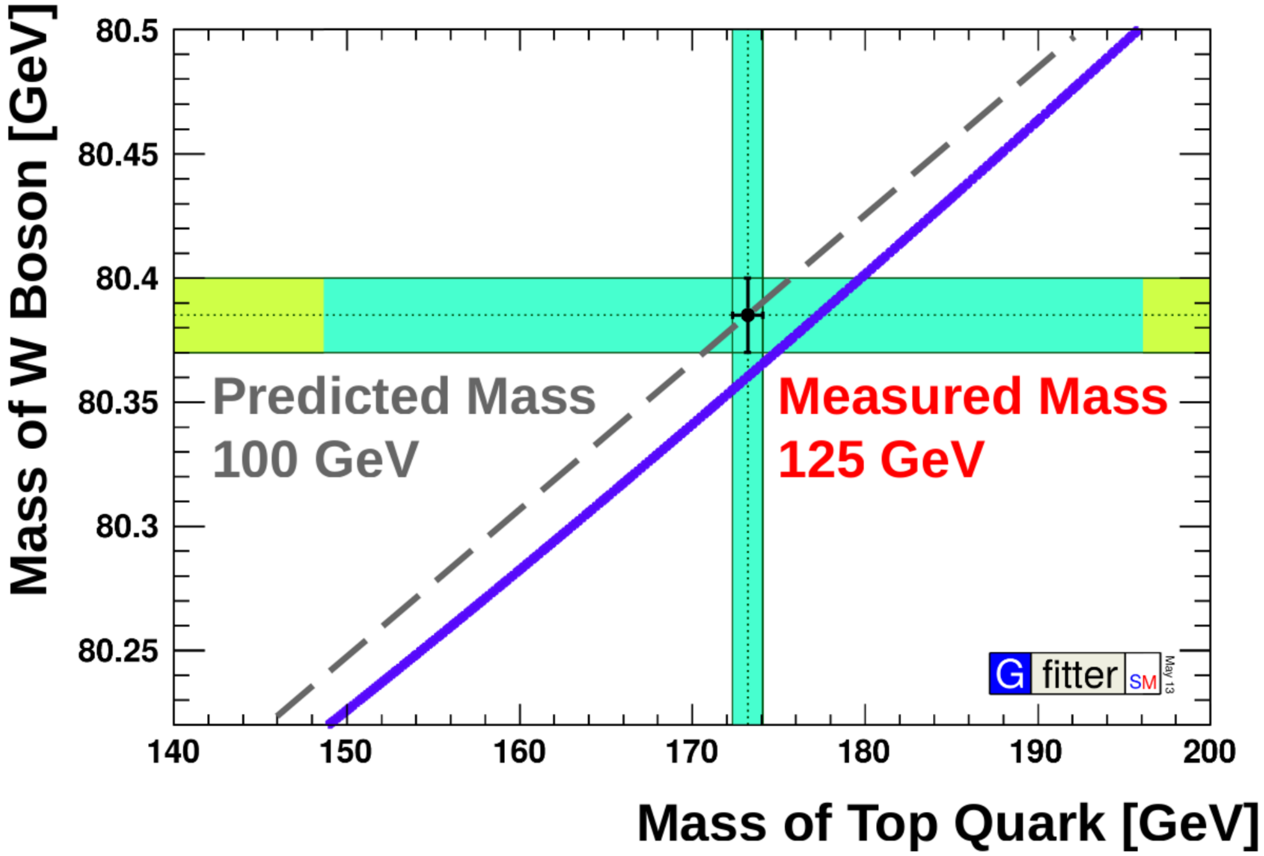
radiative corrections

$\Delta r \sim 3\ \%$



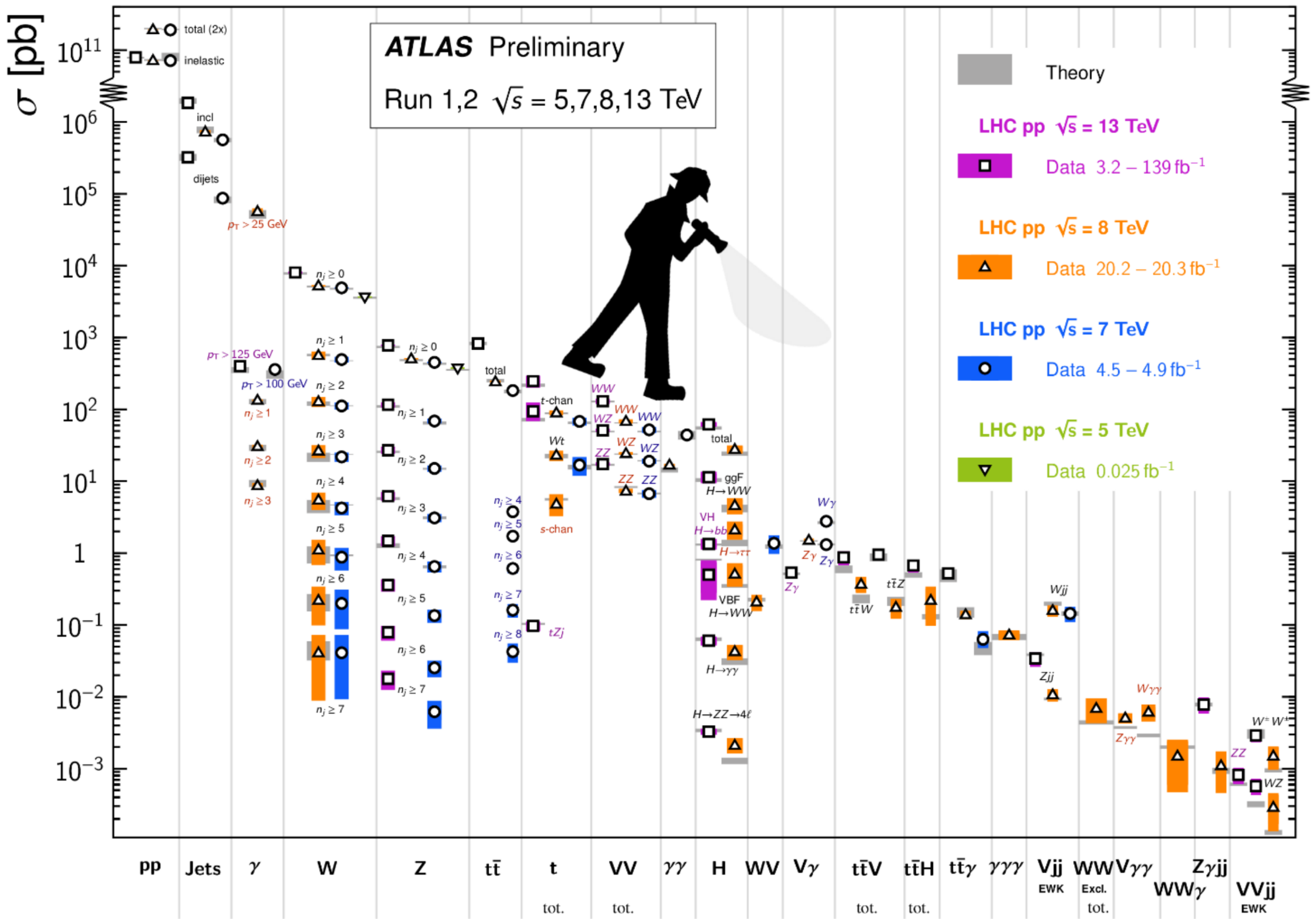
Feynman diagrams:
graphical representations of integrals
→ result: numerical prediction of probability of process

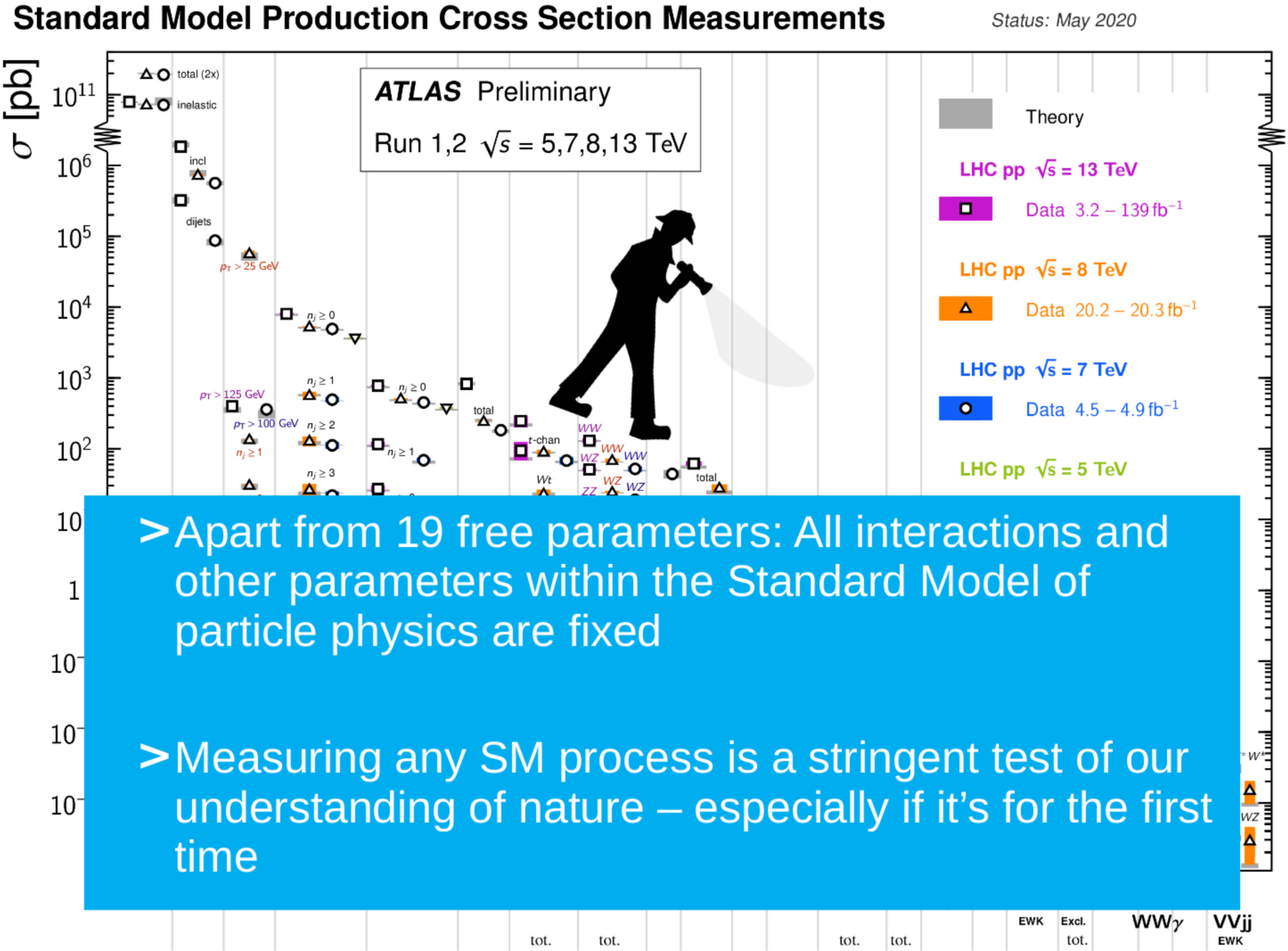
Indirect determination of Higgs boson mass



Standard Model Production Cross Section Measurements

Status: May 2020





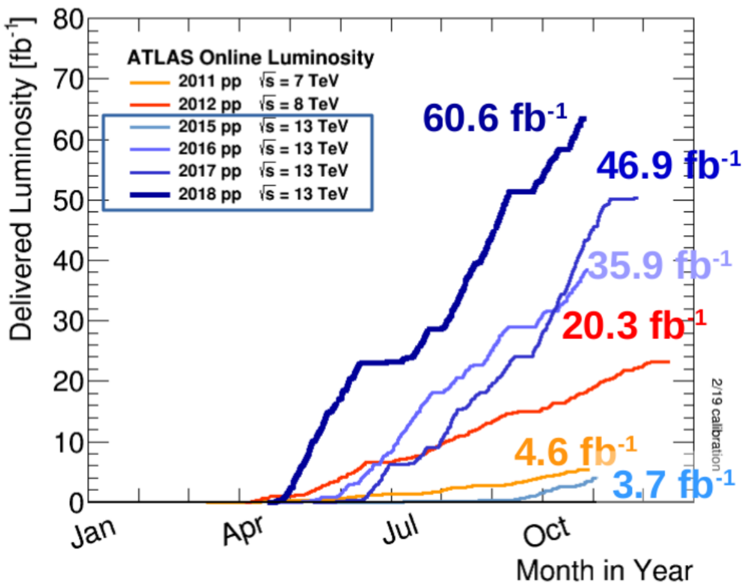
- Apart from 19 free parameters: All interactions and other parameters within the Standard Model of particle physics are fixed

- Measuring any SM process is a stringent test of our understanding of nature – especially if it’s for the first time

Using protons….

Data collected:

More than 140 fb^{-1} at 13 TeV



High energy proton-proton collisions
center-of-mass energy of $\sqrt{s}$ = 7, 8 and 13 TeV

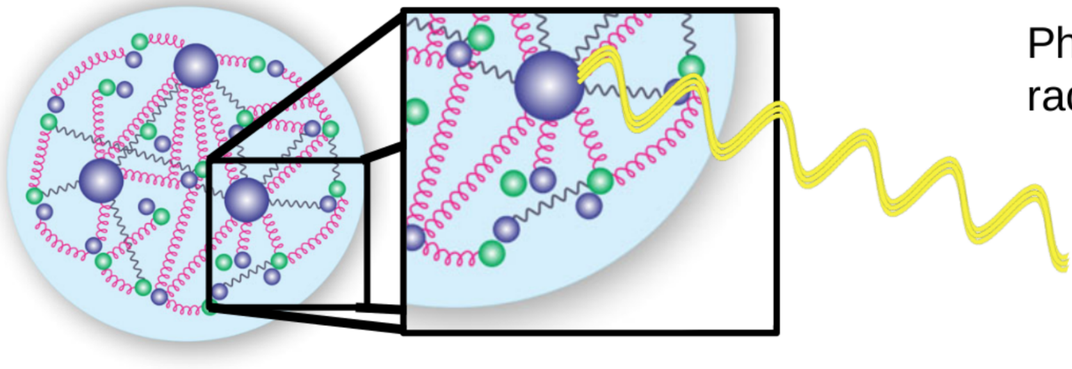
…. and other collisions (photons!)

"resolved" **or** ***dissociative*** **protons**

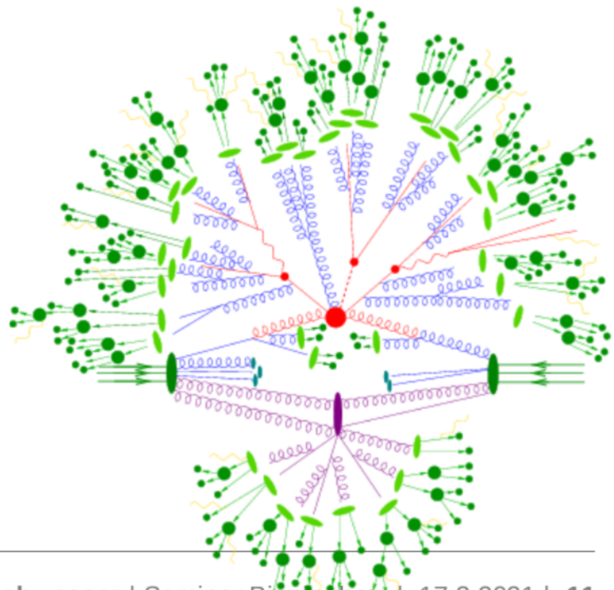
vs.

elastic **protons**

Mechanisms for photon collisions: resolved/dissociative



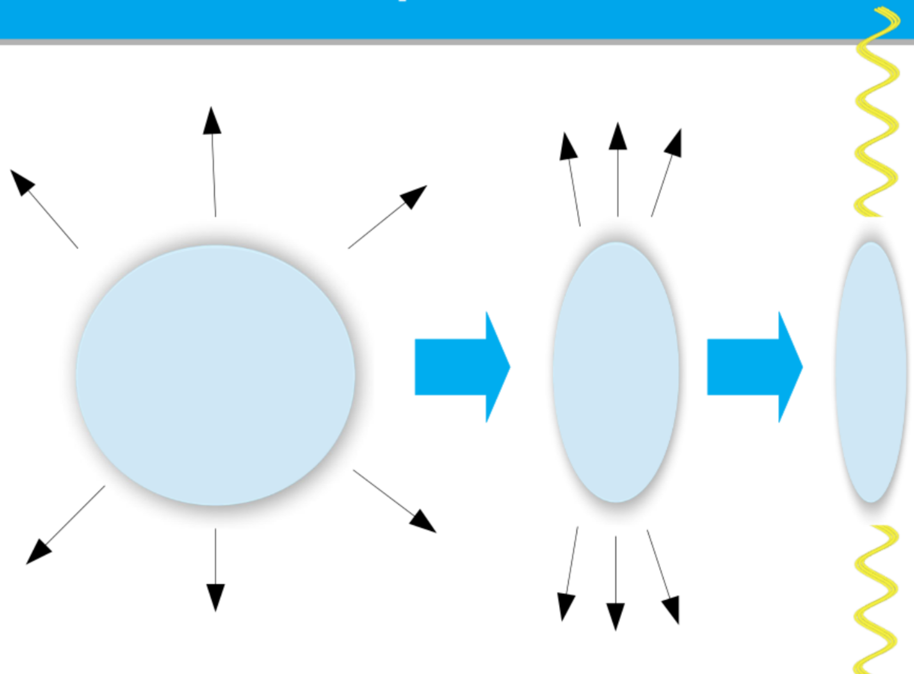
Photon is
radiated off parton



It breaks up, event looks similar to normal *pp* collision

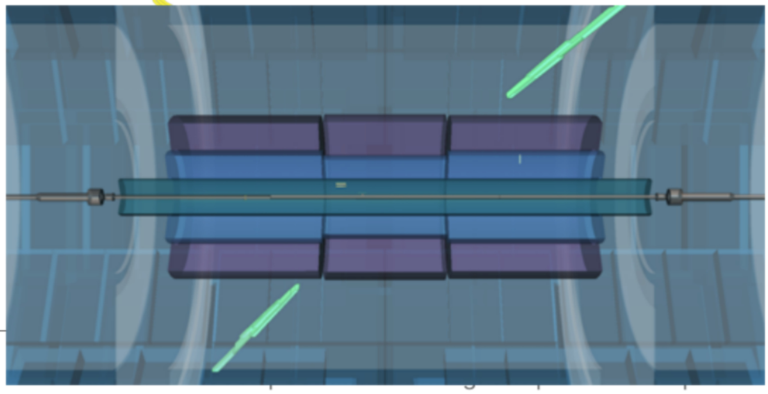
→ dissociative production

Mechanisms for photon collisions at the LHC

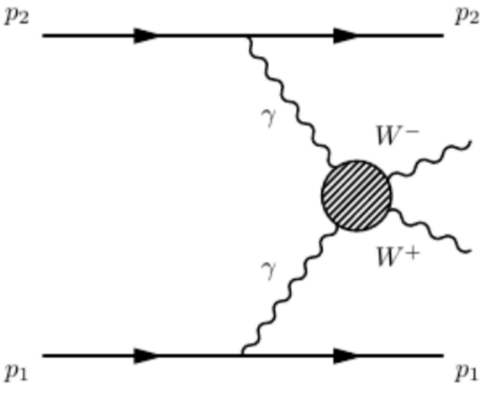


Photon is radiated off proton as a whole

“intact” proton: It continues to travel in the direction of the beam – **empty event** (here: Pb Pb $\rightarrow \gamma\gamma$, even more empty, no pileup)

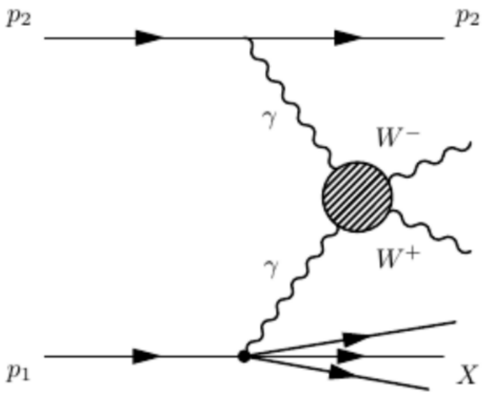


γγ → WW production at the LHC

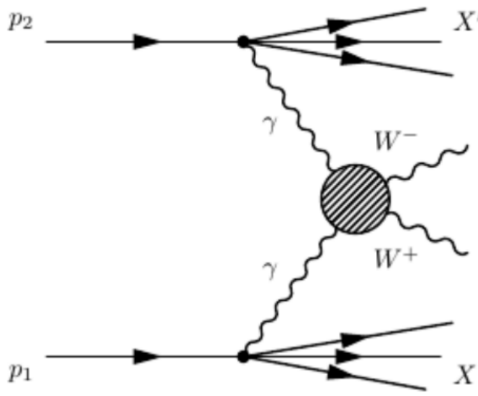


elastic (EE)

no particles other than W decay products

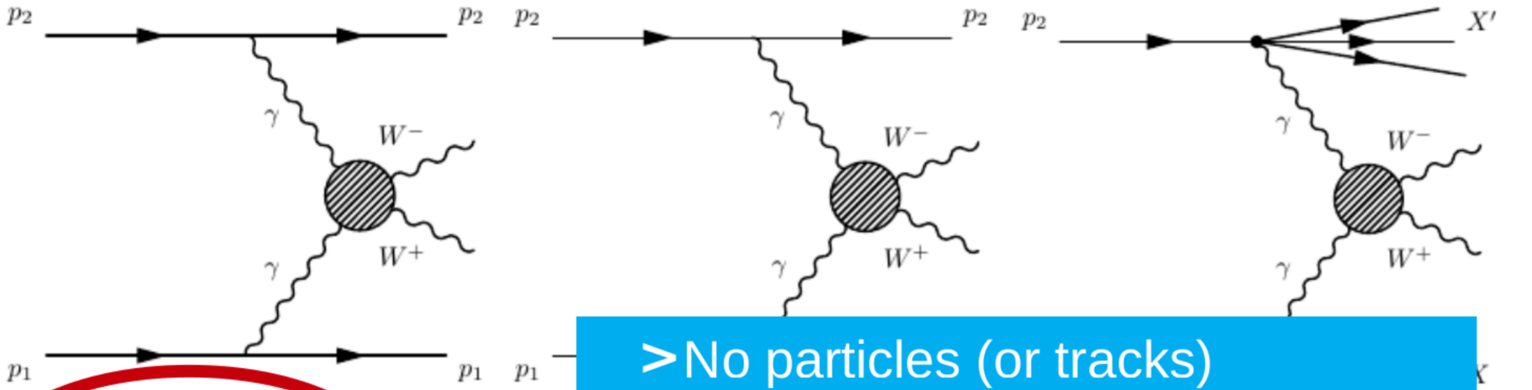


semi-dissociative (SD)



double-dissociative (DD)

$\gamma\gamma \rightarrow$ WW production at the LHC

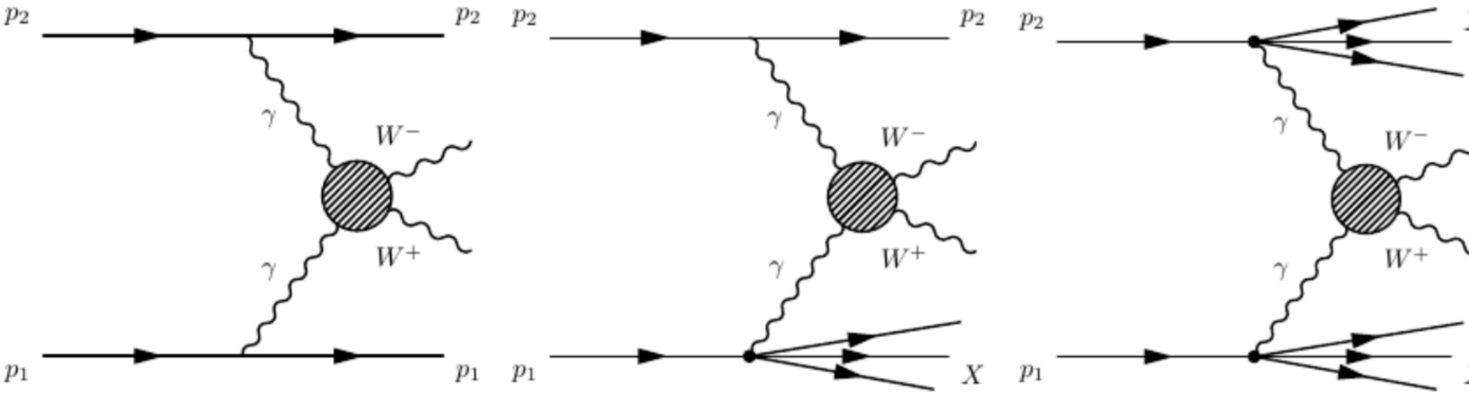


elastic (EE) semi-dis… …D)

no particles other than W decay products

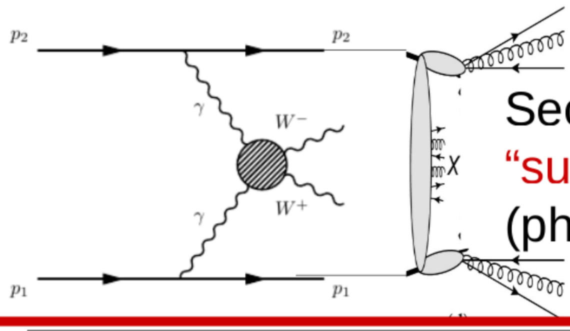
> No particles (or tracks) associated with the primary interaction vertex
> → **Track reconstruction**
> → **Vertex definition**

$\gamma\gamma \rightarrow$ WW production at the LHC



elastic (EE) semi-dissociative (SD) double-dissociative (DD)

no particles other than W decay products

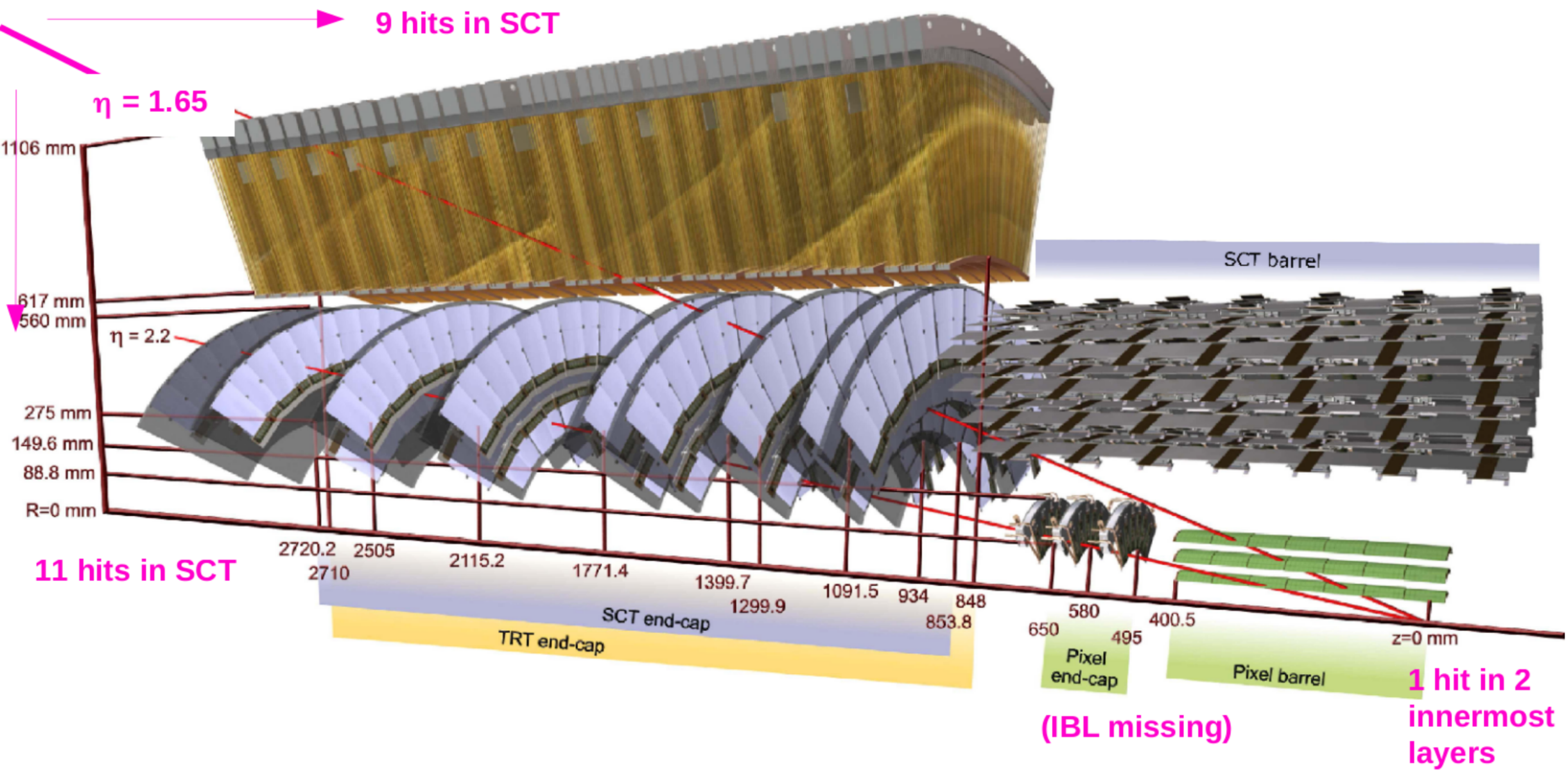


Second scattering: "survival factor" (phenomenological)

Reduces "visible" cross-section of elastic production (additional particles)

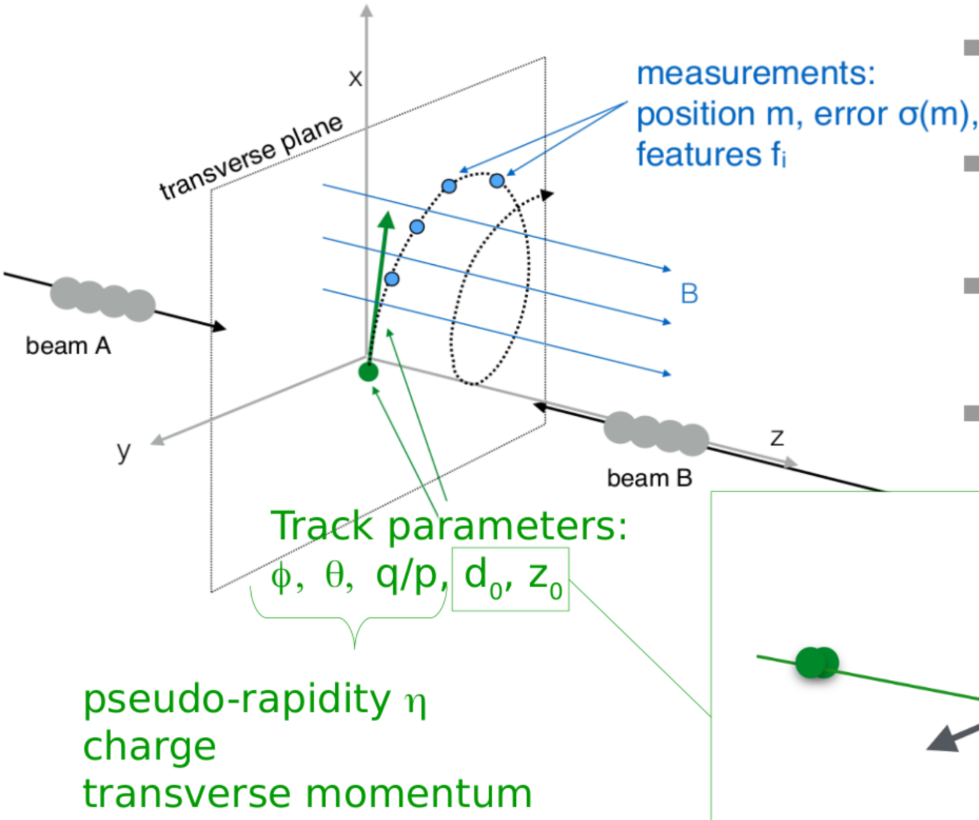
→ **Signal correction**

The ATLAS inner detector

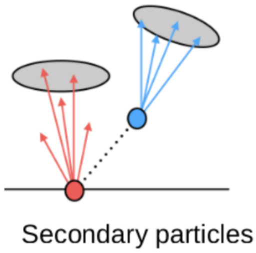


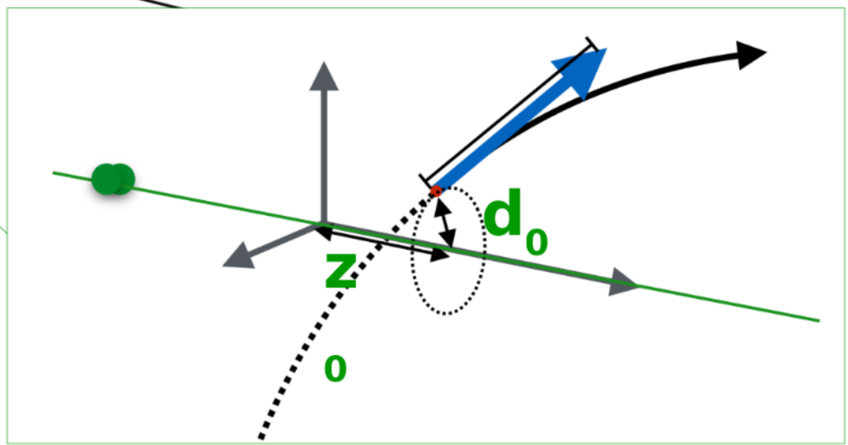
- Accurately reconstructing as many charged-particle tracks as possible is key!
- Innermost tracking layer at r = 33.5 mm (pixel size: 50 × 250 μm^2)
  Intrinsic spacial resolution: 10 × 75 μm^2

Track reconstruction



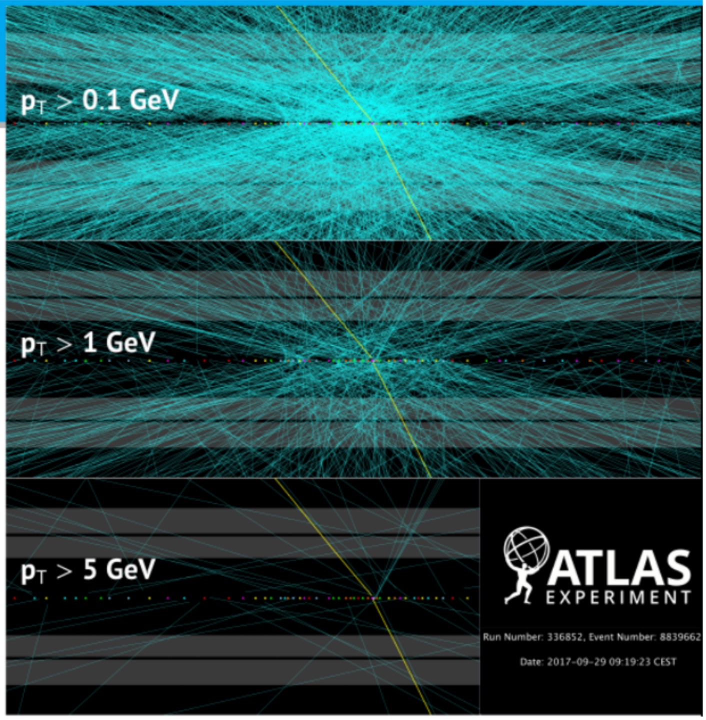
- PT > 500 MeV
- $|\eta| < 2.5$
- $|d_0|<1mm$
- **$|z_0|<1mm$**

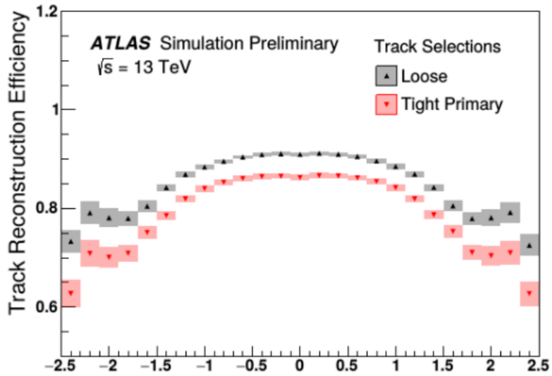




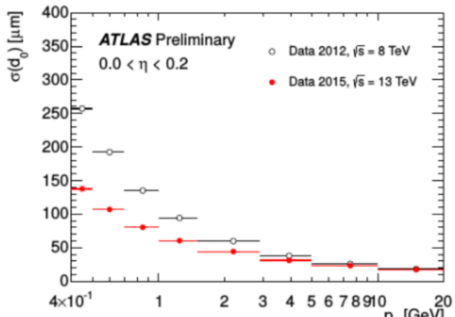
Tracking performance

- Track efficiency ~75-80%
- Tracks are the largest consumer of CPU and disk space in ATLAS → only tracks with pT > 500 MeV are available for analysis
- Lower pT → worse resolution (multiple scattering)

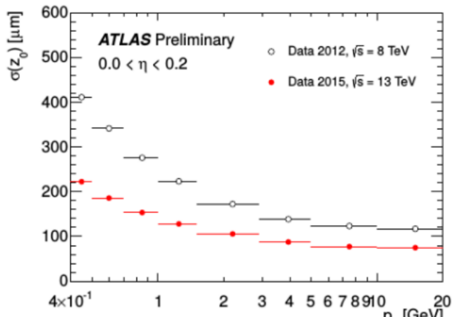




from ATL-PHYS-PUB-2015-051



from IDTR-2015-007



from IDTR-2015-007

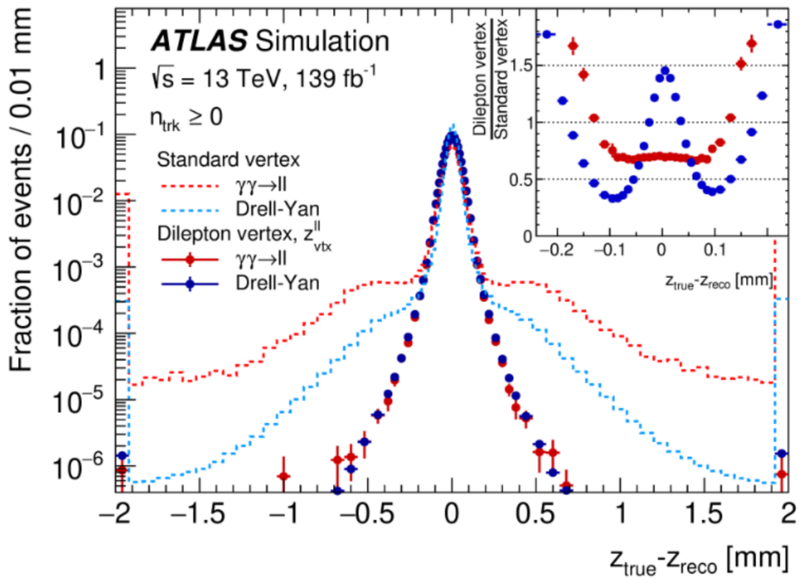
Vertex reconstruction

- ATLAS standard is to choose vertex with the largest $\sum p_T^2$ as *primary*
- Not optimal for photon-induced processes, here leptons are used to reconstruct the interaction vertex:

$$z_{\mathrm{vtx}}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

($\sin^2\theta$ parametrizes uncertainty on measured z position)

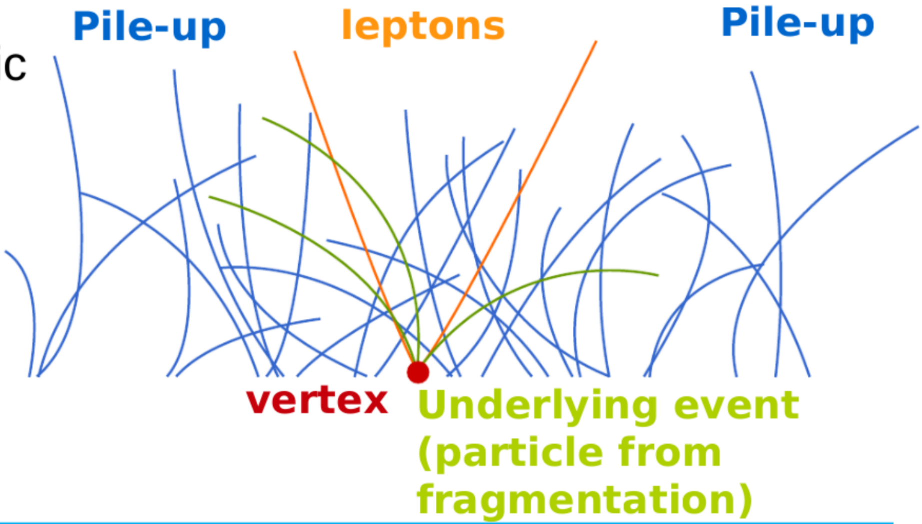
- This definition is **more efficient** and **unbiased*** by close-by pileup tracks



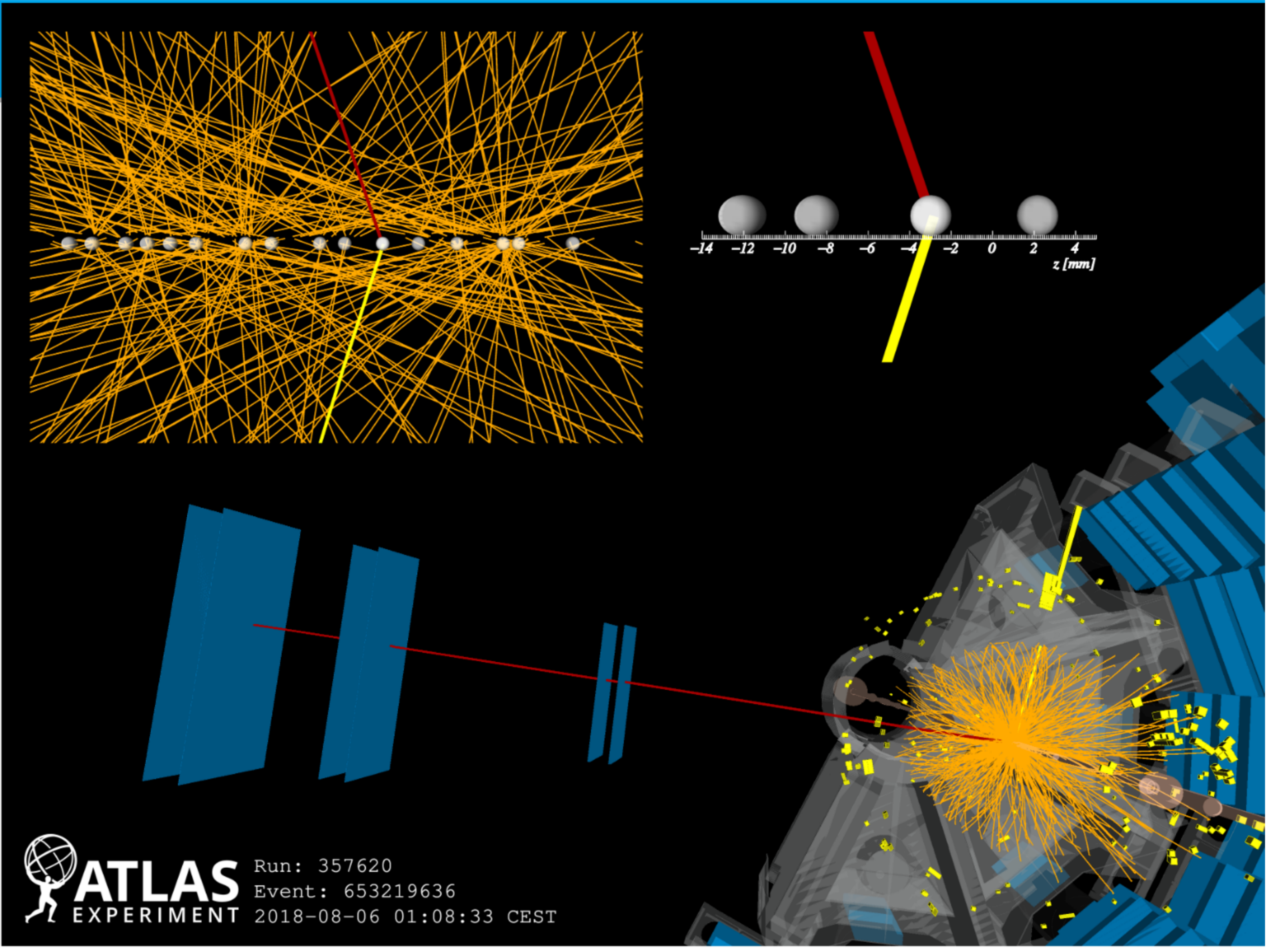
*backup

Event selection

- exactly one electron and muon with opposite electric charge
- p_T (ll) > 30 GeV, m(ll) > 20 GeV
- no tracks associated with primary interaction vertex

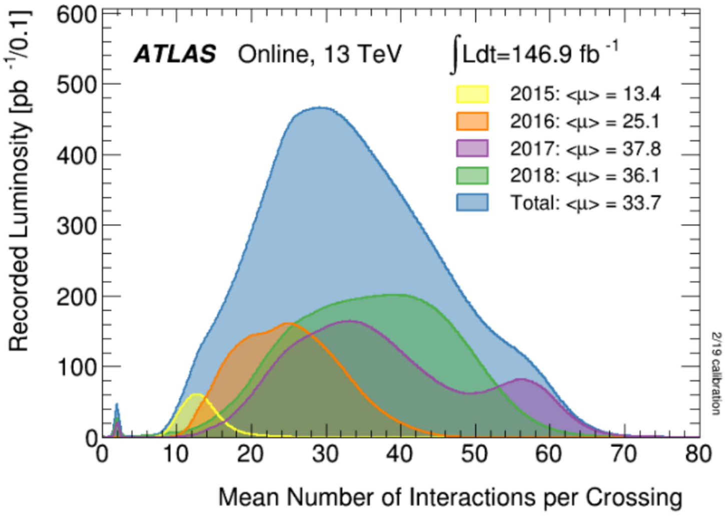


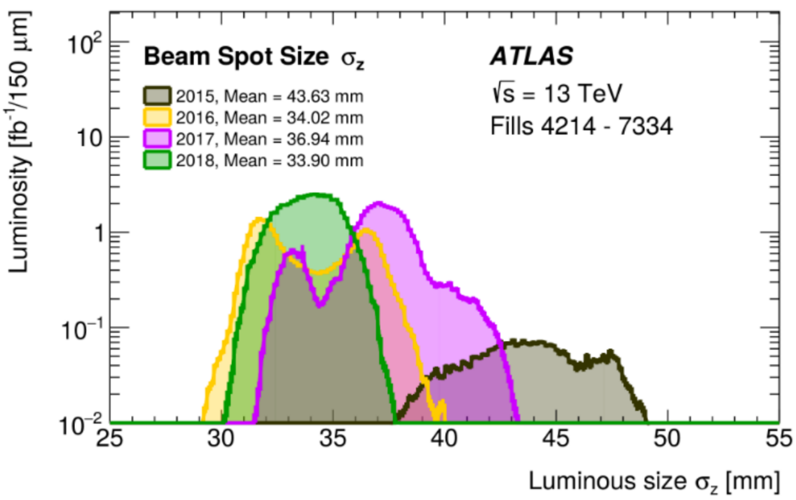
> Modeling of **pileup** (random interactions close to vertex)
>
> Modeling of **underlying event** of backgrounds
>
> **Modeling of the signal** ("survival factor")



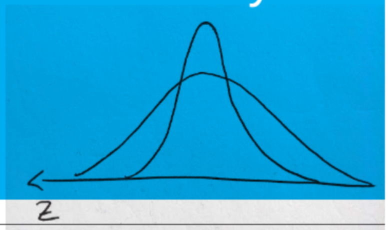
−14
−12
−10
−8
−6
−4
−2
0
2
4
z [mm]
ATLAS
EXPERIMENT
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Pile-up in the context of the measurement



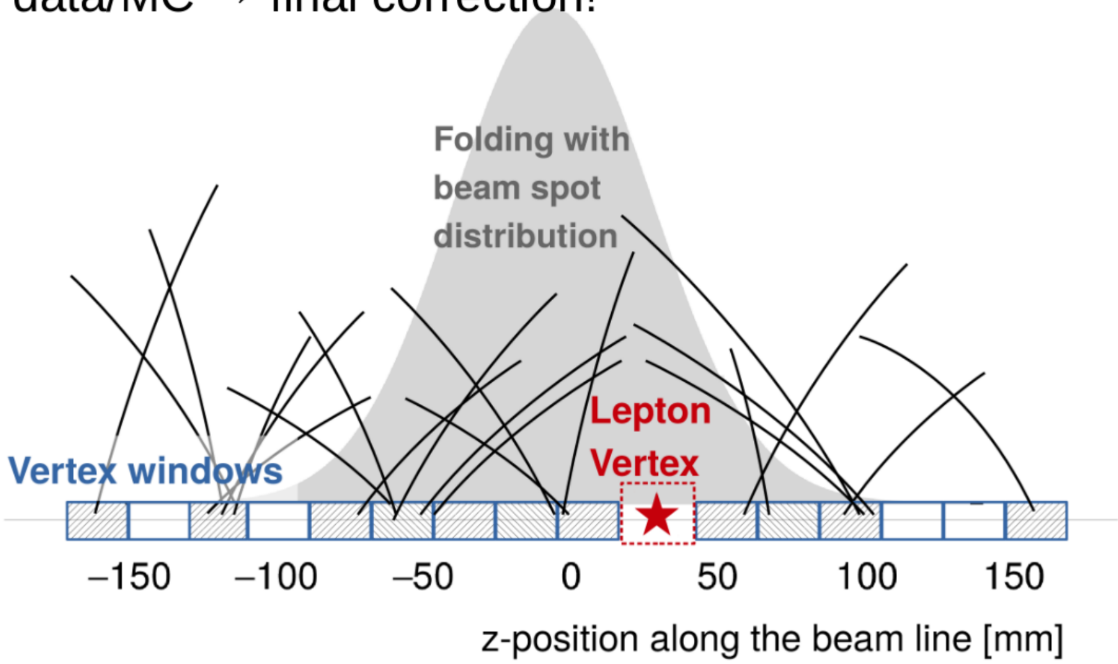


- Pile-up is the number of *pp* interactions per bunch crossing
- Longitudinal width of the beam spot determines density of additional *pp* interaction along z
- Corrected for using reweighting approach



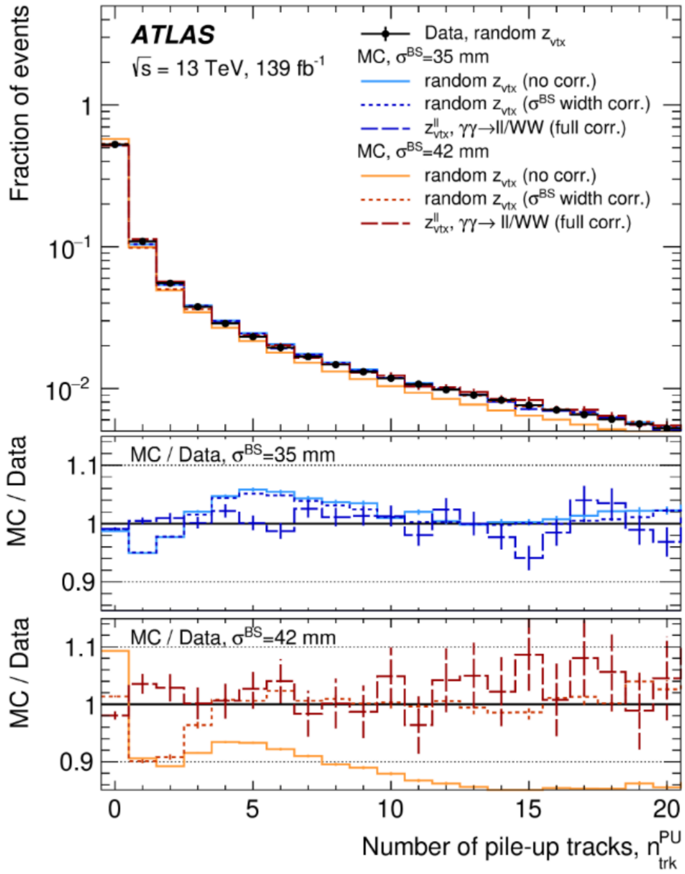
Correcting number of tracks per pile-up vertex

- Same procedure in data and MC: Sample number of tracks in random windows along z (away from lepton vertex)
- Weight with beam spot distribution
- Divide data/MC → final correction!

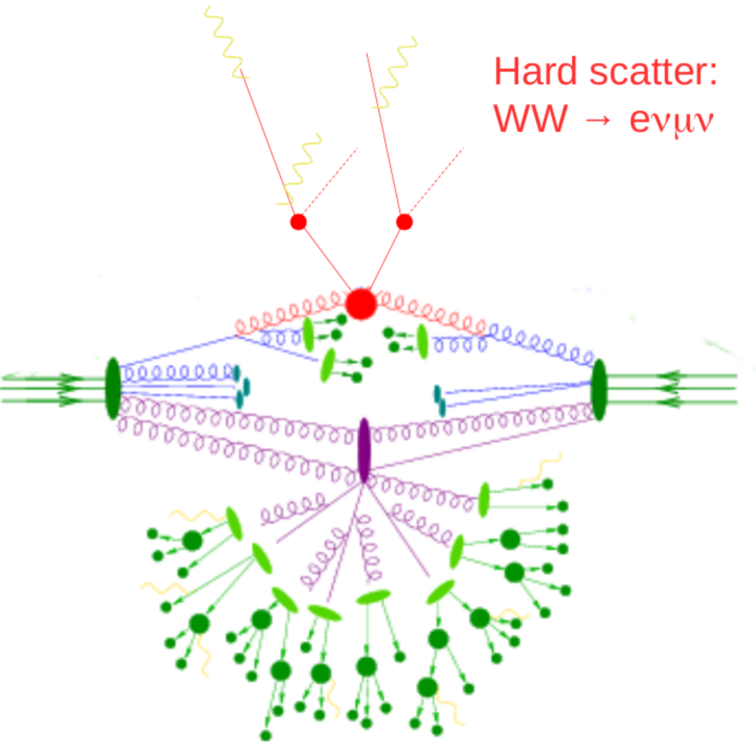


Pile-up correction at work

- Full set of correction gives good agreement between data and MC
- Efficiency to select 0-tracks in presence of pile-up is on average 52.6% for Run 2 *(exclusive efficiency)*
- Large source of efficiency loss → worsens with number of interactions*



Modelling of underlying event

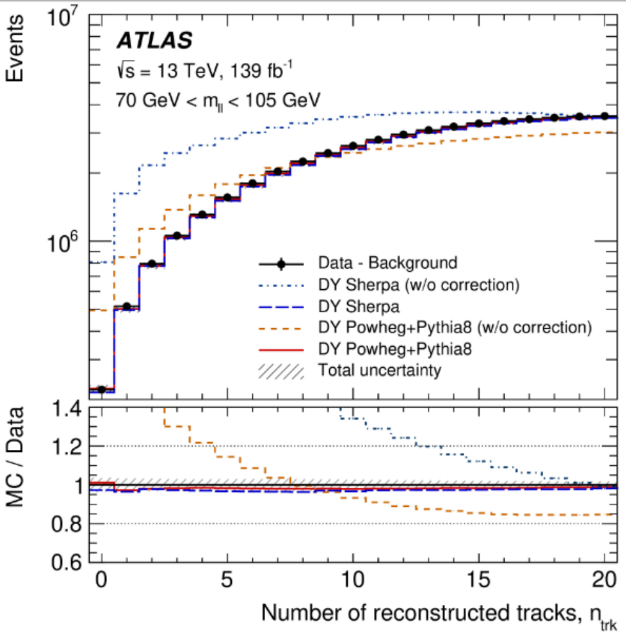


Underlying event: Interactions of proton remnants, fragmentations

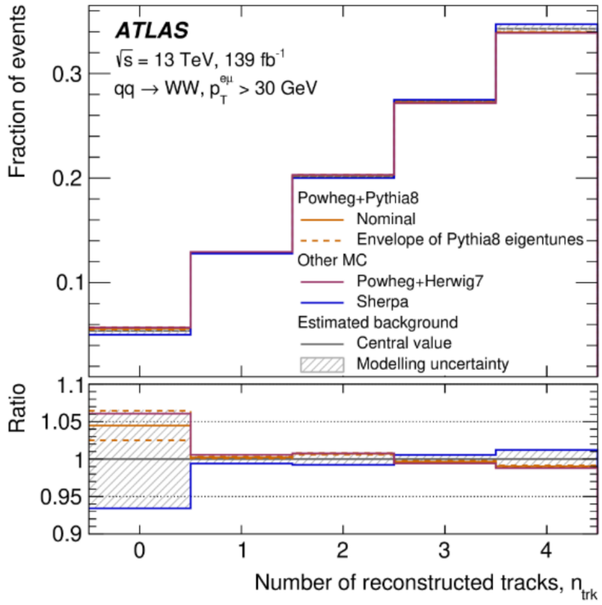
- qq/gg → WW has the same final state as γγ →WW apart from underlying event
- Problems with modelling of charge particle (track) multiplicity at low momentum are well known*
  → **need to apply in-situ correction to model WW background correctly**
- Use Z boson and unfold charged particle distribution as function of:
  – particle multiplicity
  – p_T(ll) (measure for p_T([di]boson))

*backup

Modelling of underlying event



- For qq→WW: Good agreement for $1 \leq n_{trk} \leq 4$ but $n_{trk}=0$ has large differences between hadronic models
- Use midpoint and envelope for WW prediction (7% syst.)



- Correction can be up to a factor of 5!
  → good agreement with data afterwards
- Apply unfolded charged particle distribution as function of $p_T(V)$ to DY (as function of $p_T(VV)$ to diboson events)

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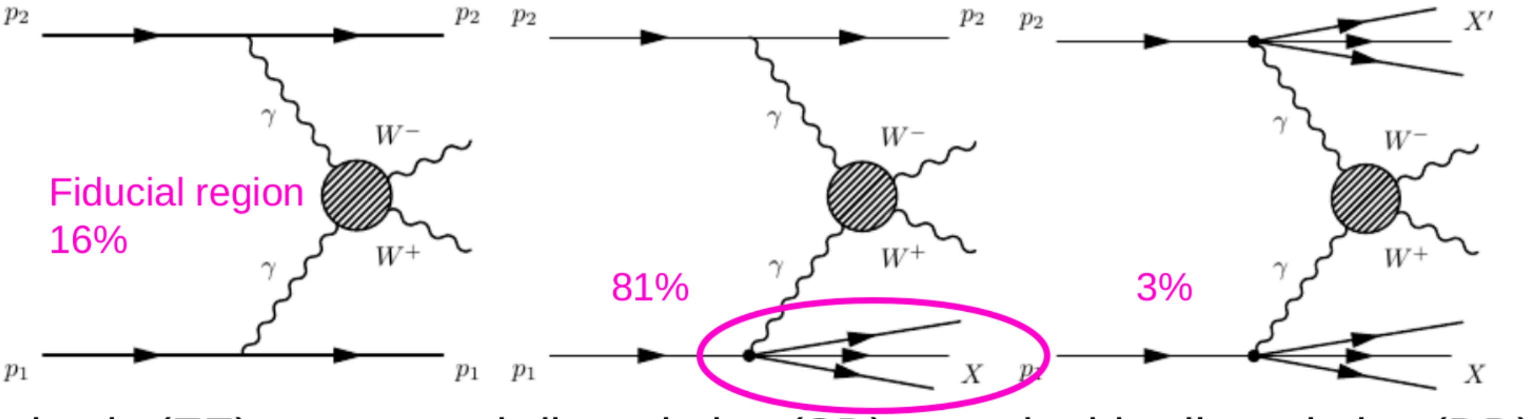
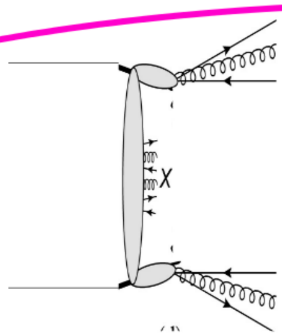
Signal Modelling: Why?



elastic (EE) semi-dissociative (SD) double-dissociative (DD)

most reliable theory

Difficult to model!!



Second scattering: "survival factor" (phenological)

Reduces "visible" cross-section of elastic production → additional particles

Signal Modelling: How?

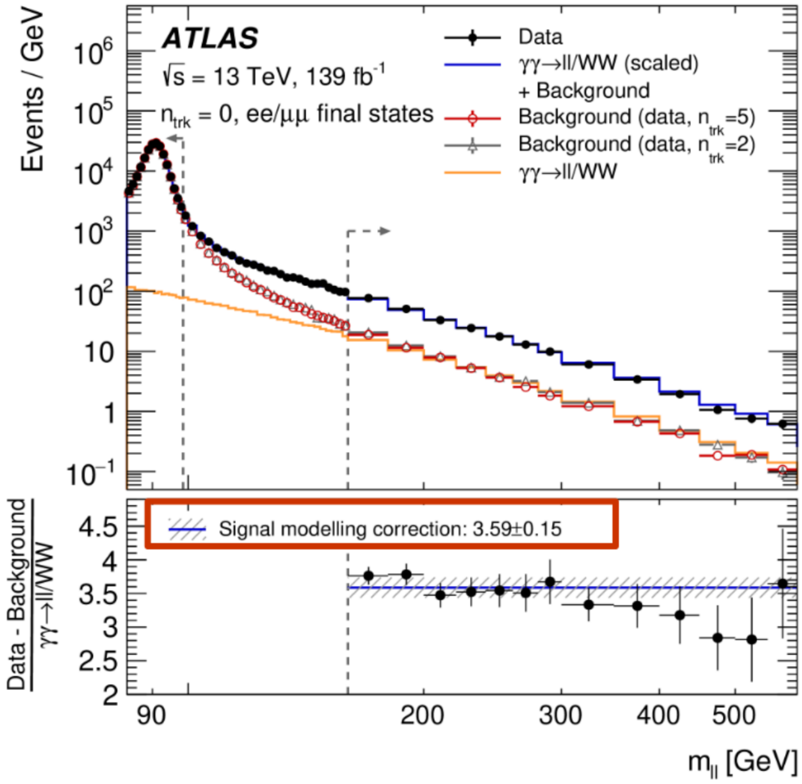
- Data-driven scaling of $\gamma\gamma \rightarrow WW$ using $\gamma\gamma \rightarrow \ell\ell$ same flavour events for a signal-like selection (n_{trk}=0, $m_{\ell\ell}$ > 160 MeV)

- **Shape** of pp-induced backgrounds extracted for **n_{trk}= 5** (less than 1% $\gamma\gamma$)

- **Normalization** from *Z*-peak region (**m_Z+/- 7.5 GeV**) (~0.5% of $\gamma\gamma$)

- Both varied for systematics ~4%

- Scaling of **$\gamma\gamma \rightarrow WW/\ell\ell$** by **3.59 ± 0.15** yields good data/MC agreement



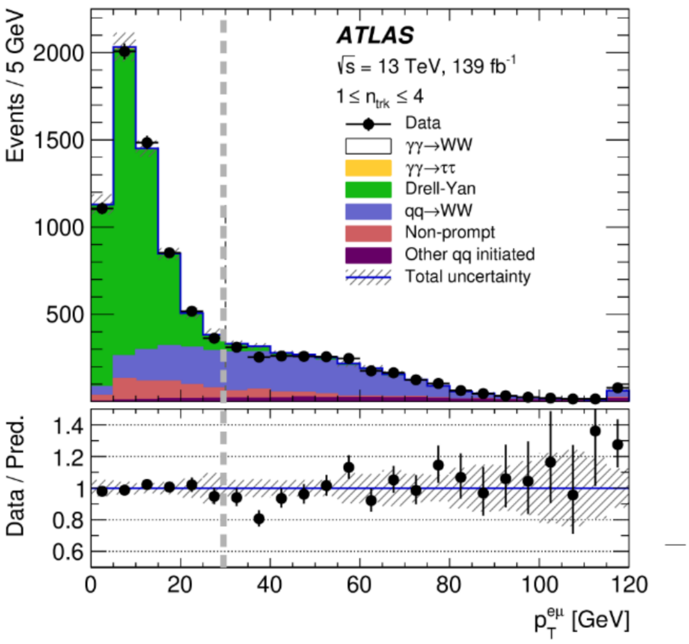
Signal extraction: Putting it all together

- Using profile LH fit over 3+1+1 regions (1 SR + 3 CR + signal modelling CR) → 4 free normalization parameters ($\gamma\gamma \to WW$, $\gamma\gamma \to ll$, DY, $qq \to WW$)

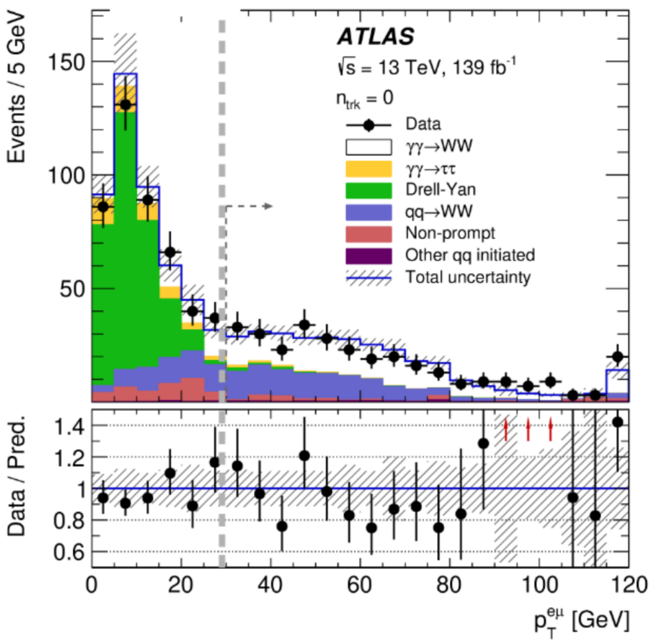
p_T (ll) < 30 GeV	CR1	CR2
p_T (ll) > 30 GeV	SR	CR3
	n_{trk}=0	$1 \le n_{trk} \le 4$

- Signal region: $\gamma\gamma \to WW$ (57%), $qq \to WW$ (33%)

CR2 CR3

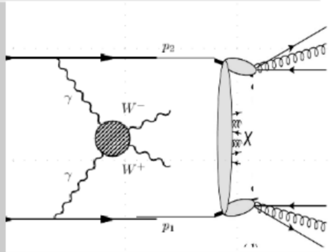


CR1 SR



Results

- Background-only hypothesis rejected with **significance of 8.4 σ** (6.7σ exp.)
- **First observation of photon-induced WW production ($\gamma\gamma \rightarrow$WW) in exclusive phase space (without any associated tracks)**
- Uncertainties* dominated by WW modelling and background statistics
- Large range of theoretical models: Uncertainty dominated by data-driven scaling or scale uncertainties (SD) and second scattering probability

	cross section	**uncertainty**
σ(meas)	**3.13 fb**	$\pm$0.31 (stat) $\pm$0.28 (syst) fb
σ(EExSF– our expectation)	0.65 fb $\times$ 3.59 **2.34 fb**	$\pm$0.15 (exp) $\pm$0.39 (transfer, ll$\rightarrow$WW) fb $\pm$0.27 (total) fb
σ(pure theory prediction)	4.3 fb $\pm$1.0 (scale) $\pm$0.12 (syst) (without second scattering)	$\times$ 0.65 = **2.8 $\pm$0.8** (total) fb $\times$ 0.82 = **3.5 $\pm$1.0** (total) fb 

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- $\gamma\gamma \rightarrow$ WW production has been observed

- How to proceed from here?

  → use the measurement to characterize the SM

  → improve the interpretation of the measurement

Characterise the Standard Model

- Effective field theory is a general SM extension
- Allows to identify deviations in a systematic (and renormalizable) way

Operators:
Which particles interact?

Coupling strength:
How strong is the interaction?

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{\mathrm{i}} \frac{c_{\mathrm{i}}^{d}}{\Lambda^{d-4}} \mathcal{O}_{\mathrm{i}}^{d}$$

Standard model

General extension: describes **any new phenomena** suppressed by **energy scale Λ^(dimension d - 4)**

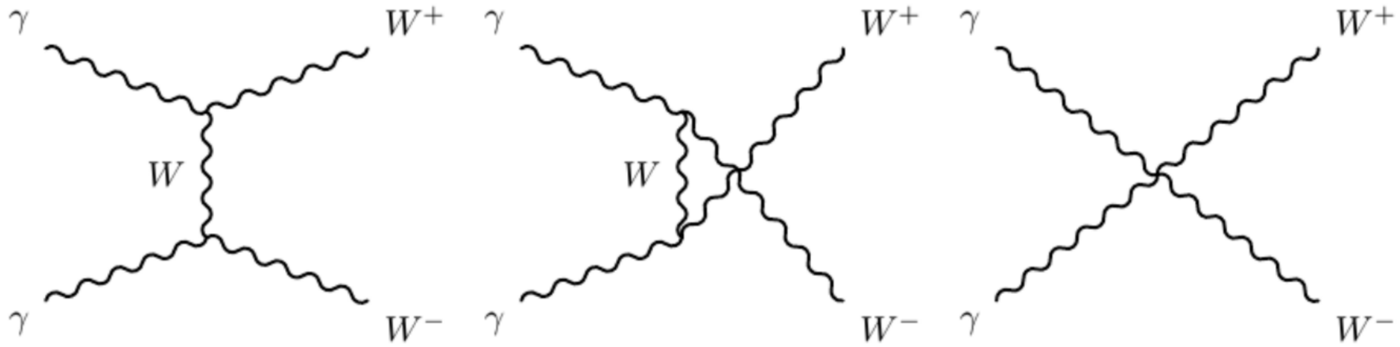
d ≤ 4 → Standard model
d = 5 → *Neutrino masses*

d ≥ 6 → Unknown phenomena

$\gamma\gamma \rightarrow$ WW is incredibly sensitive

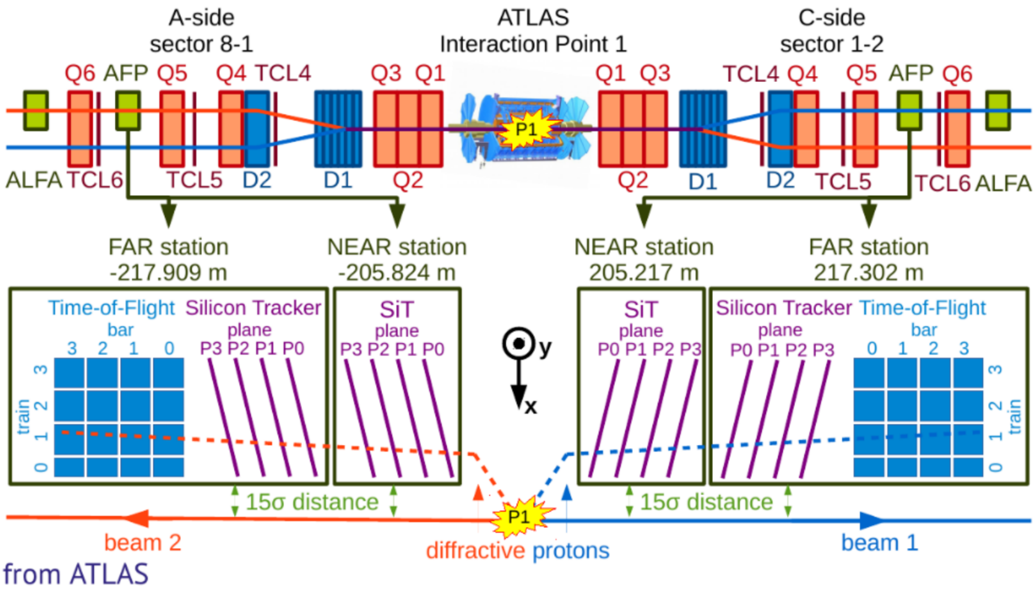
- At leading order, ***only*** diagrams with triple and quartic couplings contribute

- Incredibly sensitive to possible EFT operators → but need to improve theory prediction and measurement



A new detector for photon scattering

- The AFP spectrometer installed between 2016 and 2017 at z=200m
- Direct detection of scattered protons that leave the interaction intact



- Allows to reconstruct invariant mass of events

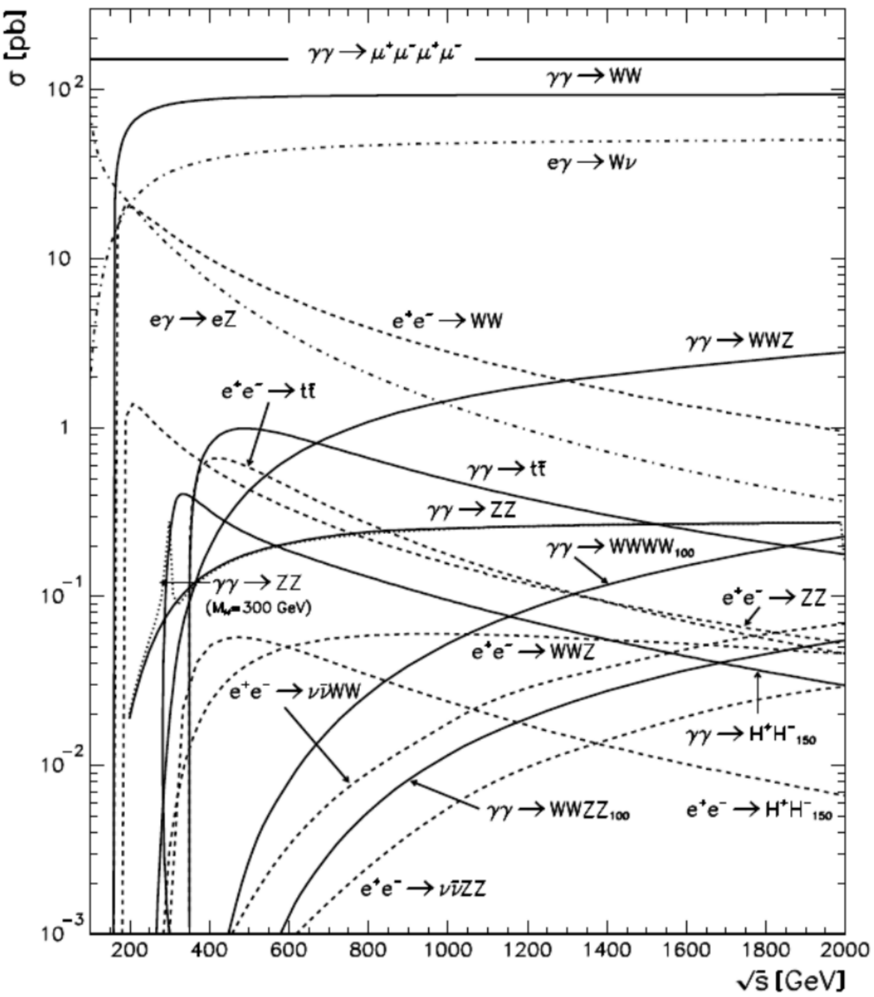
$$W = \sqrt{s\xi_1\xi_2} = m_{WW}$$

- Full event information → better EFT (and other) searches

$$\xi = 1 - E_{\text{scattered}} / E_{\text{beam}}$$

- With $\xi = 1 - E_{scattered} / E_{beam}$ with an acceptance of $0.02<\xi<0.1$

Outlook: There is much more to discover!



Take-away message

- First Observation of photon-induced WW production
- Reasonable agreement with theory prediction (albeit large uncertainties)
- Process can play a crucial role for the constraints on new physics as deviations ***from the Standard Model predictions***
- Future measurements could use proton taggers

Backup slides.

The Standard Model's biggest triumph

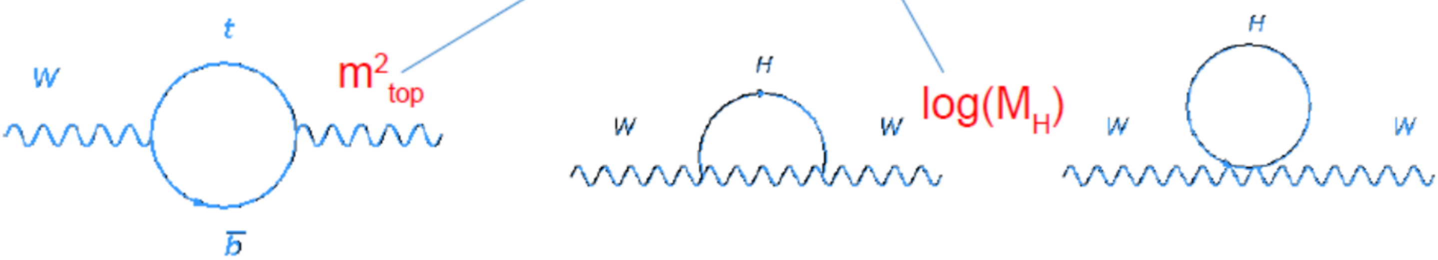
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

$$v = \left(\sqrt{2}\,G_F\right)^{-1/2} \simeq 246.22\ \mathrm{GeV} \qquad \alpha = \frac{e^2}{\hbar c}. \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

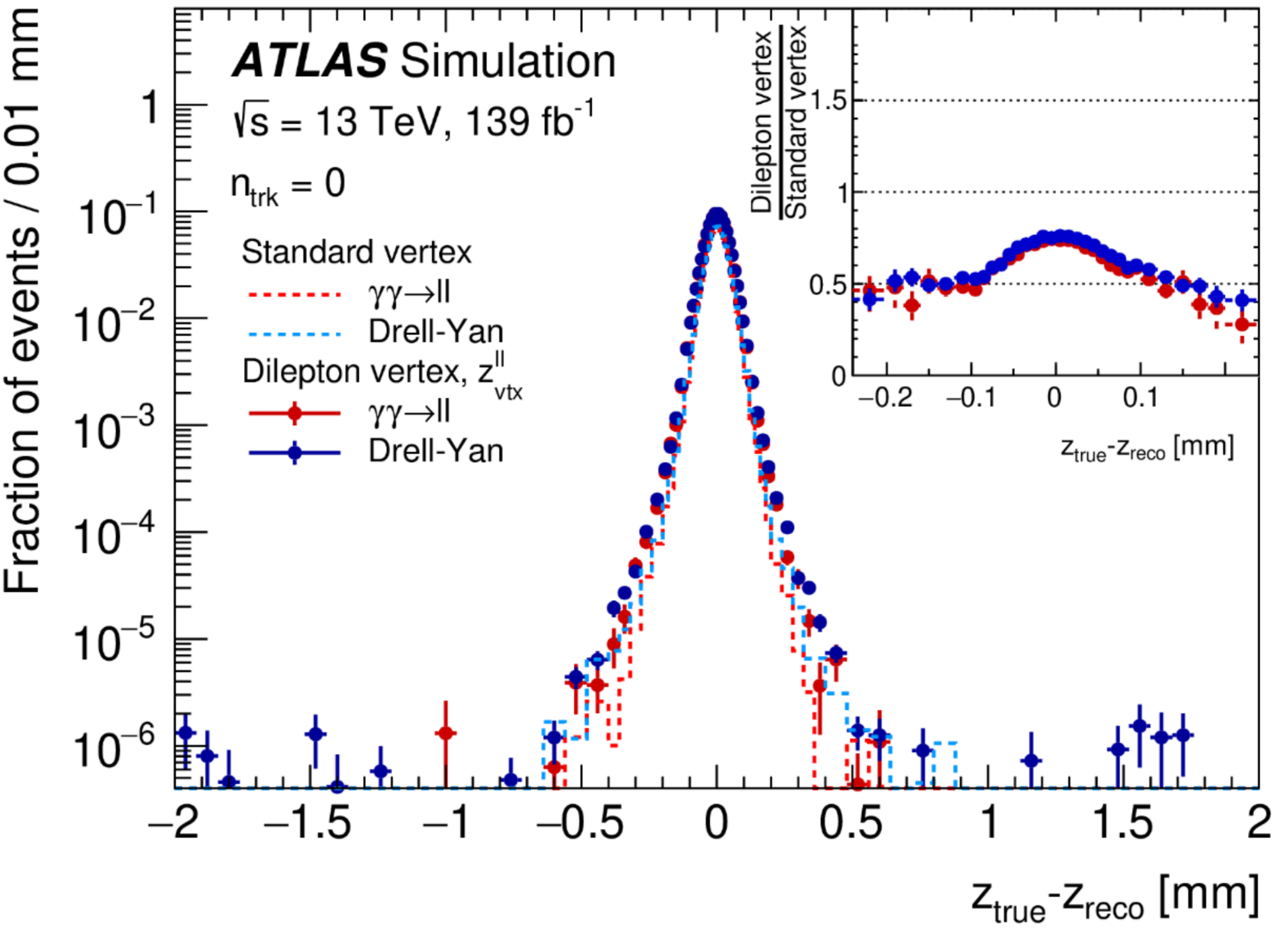
$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2} \frac{1}{\sin\theta_W\,\sqrt{1-\Delta r}}$$

radiative corrections

$\Delta r \sim 3$ %



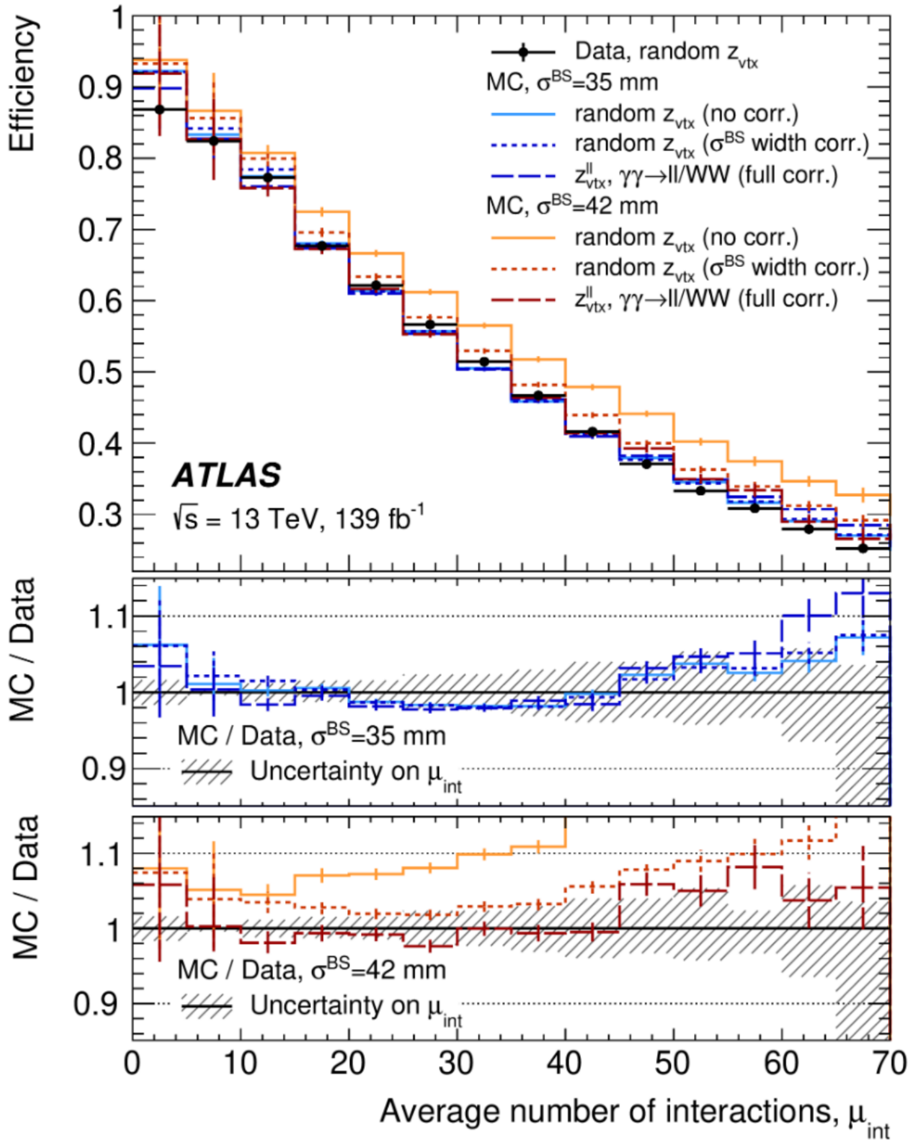
Vertex reconstruction – 0 tracks



Selected events

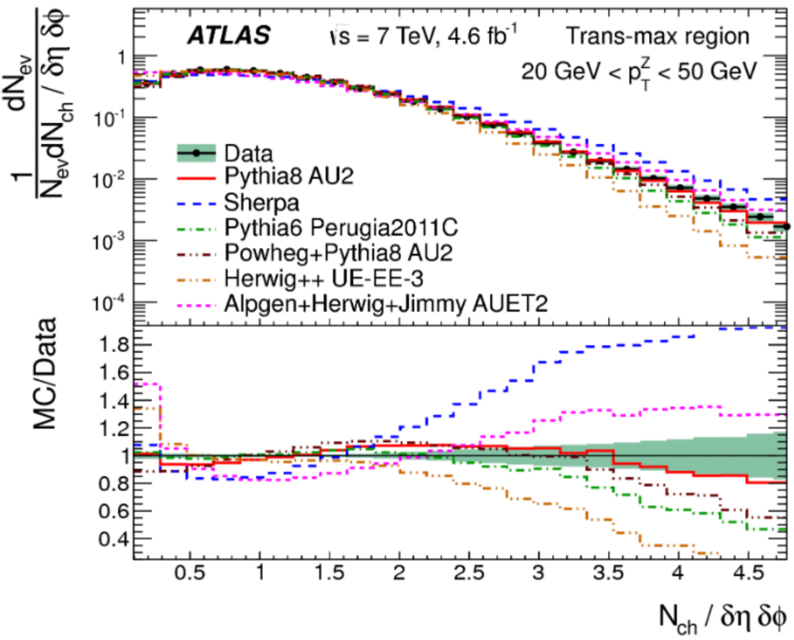
	Signal region	Control regions		
n_{trk}	$n_{\mathrm{trk}} = 0$		$1 \leq n_{\mathrm{trk}} \leq 4$	
$p_{\mathrm{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

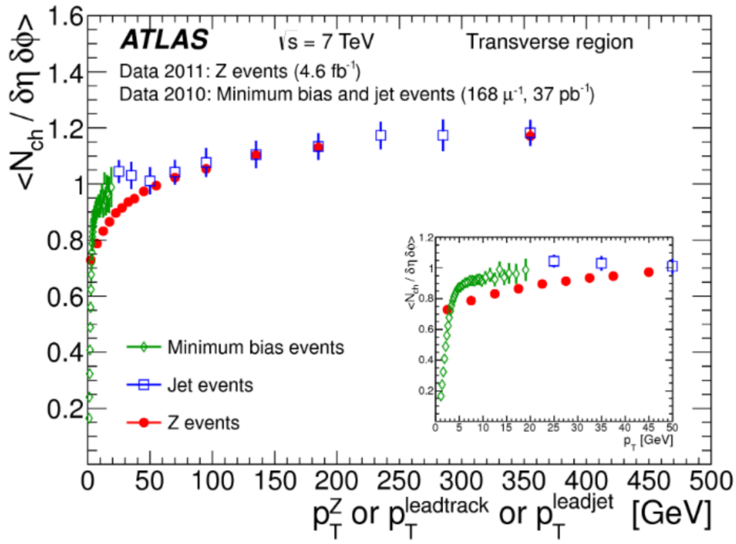
Efficiency



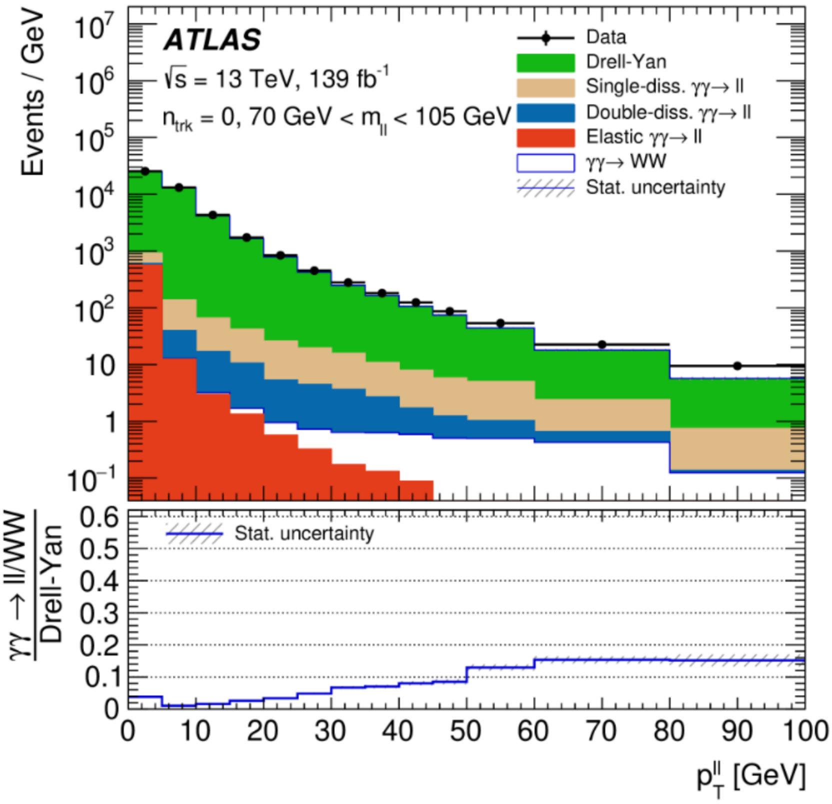
Efficiency
Data, random z_{vtx}
MC, σ^{BS}=35 mm
random z_{vtx} (no corr.)
random z_{vtx} (σ^{BS} width corr.)
z^{ll}_{vtx}, $\gamma\gamma\to$ll/WW (full corr.)
MC, σ^{BS}=42 mm
random z_{vtx} (no corr.)
random z_{vtx} (σ^{BS} width corr.)
z^{ll}_{vtx}, $\gamma\gamma\to$ll/WW (full corr.)
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
MC / Data
MC / Data, σ^{BS}=35 mm
Uncertainty on μ_{int}
MC / Data
MC / Data, σ^{BS}=42 mm
Uncertainty on μ_{int}
Average number of interactions, μ_{int}

Efficiency

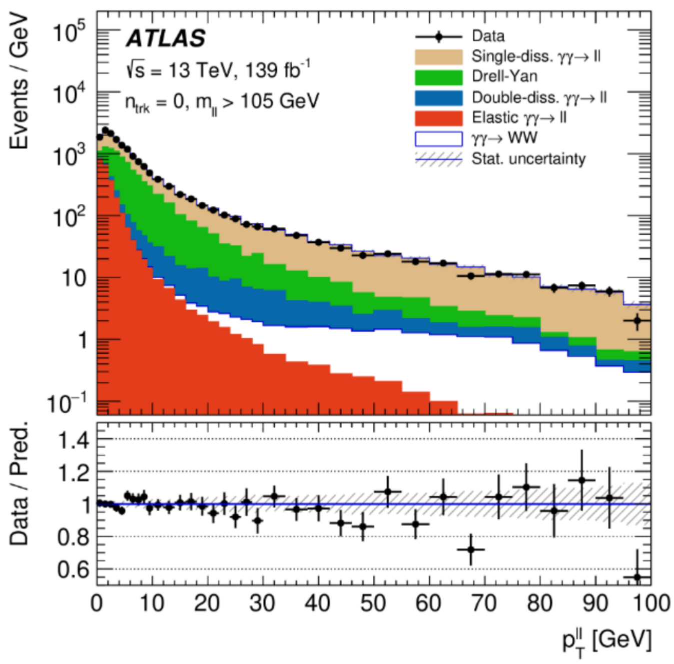

ATLAS
√s = 7 TeV, 4.6 fb-1
Trans-max region
20 GeV < p_T^Z < 50 GeV
Data
Pythia8 AU2
Sherpa
Pythia6 Perugia2011C
Powheg+Pythia8 AU2
Herwig++ UE-EE-3
Alpgen+Herwig+Jimmy AUET2
MC/Data
N_ch / δη δφ


ATLAS
√s = 7 TeV
Transverse region
Data 2011: Z events (4.6 fb-1)
Data 2010: Minimum bias and jet events (168 μ-1, 37 pb-1)
<N_ch / δη δφ>
Minimum bias events
Jet events
Z events
p_T^Z or p_T^leadtrack or p_T^leadjet [GeV]
p_T [GeV]

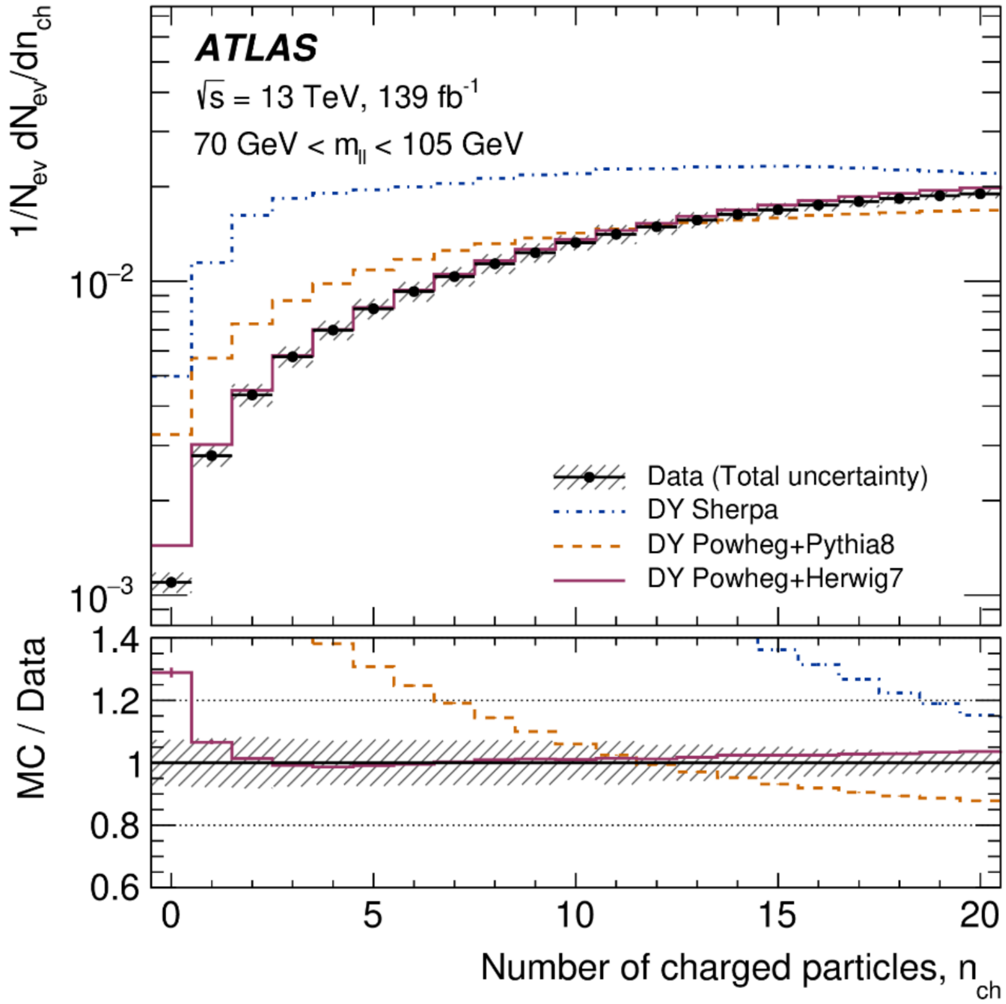
Charge particle multiplicity measurement



Derive normalisation for photon-induced processes from high-mass side band



Charge particle multiplicity measurement



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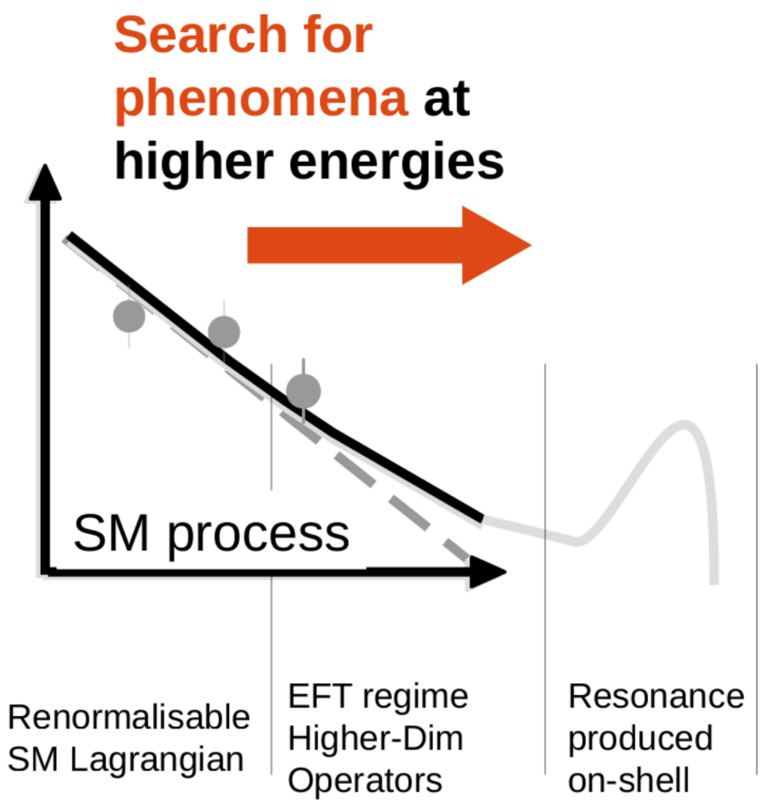
Uncertainties

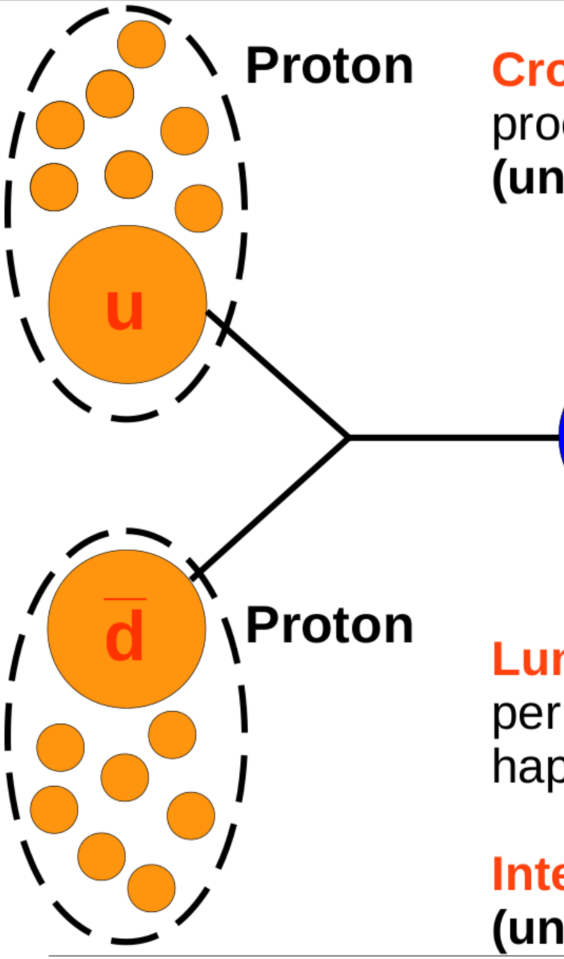
Source of uncertainty	Impact [%]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons	1.5
Background, statistical	6.7
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other backgrounds	1.7
Luminosity	1.7
Total	8.9

What if we don't reach the resonance? Effective field theory

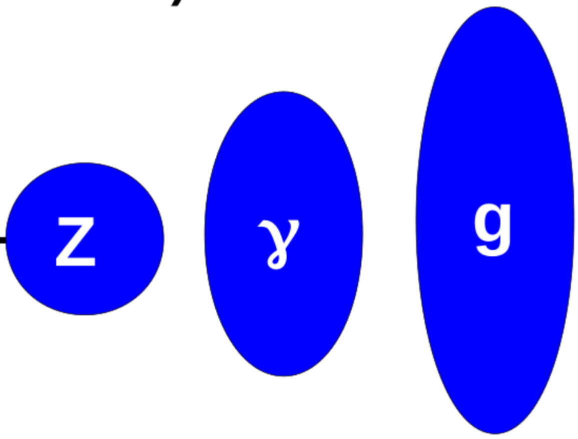


- Generic search for **deviations in distributions** sensitive to new physics effects
- Could be sensitive to much **higher energies scales** compared to resonance searches
- Detects also new physics **without resonances or very broad resonances**

Cross-section, Luminosity and Integrated Luminosity



Cross section: measure of probability of process to happen (strength of interaction) **(unit: area)**



Luminosity: How many colliding particles cross per unit area and second (how much could happen?) **(unit: 1/(area×time))**

Integrated Luminosity: size of data set **(unit: 1/area)**