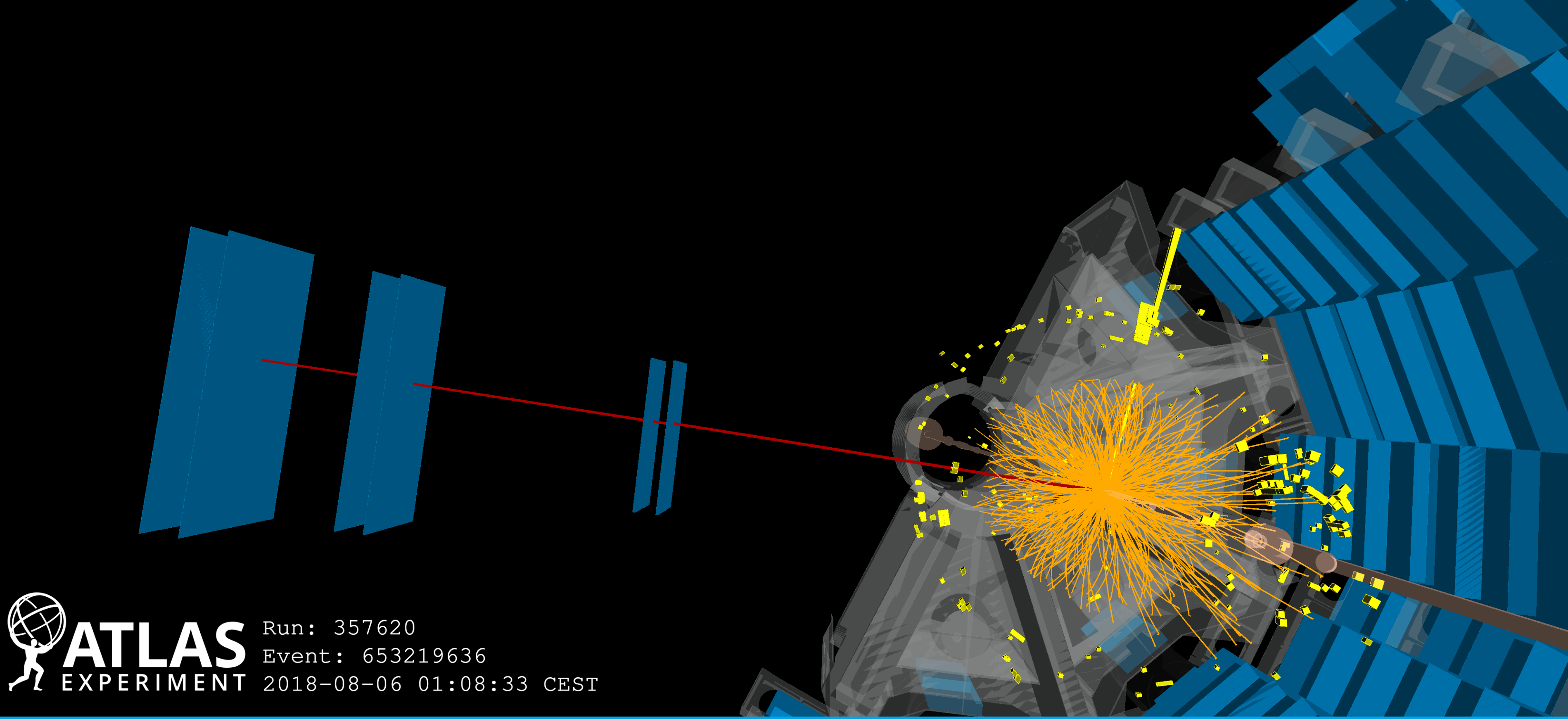
A window to new physics measurements: **Photon scattering at the LHC**



Kristin Lohwasser
University of Sheffield

Seminar, University of Warwick, November 12th 2020

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

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)

Parameters of the Standard Model [hide]

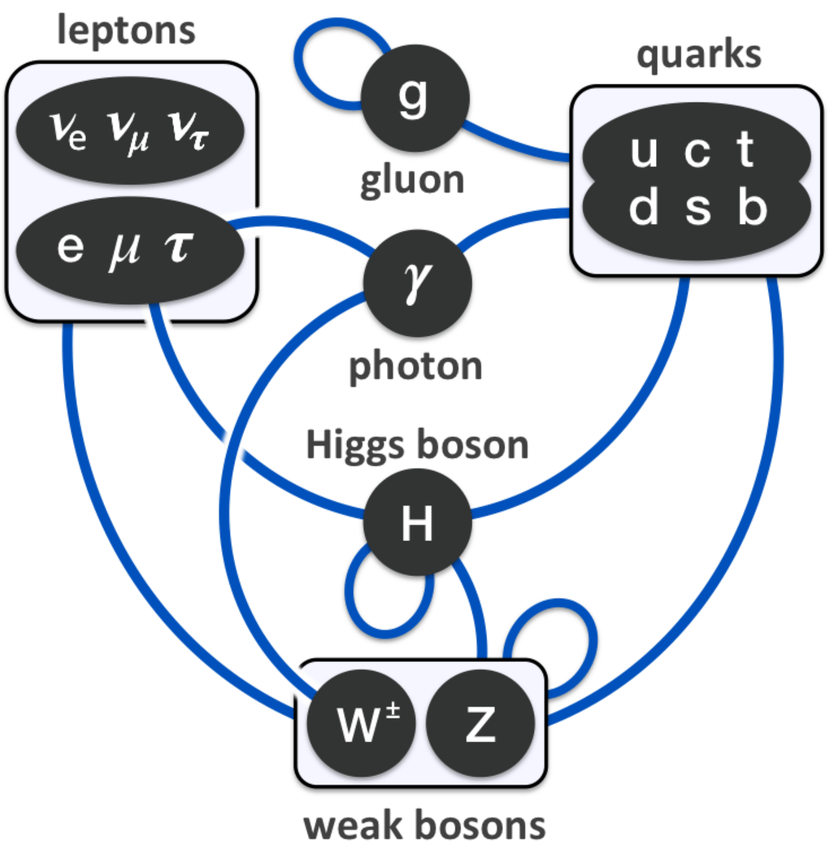
19 free parameters

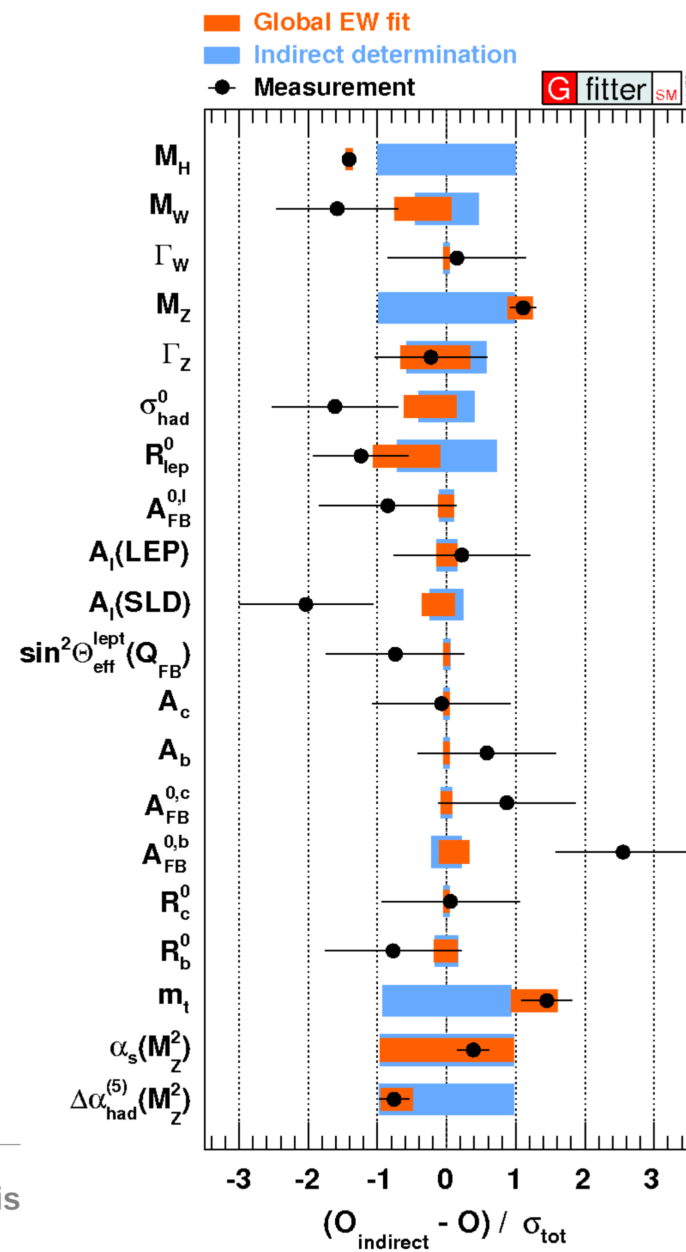
- particle masses
- CKM mixing angle (mass and electroweak eigenstates of quarks)
- Gauge couplings (strength of forces)
- Symmetry properties of QCD
- Parameters of electroweak symmetry breaking (Higgs mass and vaccum expection value)

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

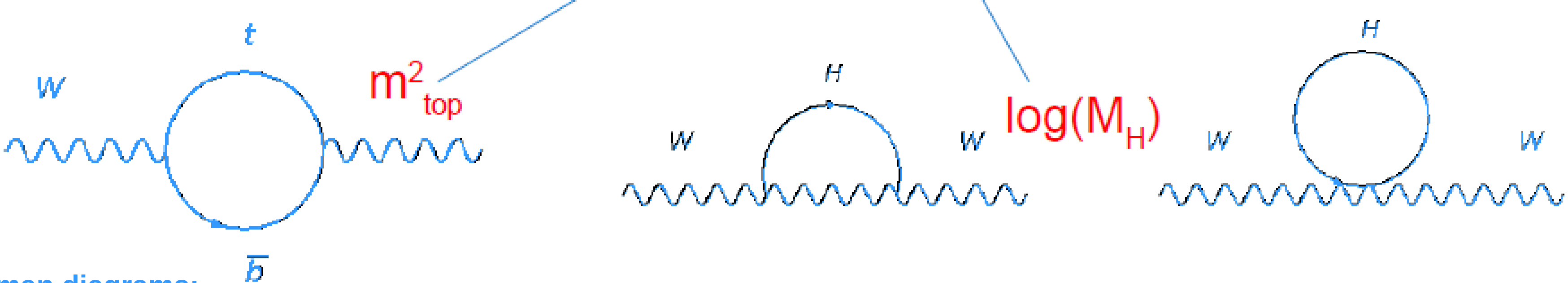
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

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

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

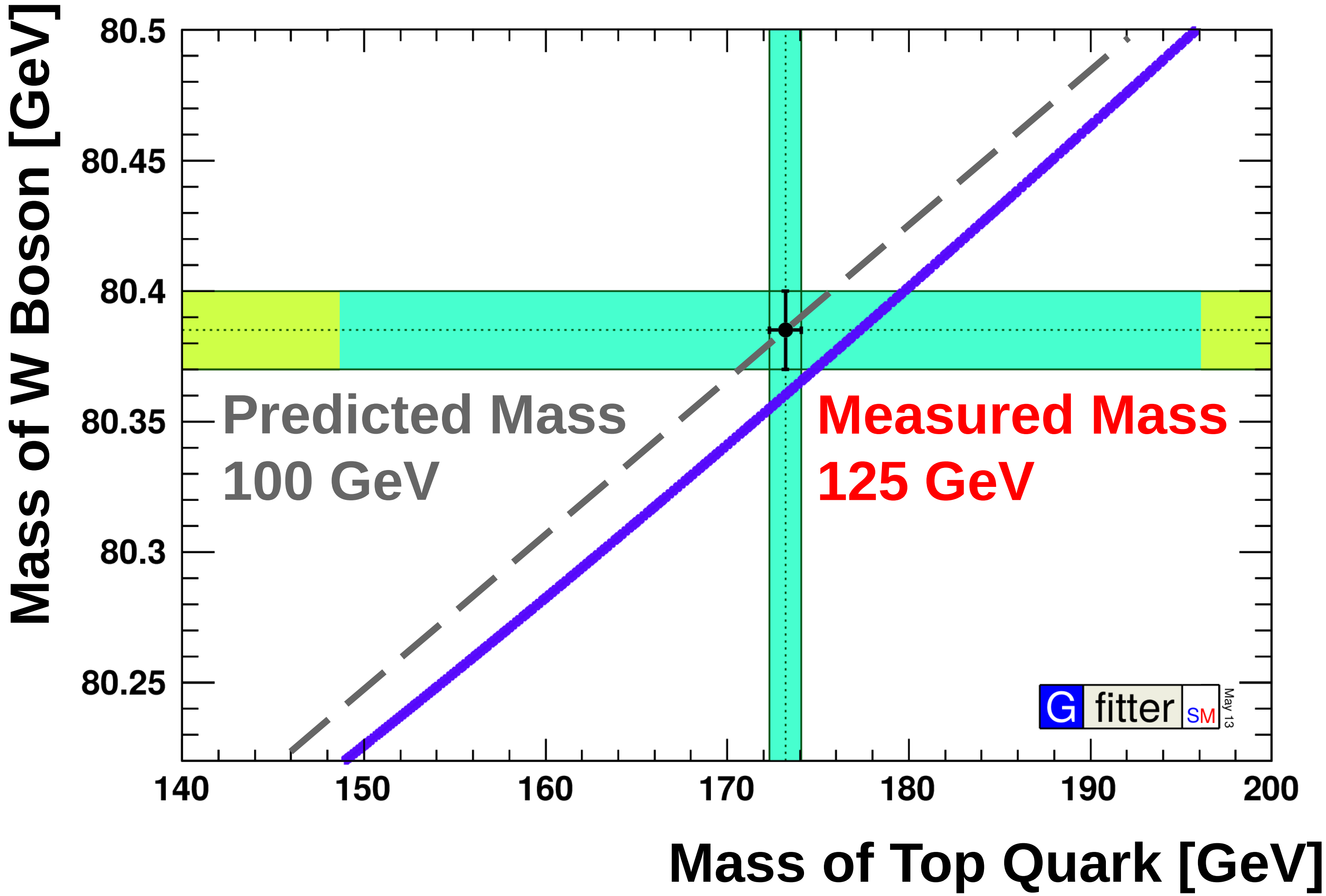
radiative corrections

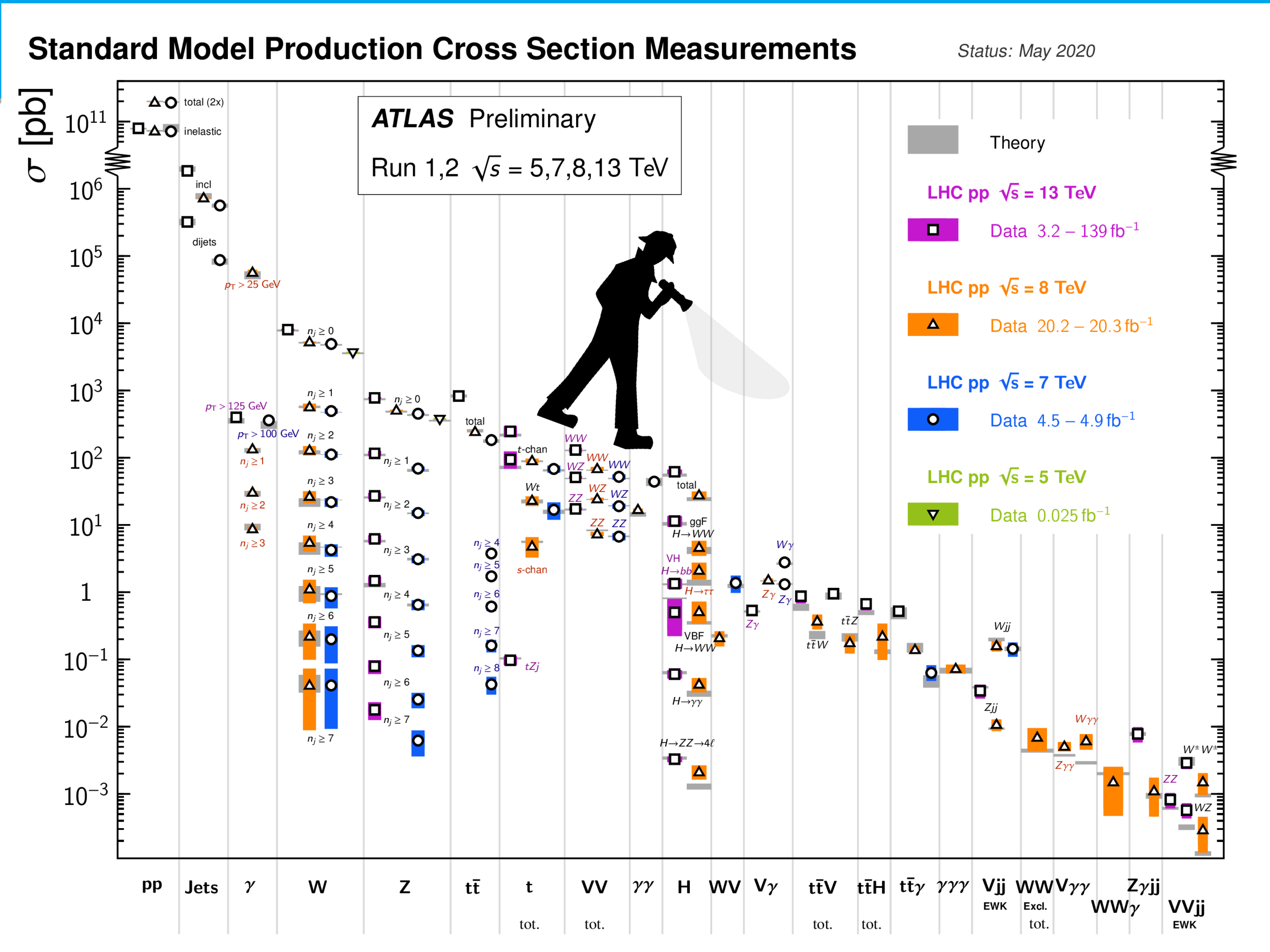
$\Delta r \sim 3\ \%$



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

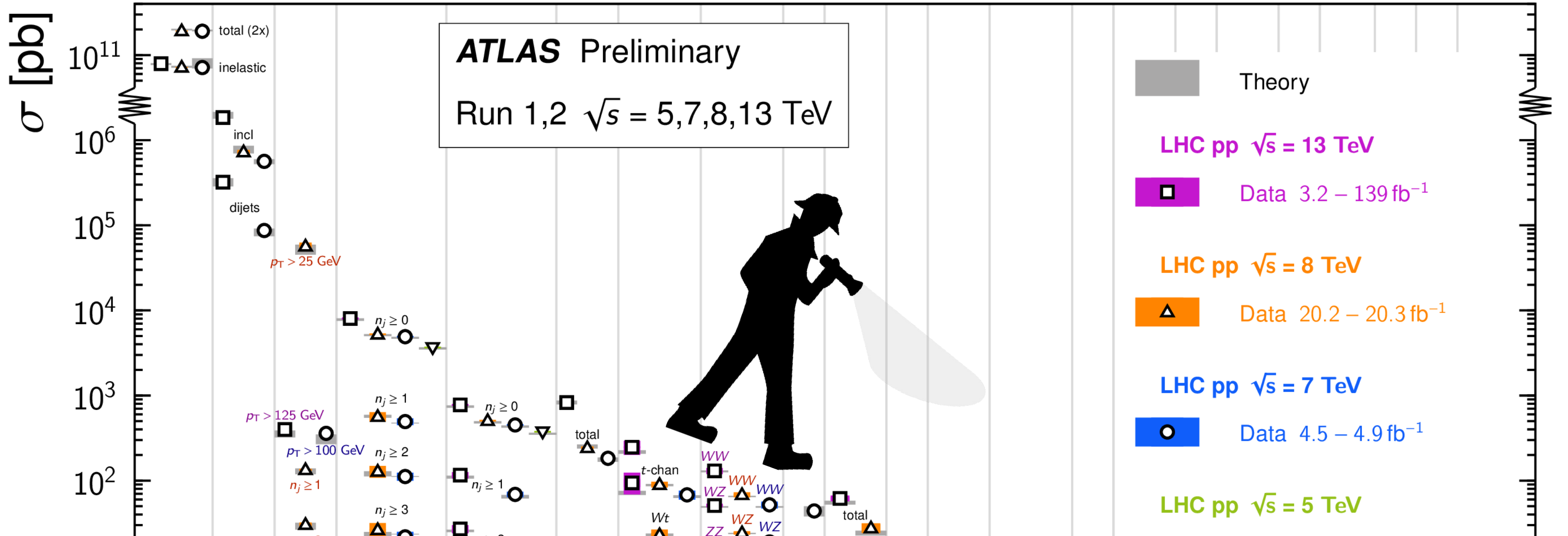
Indirect determination of Higgs boson mass





Standard Model Production Cross Section Measurements
Status: May 2020
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.025 fb⁻¹
σ [pb]
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄V
tt̄H
tt̄γ
γγγ
Vjj EWK
WW Excl.
Vγγ
WWγ
Zγjj
VVjj EWK

Standard Model Production Cross Section Measurements



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

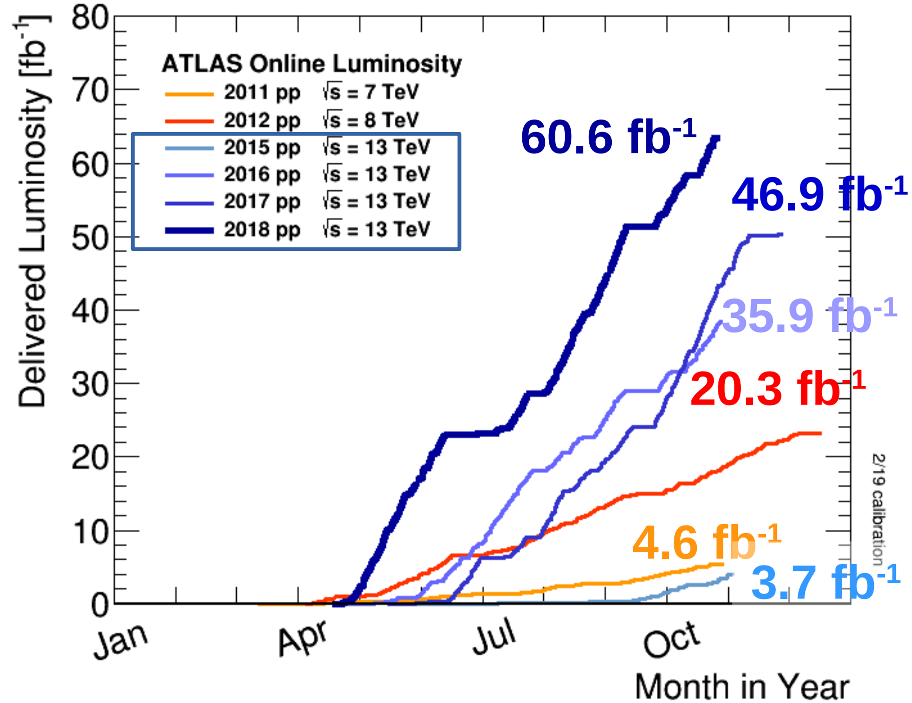
- > Measuring any SM process is a stringent test of our understanding of nature – especially if it's for the first time

Using protons….

ATLAS EXPERIMENT

Data collected:

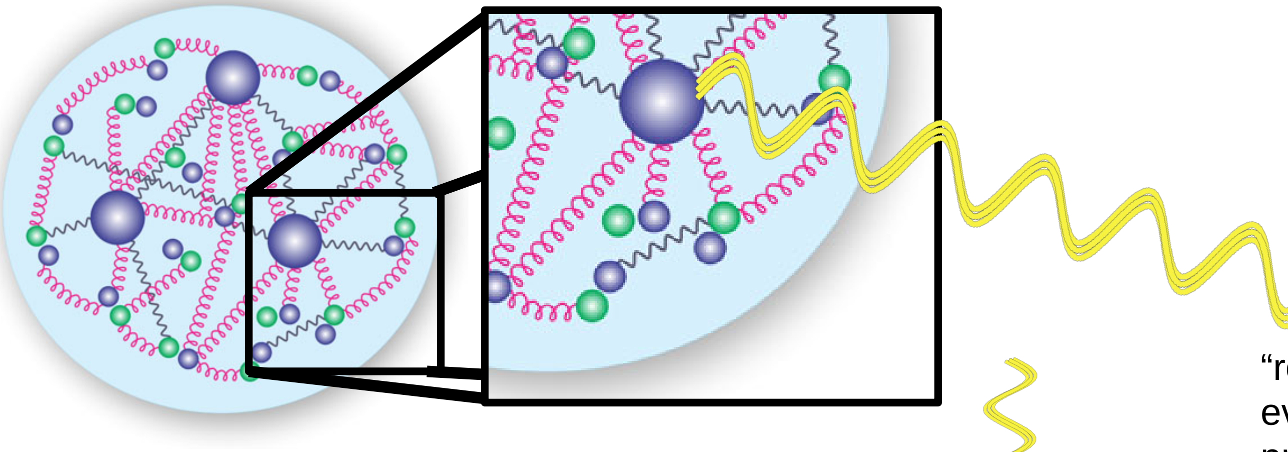
More than 140 fb^{-1} at 13 TeV

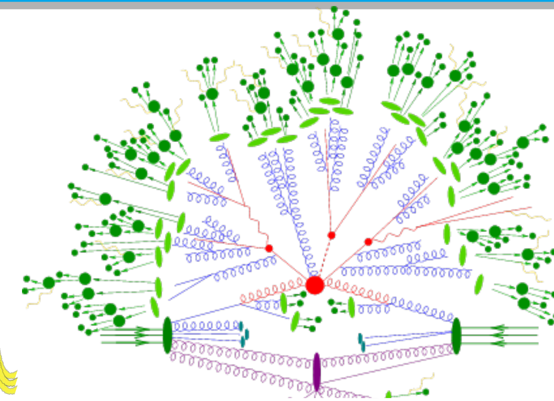


High energy proton-proton collisions
center-of-mass energy of $\sqrt{s}$ = 7, 8 and 13 TeV

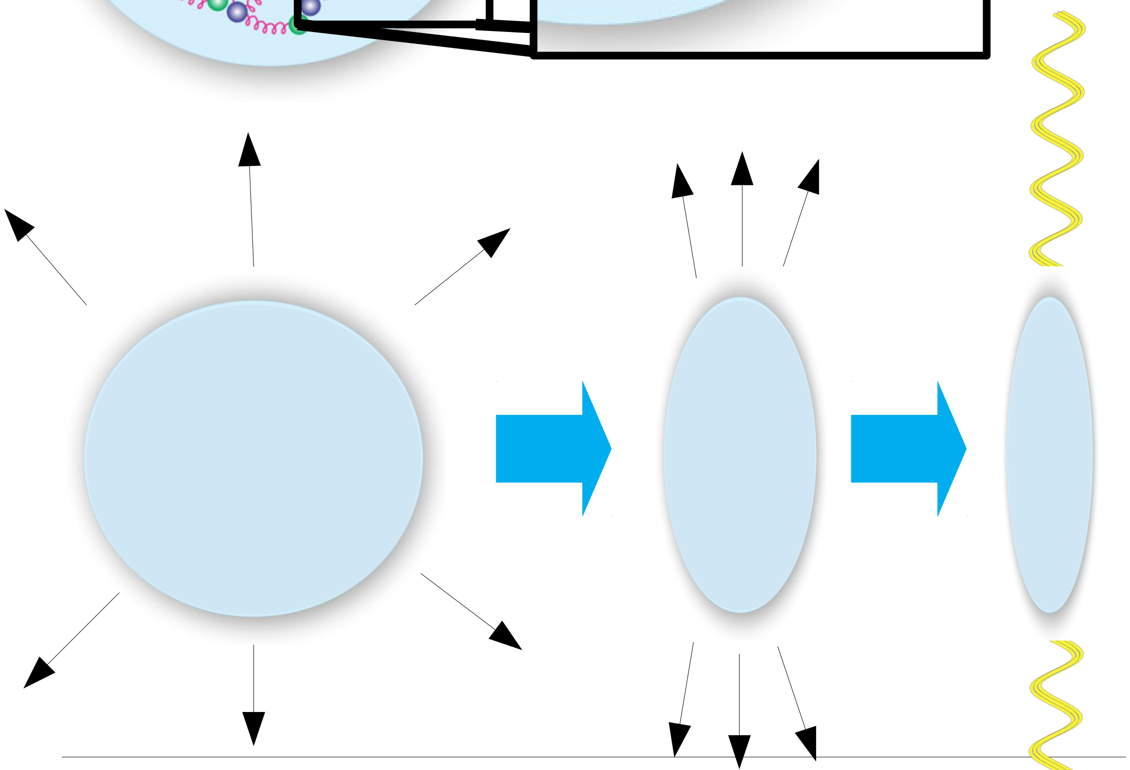
…. and other collisions

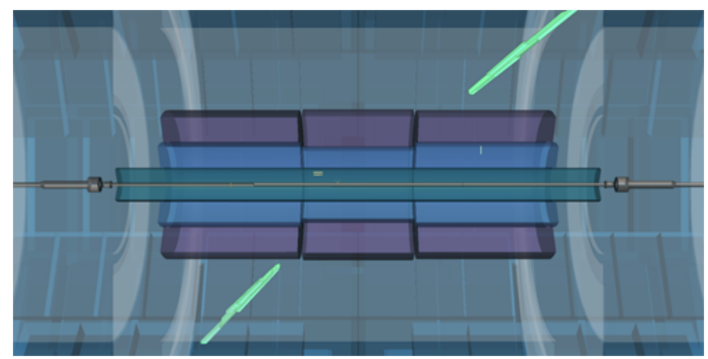
Mechanisms for photon collisions at the LHC





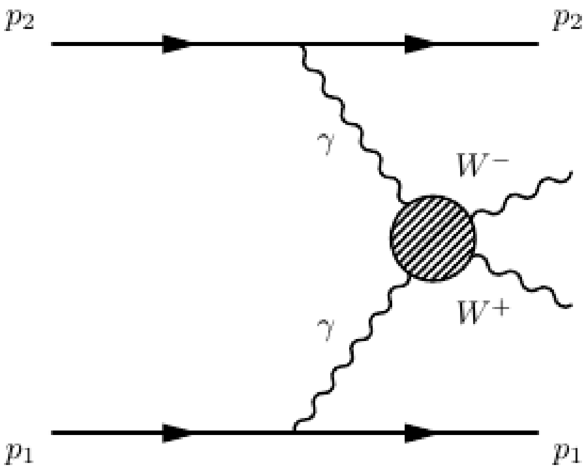
"resolved" proton: It breaks up, event looks similar to normal pp collision





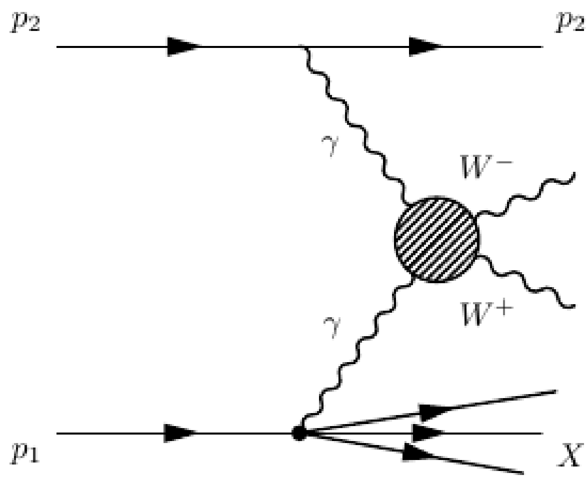
"intact" proton: It continues to travel in the direction of the beam – **empty event** (here: Pb Pb → $\gamma\gamma$, even more empty, no pileup)

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

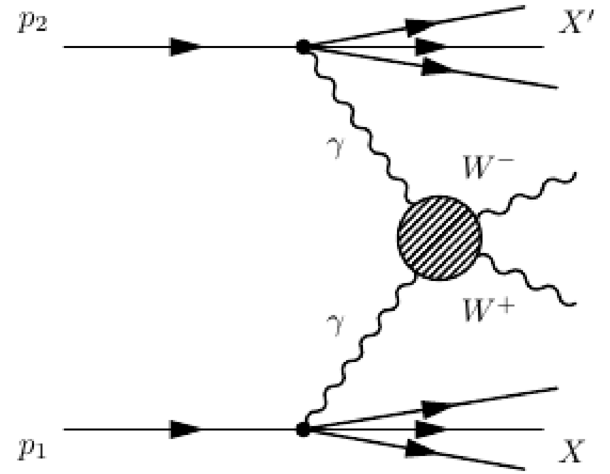


elastic (EE)

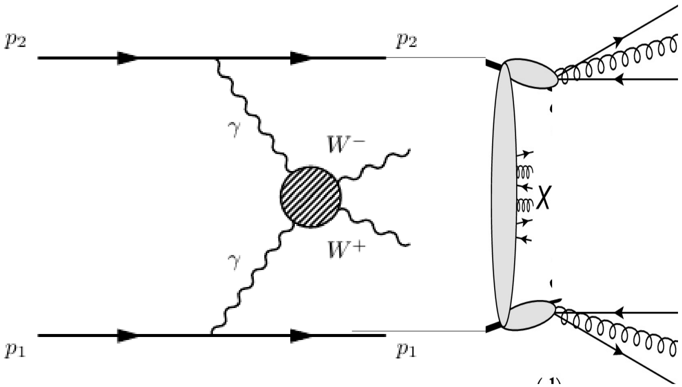
no particles other than W decay products



semi-dissociative (SD)



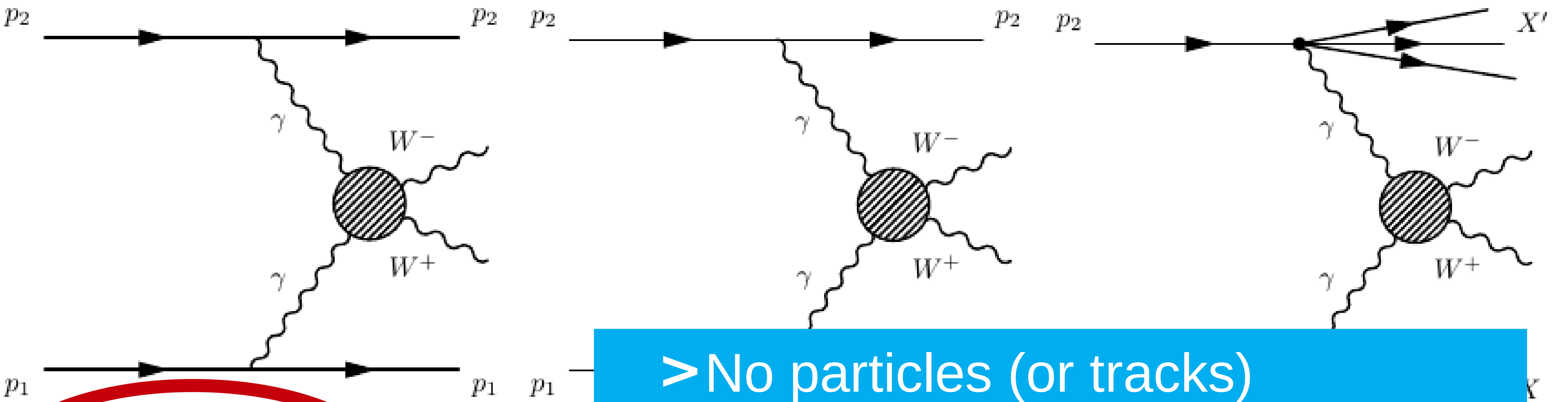
double-dissociative (DD)



Second scattering: “survival factor” (phenological)

→ Reduces “visible” cross-section of elastic production → additional particles

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



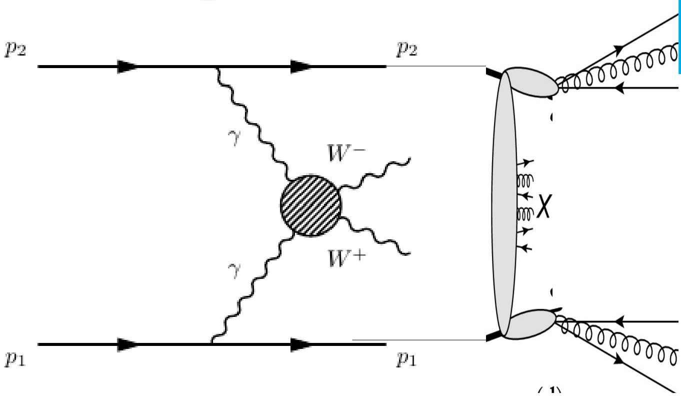
elastic (EE)

no particles other than W decay products

semi-dis

D)

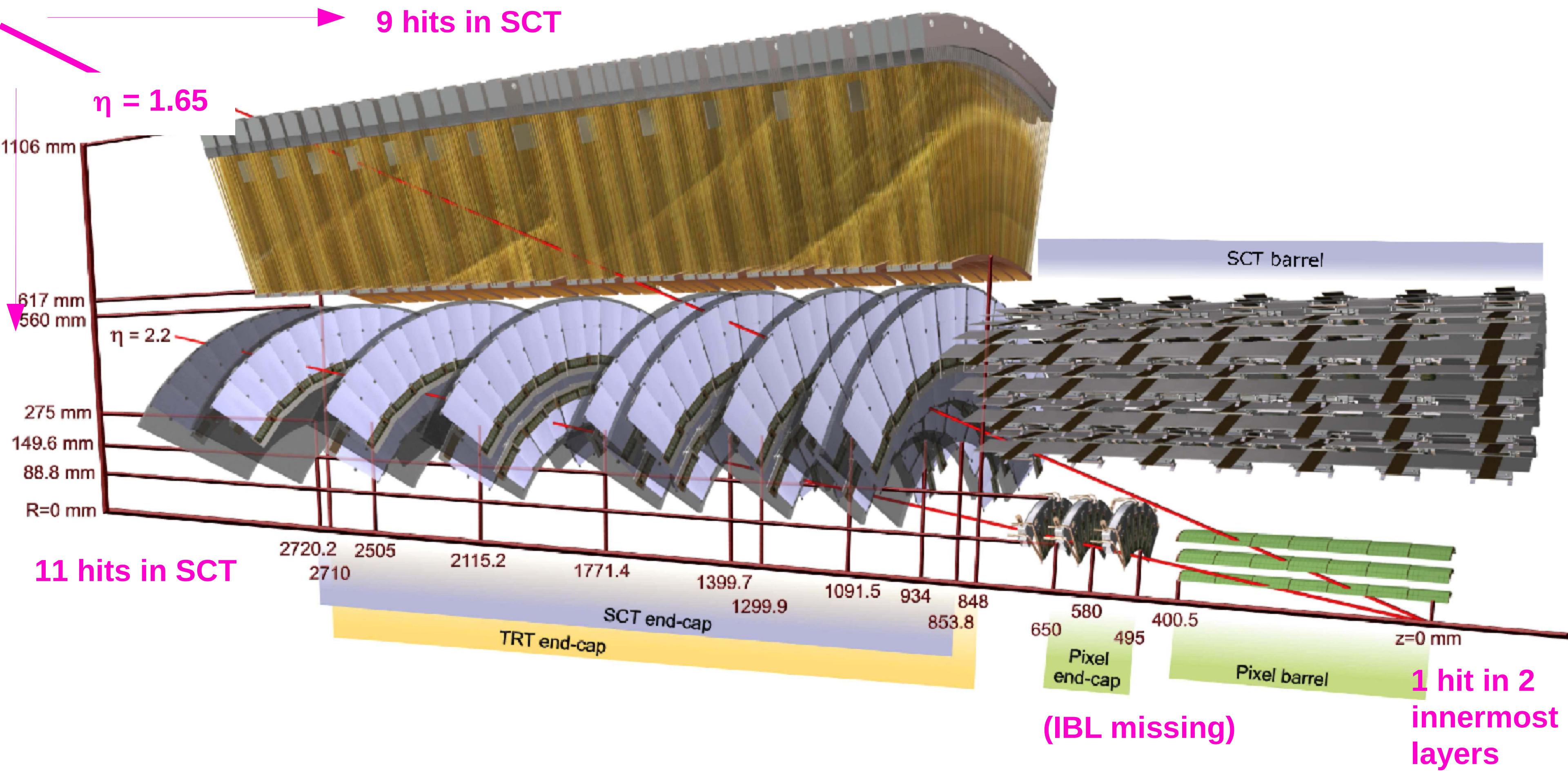
> No particles (or tracks) associated with the primary interaction vertex
> → **Track reconstruction**
> → **Vertex definition**



Second scattering: "survival factor" (phenological)

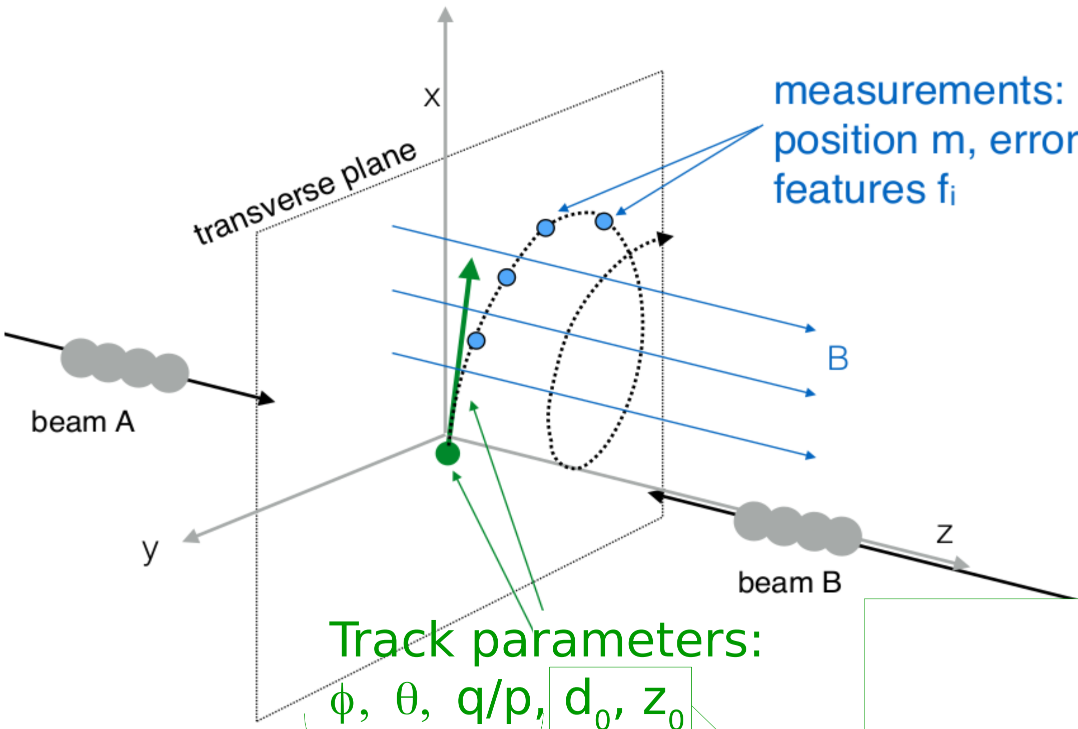
Reduces "visible cross-section of elastic production → additional particles

The ATLAS inner detector

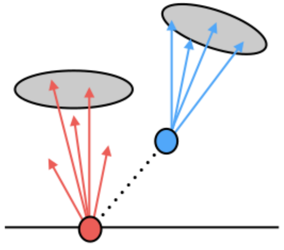


- Accurately reconstructing as many charged-particle tracks as possible is key!
- Innermost tracking layer at r = 33.5 mm (pixel size: 50 × 250 μm^2)
  Intrinsic spacial resolution: 10 × 75 μm^2

Track reconstruction



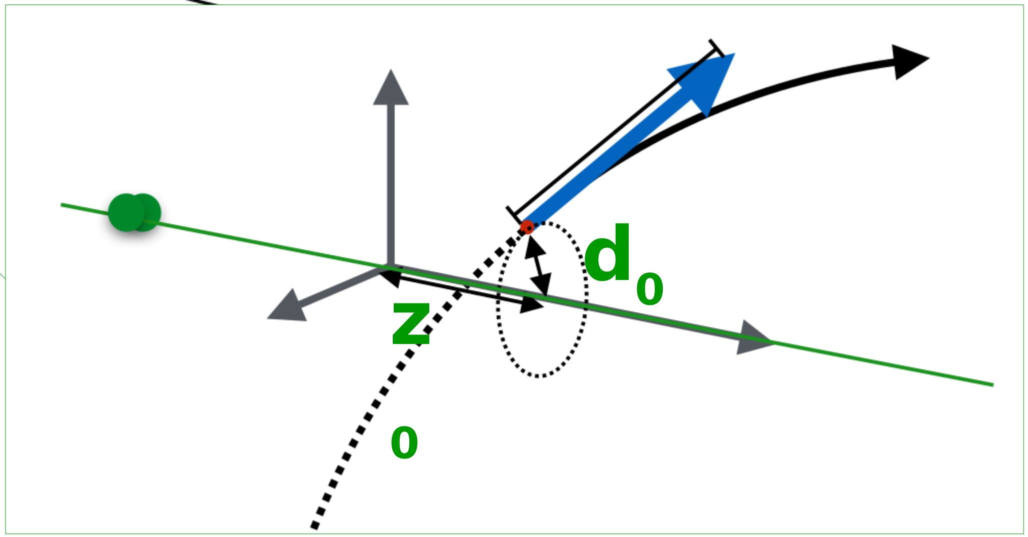
- $P_T > 500$ MeV
- $|\eta| < 2.5$
- $|d_0| < 1$mm
- **$|z_0| < 1$mm**



Secondary particles

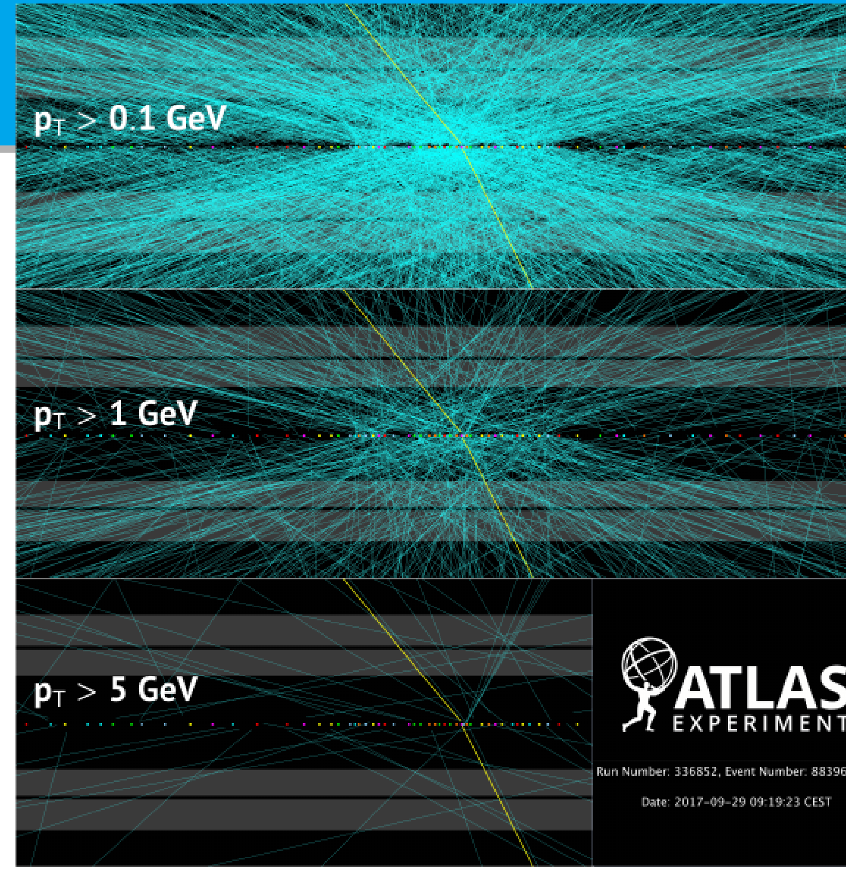
Track parameters:
ϕ, θ, q/p, d_0, z_0

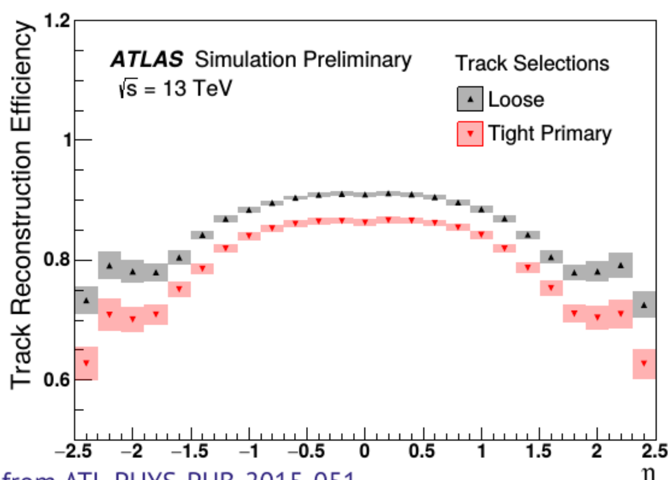
pseudo-rapidity η
charge
transverse momentum



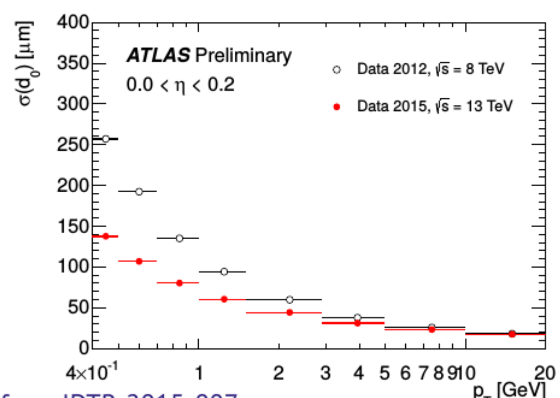
Tracking performance

- 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)

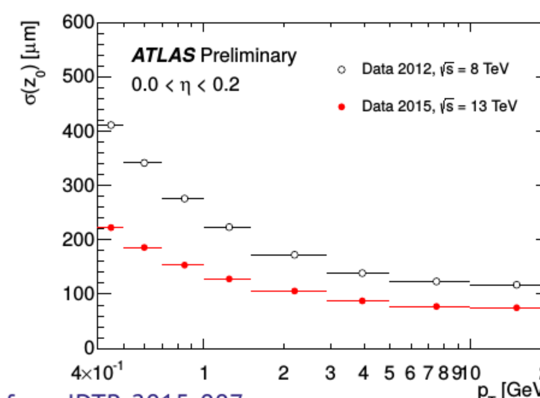




from ATL-PHYS-PUB-2015-051



from IDTR-2015-007



from IDTR-2015-007

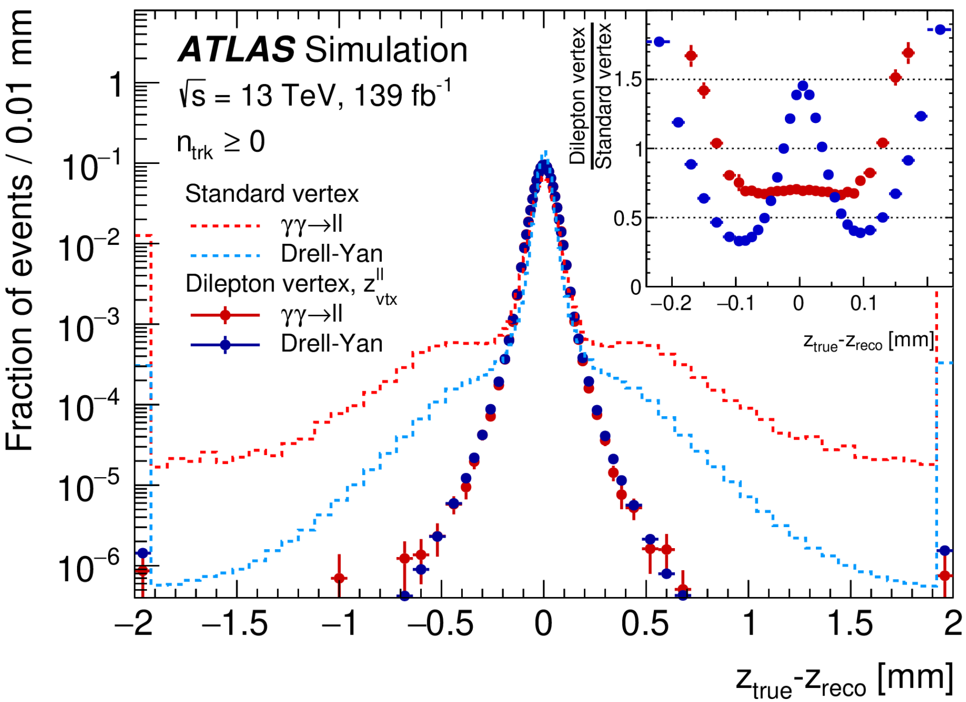
Vertex reconstruction

- 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



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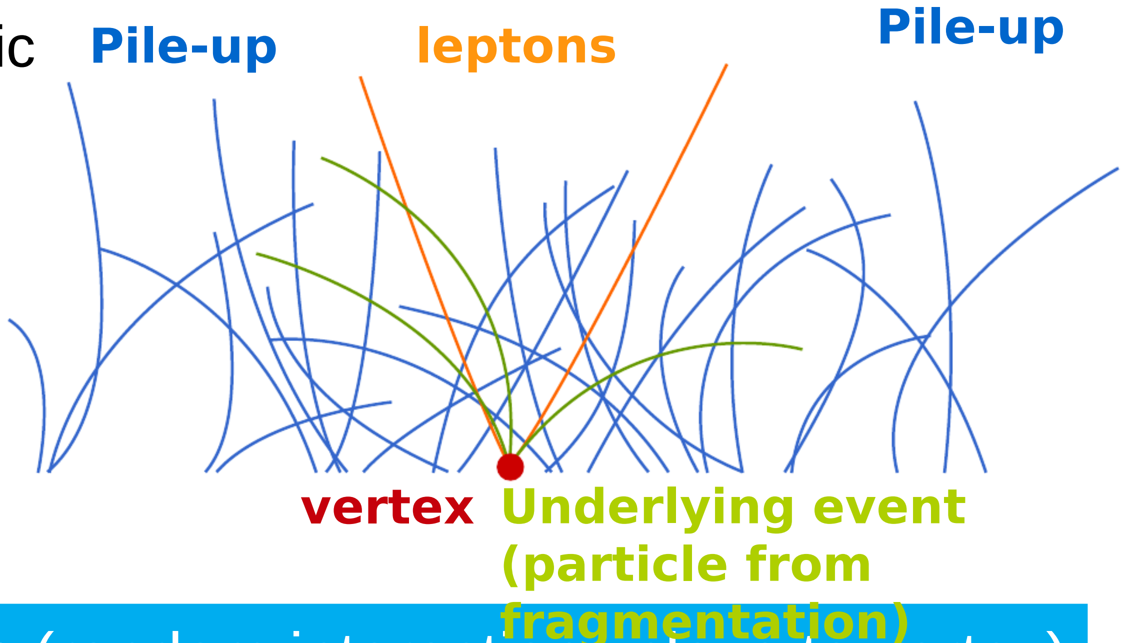
Event selection

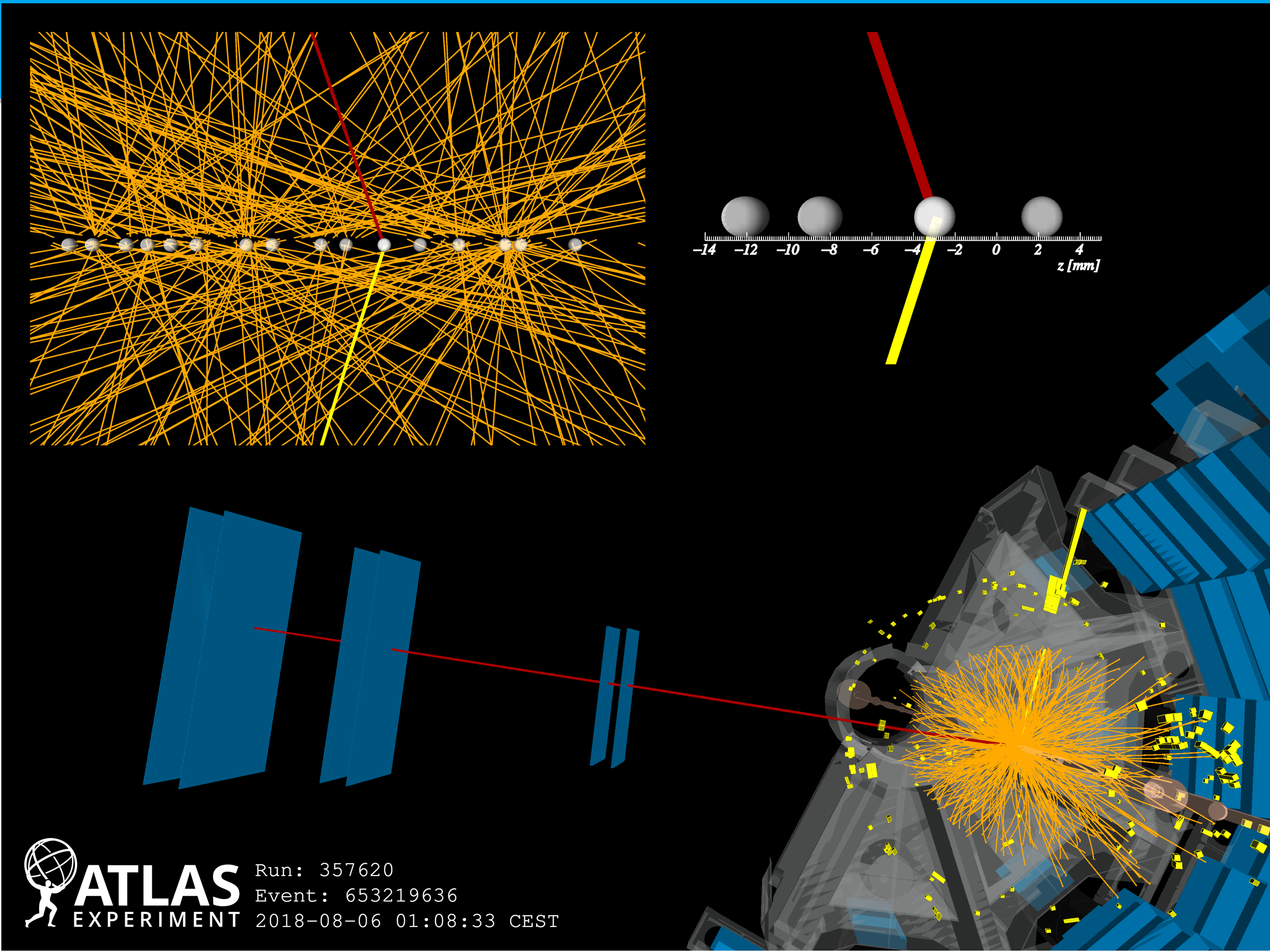
- exactly one electron and muon with opposite electric charge
- p_T (ll) > 30 GeV, m(ll) > 20 GeV
- no tracks associated with primary interaction vertex



> Modeling of **pileup** (random interactions close to vertex)

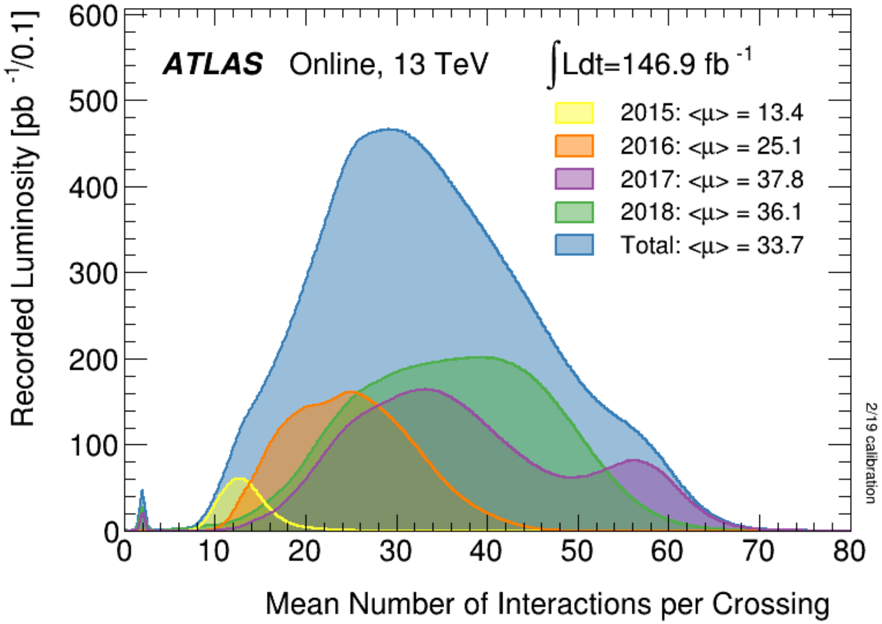
> Modeling of **underlying event** of backgrounds

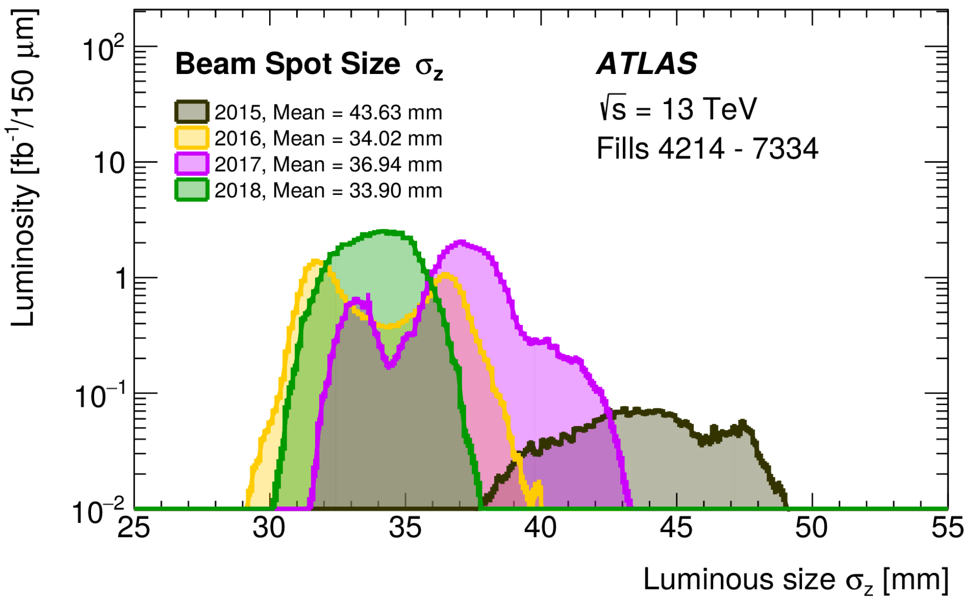
> **Modeling of the signal** ("survival factor")



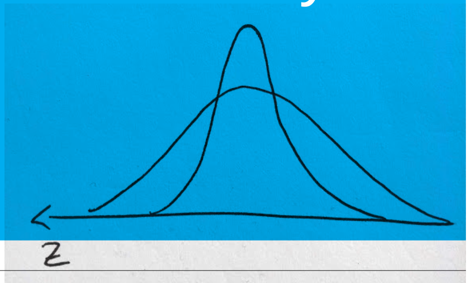
−14
−12
−10
−8
−6
−4
−2
0
2
4
z [mm]
ATLAS
EXPERIMENT
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Pile-up in the context of the measurement



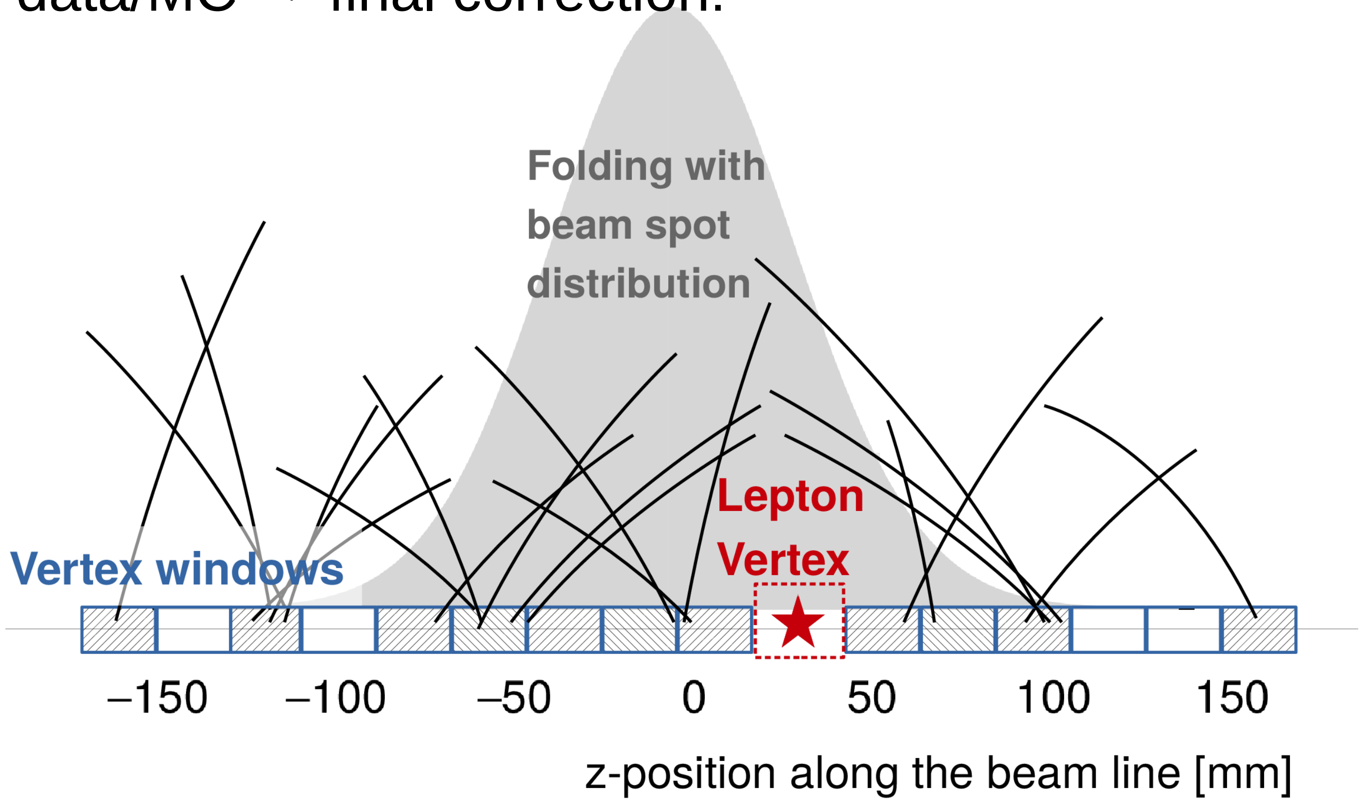


- Pile-up is the number of *pp* interactions per bunch crossing
- Longitudinal width of the beam spot determines density of additional *pp* interaction along z
- Corrected for using reweighting approach



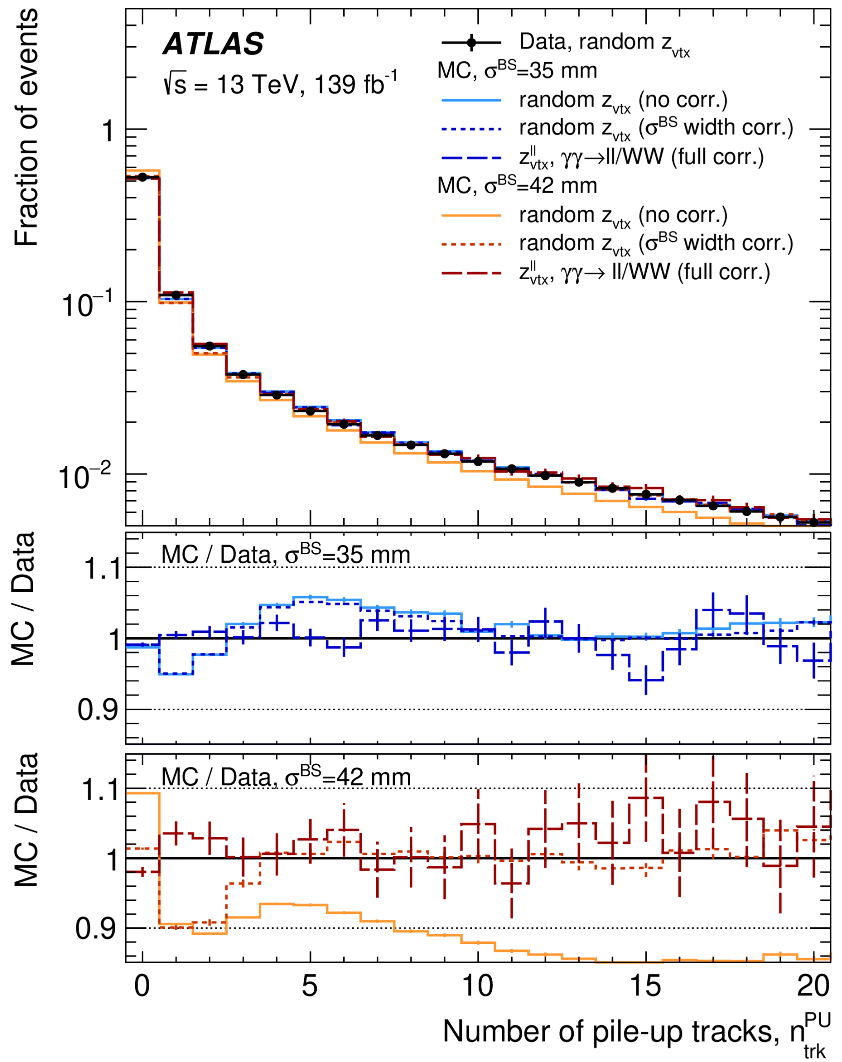
Correcting number of tracks per pile-up vertex

- 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!



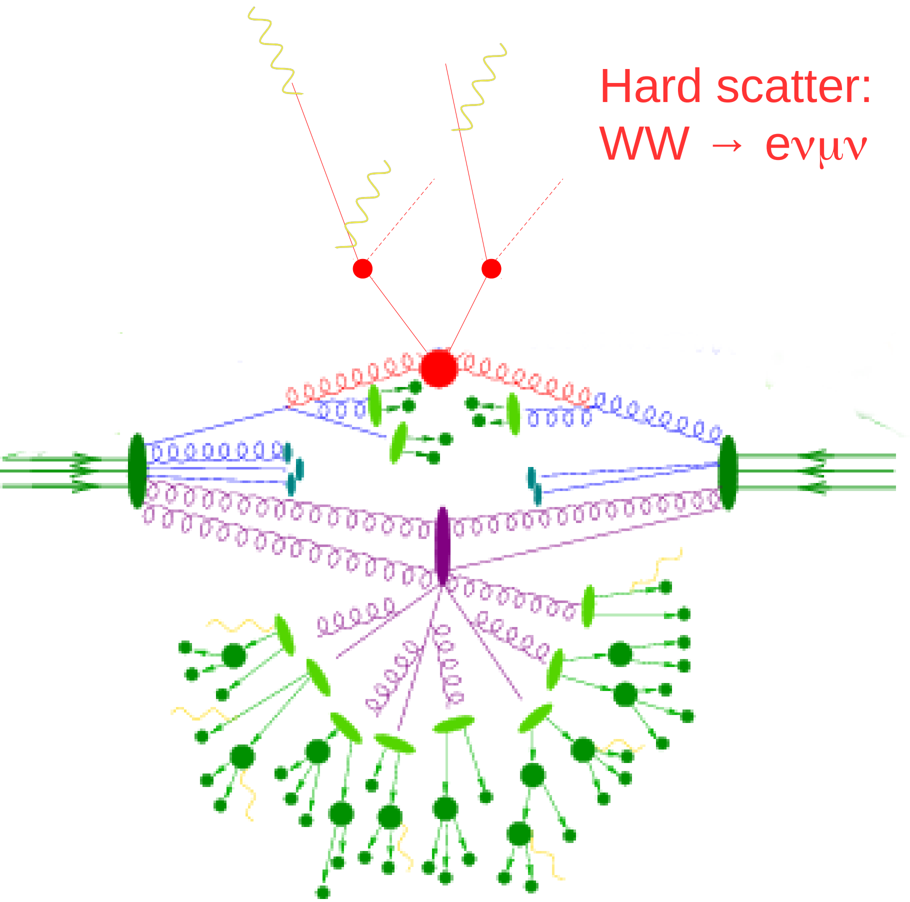
Pile-up correction at work

- 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*



*backup

Modelling of underlying event

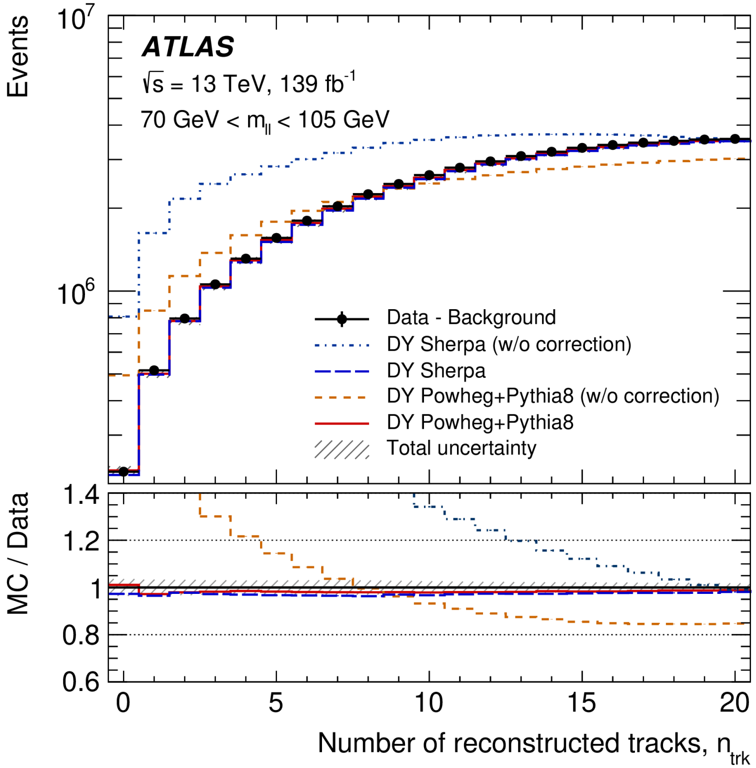


Underlying event: Interactions of proton remnants, fragmentations

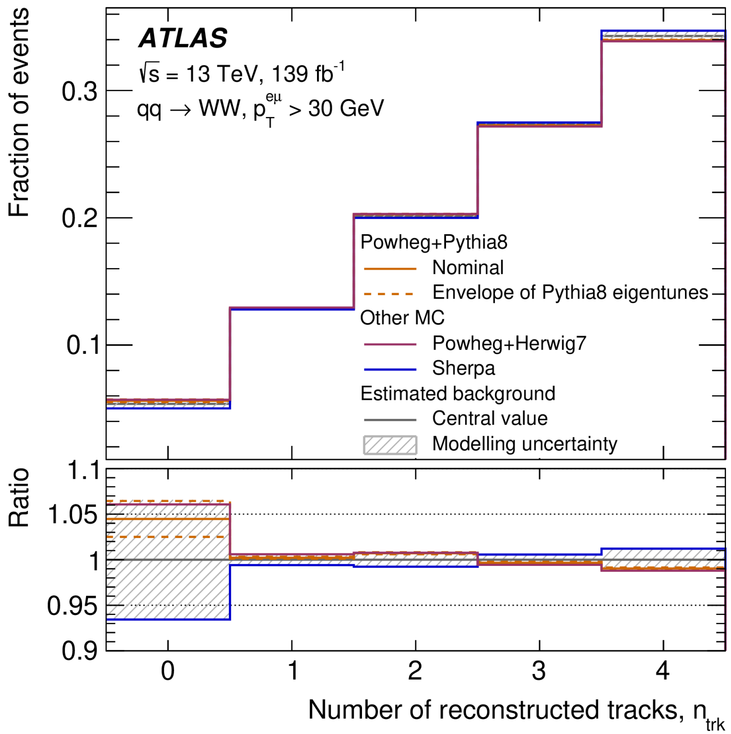
- qq/gg → WW has the same final state as γγ → WW apart from underlying event
- Problems with modelling of charge particle (track) multiplicity at low momentum are well known*
  → **need to apply in-situ correction to model WW background correctly**
- Use Z boson and unfold charged particle distribution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

*backup

Modelling of underlying event



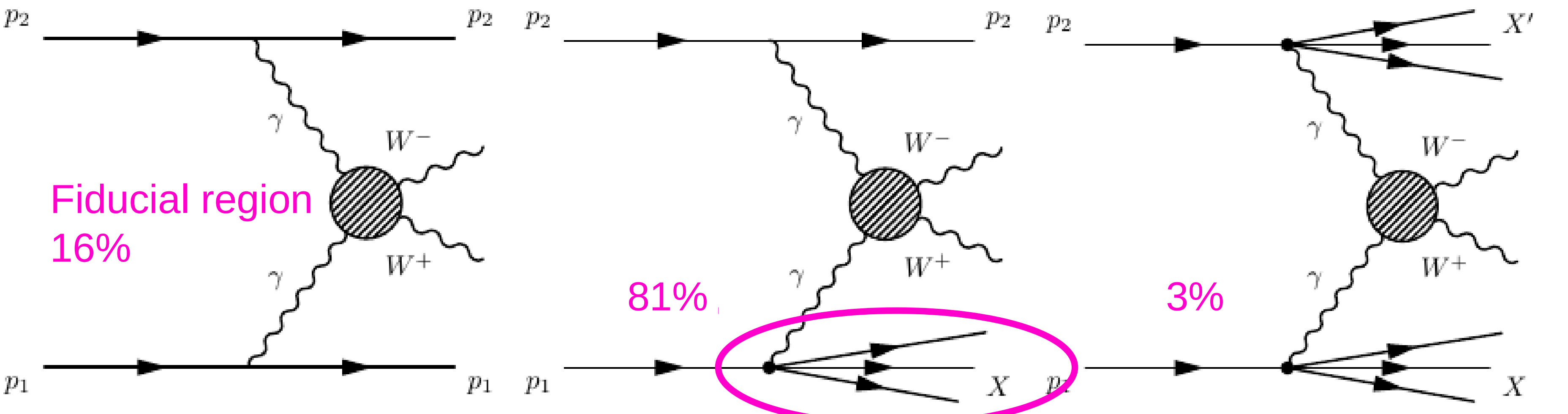
- For $qq \rightarrow WW$: Good agreement for $1 \leq n_{trk} \leq 4$ but $n_{trk}=0$ has large differences between hadronic models
- Use midpoint and envelope for WW prediction (7% syst.)



- 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)

*backup

Signal Modelling: Why?



Fiducial region 16%

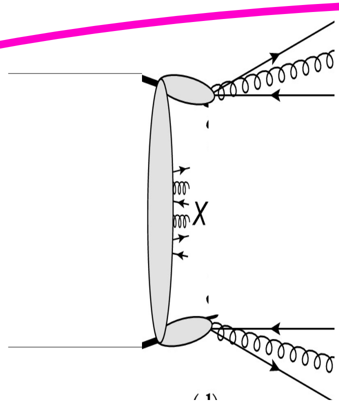
81%

3%

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

most reliable theory

Difficult to model!!



Second scattering: "survival factor" (phenological)

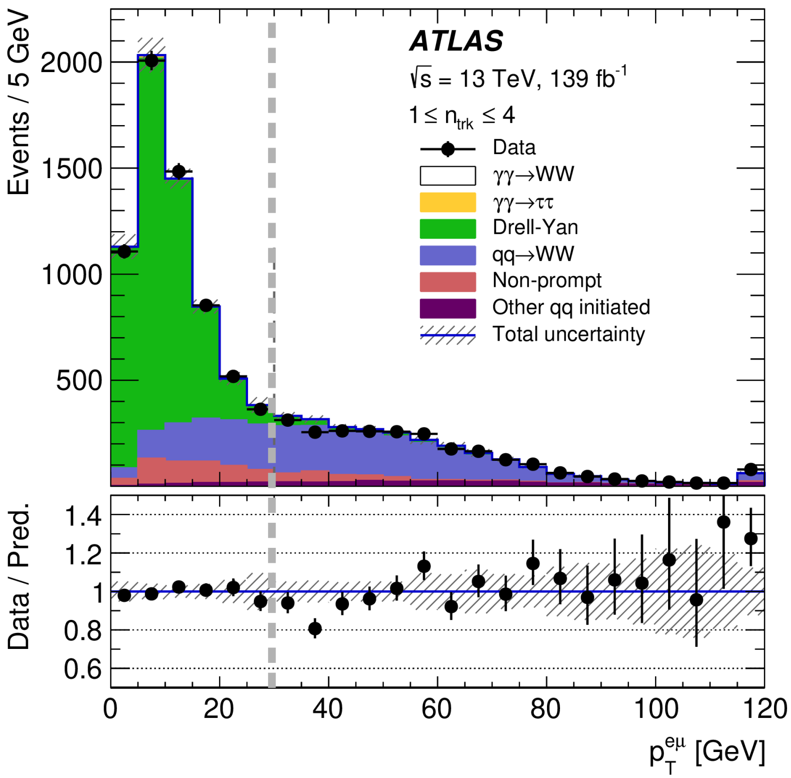
Reduces "visible" cross-section of elastic production → additional particles

Signal extraction: Putting it all together

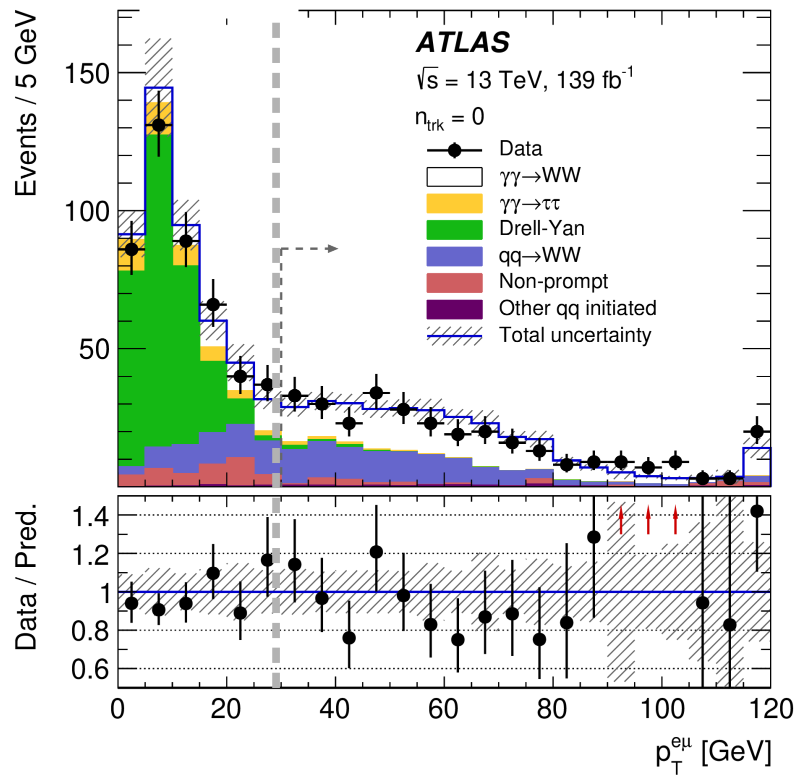
- Using profile LH fit over 3+1+1 regions (1 SR + 3 CR + signal modelling CR) → 4 free normalization parameters ($\gamma\gamma \to WW$, $\gamma\gamma \to ll$, DY, $qq \to WW$)
- Signal region: $\gamma\gamma \to WW$ (57%), $qq \to WW$ (33%)

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

CR2 CR3



CR1 SR



Results

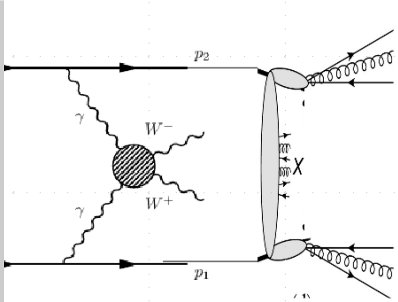
- Background-only hypothesis rejected with **significance of 8.4 σ** (6.7σ exp.)

- **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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- $\gamma\gamma \to$ WW production has been observed

- How to proceed from here?

  $\to$ use the measurement to characterize the SM

  $\to$ 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 $\Lambda^{\text{(dimension d - 4)}}$**

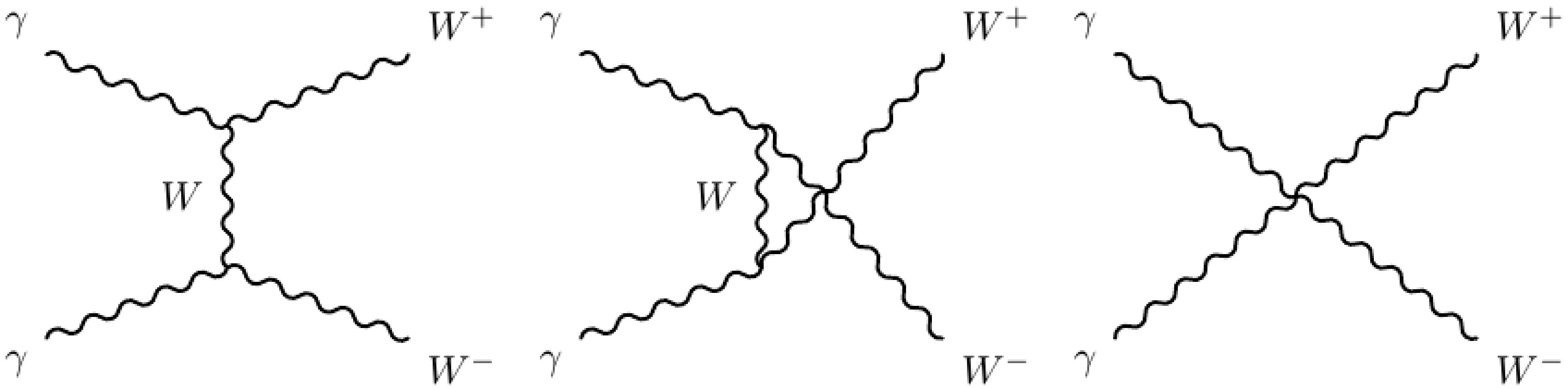
d ≤ 4 → Standard model

d = 5 → *Neutrino masses*

d ≥ 6 → Unknown phenomena

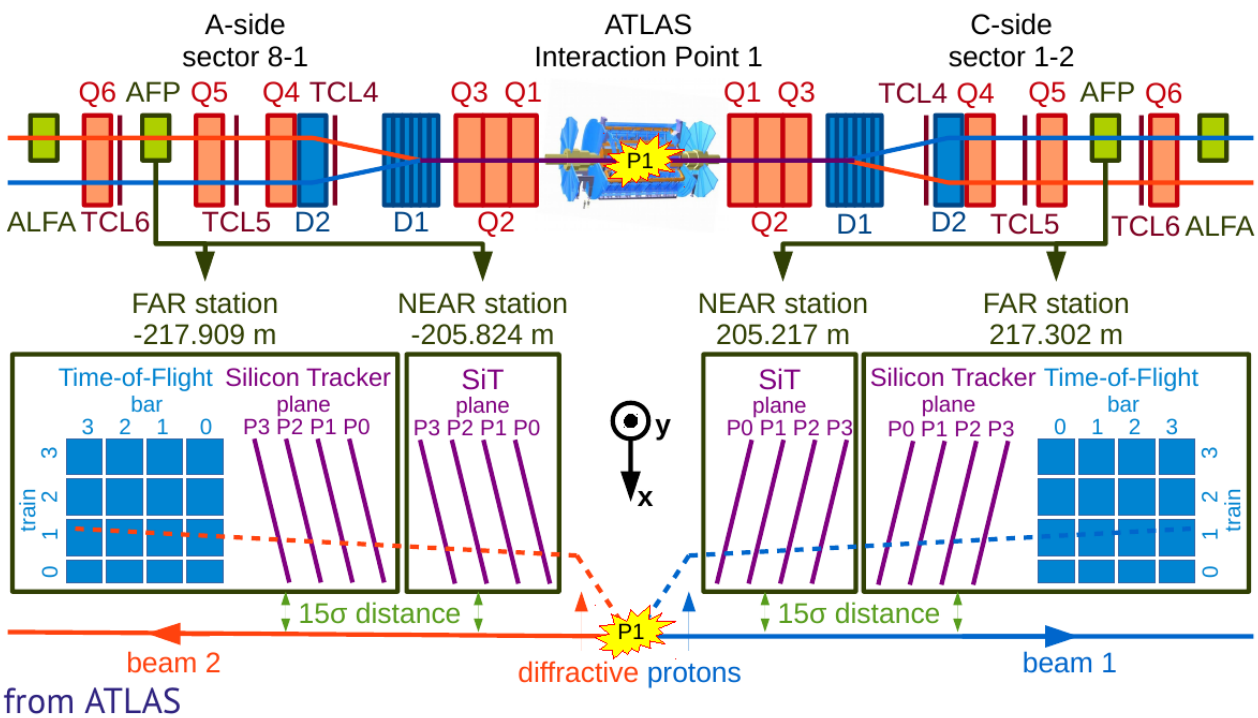
$\gamma\gamma \rightarrow$ WW is incredibly sensitive

- 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 $0.02<\xi<0.1$

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

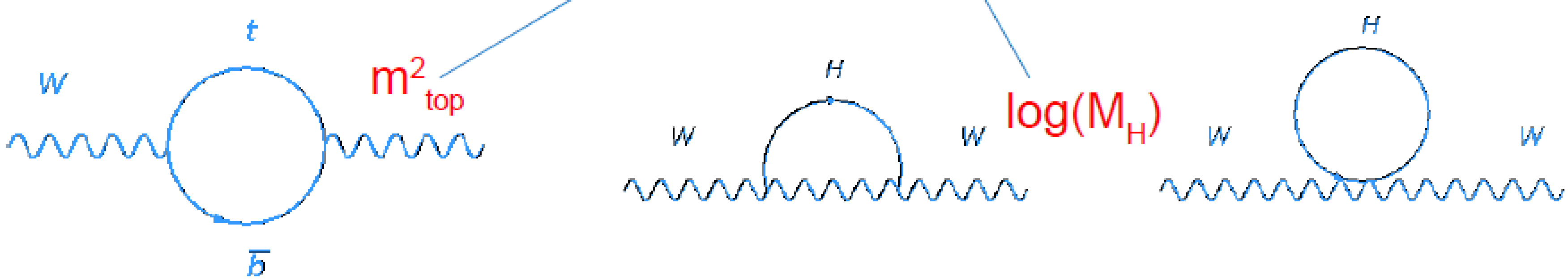
- 1961 Glashow: Unification of electromagnetic and weak force
- 1964 Brout, Englert, Guralnik, Hagen, Higgs: Higgs mechanism
- 1967 Weinberg, Salam: Mechanism of electroweak symmetry breaking

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

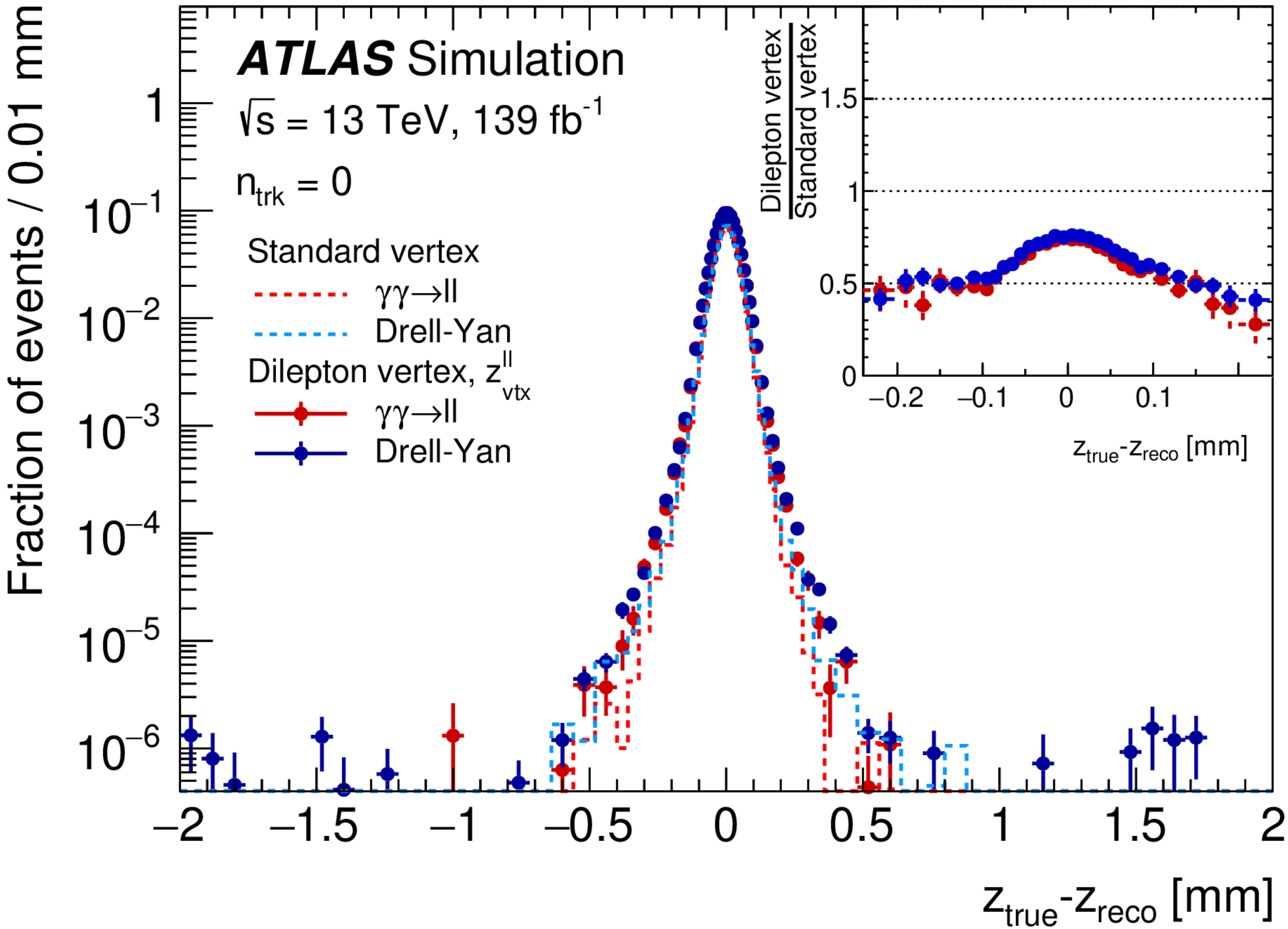
$$m_W = \left(\frac{\pi\, \alpha_{EM}}{\sqrt{2}\, G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1 - \Delta r}}$$

radiative corrections

$\Delta r \sim 3\ \%$



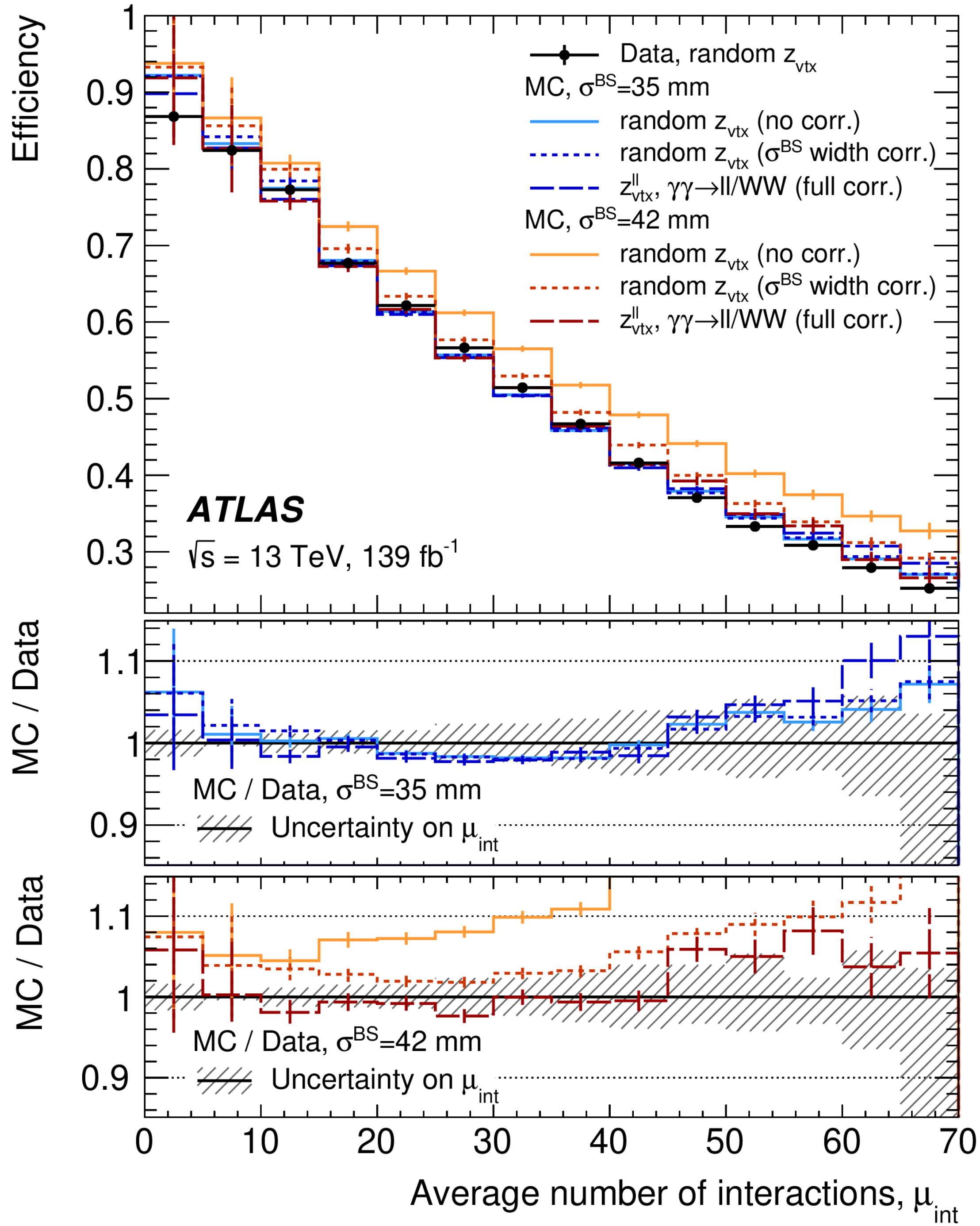
Vertex reconstruction – 0 tracks



Selected events

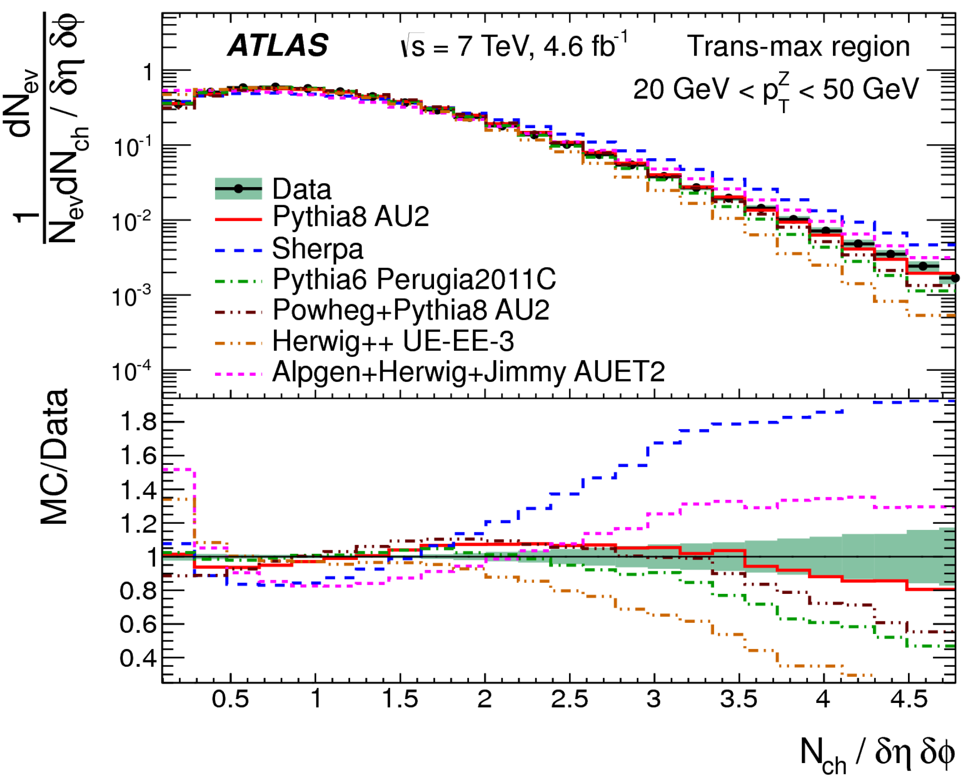
	Signal region	Control regions		
n_{trk}	$n_{\text{trk}} = 0$		$1 \leq n_{\text{trk}} \leq 4$	
$p_{\text{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 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

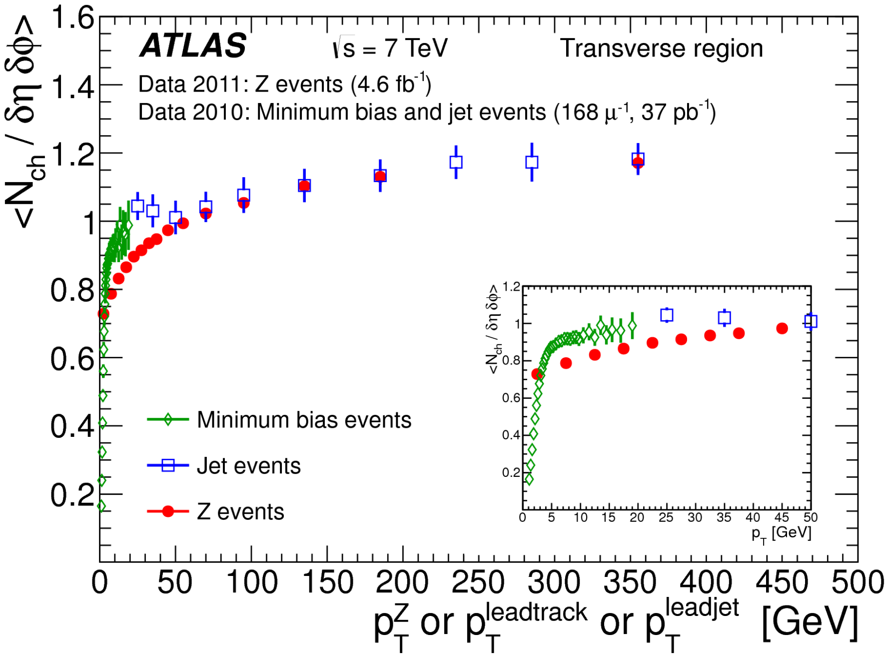
Efficiency



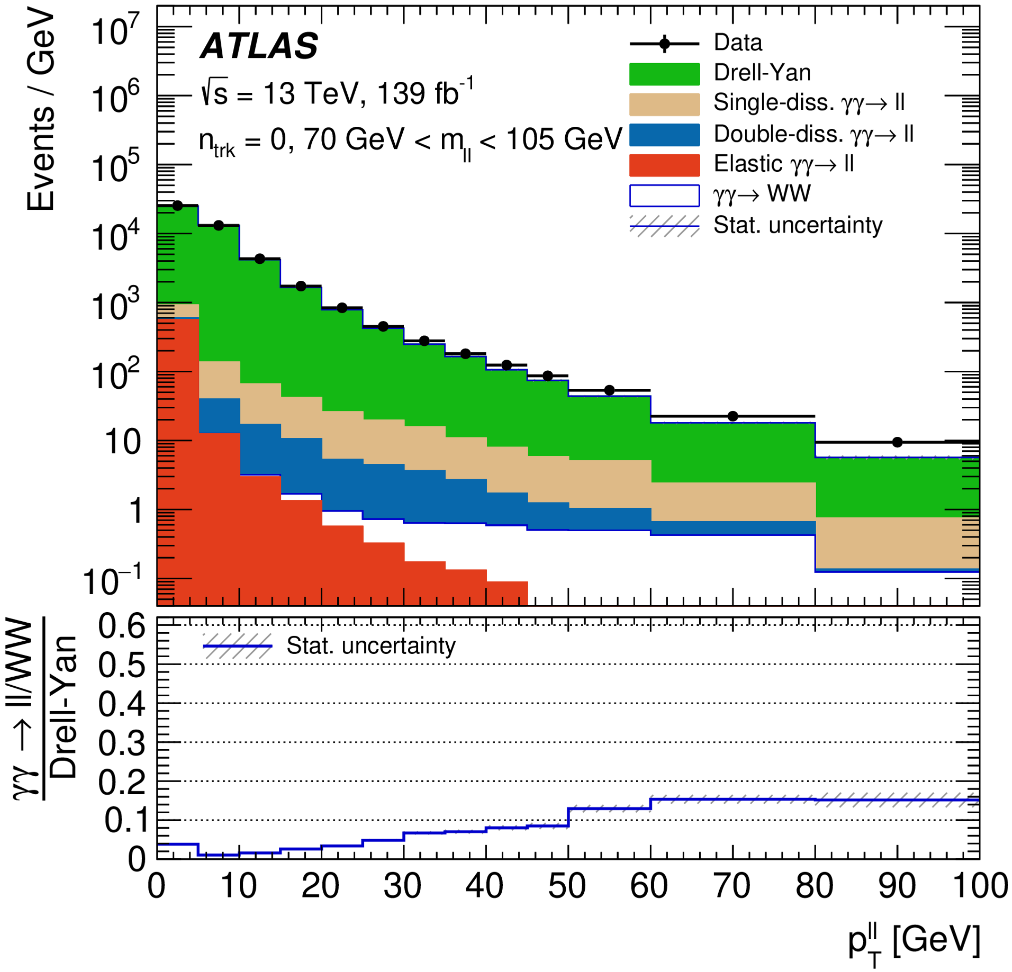
Efficiency
Data, random z_{vtx}
MC, σ^{BS}=35 mm
random z_{vtx} (no corr.)
random z_{vtx} (σ^{BS} width corr.)
z^{ll}_{vtx}, $\gamma\gamma\to$ll/WW (full corr.)
MC, σ^{BS}=42 mm
random z_{vtx} (no corr.)
random z_{vtx} (σ^{BS} width corr.)
z^{ll}_{vtx}, $\gamma\gamma\to$ll/WW (full corr.)
ATLAS
$\sqrt{s}$ = 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

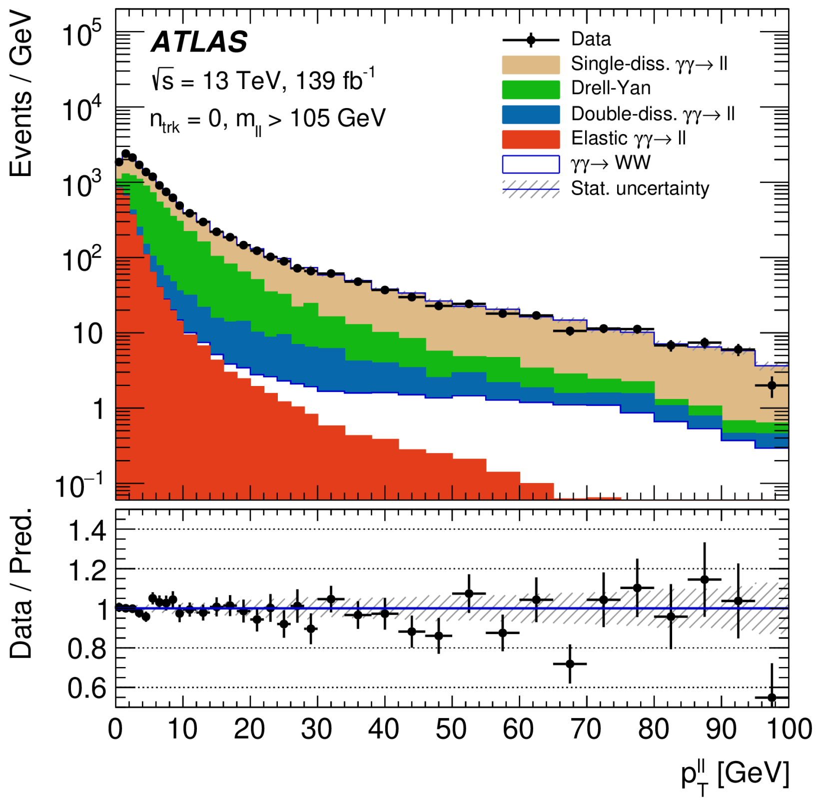

ATLAS
√s = 7 TeV, 4.6 fb-1
Trans-max region
20 GeV < p_T^Z < 50 GeV
Data
Pythia8 AU2
Sherpa
Pythia6 Perugia2011C
Powheg+Pythia8 AU2
Herwig++ UE-EE-3
Alpgen+Herwig+Jimmy AUET2
MC/Data
N_ch / δη δφ


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)
Minimum bias events
Jet events
Z events
<N_ch / δη δφ>
p_T^Z or p_T^leadtrack or p_T^leadjet [GeV]
p_T [GeV]

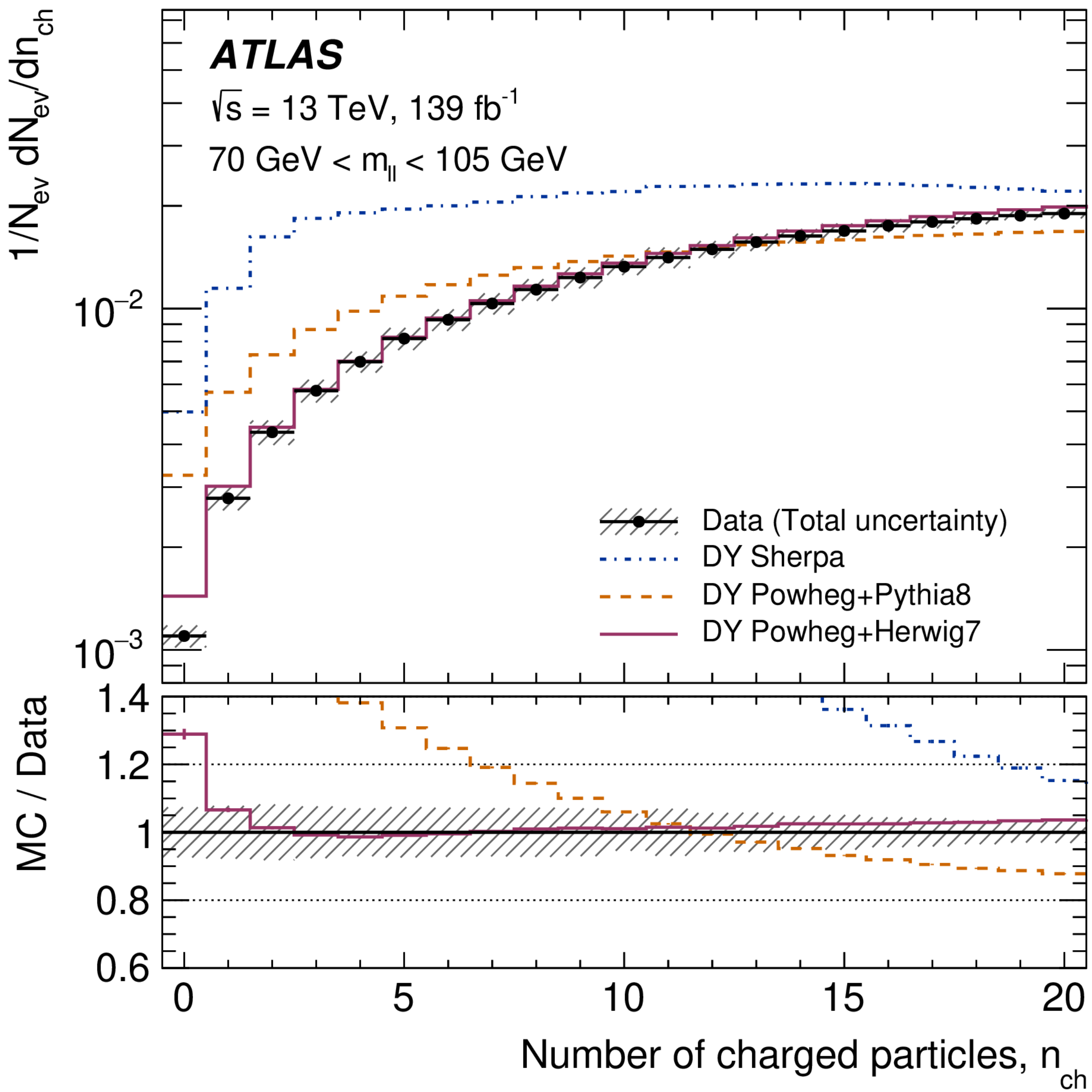
Charge particle multiplicity measurement



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



Charge particle multiplicity measurement



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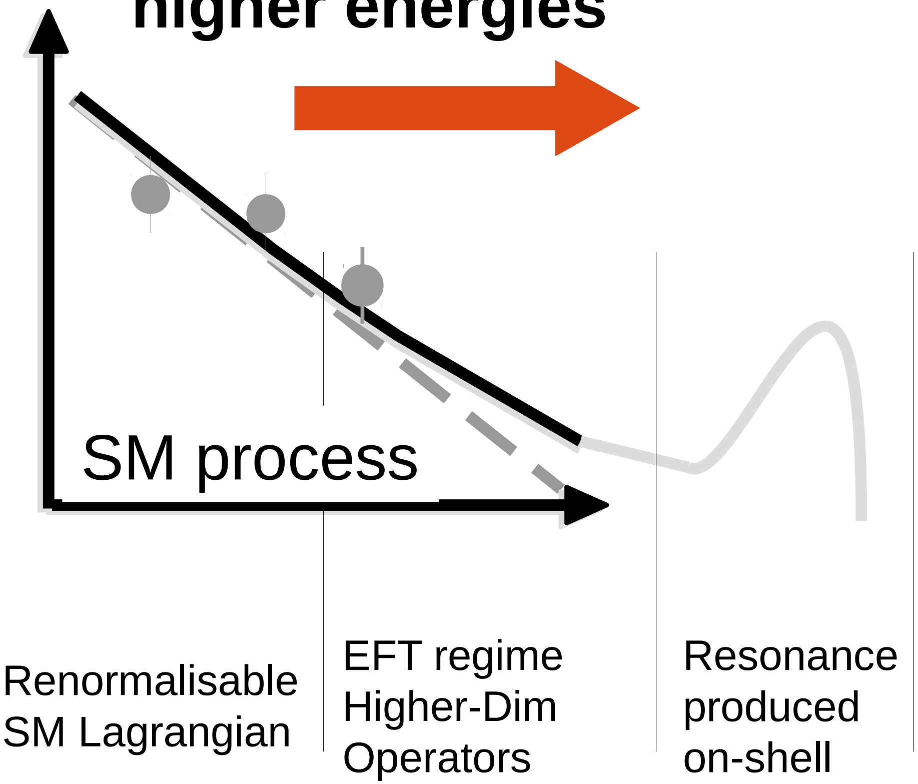
Uncertainties

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

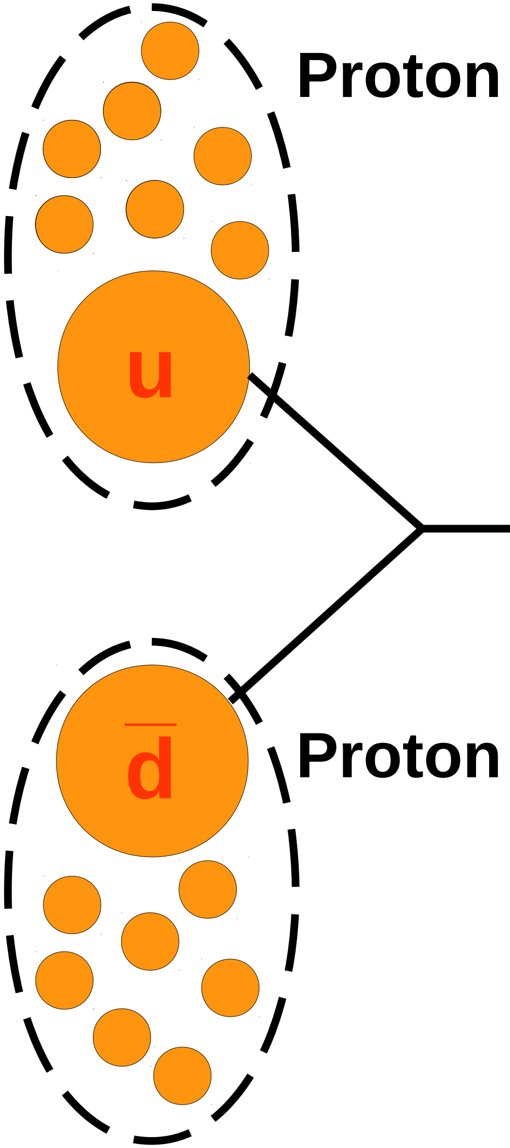
What if we don't reach the resonance? Effective field theory

Search for phenomena at higher energies

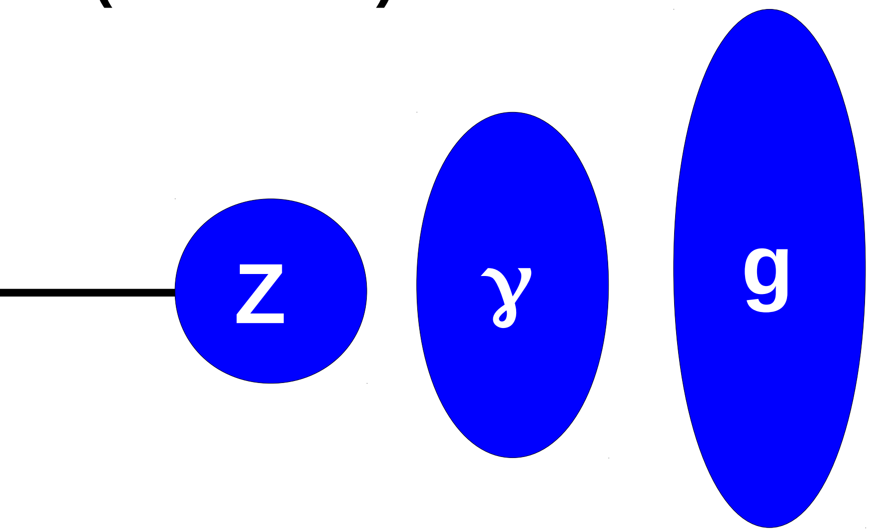


- Generic search for **deviations in distributions** sensitive to new physics effects
- Could be sensitive to much **higher energies scales** compared to resonance searches
- Detects also new physics **without resonances or very broad resonances**

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)**