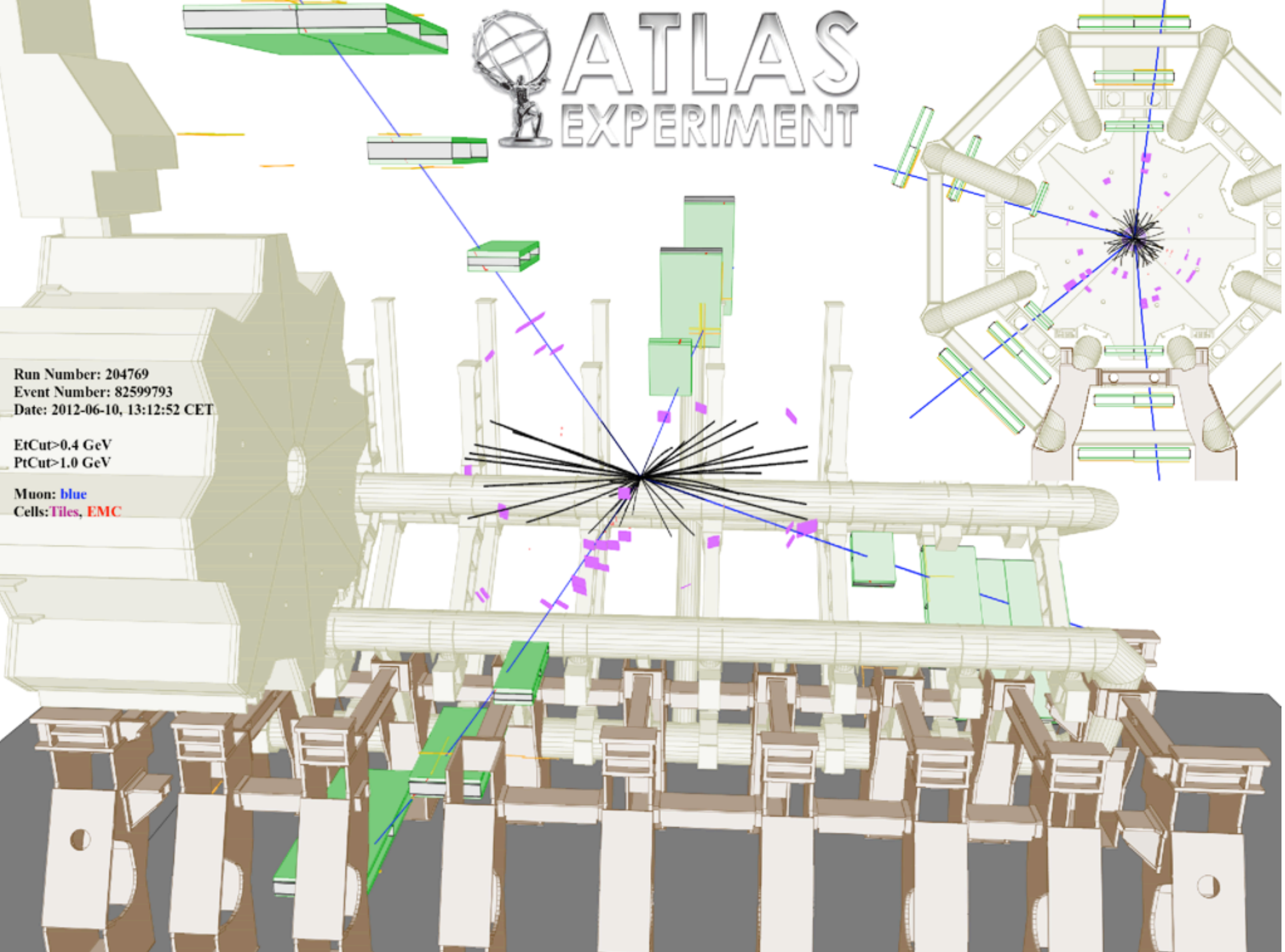

Vector boson scattering from an experimental perspective (II)

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HiggsTools Summer School on Higgs Physics
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Introduction

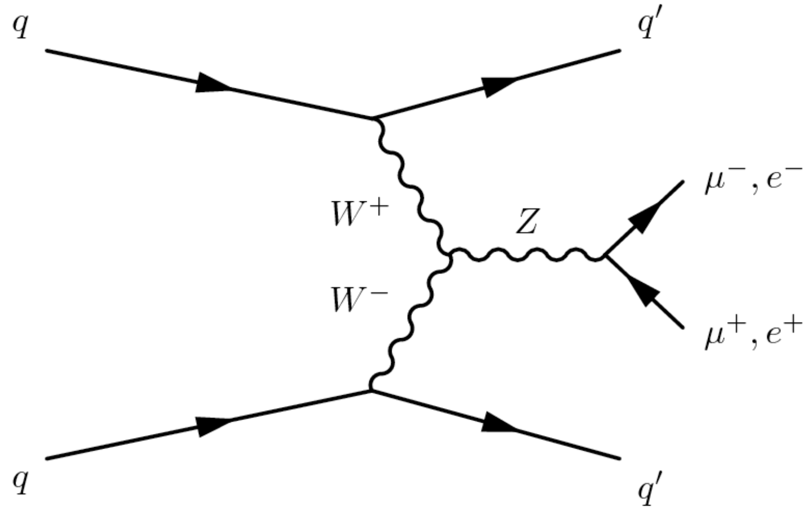
Trilinear and quartic couplings can probe different aspects:
- TGC: Non-abelian gauge structure of the SM
- QGC: Mechanism of spontaneous symmetry breaking

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.

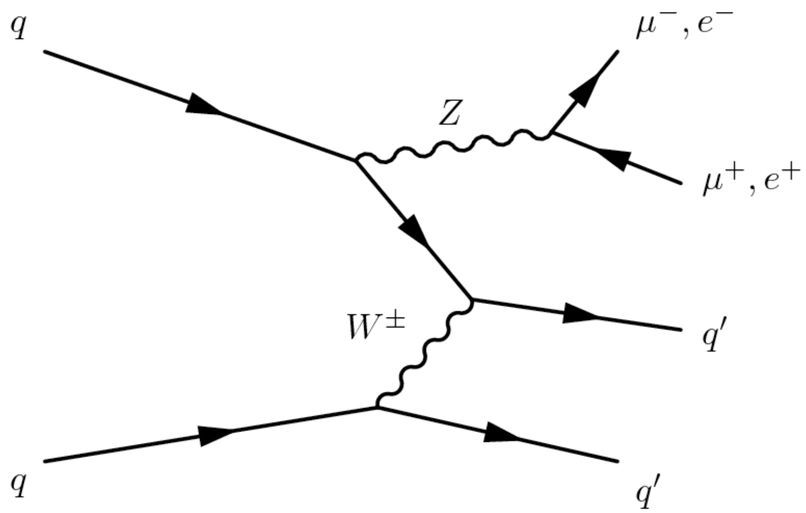
To this end, we really need to study the scattering of massive vector bosons

Electroweak production of a Z boson with di-jets

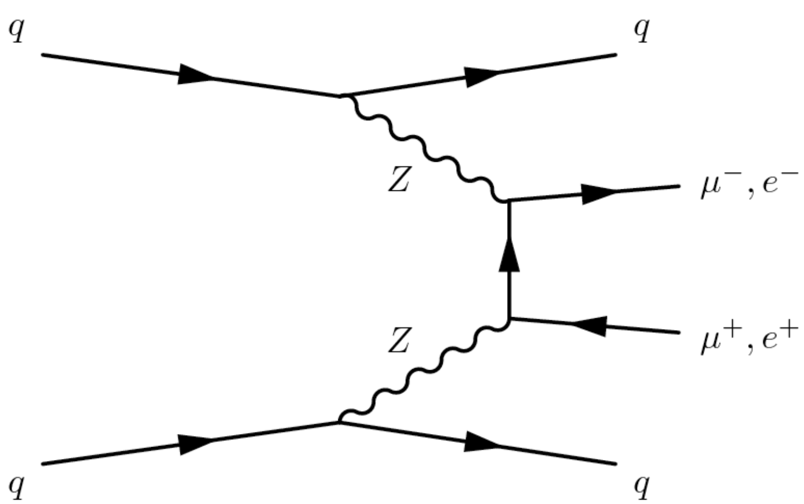
EW Z(→ll)jj production defined
to include all contributions to lljj with a t-channel
exchange of an EW gauge boson



VBF
α_{ew}^4

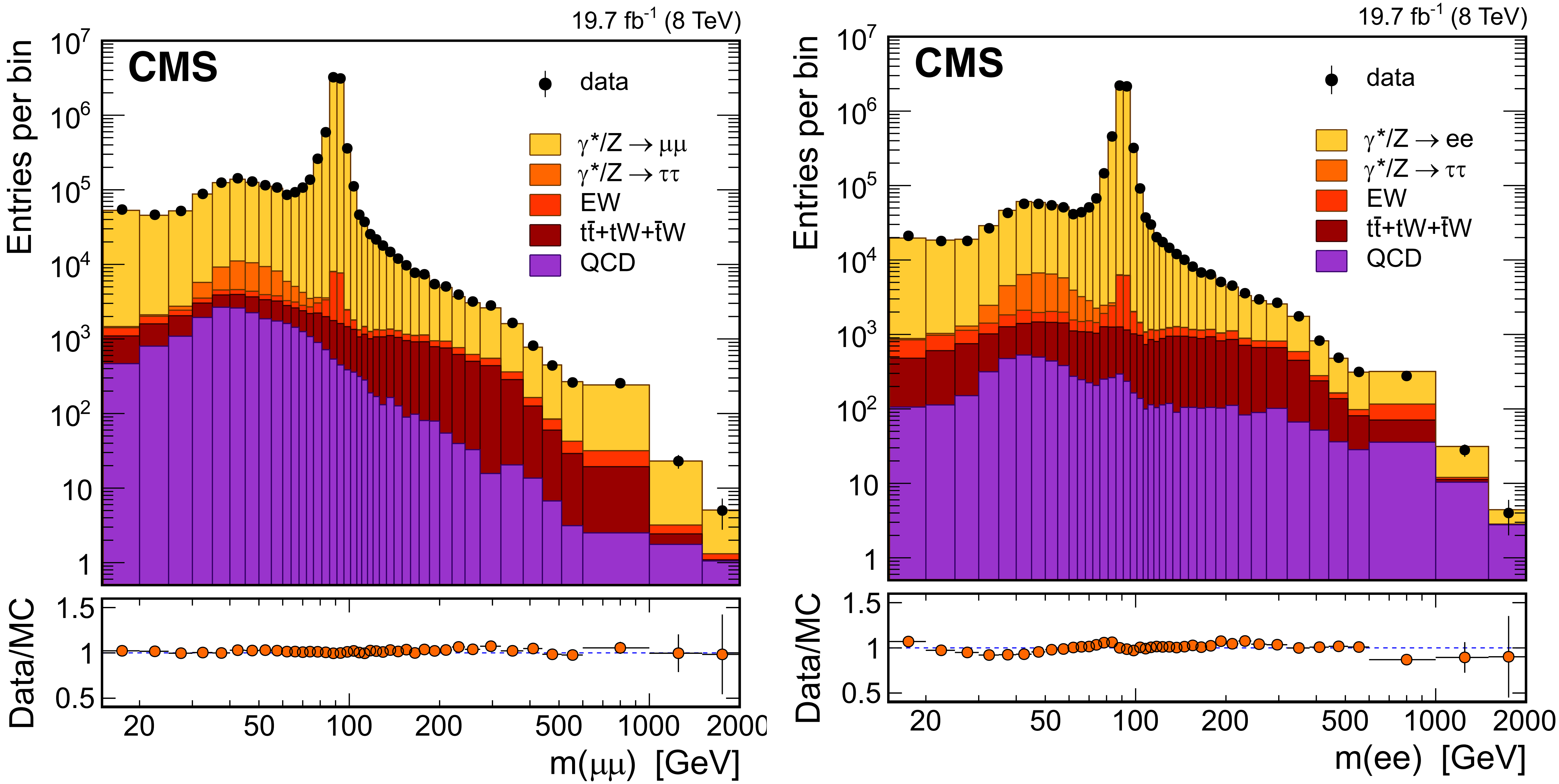


Z boson bremsstrahlung
α_{ew}^4



non-resonant lljj
α_{ew}^4

Inclusive Z→ll

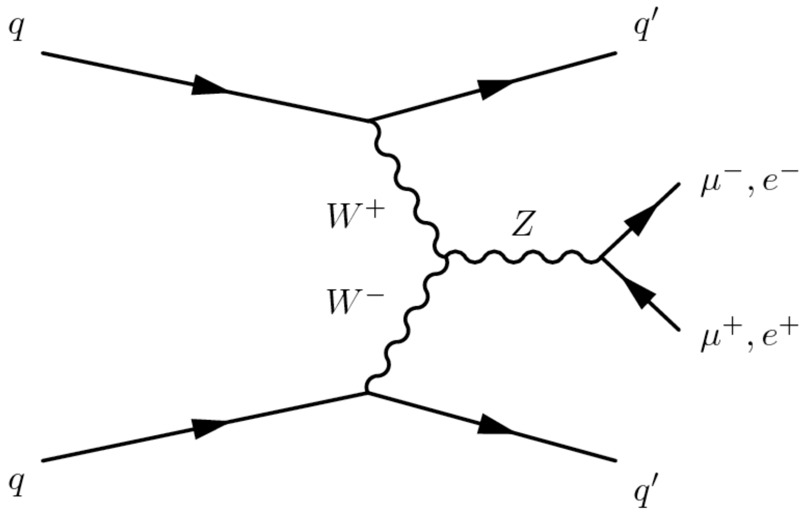


It is "known" that the Z→ll final state is "clean"

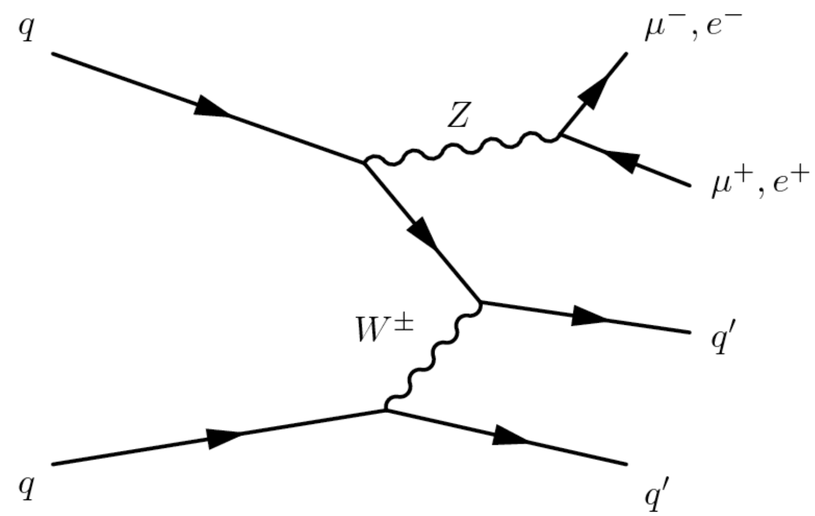
Then one would think observing EW Z(→ll)jj is "trivial"

Electroweak production of a Z boson with di-jets

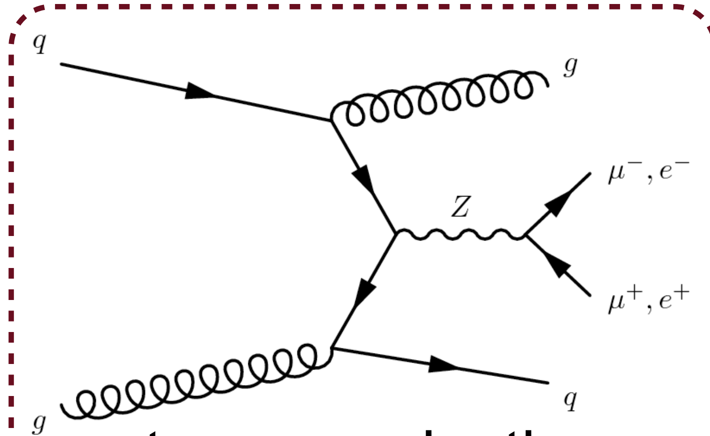
EW Z(→ll)jj production defined
to include all contributions to lljj with a t-channel
exchange of an EW gauge boson



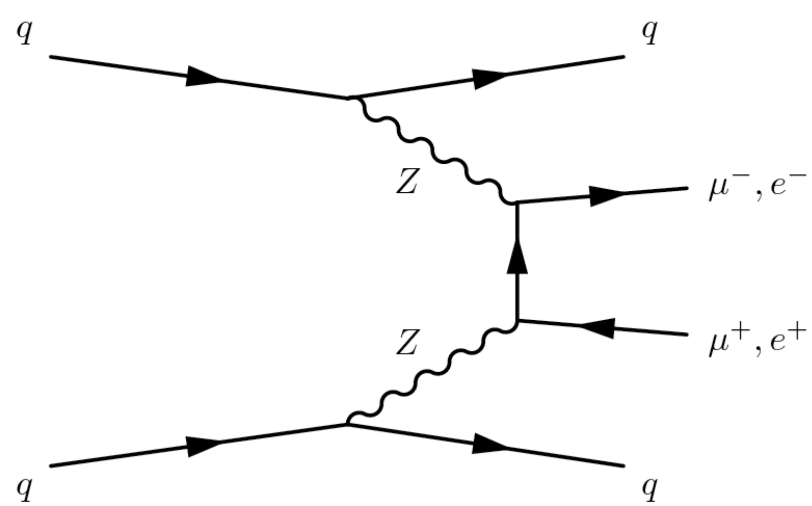
VBF
α_{ew}^4



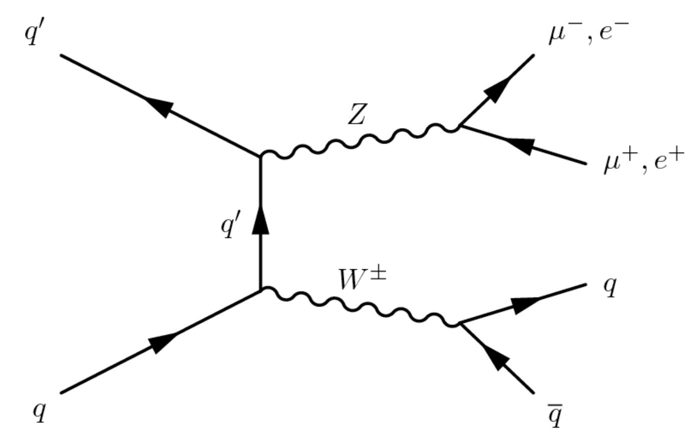
Z boson bremsstrahlung
α_{ew}^4



strong production
$\alpha_{ew}^2\alpha_s^2$



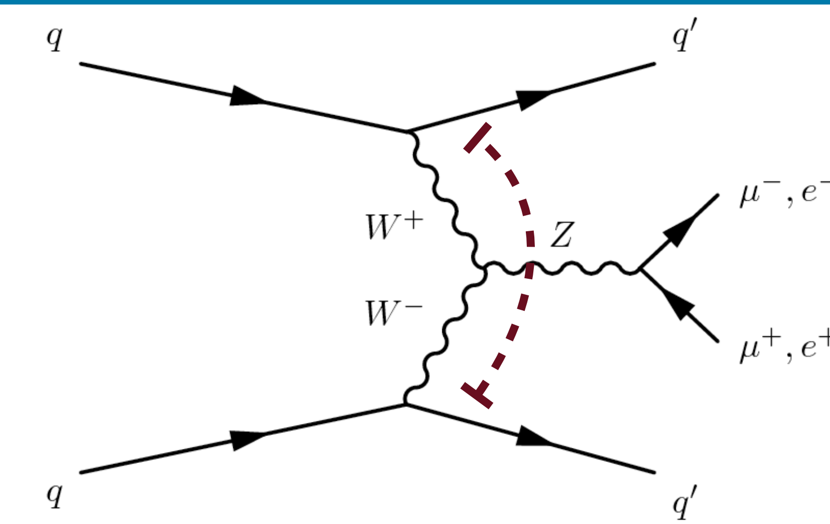
non-resonant lljj
α_{ew}^4



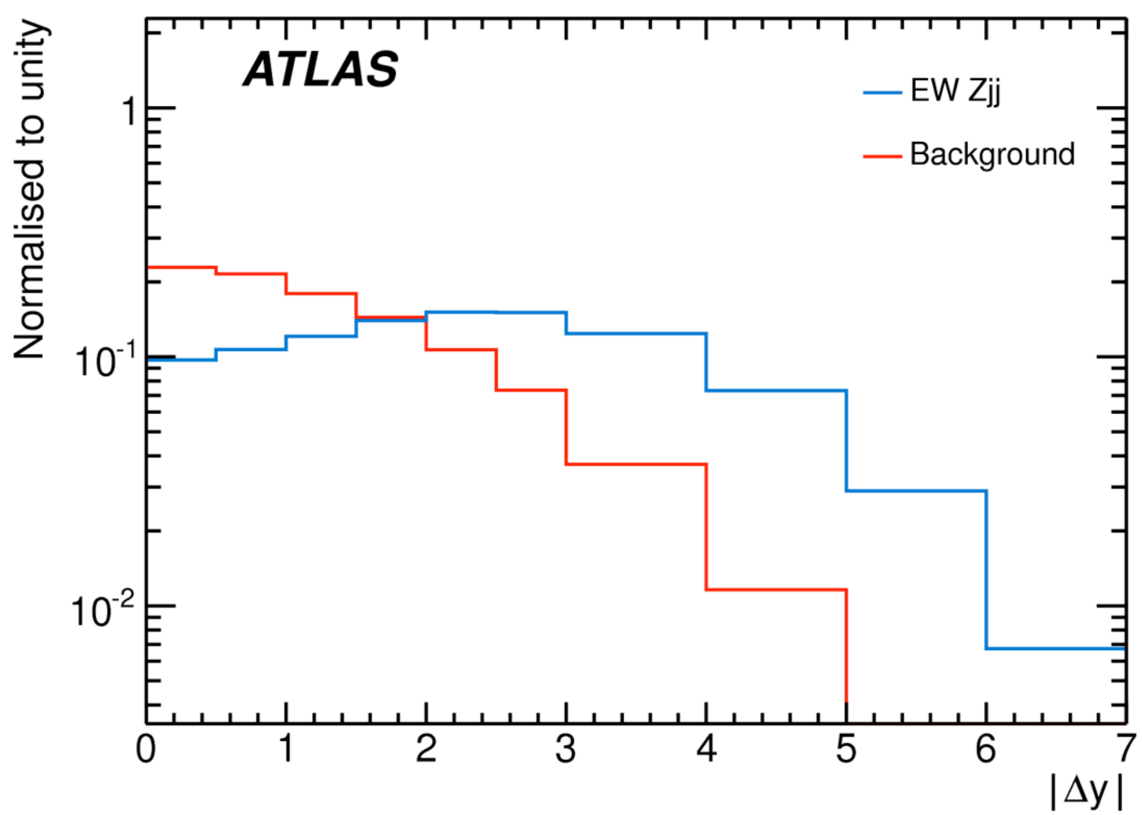
di-boson initiated
α_{ew}^4

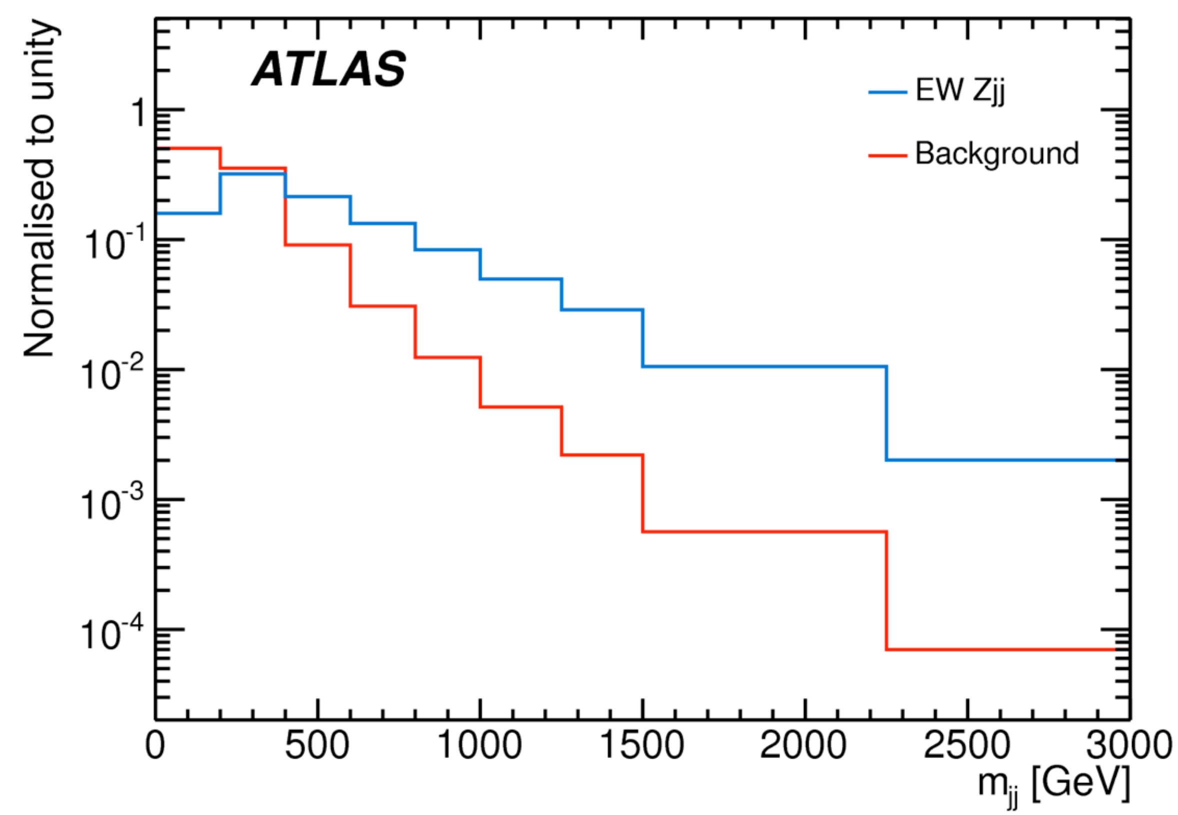
Electroweak production of a Z boson with di-jets

Study Zjj production and "observe" EW Zjj
CMS: 5 fb^{-1} of 7 TeV data JHEP 10 (2013) 062
ATLAS: 20.3 fb^{-1} of 8 TeV data JHEP 04 (2014) 031



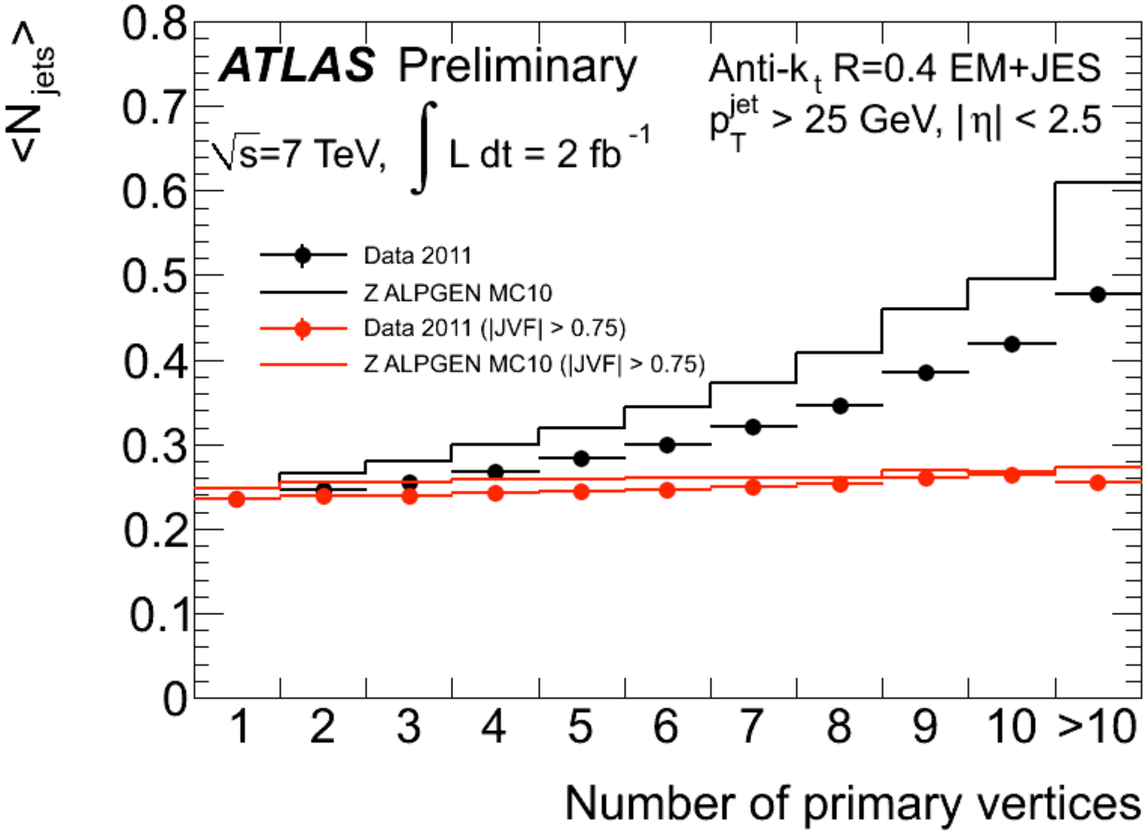
Modeling of EW and strong Zjj (interference neglected):
Sherpa (Matrix Element ⊕ parton shower)
Powheg Box (+PYTHIA)
[Diboson contribution (small) through Sherpa]
Overall normalisation to Powheg Zjj NLO prediction



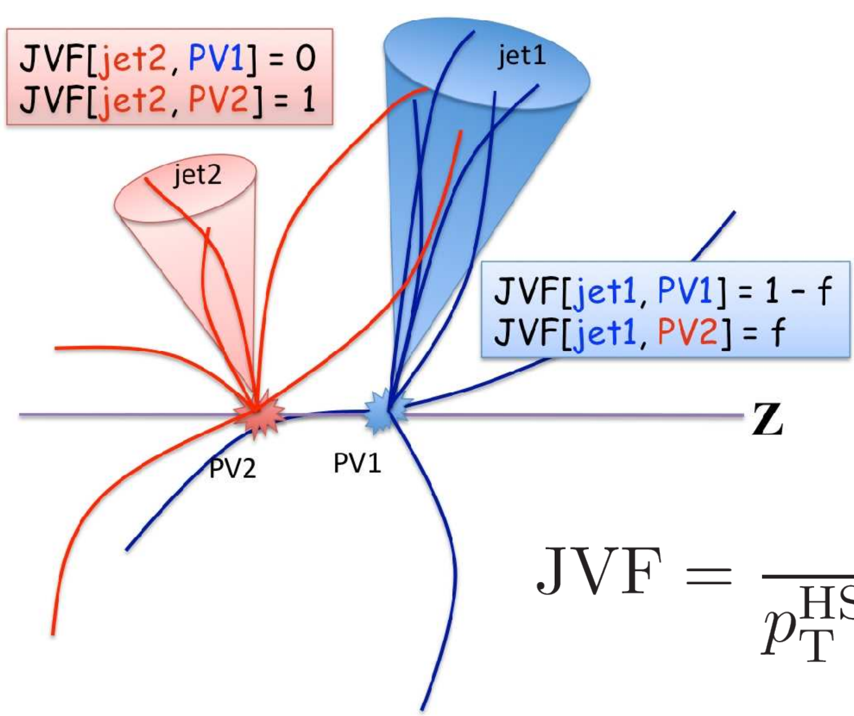


Jet activity both in terms of kinematics of the events, and as additional hadronic activity are crucial to separate EW and strong production

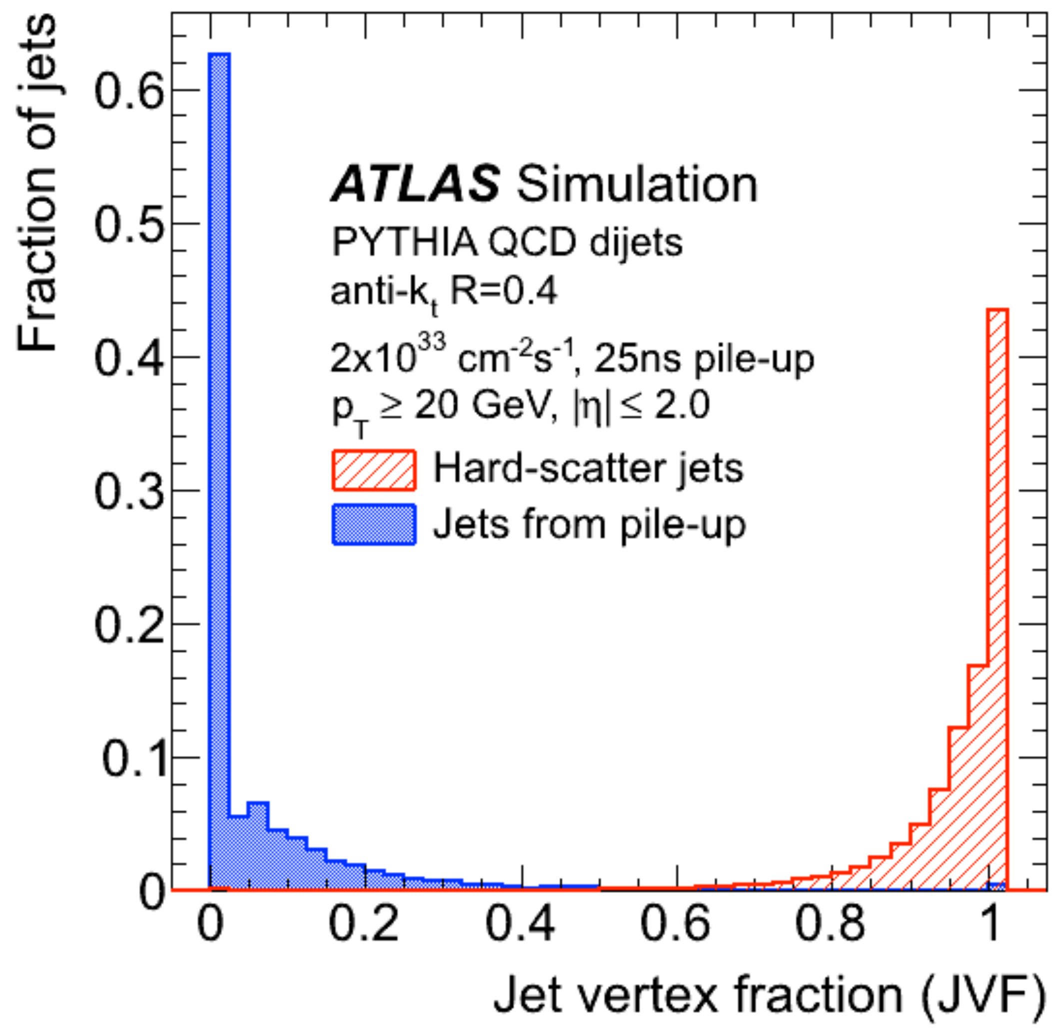
Pile-up...again...



Jets from pile-up interactions may pass event selection
→ more background in our search/study
Use reconstructed tracks to associate jets to hard-scattering primary vertex



$$\mathrm{JVF} = \frac{p_{\mathrm{T}}^{\mathrm{HS}}}{p_{\mathrm{T}}^{\mathrm{HS}} + p_{\mathrm{T}}^{\mathrm{PU}}}$$



Event Selection

JHEP04(2014)031

Two prong effort:
- Observe EWK Zjj production
- Improve modeling of strong Zjj production

Fewer selection criteria to study Zjj production in simpler topologies

Optimized for EWK Zjj observation

Suppress EW and enhance strong production

<table>
<tr><th>Object</th><th>baseline</th><th>high-mass</th><th>search</th><th>control</th><th>high-p_{T}</th></tr>
<tr><td>Leptons</td><td colspan="5">$|\eta^{\ell}| < 2.47,\ p_{\mathrm{T}}^{\ell} > 25\,\mathrm{GeV}$</td></tr>
<tr><td rowspan="2">Dilepton pair</td><td colspan="5">$81 \leq m_{\ell\ell} \leq 101\,\mathrm{GeV}$</td></tr>
<tr><td colspan="2">—</td><td colspan="2">$p_{\mathrm{T}}^{\ell\ell} > 20\,\mathrm{GeV}$</td><td>—</td></tr>
<tr><td rowspan="3">Jets</td><td colspan="5">$|y^{j}| < 4.4,\ \Delta R_{j,\ell} \geq 0.3$</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_1} > 55\,\mathrm{GeV}$</td><td>$p_{\mathrm{T}}^{j_1} > 85\,\mathrm{GeV}$</td></tr>
<tr><td colspan="4">$p_{\mathrm{T}}^{j_2} > 45\,\mathrm{GeV}$</td><td>$p_{\mathrm{T}}^{j_2} > 75\,\mathrm{GeV}$</td></tr>
<tr><td>Dijet system</td><td>—</td><td>$m_{jj} > 1\,\mathrm{TeV}$</td><td colspan="2">$m_{jj} > 250\,\mathrm{GeV}$</td><td>—</td></tr>
<tr><td>Interval jets</td><td colspan="2">—</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} = 0$</td><td>$N_{\mathrm{jet}}^{\mathrm{gap}} \geq 1$</td><td>—</td></tr>
<tr><td>Zjj system</td><td colspan="2">—</td><td>$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$</td><td>$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$</td><td>—</td></tr>
</table>

$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\,\ell_1} + \vec{p}_{\mathrm{T}}^{\,\ell_2} + \vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\,\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\,\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{\,j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\,j_2}\right|}$$

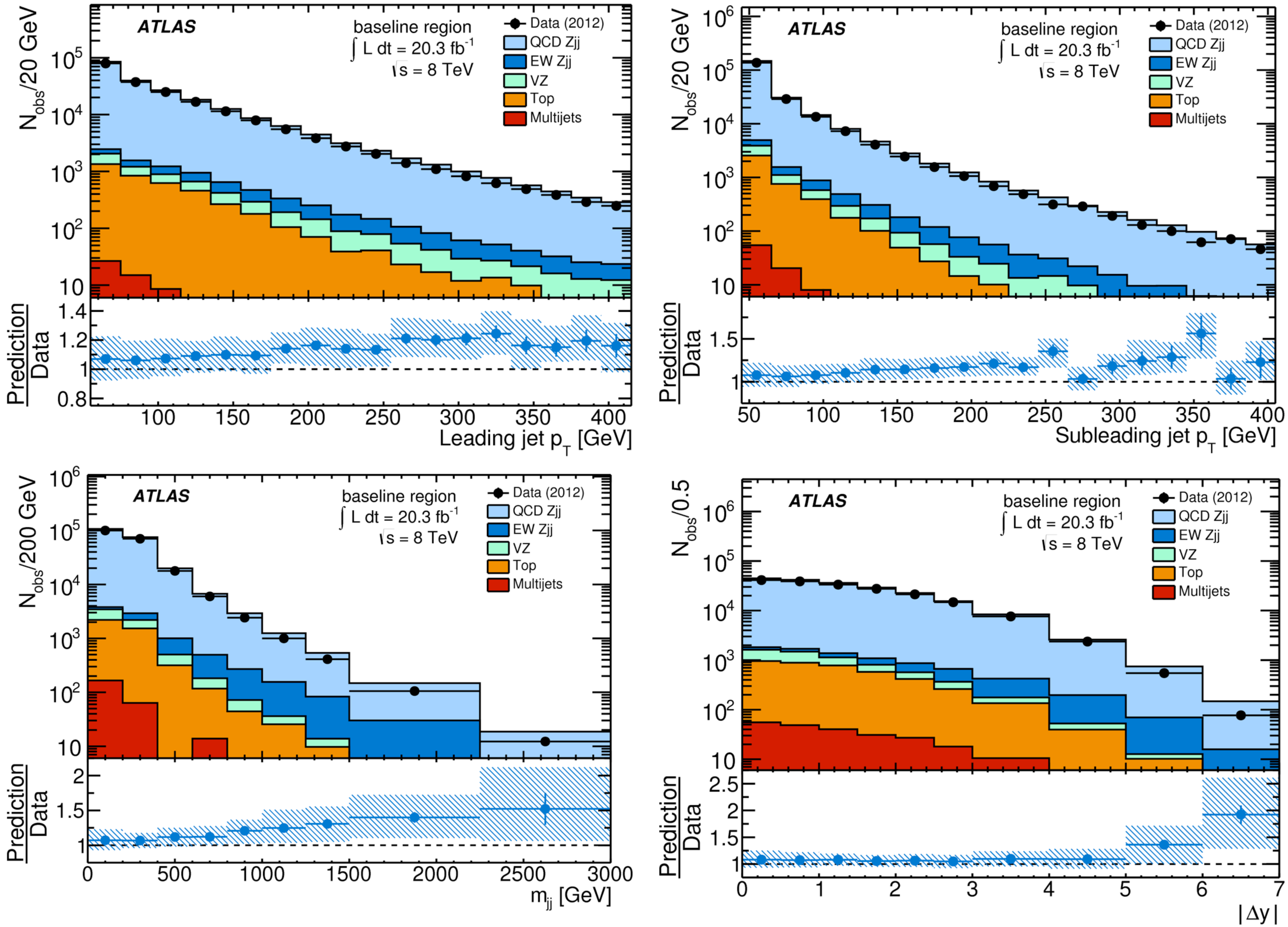
Z(→ll)jj: Composition of regions

JHEP04(2014)031

Process	Composition (%) *baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

Common issue among VBS/VBF type of studies.
Main background arise from strong production of the same final state, resulting in poor S/B
→ Modeling of this contribution is crucial

Z(→ll)jj: Data-MC comparisons



Overall adequate description of data
some discrepancies at high jet p_T and high m_{jj}

JHEP04(2014)031

Fiducial cross section

Measure fiducial cross sections in phase space that mimics experimental selections (fiducial regions)

$$\sigma^{\mathrm{fid.}} = \frac{N^{\mathrm{obs.}} - N^{\mathrm{bkg}}}{\mathcal{L} \cdot \epsilon}$$

$$\epsilon = \frac{N_{\mathrm{signal\ region,\ reco-level}}}{N_{\mathrm{fiducial\ region,\ particle-level}}}$$

Estimated with detector simulation
Accounting for experimental effects: trigger efficiencies, object reconstruction, e.t.c.

~0.80-0.92 for μμ
~0.64-0.71 for ee
depending on region

Fiducial cross section

ATLAS NOTE

ATL-PHYS-PUB-2015-013

6th June 2015

Proposal for particle-level object and observable definitions for use in physics measurements at the LHC

The ATLAS Collaboration

- "Born leptons"

leptons "prior to QED Final State Radiation (FSR)"

[considered at the lowest-order diagram in the α_{QED} for the process under study]

Here one needs to neglect, e.g., interference effects between initial and final state QED radiation in the case of W and Z boson production.

- "Bare" leptons

leptons "after to QED Final State Radiation (FSR)"

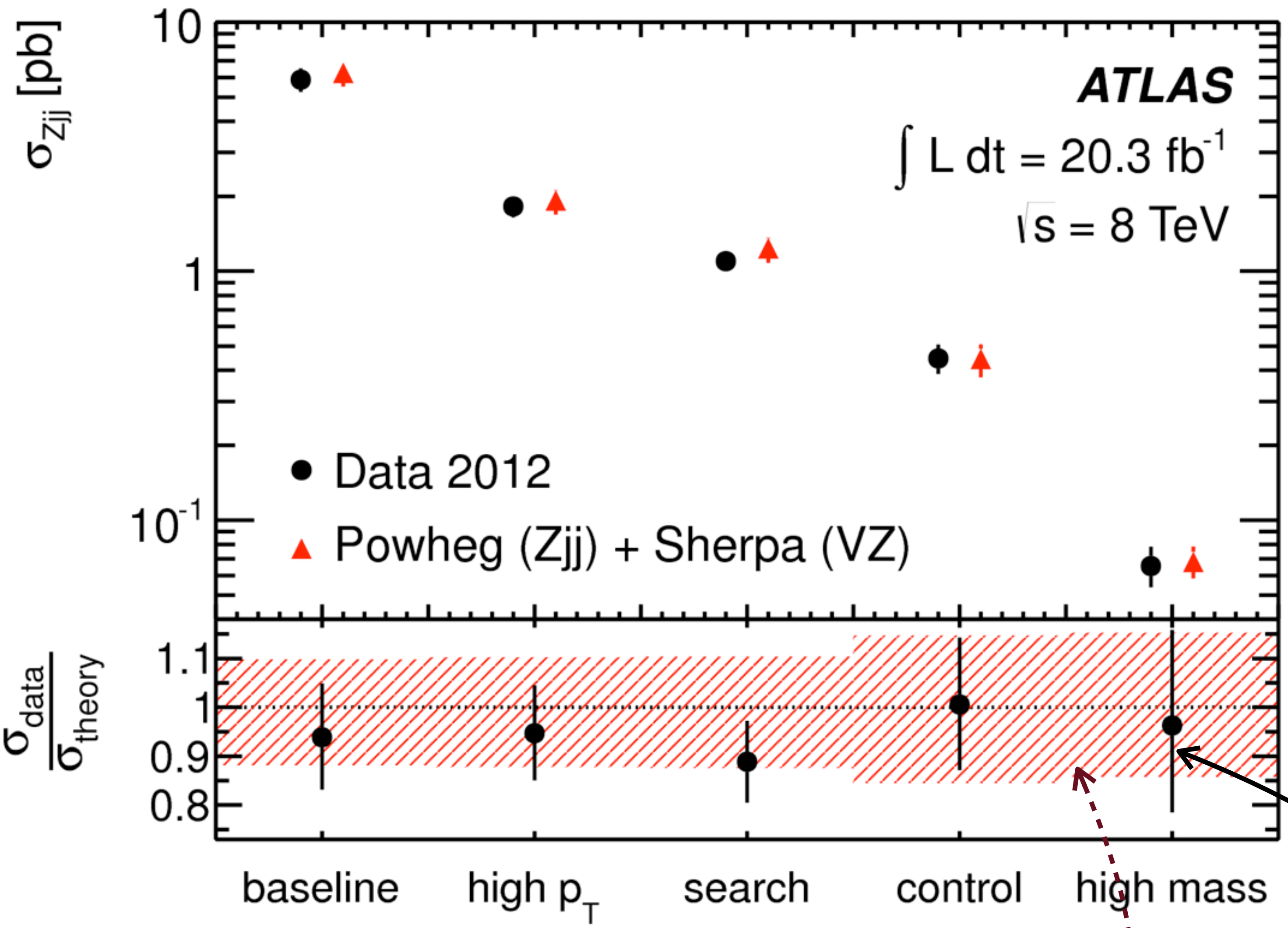
Implementation of QED radiation depends in the details of MC generators.

- "Dressed" leptons

A cone or jet algorithm is used to cluster all photons around the bare lepton direction, forming a lepton after partial QED radiation recovery.

Usually fiducial cross-sections are reported at the "Dressed" level, to study of intermediate states (W,Z,etc) the observables are provided at the "Born" and/or "Dressed" levels to facilitate comparison with prediction

Z(→ll)jj: Fiducial cross sections



total uncertainty on the predictions

total uncertainty on measurement

Statistical uncertainty negligible

Systematic uncertainty dominant mostly Jet Energy Scale uncertainty 7.5-19%

Fiducial region	σ_{fid} (pb)
baseline	5.88 ± 0.01 (stat) ± 0.62 (syst) ± 0.17 (lumi)
high-p_T	1.82 ± 0.01 (stat) ± 0.17 (syst) ± 0.05 (lumi)
high-mass	0.066 ± 0.001 (stat) ± 0.012 (syst) ± 0.002 (lumi)
search	1.10 ± 0.01 (stat) ± 0.09 (syst) ± 0.03 (lumi)
control	0.447 ± 0.004 (stat) ± 0.059 (syst) ± 0.013 (lumi)

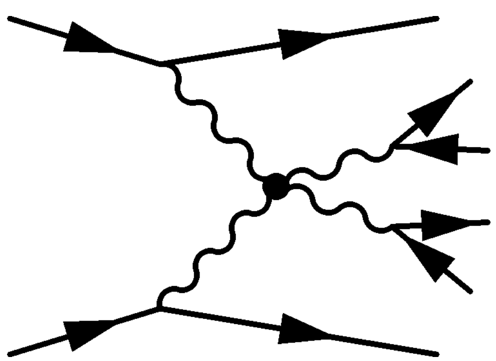
Fiducial region	σ_{theory} (pb)
baseline	6.26 ± 0.06 (stat) $^{+0.50}_{-0.60}$ (scale) $^{+0.29}_{-0.35}$ (PDF) $^{+0.19}_{-0.25}$ (model)
high-p_T	1.92 ± 0.02 (stat) $^{+0.17}_{-0.20}$ (scale) $^{+0.09}_{-0.10}$ (PDF) $^{+0.05}_{-0.07}$ (model)
high-mass	0.068 ± 0.001 (stat) $^{+0.009}_{-0.009}$ (scale) $^{+0.004}_{-0.003}$ (PDF) $^{+0.004}_{-0.002}$ (model)
search	1.23 ± 0.01 (stat) $^{+0.11}_{-0.13}$ (scale) $^{+0.06}_{-0.07}$ (PDF) $^{+0.03}_{-0.04}$ (model)
control	0.444 ± 0.005 (stat) $^{+0.051}_{-0.054}$ (scale) $^{+0.021}_{-0.025}$ (PDF) $^{+0.032}_{-0.034}$ (model)

e.g. underlying event tuning

Now go ahead to study differential distributions in the fiducial regions
Variables sensitive to the kinematics of the di-jet and the color flow

Unfolding (1/3)

Often one would like to measure distribution f(x) of quantity x.
Ideal detector: measure x in each event
→ obtain f(x) through histogram of measured x
Real detector:
1) Acceptance [Probability to observe an event is not 1, and depends on x]
2) Transformation [Instead of x, a related quantity y is measured (potential due to non-linear detector response)]
3) Resolution [Measured y is smeared due to finite resolution. Only statistical relation between variable x and measured quantity y]
Also physics effects, e.g. radiation, hadronization, etc



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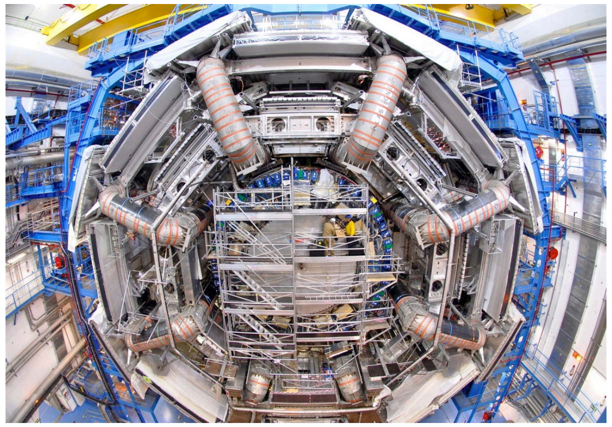

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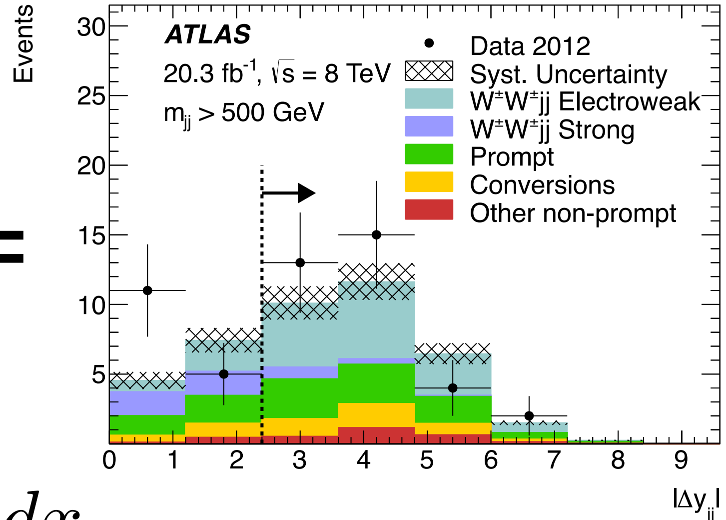


$$g(y) = \int R(y,x) f(x) dx$$

Response function

Determining f(x) given g(y) is called unfolding or deconvolution.
If R not dominantly diagonal → Maximum Likelihood Estimators give too large variance for estimated f(x) to be of any use (statistical fluctuations magnified)
In unfolding one accepts a (small) bias, in exchange for a (large) reduction in variance
Several approaches to overcome this difficulty

Unfolding (2/3)

Correction factor method

Estimators with smaller variances, based on multiplicative correction factors derived from MC:

$$\hat{\mu}_i = C_i(n_i - \mathrm{bkg}_i) \quad C_i = \frac{\mu_i^{MC}}{\nu_i^{MC}}$$

Works well for C_i~1 (i.e. migration is small, smearing effect smaller than bin size) with a bias of :

$$b_i = \left(\frac{\mu_i^{MC}}{\nu_i^{MC}} - \frac{\mu_i}{\nu_i^{sig}} \right) \nu_i^{sig}$$

(except if the MC simulation is equivalent to Nature)

Regularized unfolding

Obtain a smooth result around the ML solution

$$\phi(\mu, \lambda) = \alpha \ln \mathcal{L}(\mu) + S(\mu) + \lambda \left[n_{\mathrm{tot}} - \sum_i \nu_i \right]$$

(optional) constraint for unbiased estimate of total entries

regularization parameter

regularisation function (e.g. mean square of 2nd derivatives)

Iterative unfolding

Initial estimate of the true distribution: $\hat{\mu}_0 = n_{\mathrm{tot}} p_0$

and iteratively update through:

$$\hat{\mu}_i = \frac{1}{\epsilon_i} \sum_j \left(\frac{R_{ij} p_i}{\sum_k R_{jk} p_k} \right) n_j \longrightarrow p_i' = \hat{\mu}_i / \mu_{\mathrm{tot}}$$

Updated estimate of g(x) in each iteration, stopping criterion (otherwise same issues as with MLE) decided a priori. Usually a χ^2 estimate of difference wrt previous iteration.

Unfolding (3/3)

Unfolding not always necessary

(discovery, limit setting, parameter estimation)

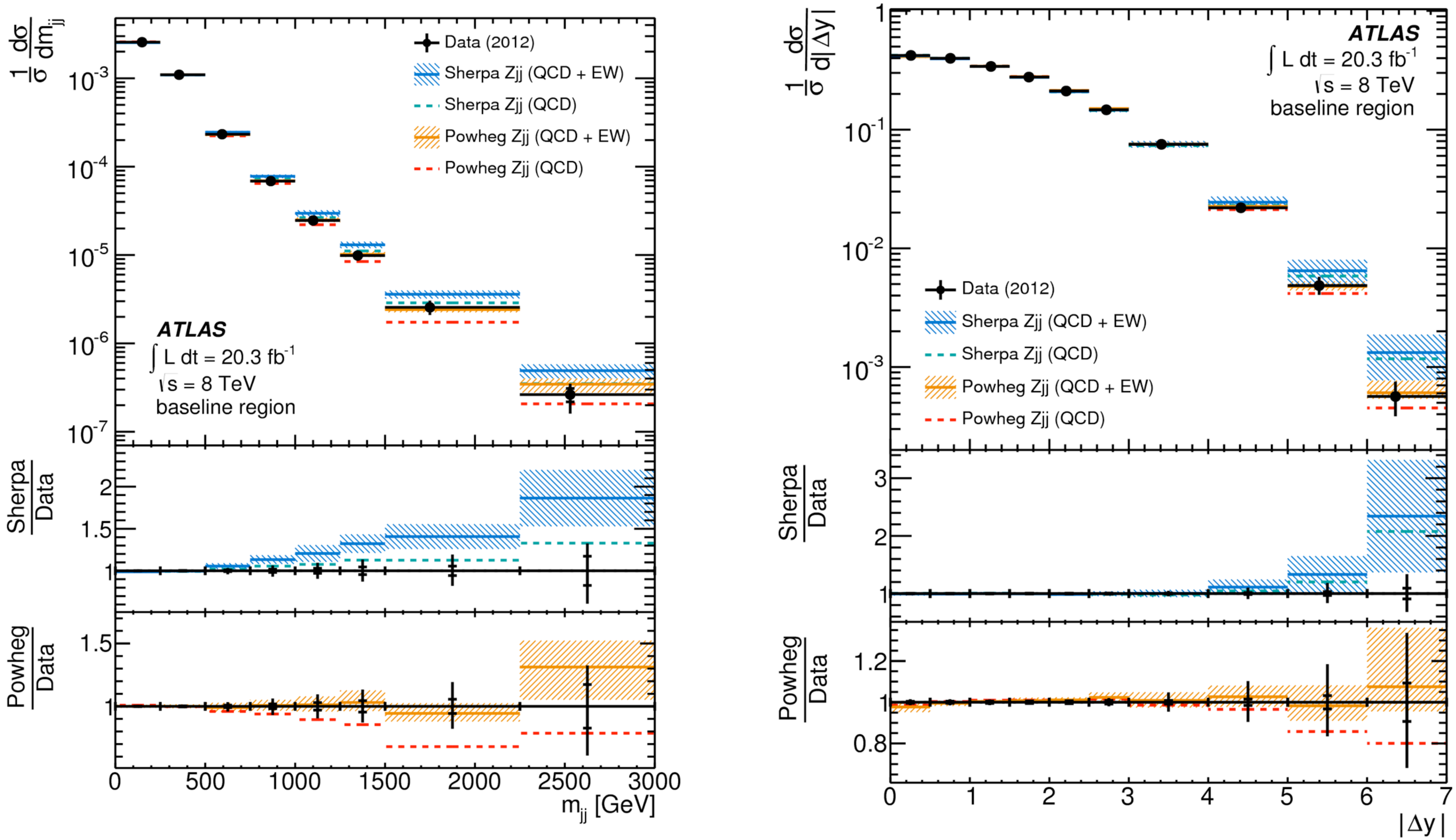
One can compare measurements and model predictions at the uncorrected distribution level → if measurements are reported with expected background, response matrix and uncertainties (which is not always practical/feasible)

Unfolding yields an estimate of the distribution we think we have measured and can be compared to different measurements (e.g. from different experiments).
Also, could demonstrate features which may not be recognizable in the uncorrected distribution (e.g. image reconstruction)

Note: Unfolded distributions come with covariance matrix
→ needed when testing models

Z(→ll)jj: Differential distributions

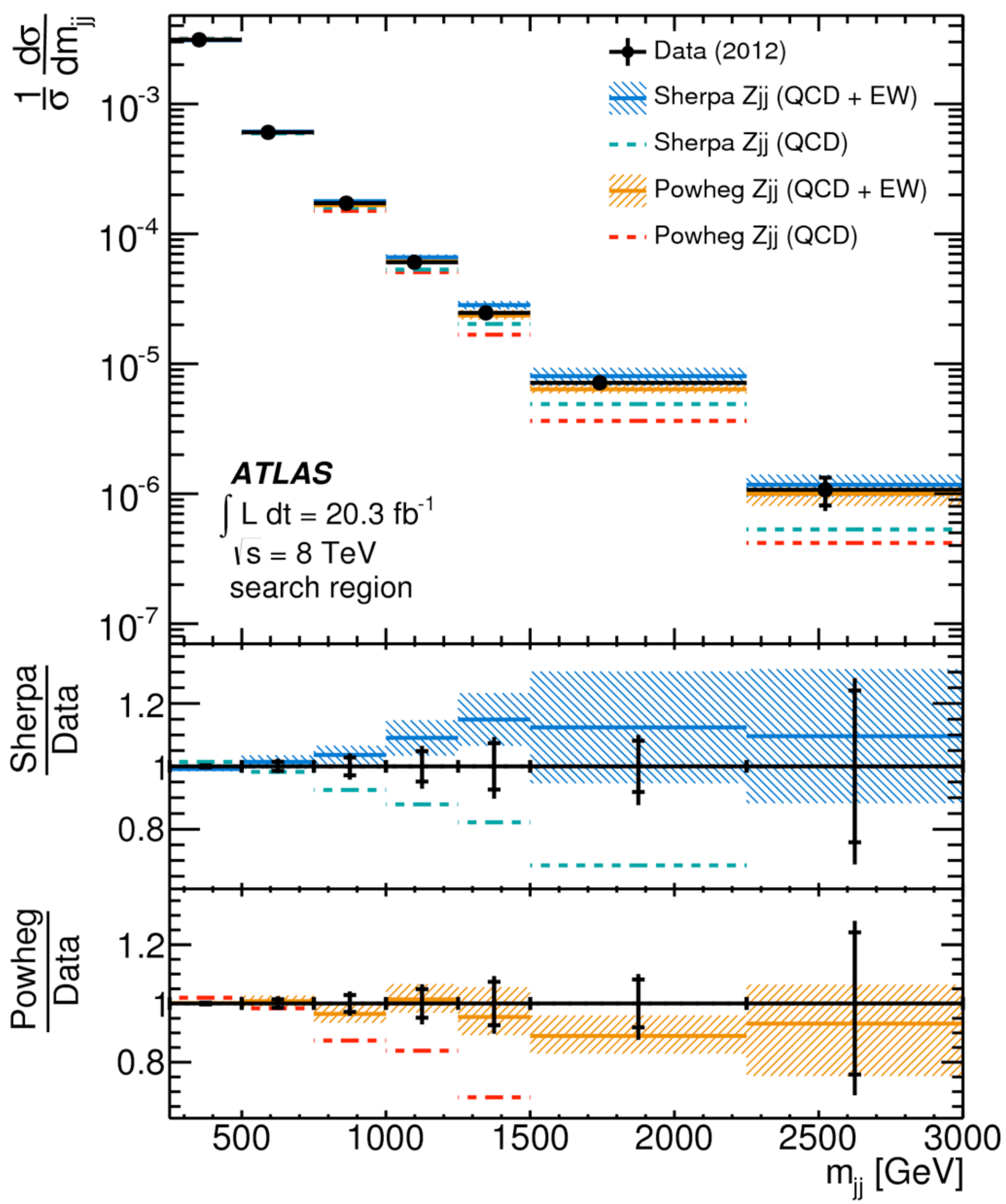
Baseline region

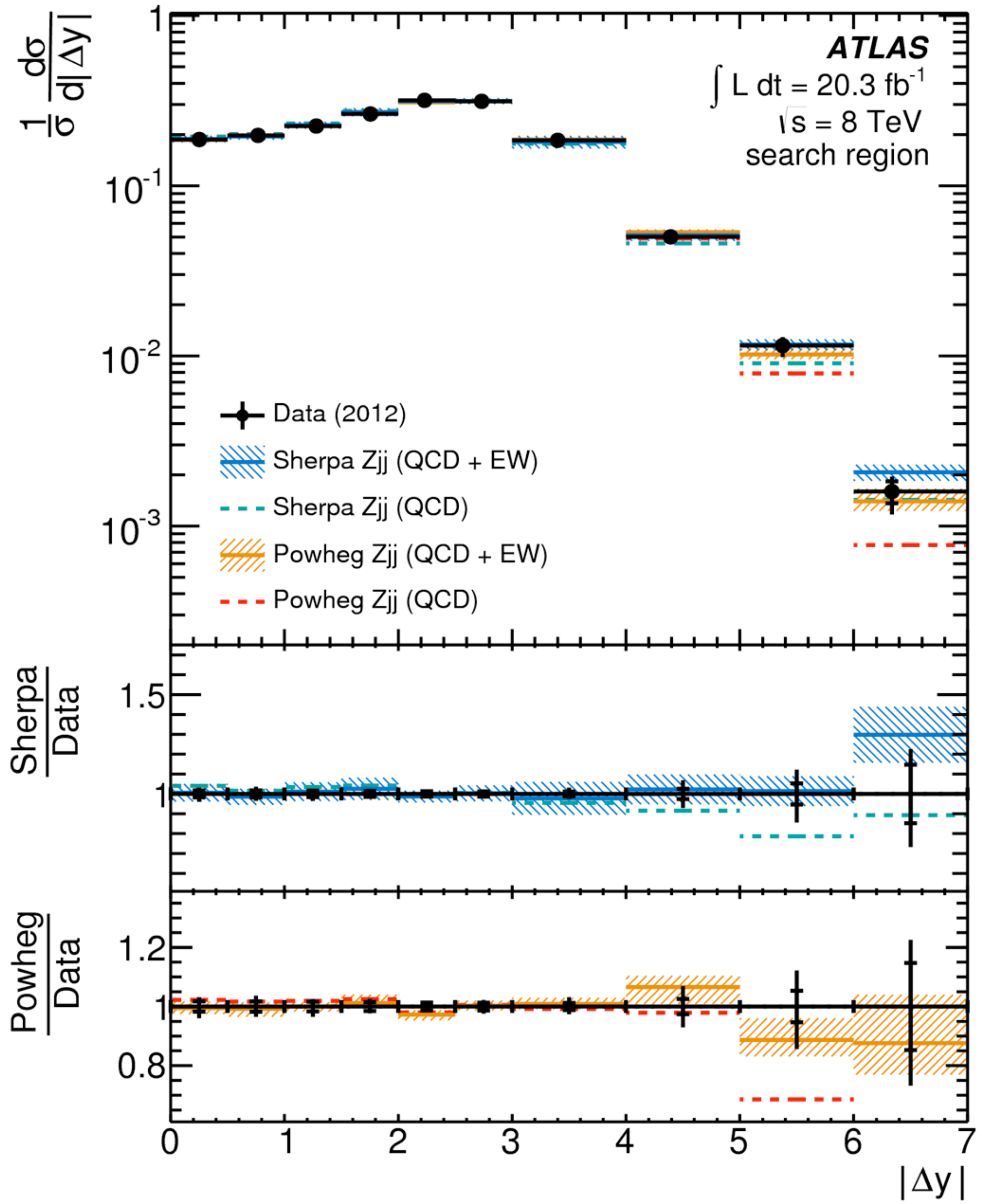


Both distributions sensitive to the differences between EW and QCD production

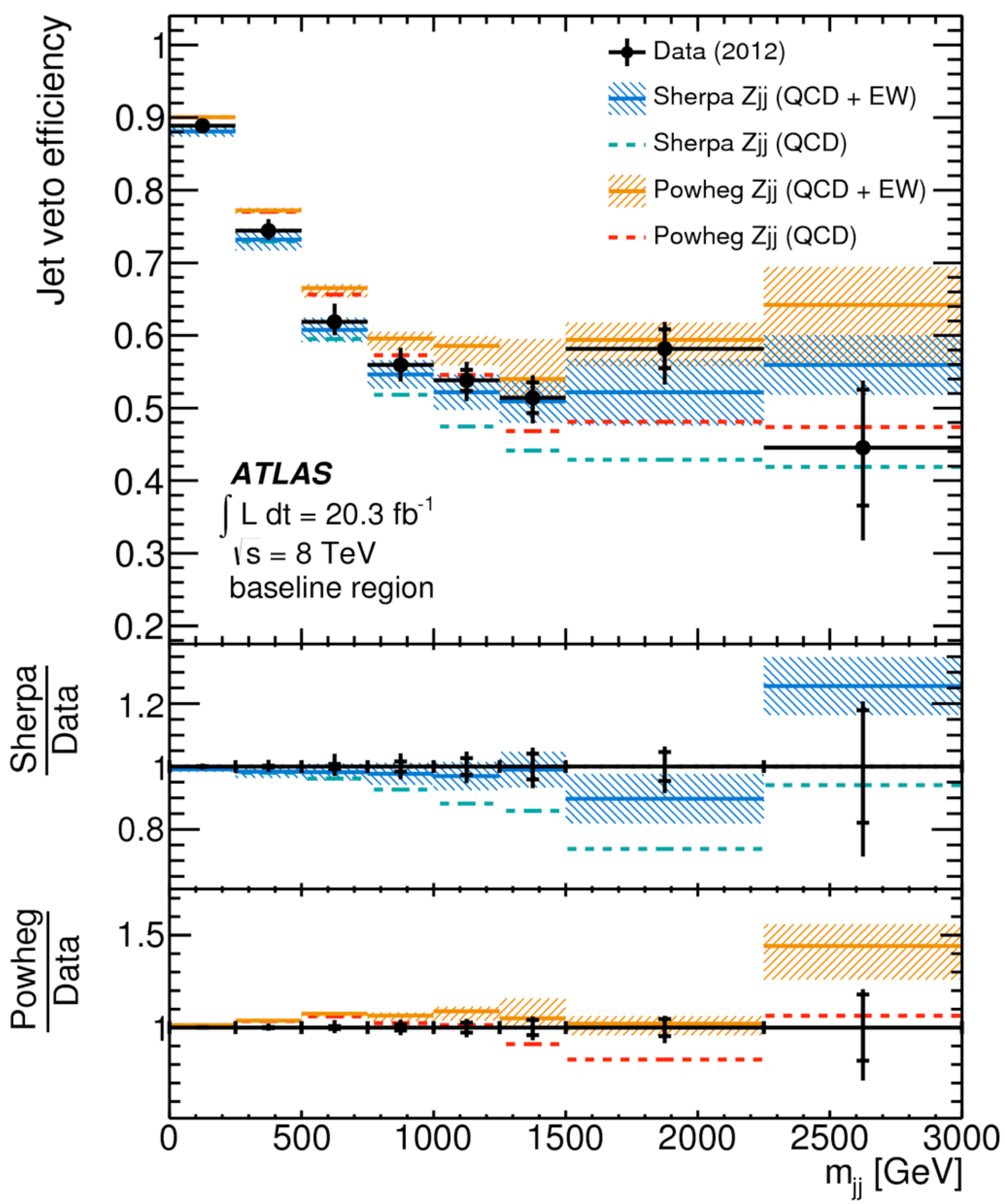
Z(→ll)jj: Differential distributions

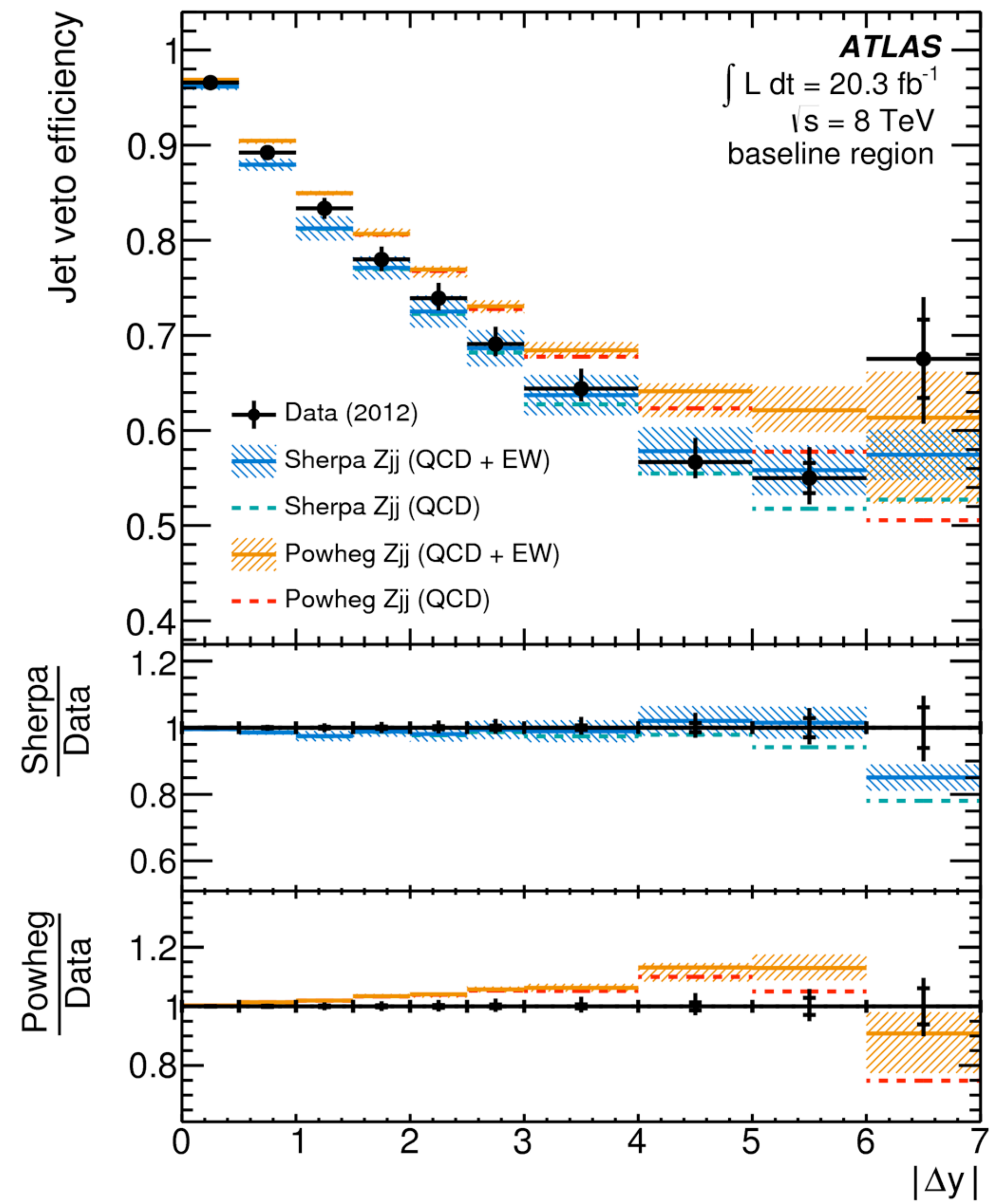
Search region





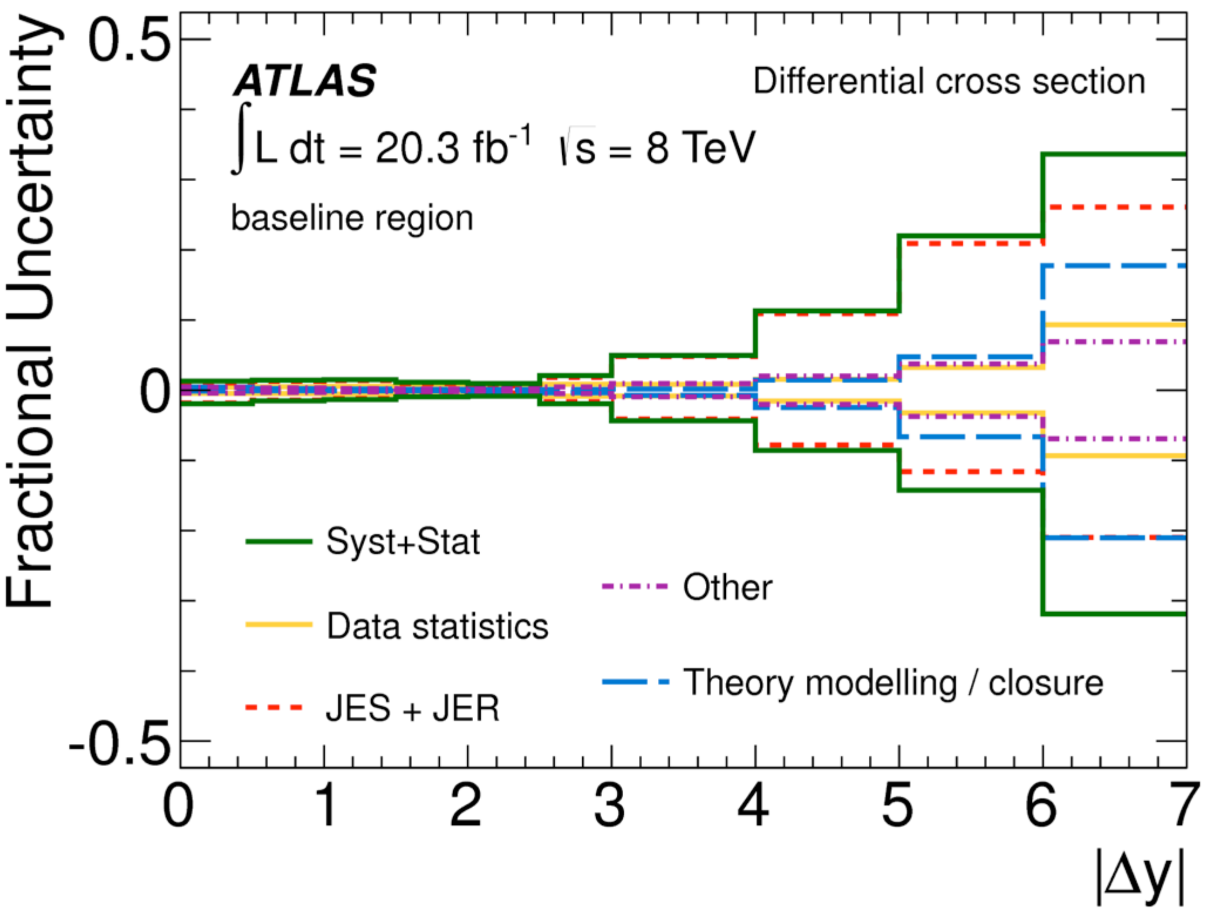
Z(→ll)jj: Jet Veto Efficiency

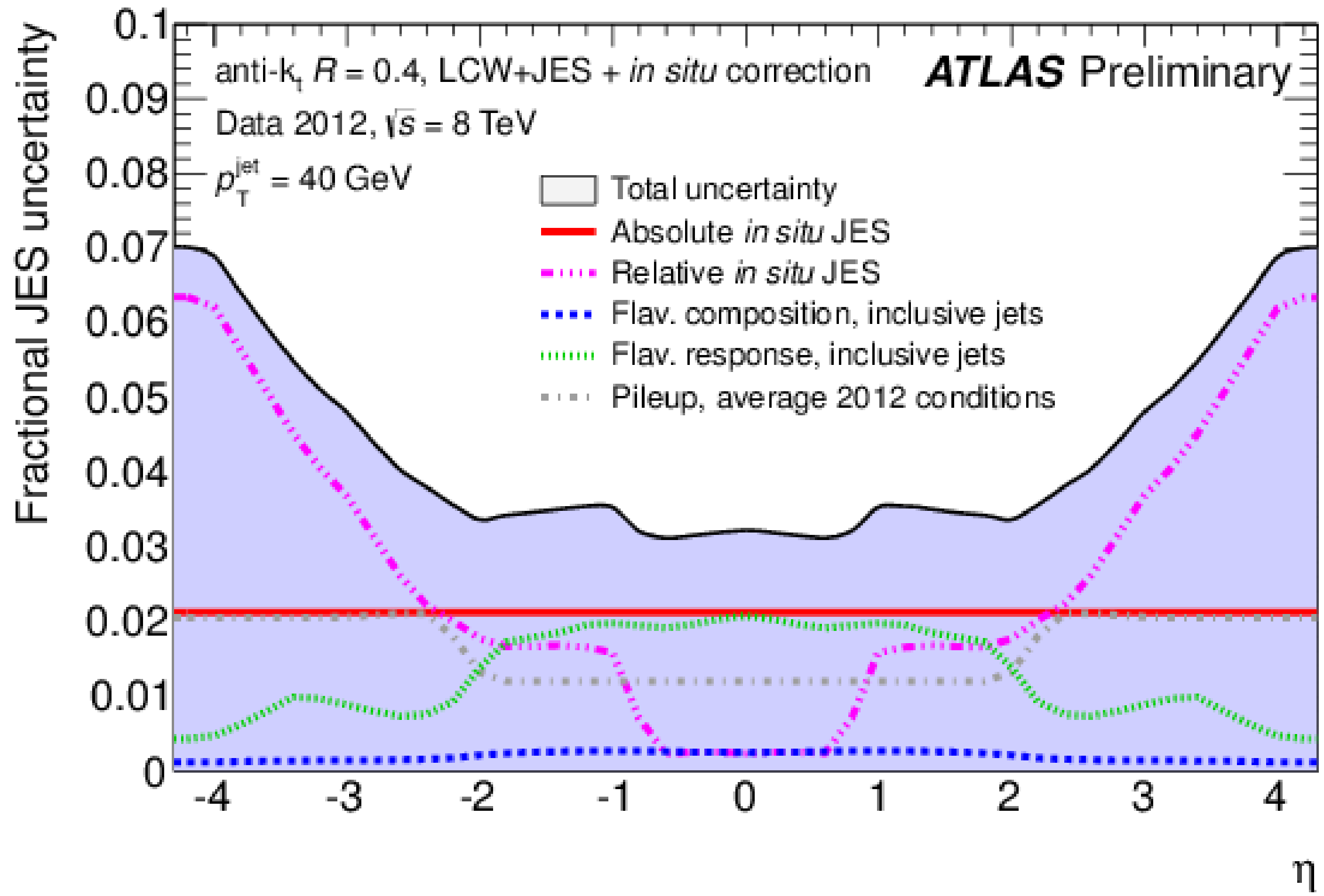




Overall quite good description of the data,
Sherpa gives better description for variables related to additional jet activity

Z(→ll)jj: Uncertainties





Jet Energy Scale and Resolution uncertainties dominant at high $|\Delta y_{jj}|$
Forward region dominate by jet η response
(studied using pT balance in di-jet event and other techniques)
Theory modeling also more important than data statistics

Extracting the EW Zjj component: Templates

To obtain EW Zjj contribution a Maximum Likelihood fit is performed in m_{jj} in the search region.

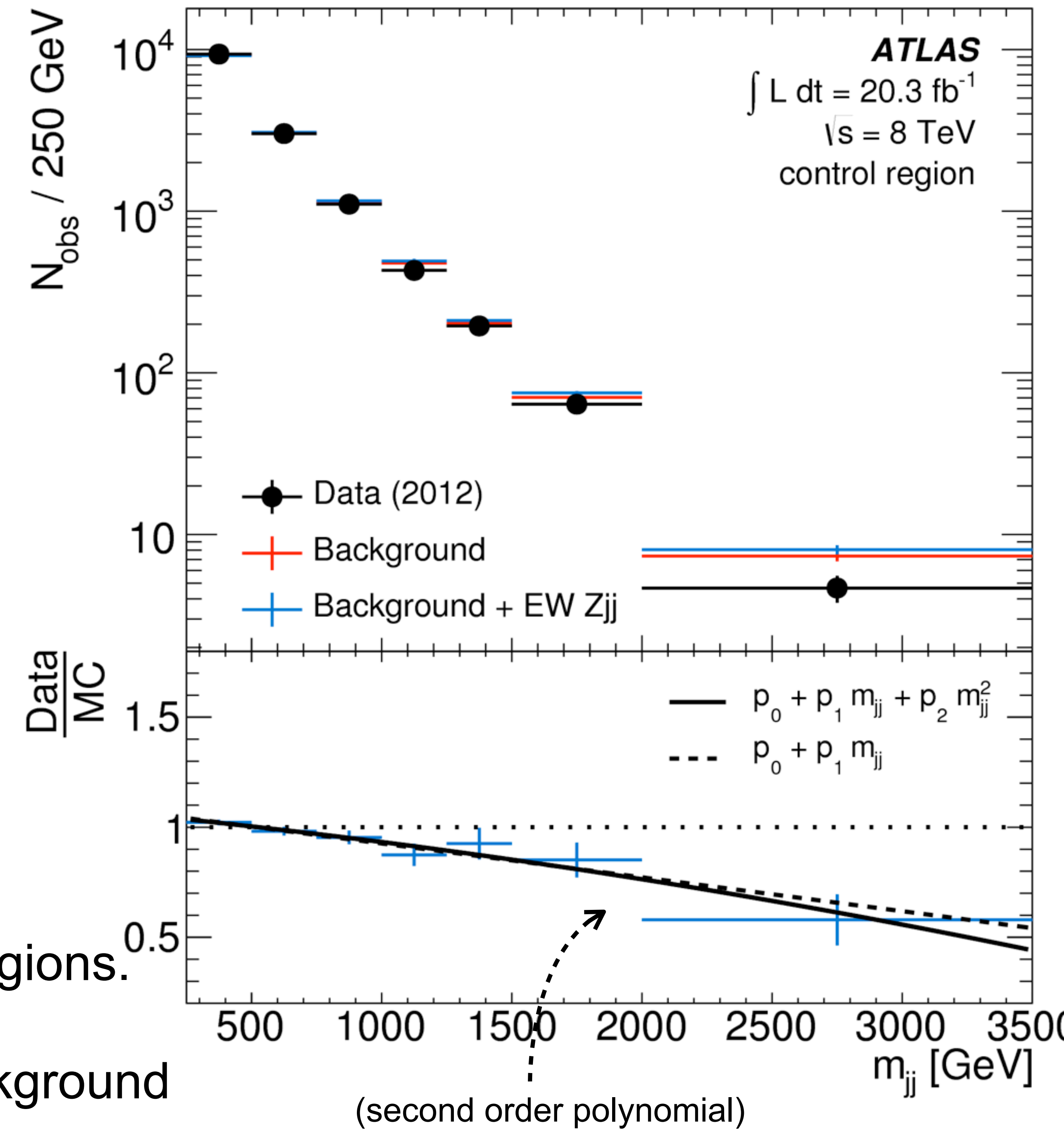
<u>Model</u>
EWK Zjj: Simulation (Sherpa)
Strong Zjj: Simulation (Sherpa) + data-driven
(plus the small diboson/ttbar contributions)

From baseline region established that strong Zjj simulation does not describe well the data.

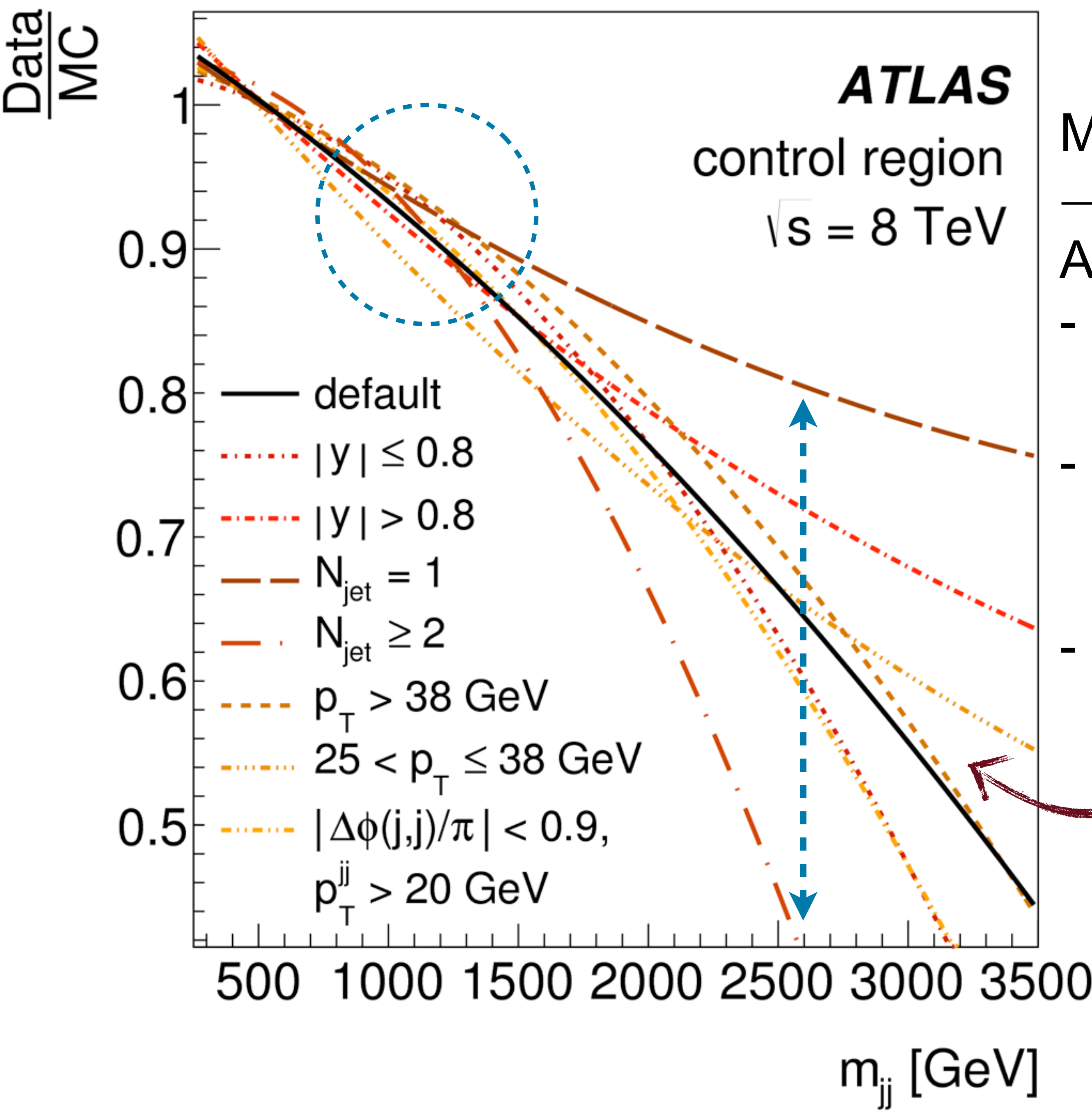
Data-driven procedure:
Derive reweighting function is defined Data/MC in control region → Apply to simulated background template in the search region.

Constrain generator modeling of m_{jj} with data, MC used to extrapolate from control to search regions.

Experimental and theory systematics on the background templates are reduced.



Extracting the EW Zjj component: Template Variations



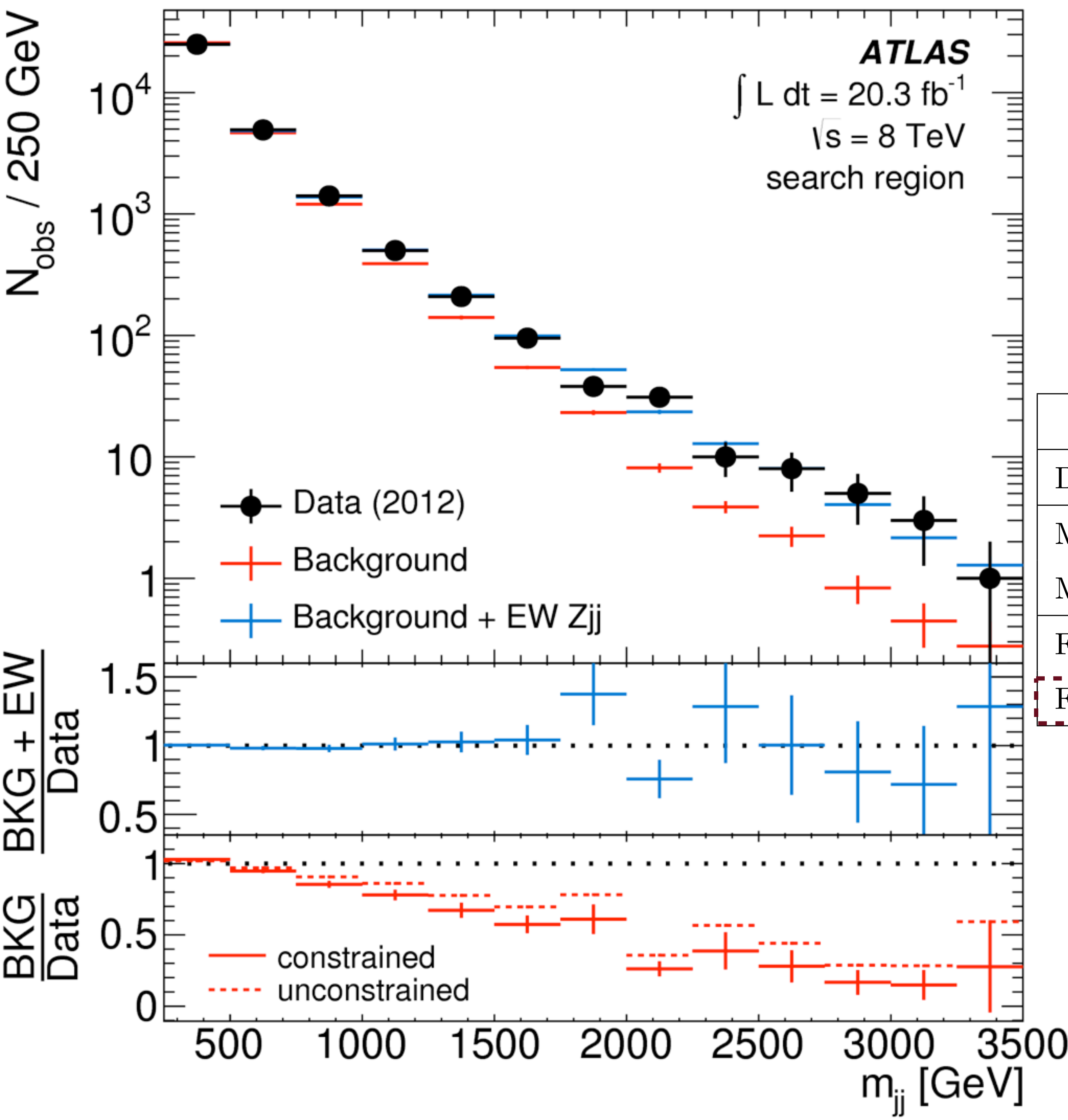
Modeling of m_{jj} for strong Zjj crucial

→ Uncertainty directly impact sensitivity to EW Zjj

A number of tests performed:

- Choice of function.
  - Use 1st order polynomial instead of 2nd order.
  - Fitted signal changed <2%
- Choice of event generator
  - Reweight Sherpa to Powheg.
  - Powheg much better description of m_{jj},and reweighting function becomes flatter. Result consistent within 0.8%
- Probe dependance on choice of control region
  - Control region split in various subregions (probing di-jet activity in the rapidity interval between the two leading jets).
  - Fit result: maximum 5% spread between subregion, probably statistical in nature
  - (reweighting functions statistically consistent)

Extracting the EWK Zjj component: Fit



	Electron	Muon	Electron+muon
Data	14248	17938	32186
MC predicted N_{bkg}	$13700 \pm 1200\,^{+1400}_{-1700}$	$18600 \pm 1500\,^{+1900}_{-2300}$	$32600 \pm 2600\,^{+3400}_{-4000}$
MC predicted N_{EW}	$602 \pm 27 \pm 18$	$731 \pm 29 \pm 22$	$1333 \pm 50 \pm 40$
Fitted N_{bkg}	$13351 \pm 144 \pm 29$	$17201 \pm 161 \pm 31$	$30530 \pm 216 \pm 40$
Fitted N_{EW}	$897 \pm 92 \pm 27$	$737 \pm 98 \pm 28$	$1657 \pm 134 \pm 40$

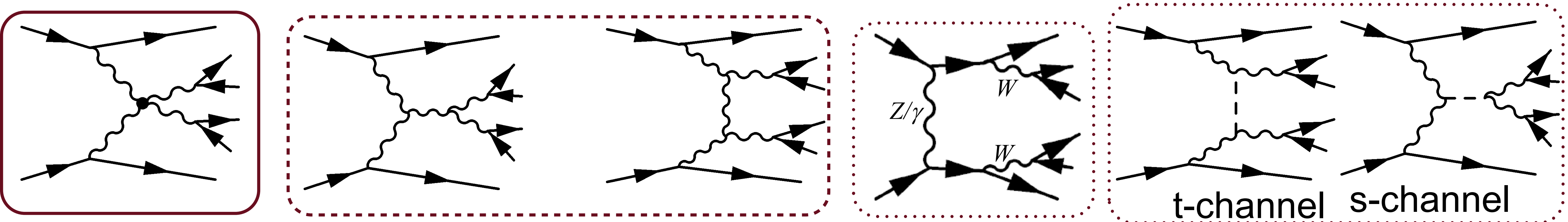
Observed significance well above 5σ

Fiducial cross section measurement for EW Zjj production in the search region:

$$\sigma_{\mathrm{EW}} = 54.7 \pm 4.6\,(\mathrm{stat})\,^{+9.8}_{-10.4}\,(\mathrm{syst}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{fb}.$$

$$46.1 \pm 0.2\,(\mathrm{stat})\,^{+0.3}_{-0.2}\,(\mathrm{scale}) \pm 0.8\,(\mathrm{PDF}) \pm 0.5\,(\mathrm{model})\ \mathrm{fb},$$ Powheg EW Zjj

Back to QGC

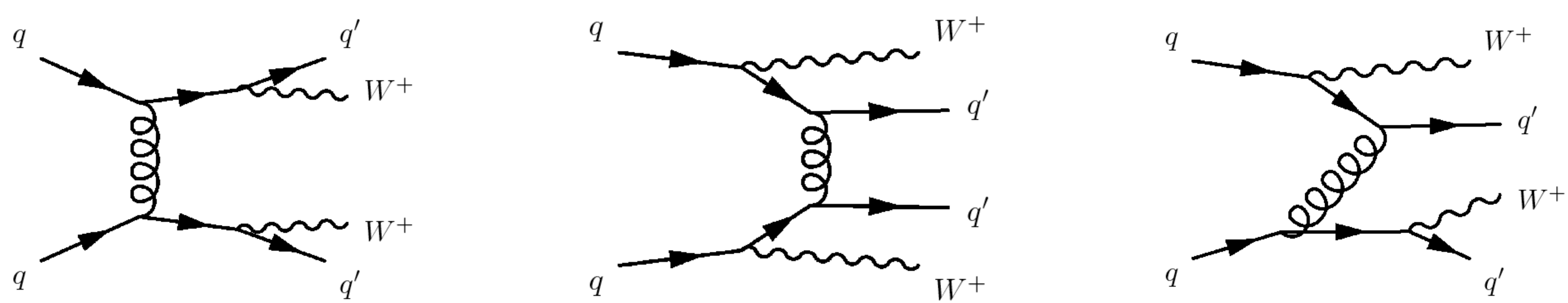


QGC TGC fermion-mediated Higgs-mediated

Two classes of processes give rise to VVjj final states:

VVjj-EW (electroweak mediated): exclusively electroweak processes, $O(\alpha_{ew}^{6})$, and contains the VBS signal under investigation.
[processes with three decaying vector bosons, with one V→jj, can be separated gauge invariantly and are suppressed by kinematic requirements. Hence, not important in the signal region.]

VVjj-QCD (QCD mediated): contains processes $O(\alpha_{ew}^{4}\alpha_{s}^{2})$ can be suppressed by topological selection requirements.



EW VVjj: Which final state?

Final state	Process	VVjj-EW	VVjj-QCD	S/B
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign, arbitrary flavor)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	~1
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb	~0.03
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb	~0.015
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	~0.04
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb	~0.014

Leading-order cross-sections calculated at √s=8 TeV using SHERPA
[2 leptons p_T>5 GeV, m_{ll}>4 GeV, ≥2 jets p_T>10 GeV]

→ No leading-order gluon-gluon initial state contributions to $W^{\pm}W^{\pm}$jj

→ Only t-channel Higgs exchange contributes to $W^{\pm}W^{\pm}$jj

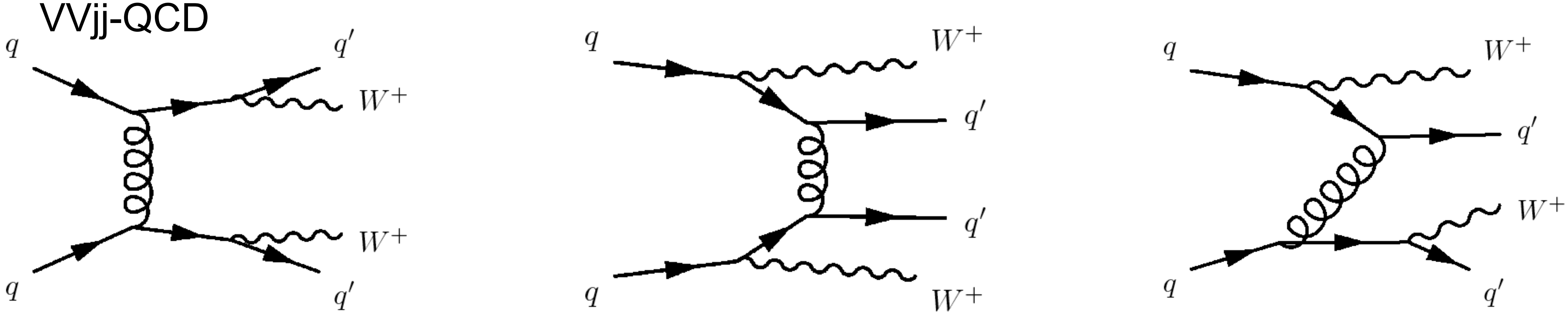
→ Same-sign WW ensures small SM backgrounds (VV production, ttbar, Z+jets,...)

CMS: 19.4 fb^{-1} of 8 TeV data, published as PRL 114, 051801 (2015)

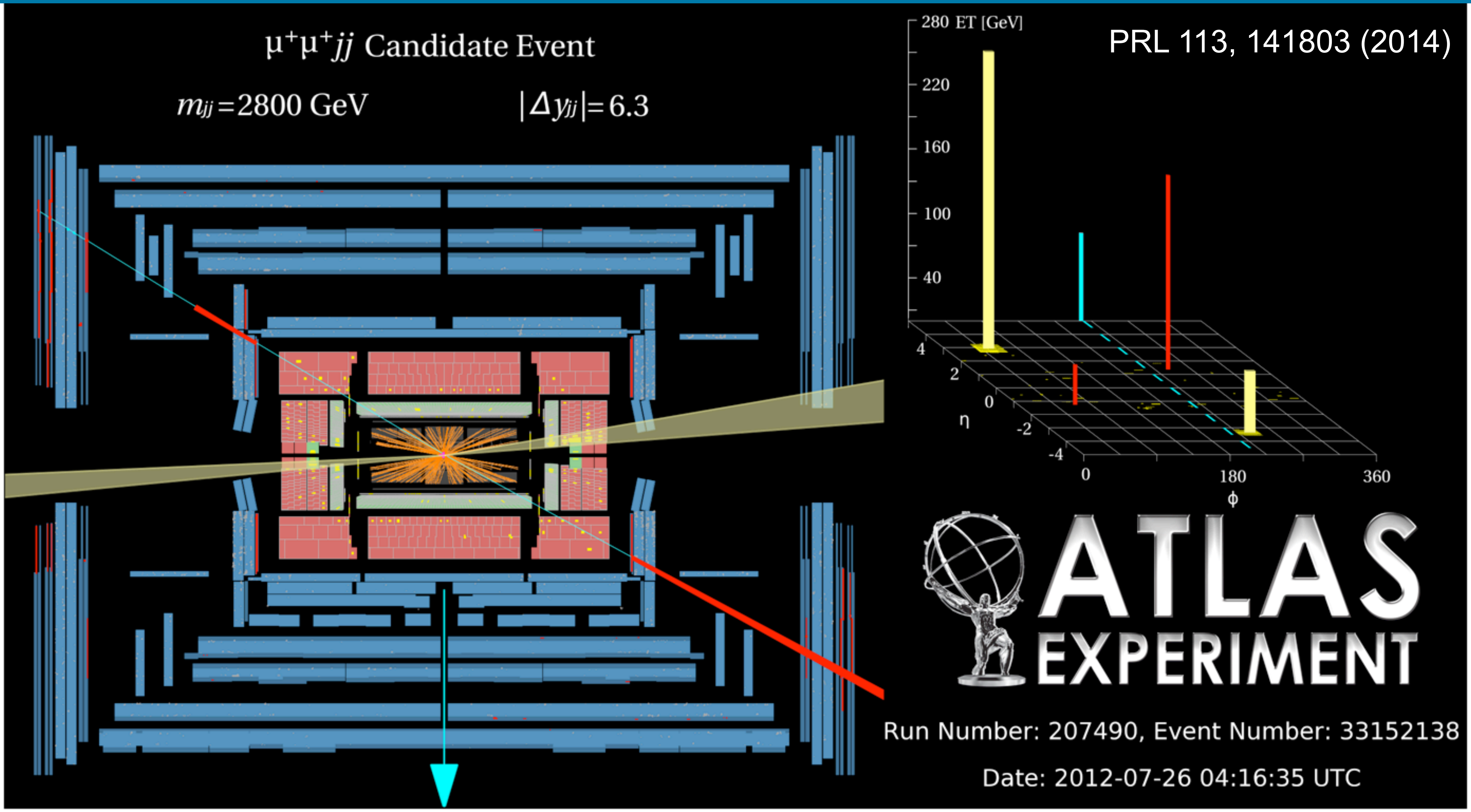
ATLAS: 20.3 fb^{-1} of 8 TeV data, published as PRL 113, 141803 (2014)

EW $W^{\pm}W^{\pm}$jj production interferes with strong $W^{\pm}W^{\pm}$jj O(10%) effect [depends on region] → SHERPA

VVjj-QCD



EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: Event Display



<u>Selection:</u> (ATLAS as example)

- Two isolated same-sign leptons (p_T>25 GeV, $|\eta|$<2.5): $e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$
- MET>40 GeV
- ≥2 jets with p_T>30 GeV and $|\eta|$<4.5
- veto 3rd lepton with looser p_T/id/isolation requirements (WZ veto)
- $|m_{ee}-m_Z|$>10 GeV (Z veto)
- reject events with b-tags (ttbar veto)
- m_{jj}>500 GeV (inclusive region)
  - m_{jj}>500 GeV and $|\Delta y_{jj}|$>2.4 (VBS region)

EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: Backgrounds

Prompt Lepton Backgrounds:

strong $W^{\pm}W^{\pm}$+jj
- Modeled with SHERPA

WZ/γ*+jets → $l^{\pm}l^{\pm}l^{\mp}\nu$+jets, where on lepton outside acceptance or failing selection
- ~ 90% of the prompt lepton background (20% of that from EWK production)
- Modeled with SHERPA taking into account both strong and EWK production

ZZ+jets and ttbar+W/Z also considered
- Modeled with MadGraph

Double parton scattering contributions (WZ/γ*⊕di-jet) found to be negligible after m_{jj}>500GeV

Non-prompt Lepton backgrounds:

- Non-prompt leptons arise from hadron decays in jets
- W+jets, ttbar, single top, multijet production
- Data-driven from events passing all selections, but a lepton is non-isolated or looser quality

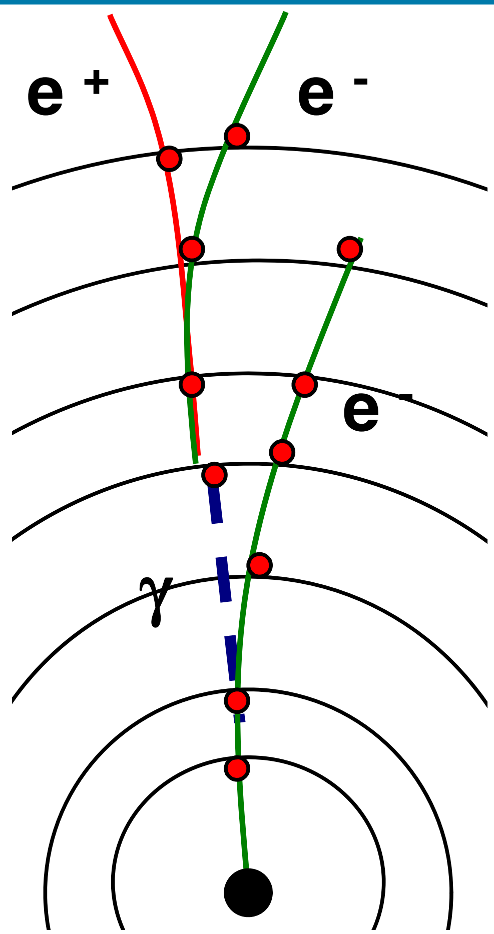
Conversion backgrounds:

Wγ + jets production, including EWK Wγjj
- Modeled with simulation using ALPGEN (and SHERPA for the EWK component)
- Uncertainty of ±17%

Processes with prompt opposite charge leptons, where charge misidentification occurs
- Main sources ttbar, DY pair production
- Estimated using data

In both cases there is a $\gamma \rightarrow e^{+}e^{-}$ conversion involved

Charge misIdentification

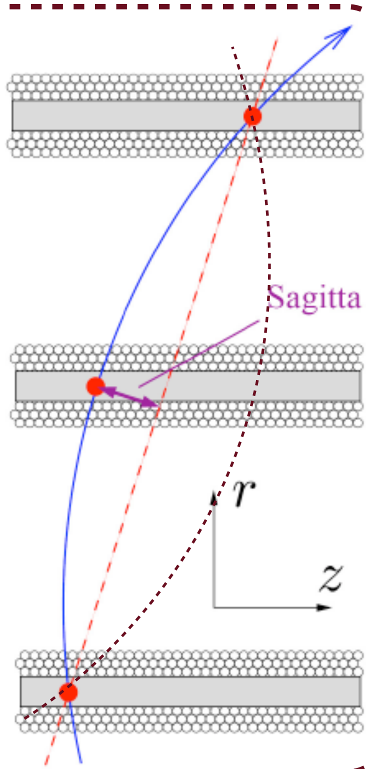


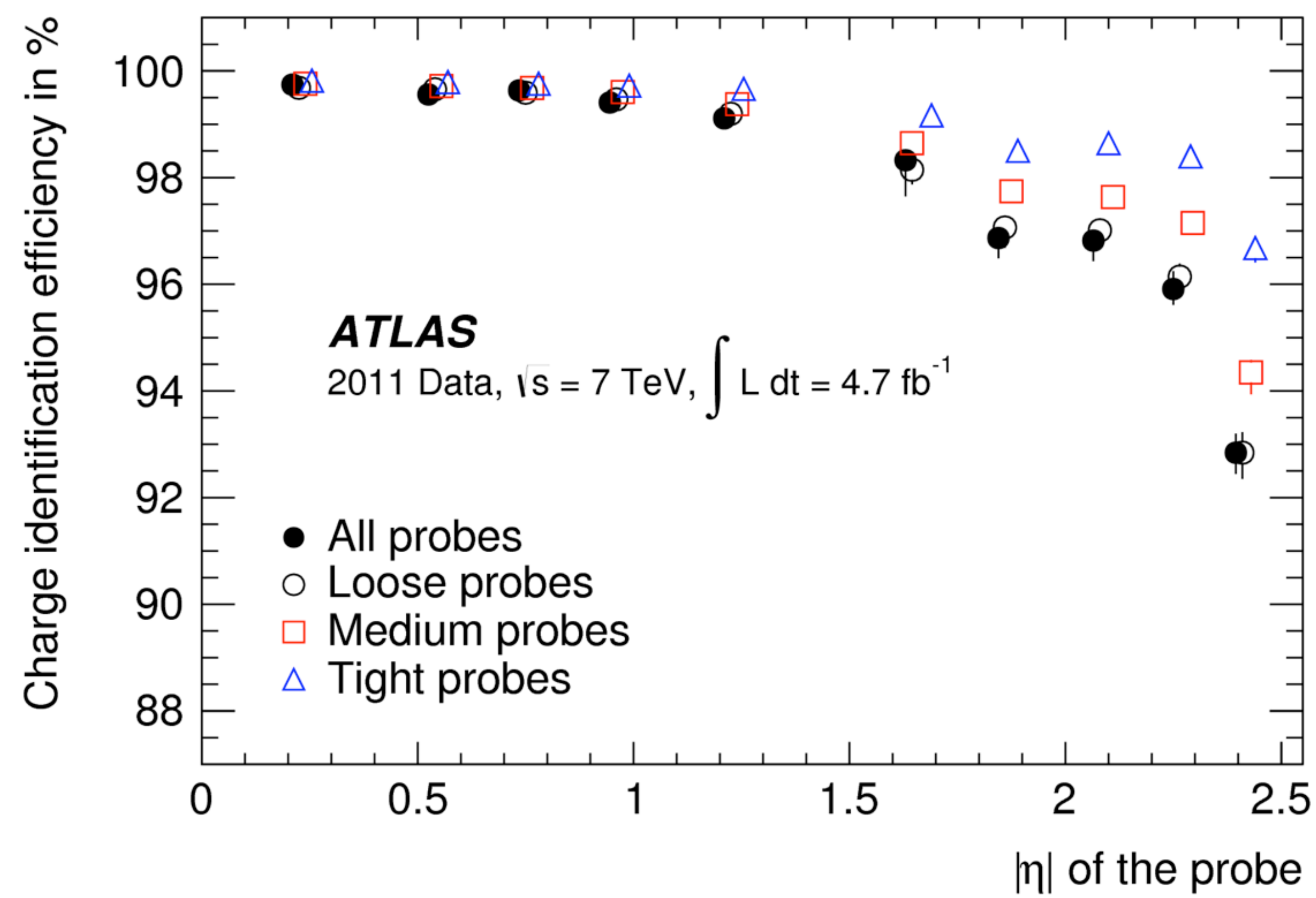
Electron charge mis-identification: typically early bremsstrahlung with subsequent conversion to e^+e^-

To reconstruct an electron the electromagnetic cluster should be matched with a track in the inner detector → quality criteria applied (charge mis-identification rate reduced - also overall efficiency)

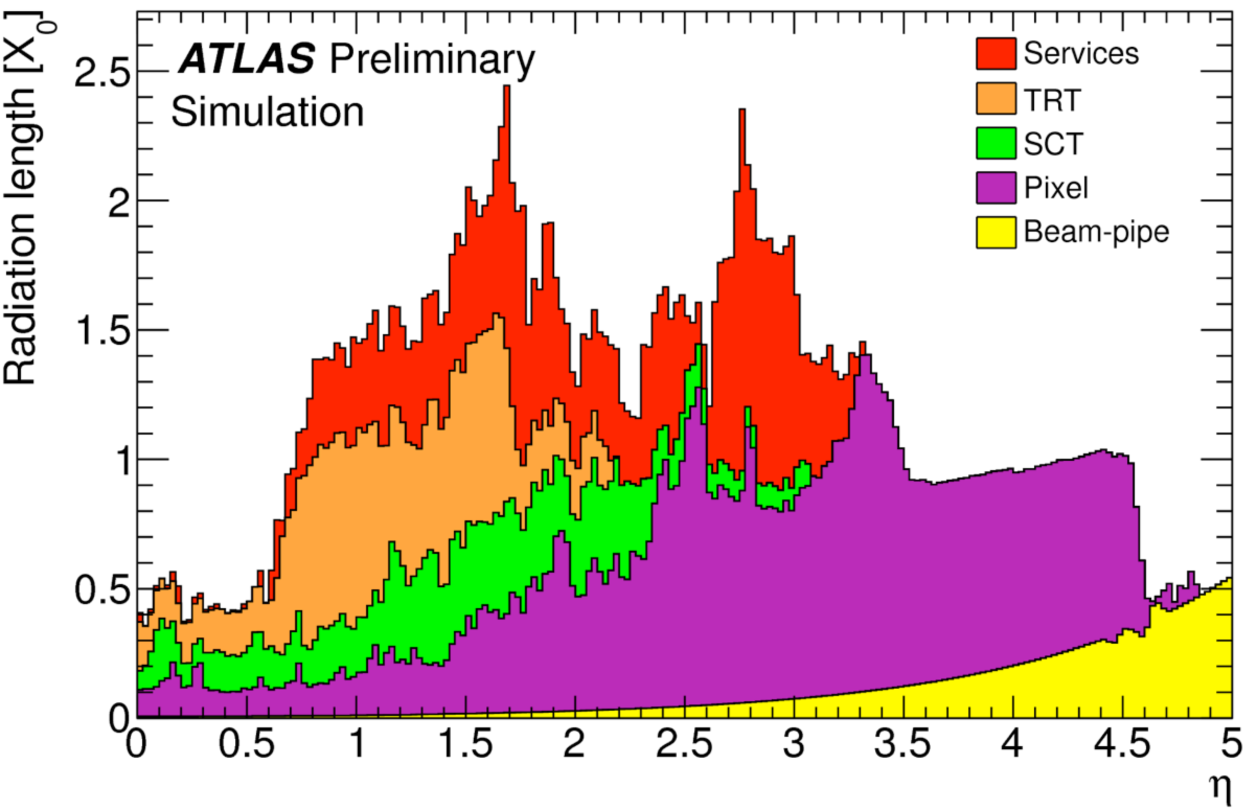
Charge misidentification rate estimated fro Z→ee decays, and then applied to events passing selection, but required to be same-charge.

Muon charge misID relates to mis-measurement of the bending direction.
Relevant for high p_T muons





Material distribution



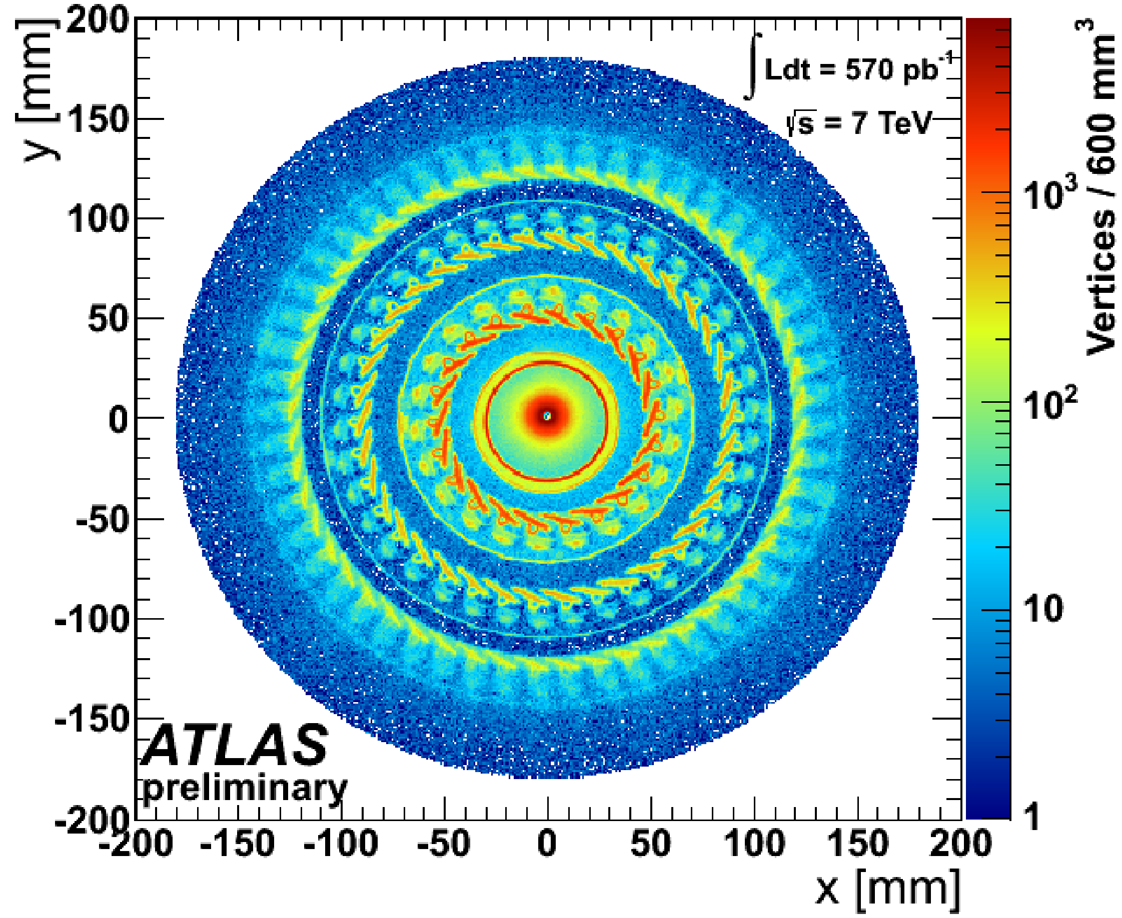
Electron charge mis-identification rates sensitive in the amount of material

Simulation-based estimates involving conversions:
careful assessment/validation of
detector material needed
→ particularly important for local effects
[also relevant for cases like h→γγ]

Starting point is an as detailed as possible geometrical model of the "as-built" detector.

This is sub-sequently refined using collision data
[$\gamma \rightarrow e^+e^-$, hadronic interactions, e.t.c.]

Methods precise to the 5-10% level,
but sensitive to local variations



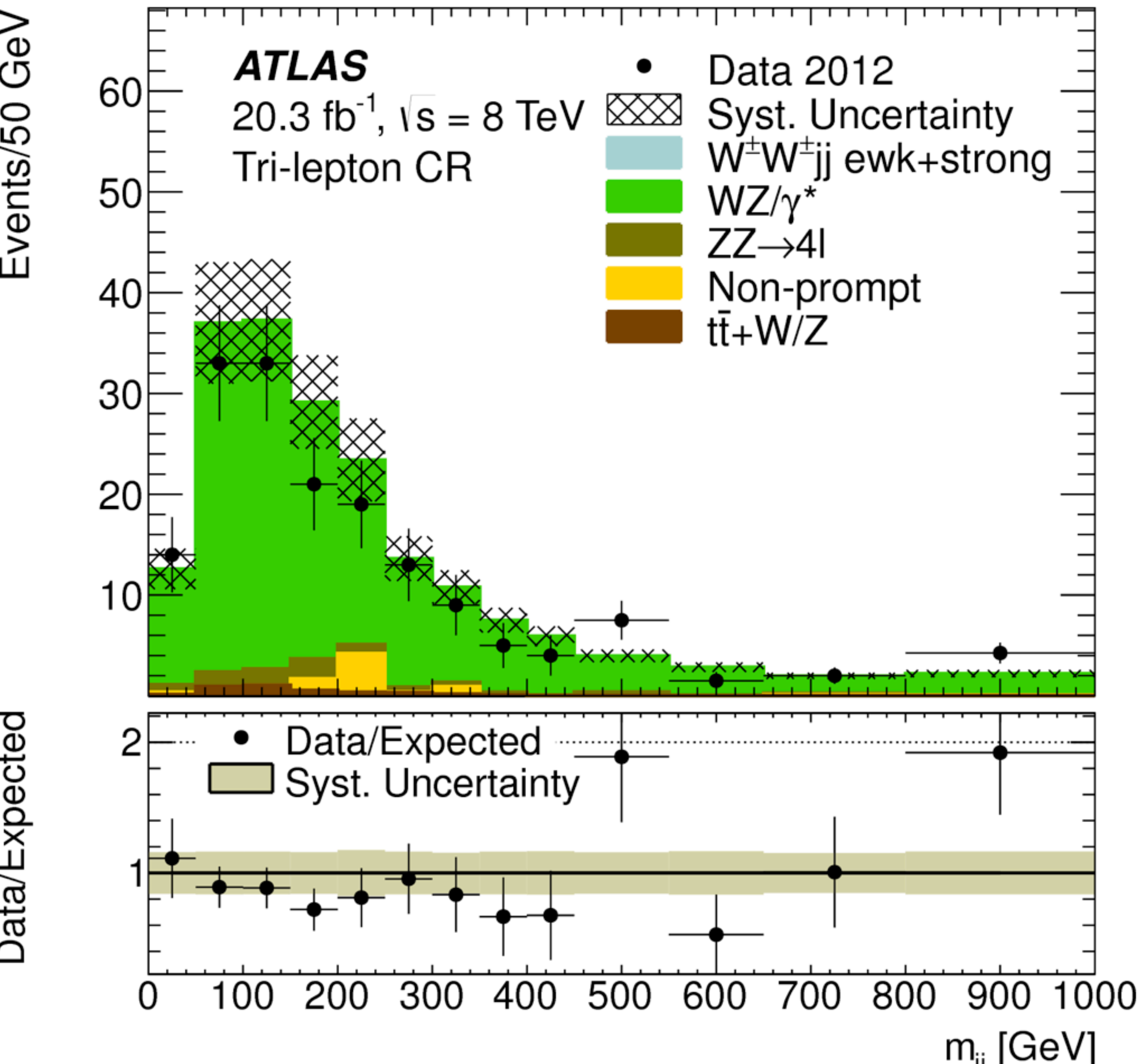
Data-driven background estimates

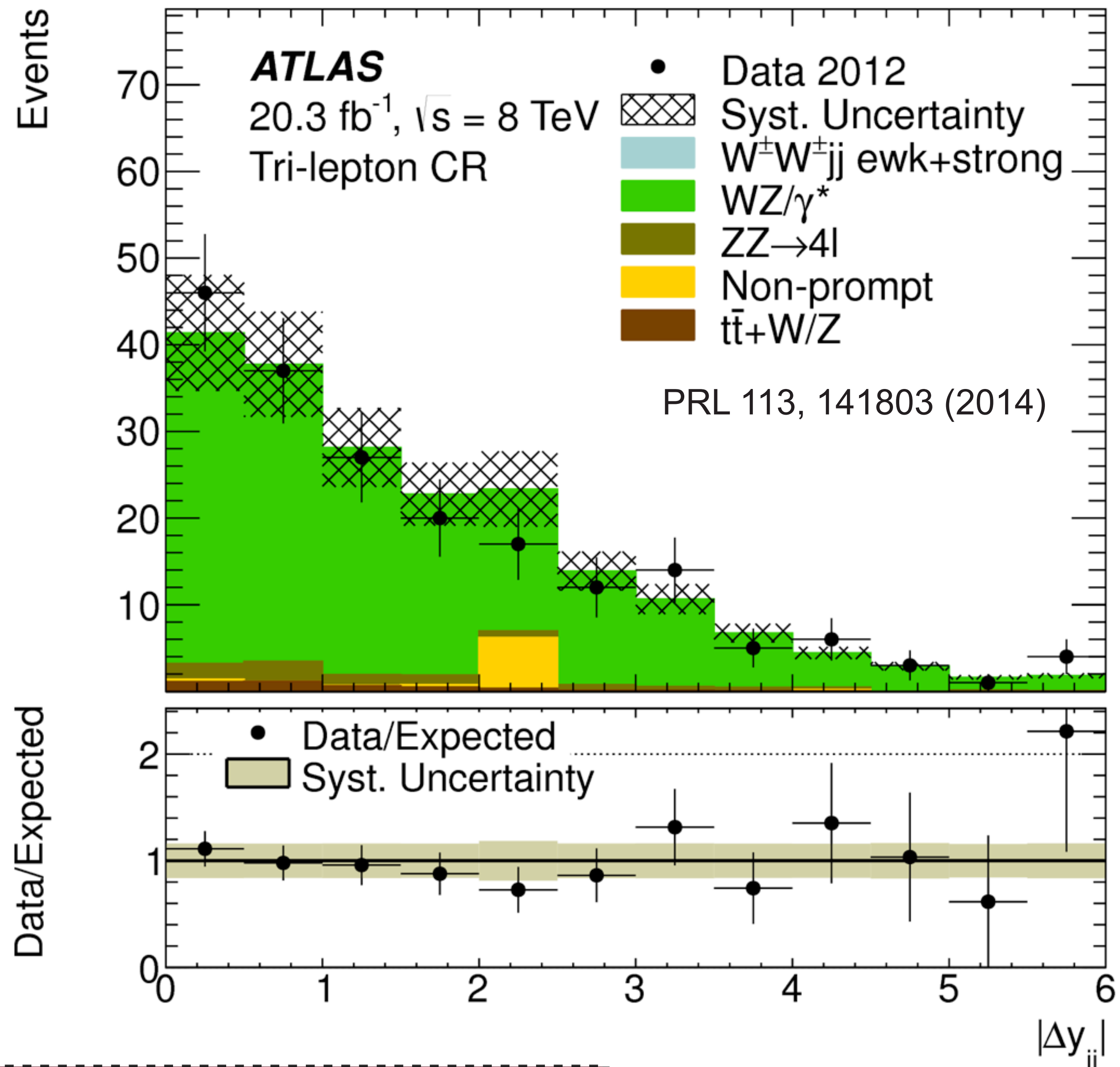
Background modeling (normalisation/shape) checked in control-regions with similar phase space to Signal Region:

- Tri-lepton CR:
  - Inverting third lepton veto, removing m_{jj} and $|\Delta y_{jj}|$ requirements
  - Testing modeling of prompt backgrounds
- ≤1jet CR:
  - Require at most one jet
  - Testing conversion and prompt backgrounds
- b-tag CR:
  - Require at least one b-tagged jet
  - Testing non-prompt leptons
- Overall validation of background model by inverting m_{jj}

Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: Tri-lepton control region

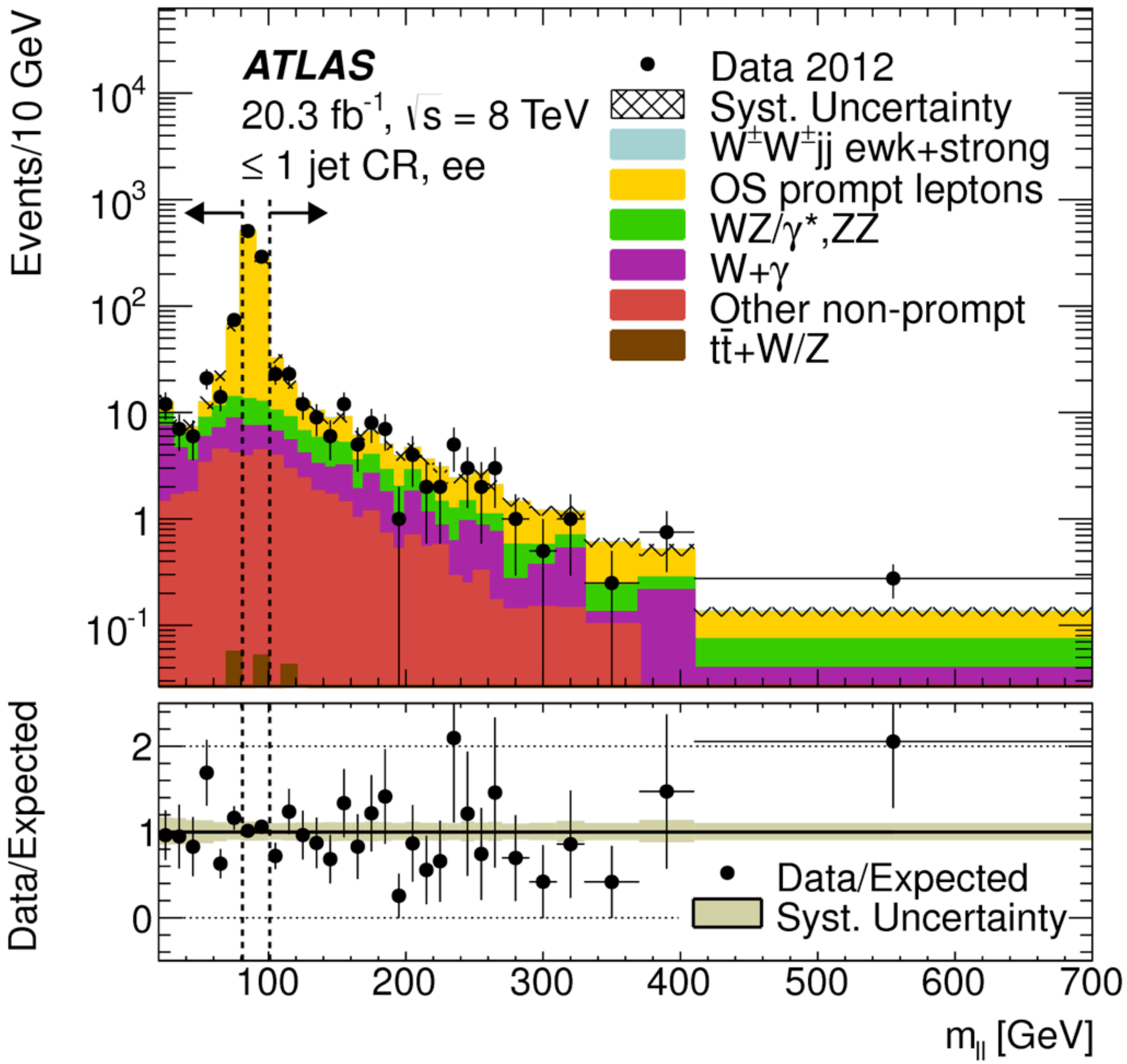




Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

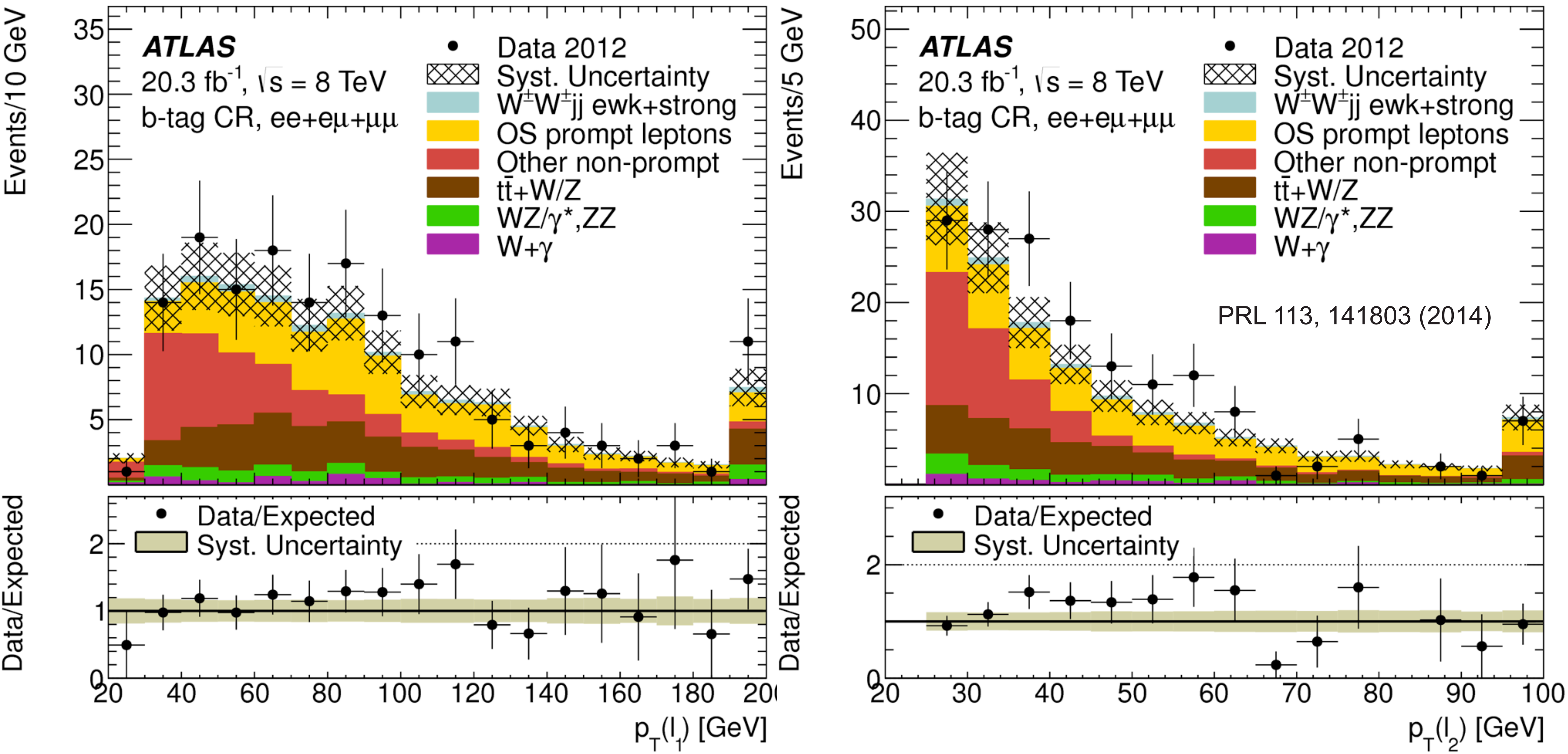
EW $W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$: ≤1 jet control region

PRL 113, 141803 (2014)



≤ 1 jet Control Region				
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj ewk+strong	2.72 ± 0.30	8.2 ± 0.8	4.2 ± 0.4	15.1 ± 1.5
$WZ/\gamma^*, ZZ$	46 ± 8	130 ± 23	75 ± 13	250 ± 40
$W+\gamma$	39 ± 11	59 ± 17	–	98 ± 29
$t\bar{t}+W/Z$	0.34 ± 0.15	0.8 ± 0.4	0.56 ± 0.25	1.7 ± 0.7
OS prompt leptons	152 ± 17	24 ± 4	–	177 ± 21
Other non-prompt	38 ± 15	65 ± 26	8 ± 5	111 ± 30
Total Predicted	278 ± 28	290 ± 40	88 ± 14	650 ± 70
Data	288	328	101	717

EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: b-tag control region



Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: Putting everything together

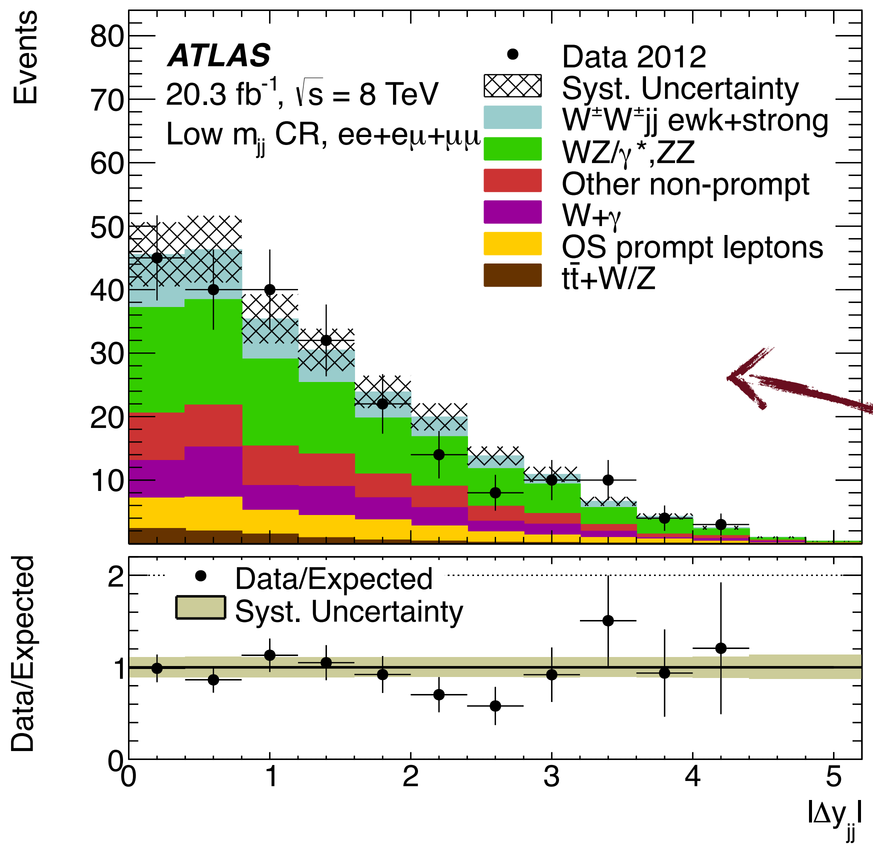
Inclusive Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5
Data				
S/B	~0.4	~0.7	~1.1	

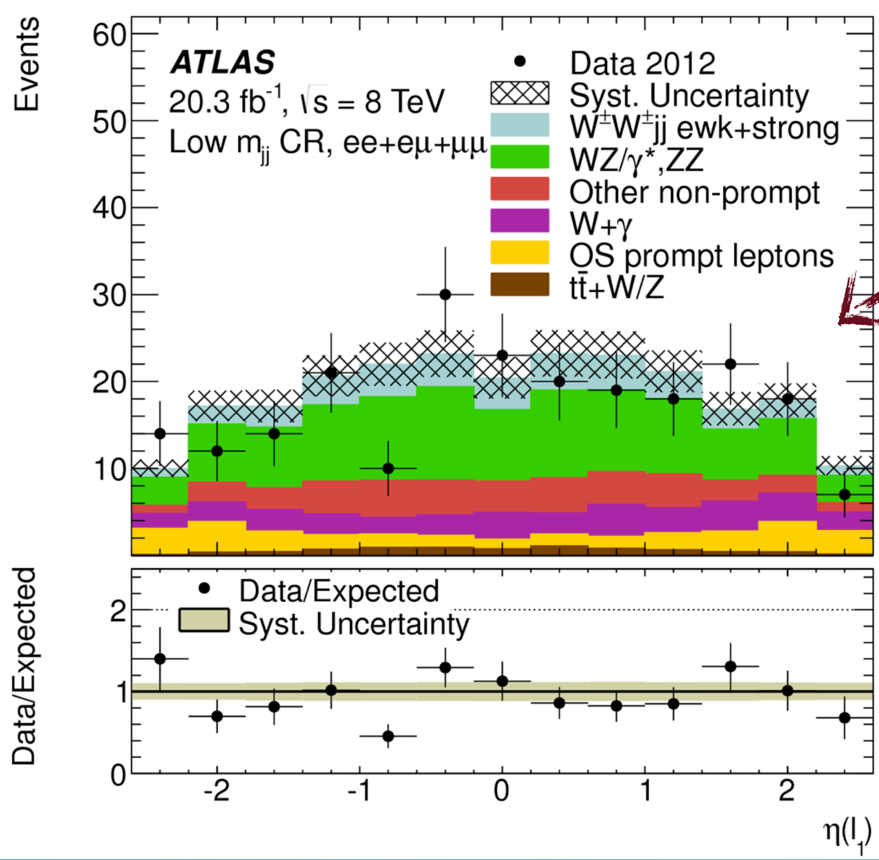
Signal is EWK WWjj
(illustration)

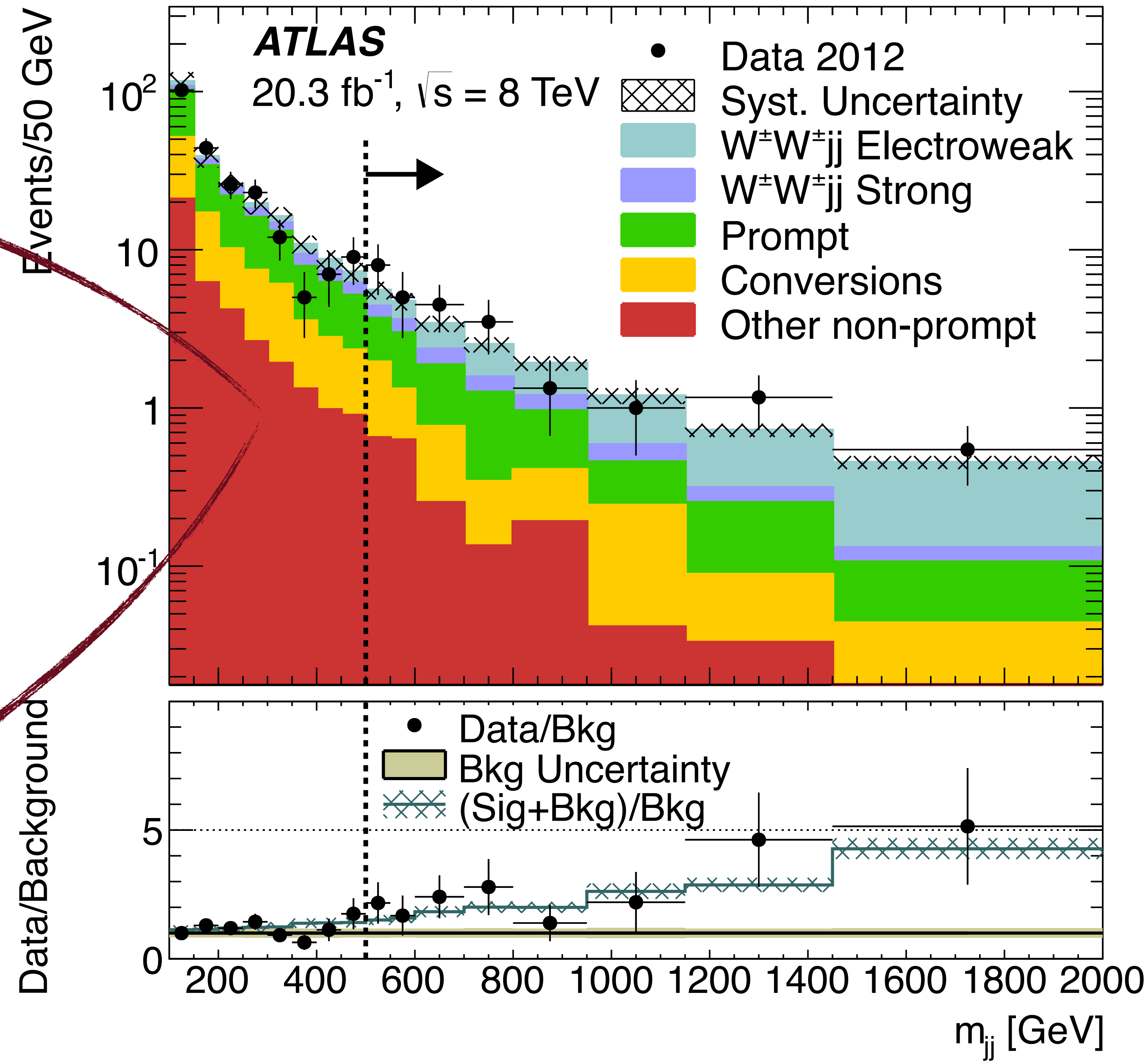
“blinded” signal region

EW W±W±jj→l±νl±νjj: inclusive signal/validation region

PRL 113, 141803 (2014)



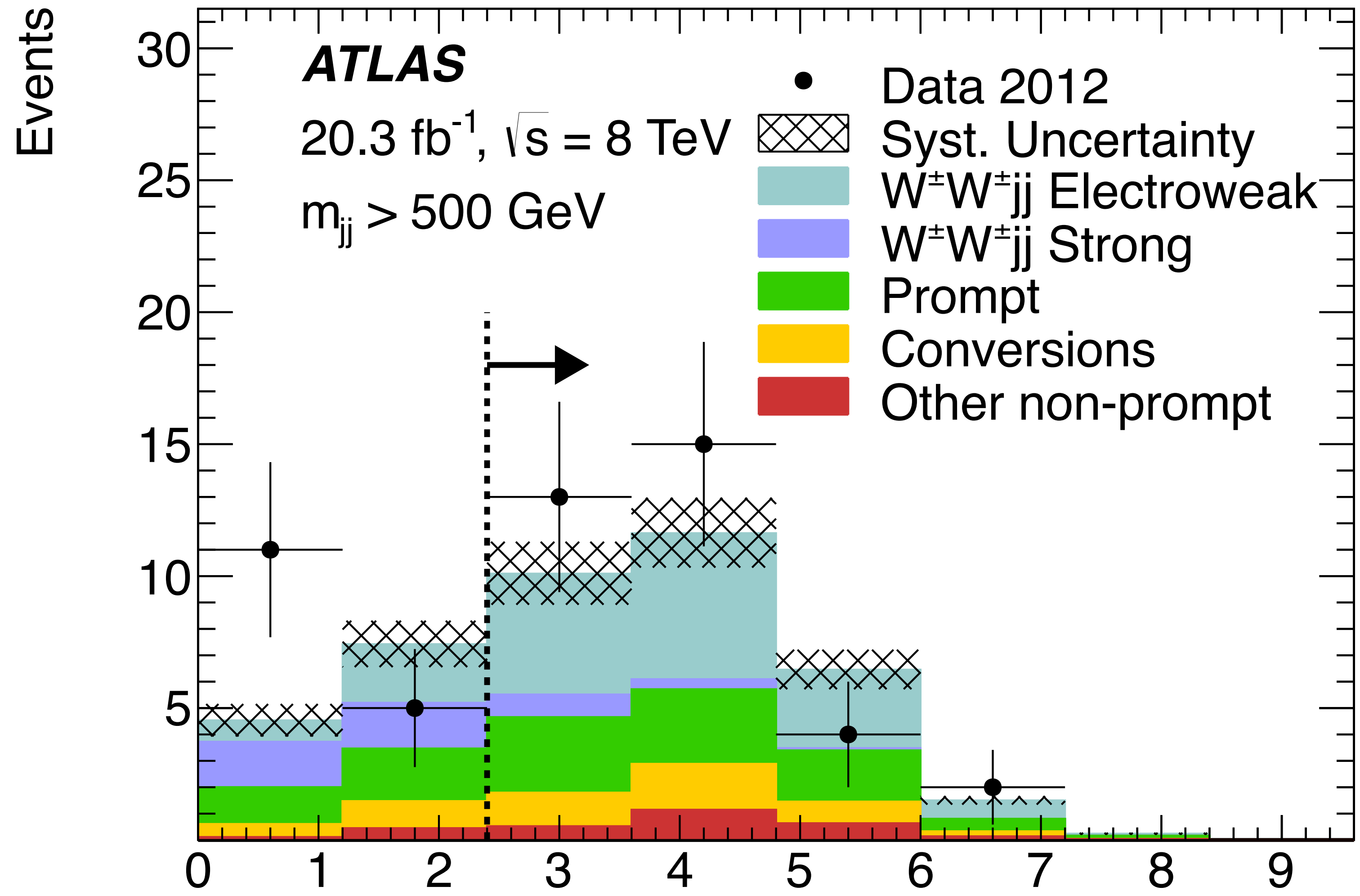




Same-charge WW production is observed at 4.5σ (3.4σ expected)

EW $W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$: VBS signal

PRL 113, 141803 (2014)

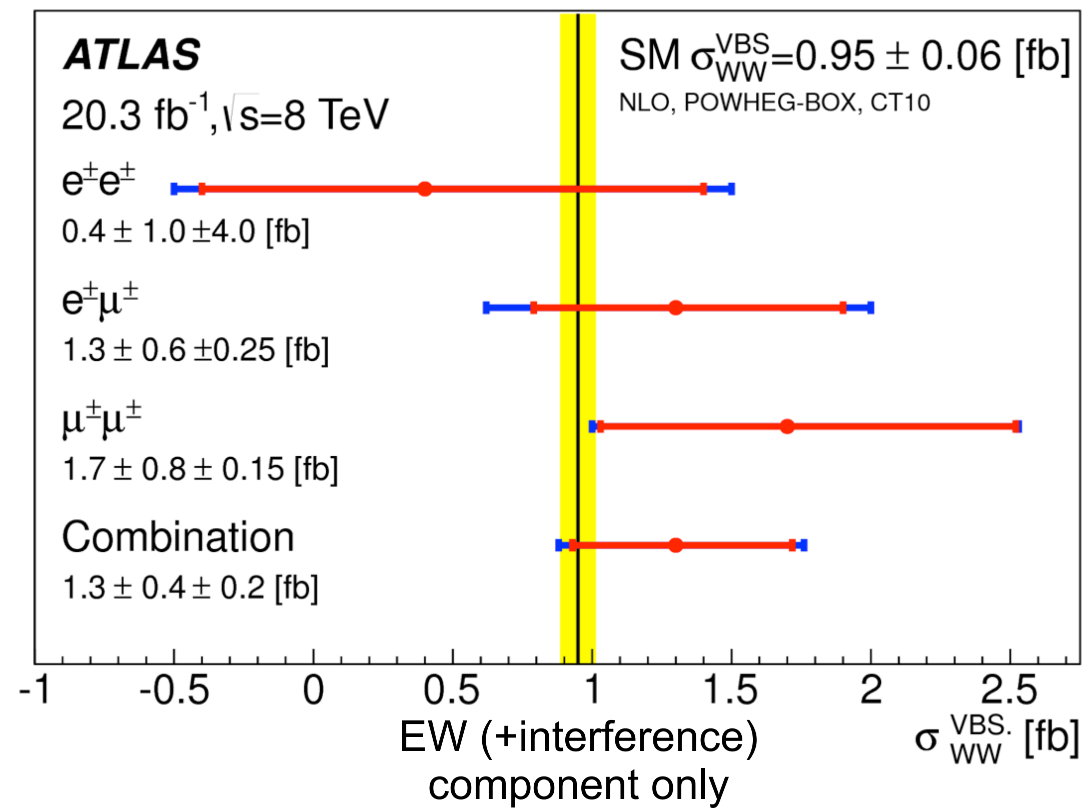


VBS Signal Region	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^\pm W^\pm$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t}+W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34
S/B	~0.5	~0.9	~1.5	

almost at the $h \rightarrow ZZ \rightarrow 4l$ level

EW same-charge WW production observed at 3.6σ (2.8σ expected)

CMS with a similar analysis got EW same-charge WW production observed at 1.9σ (2.9σ expected)
[PRL 114,0151801 (2015)]



EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: ATLAS/CMS

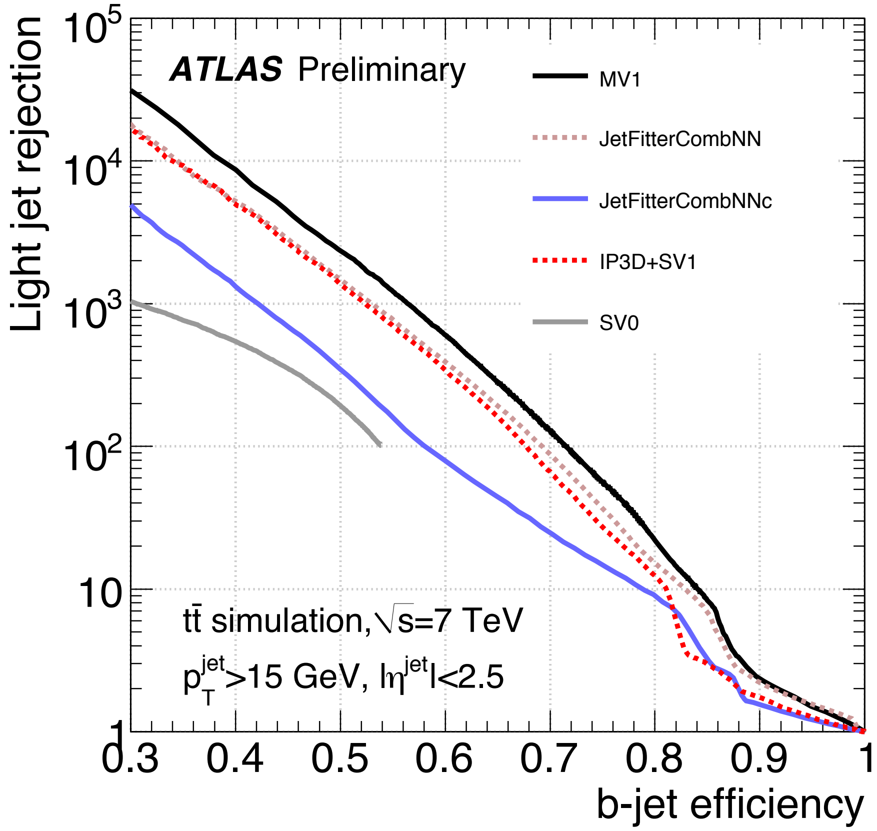
VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
$WZ/\gamma^*, ZZ, t\bar{t} + W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W + \gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

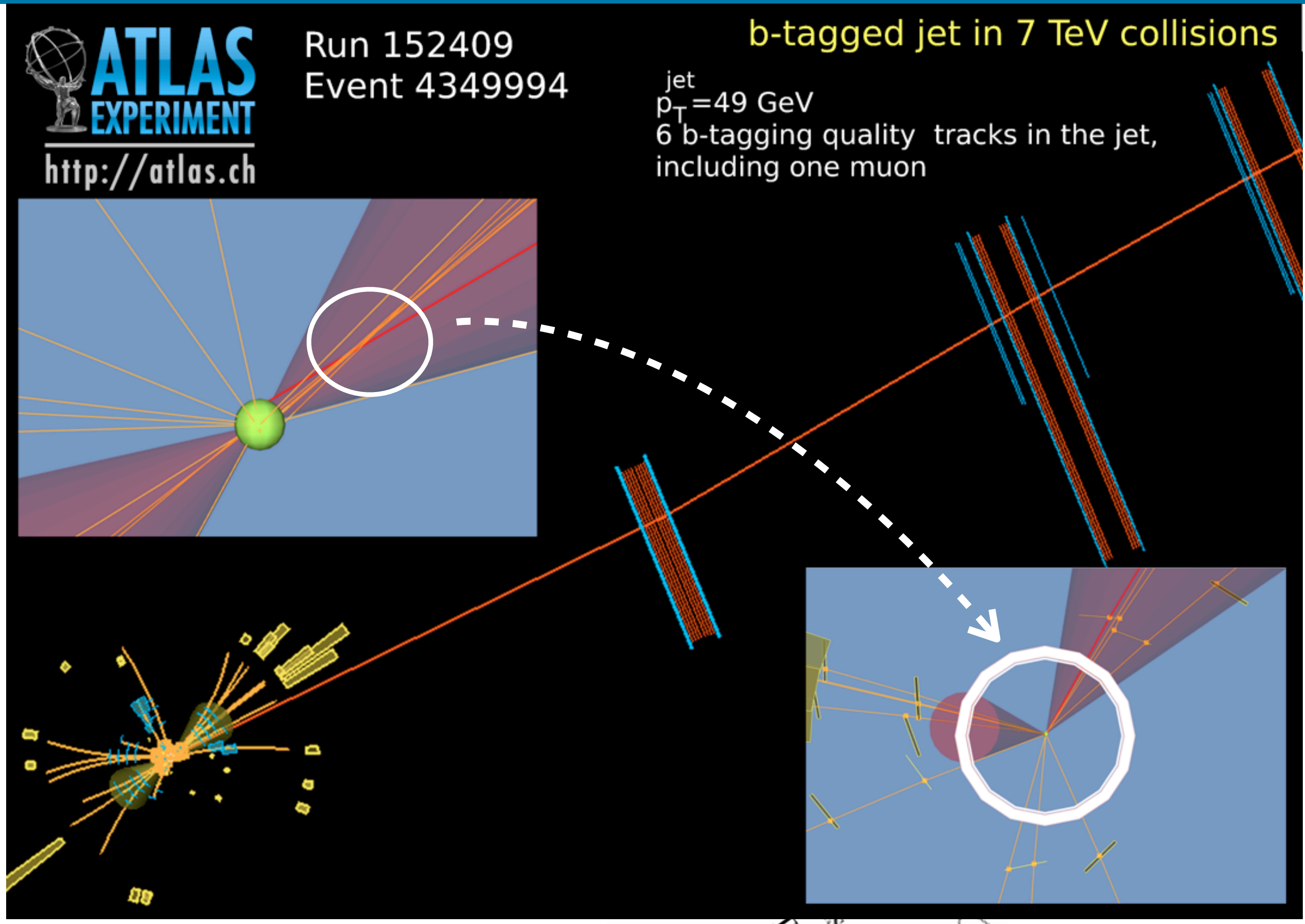
	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
W^+W^+	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
W^-W^-	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	···	···	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

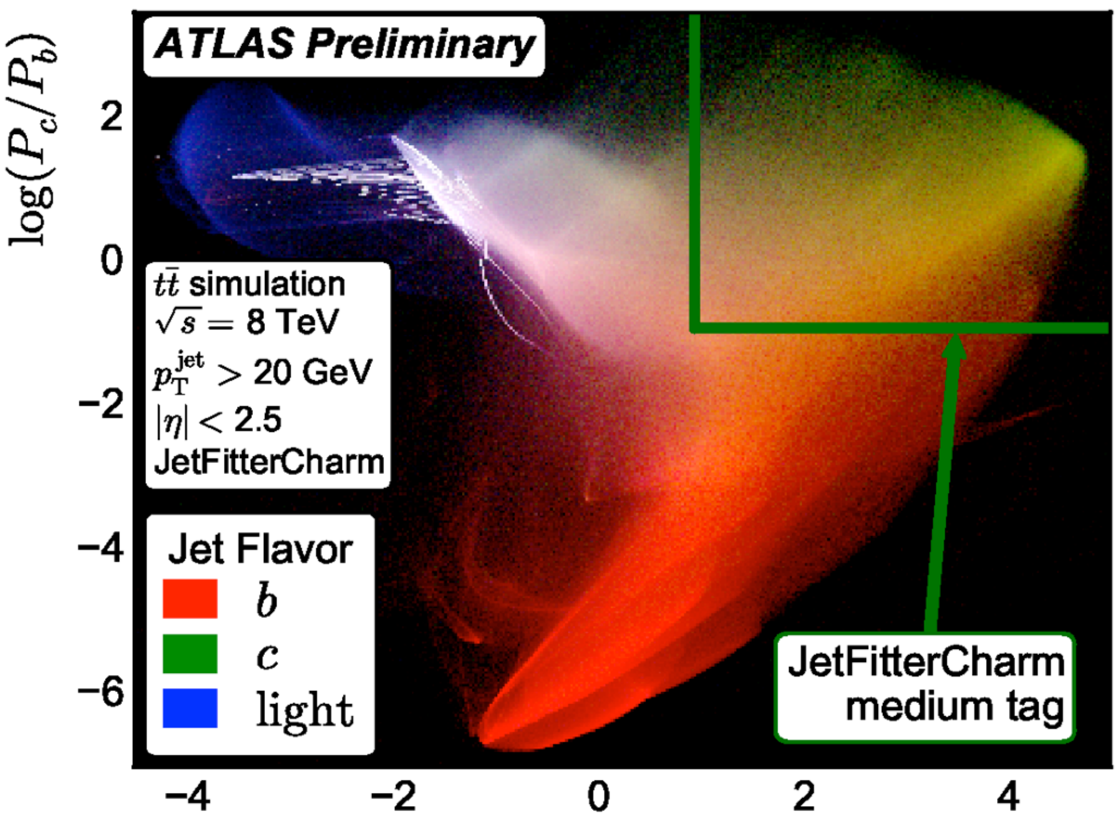
Without going into the details of the CMS analysis, it worths noting:

1) structure similar for both experiments (in terms of selections/control regions)
2) similar expected sensitivity (2.8σ vs 2.9σ)
3) background composition differs
   - ATLAS: lower non-prompt background component (isolation re-optimization)
   - CMS: lower "WZ" component (3rd lepton veto/b-tag veto including soft-μ tag)
   - CMS: (much)lower charge mis-identification contribution
   - Differences discussed and understood

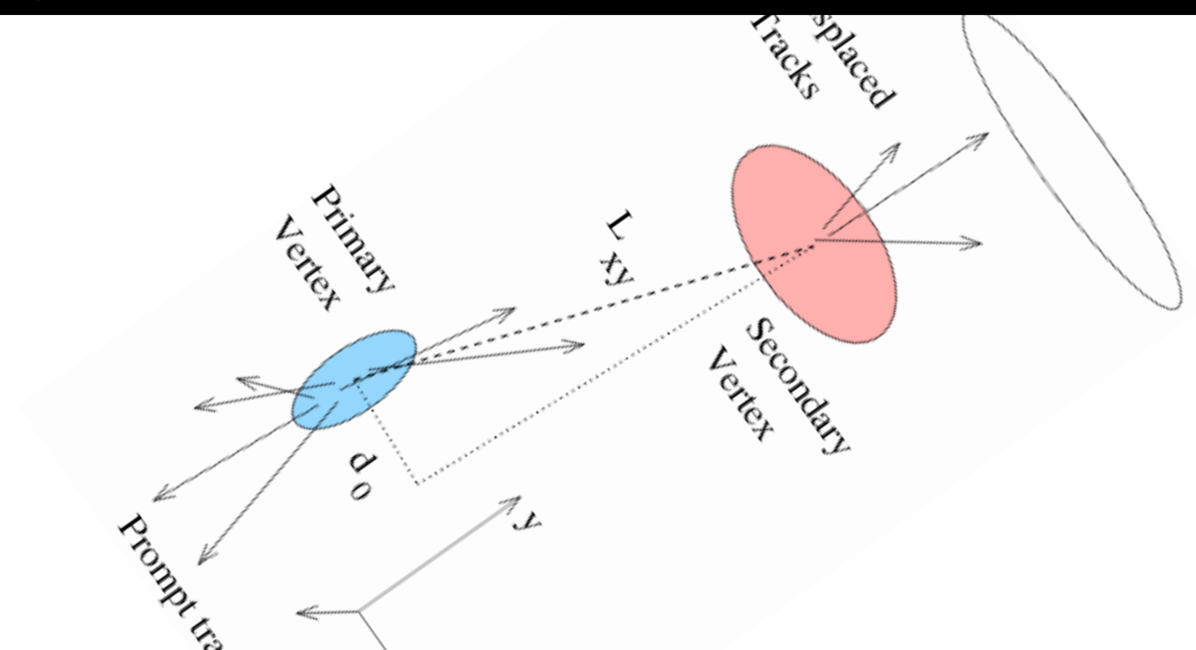
A word about b-tagging







New development: Charm Tagging $\log(P_c/P_{light})$

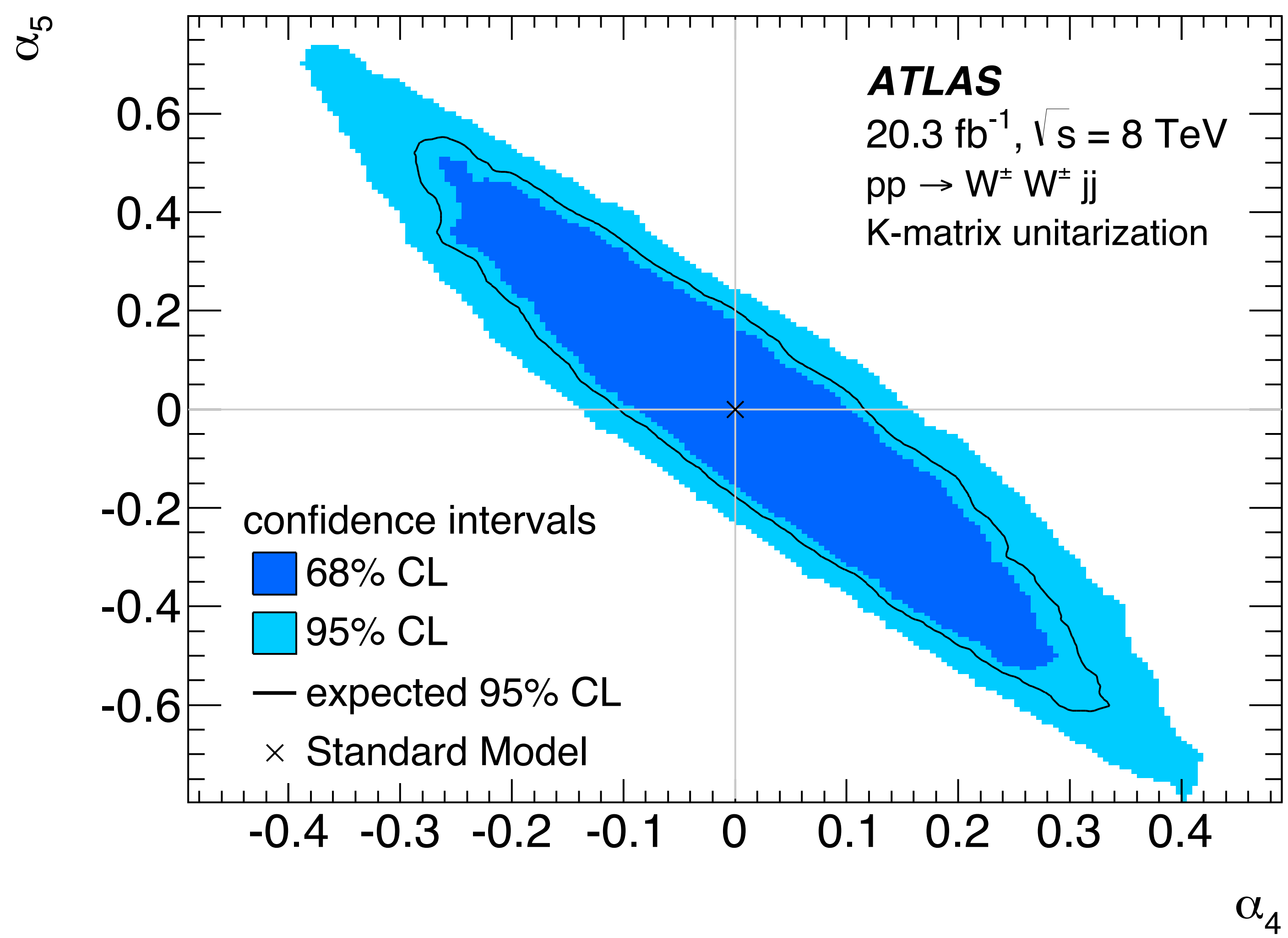


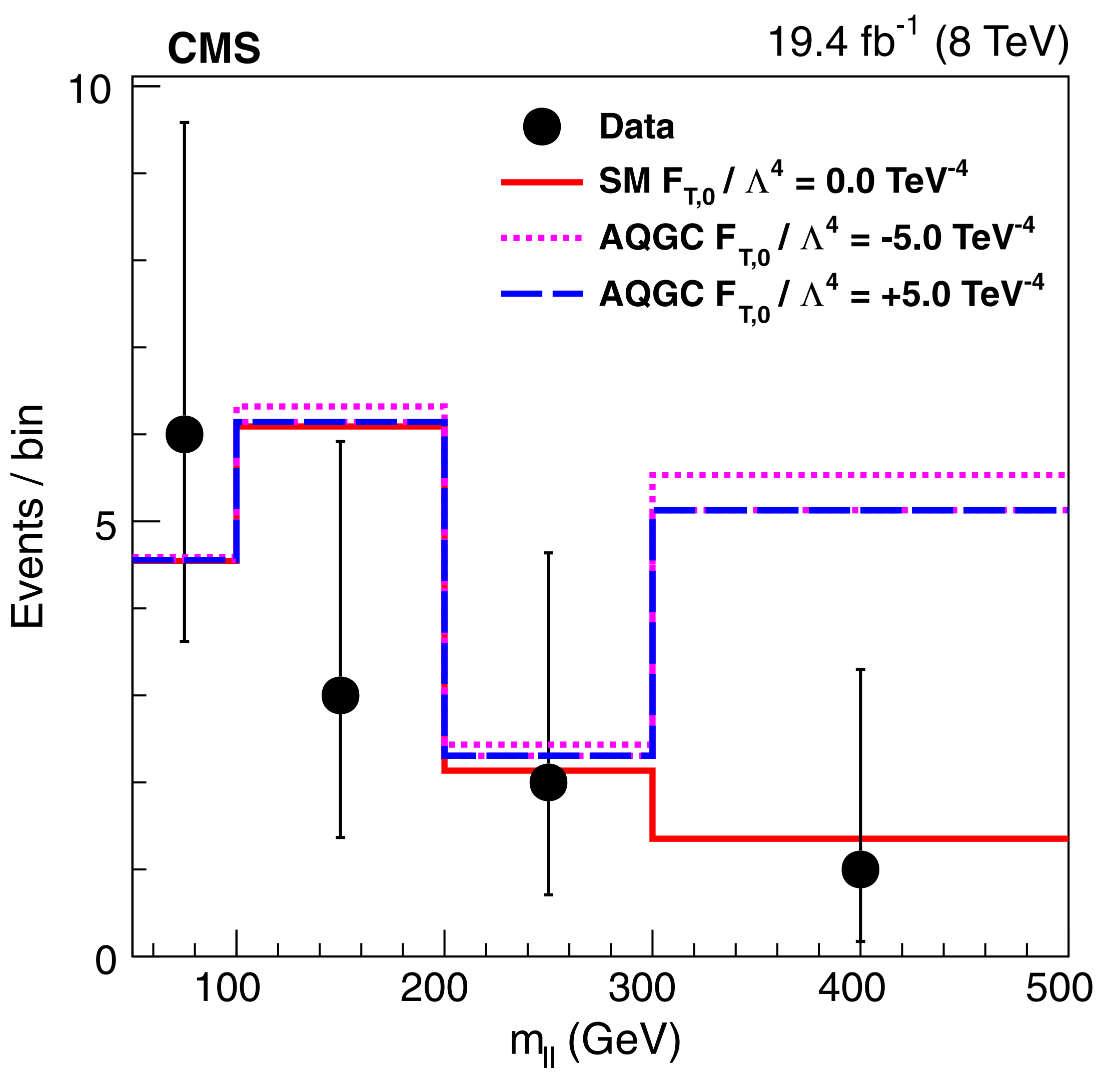
cτ = 492 μm

EW $W^{\pm}W^{\pm}jj \rightarrow l^{\pm}\nu l^{\pm}\nu jj$: aQGC

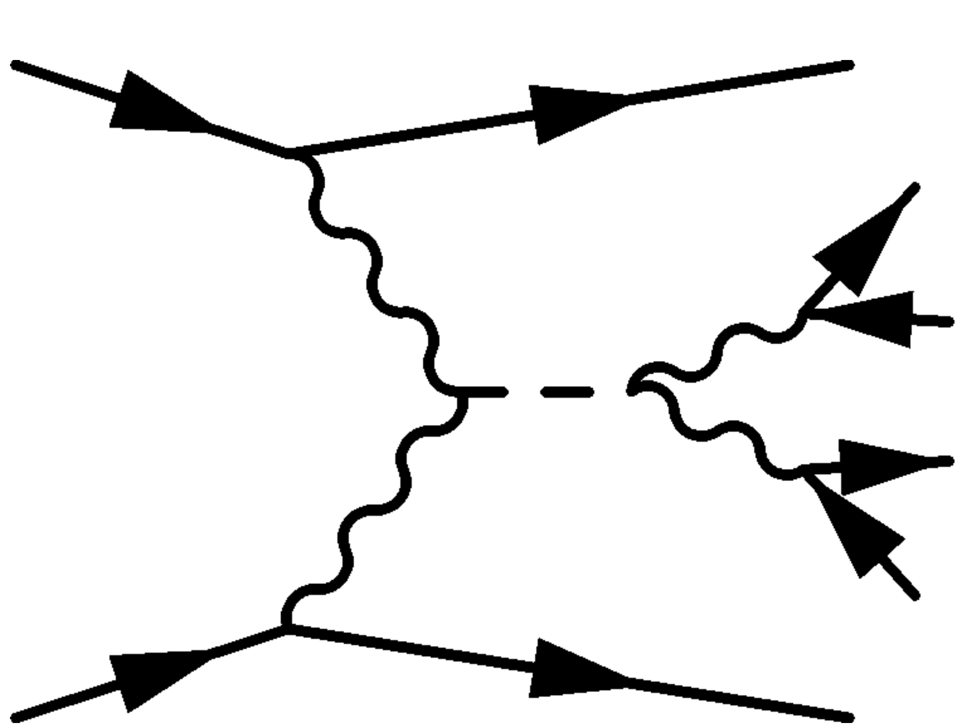
The two experiments followed different approaches here:

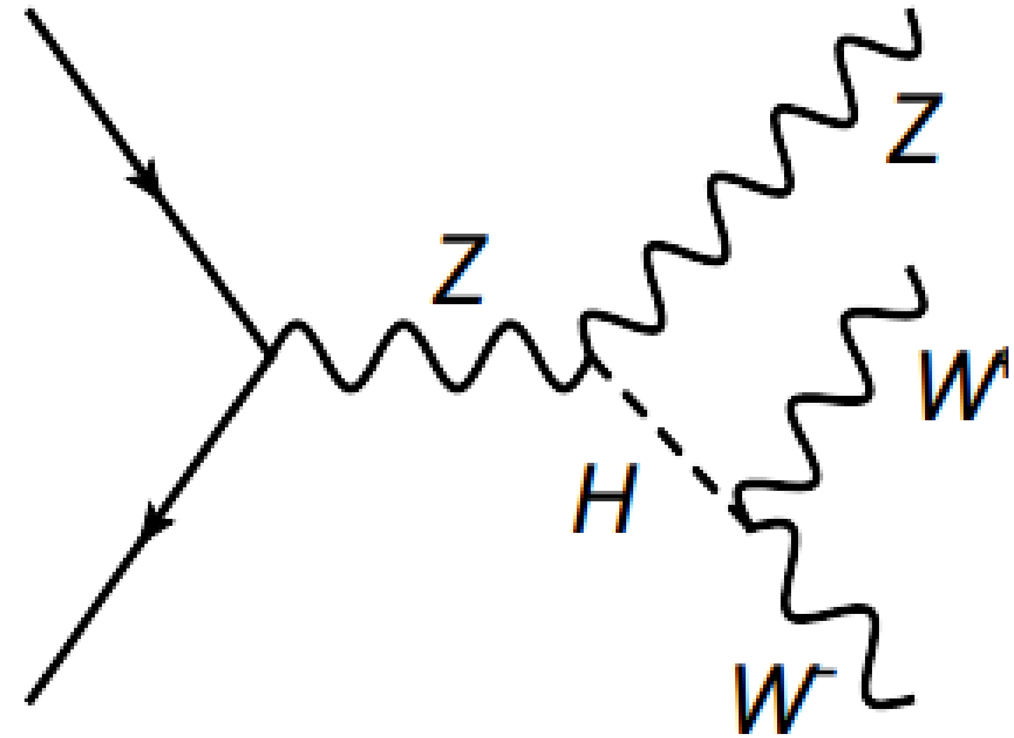
1) ATLAS used the production cross-section as observable to study aQGC
   CMS used shape analysis with m_{ll} as discriminant
2) Results reported in different parametrizations:
   ATLAS: dim-4 operators (non-linear realization of effective Lagrangian) and unitarization
   CMS: dim-8 operators (linear-realization of the effective Lagrangian) and no form factors



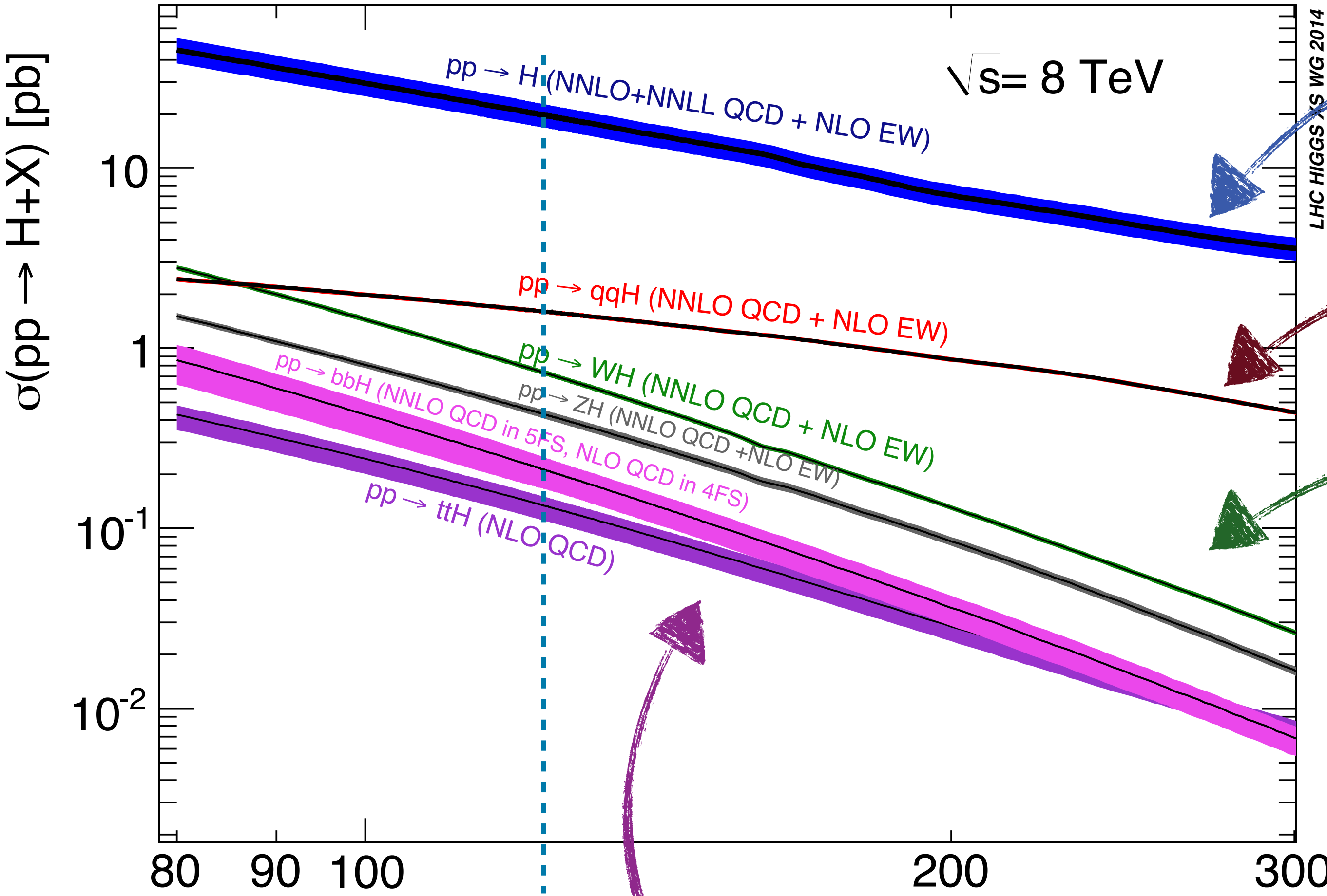


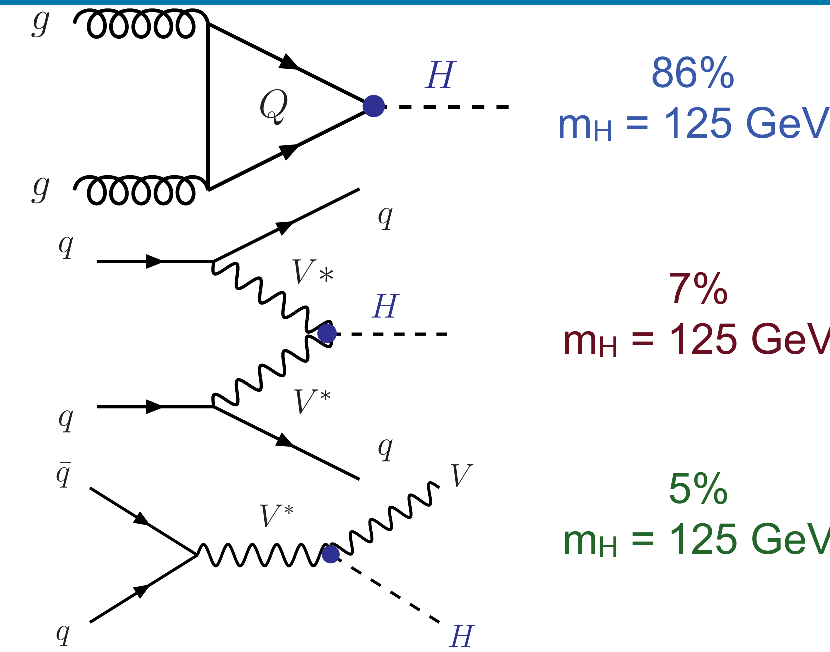
and the Higgs...

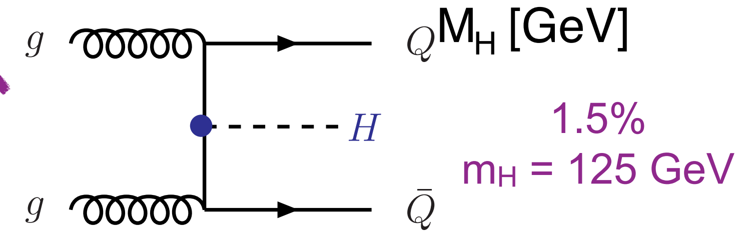


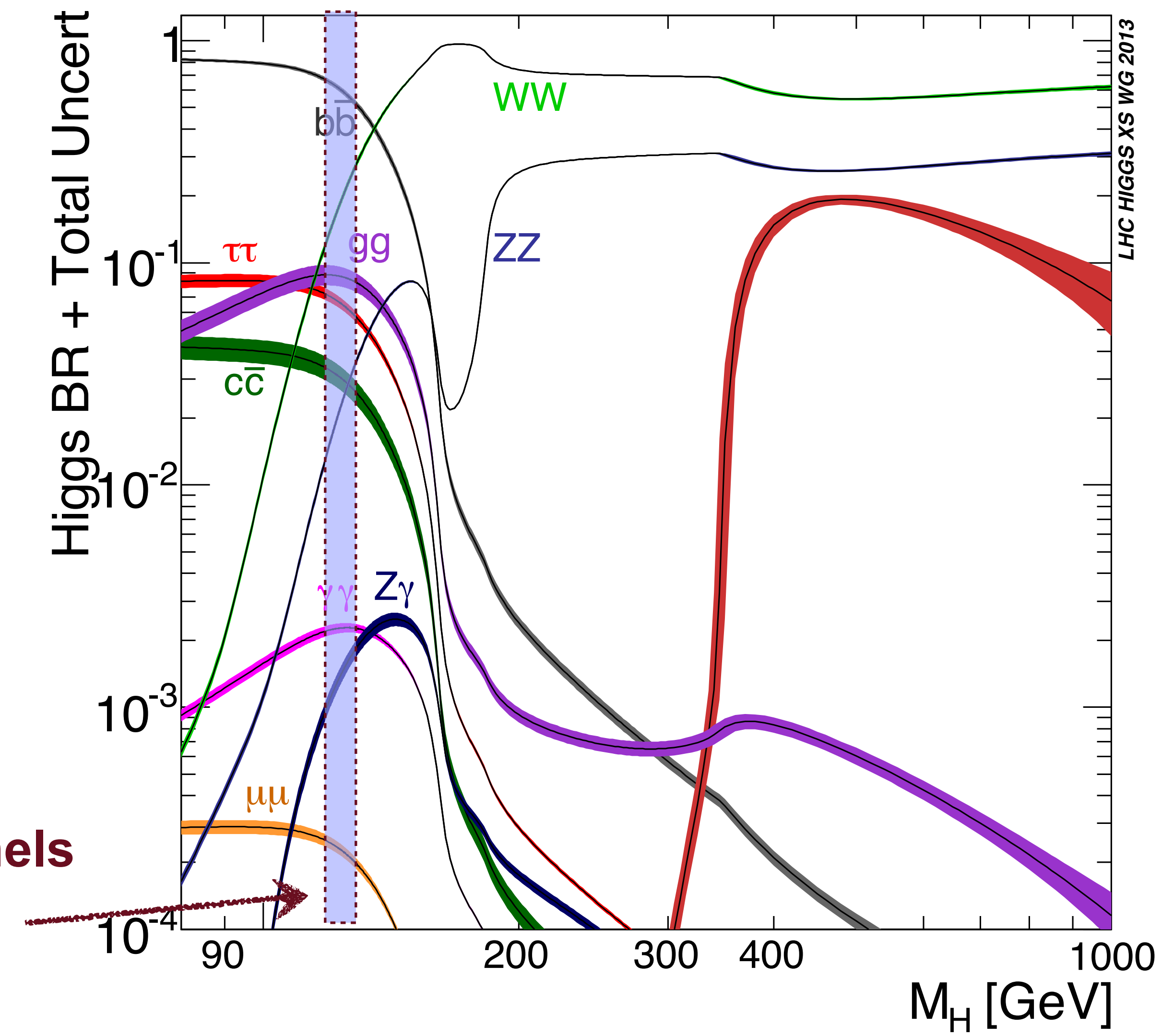


SM Higgs boson production and decay at the LHC



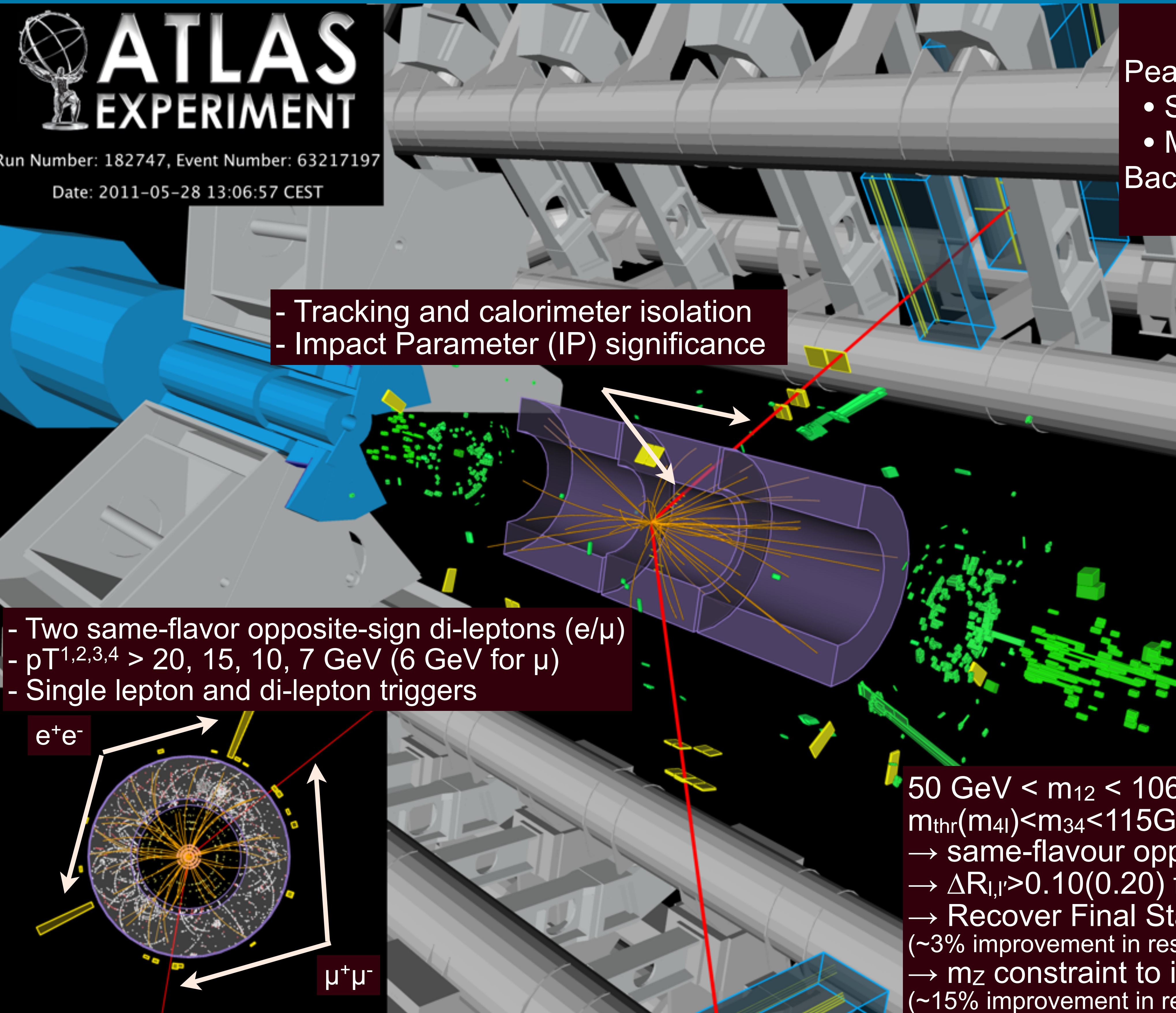






m_H~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

$H \to ZZ^{(*)} \to 4l$



$H \to ZZ^{(*)} \to 4l$ (l=e,μ)

Peak in m_{4l} spectrum:

- S/B~1.7 @ m_H=125 GeV
- Mass resolution~1.6-2.2 GeV

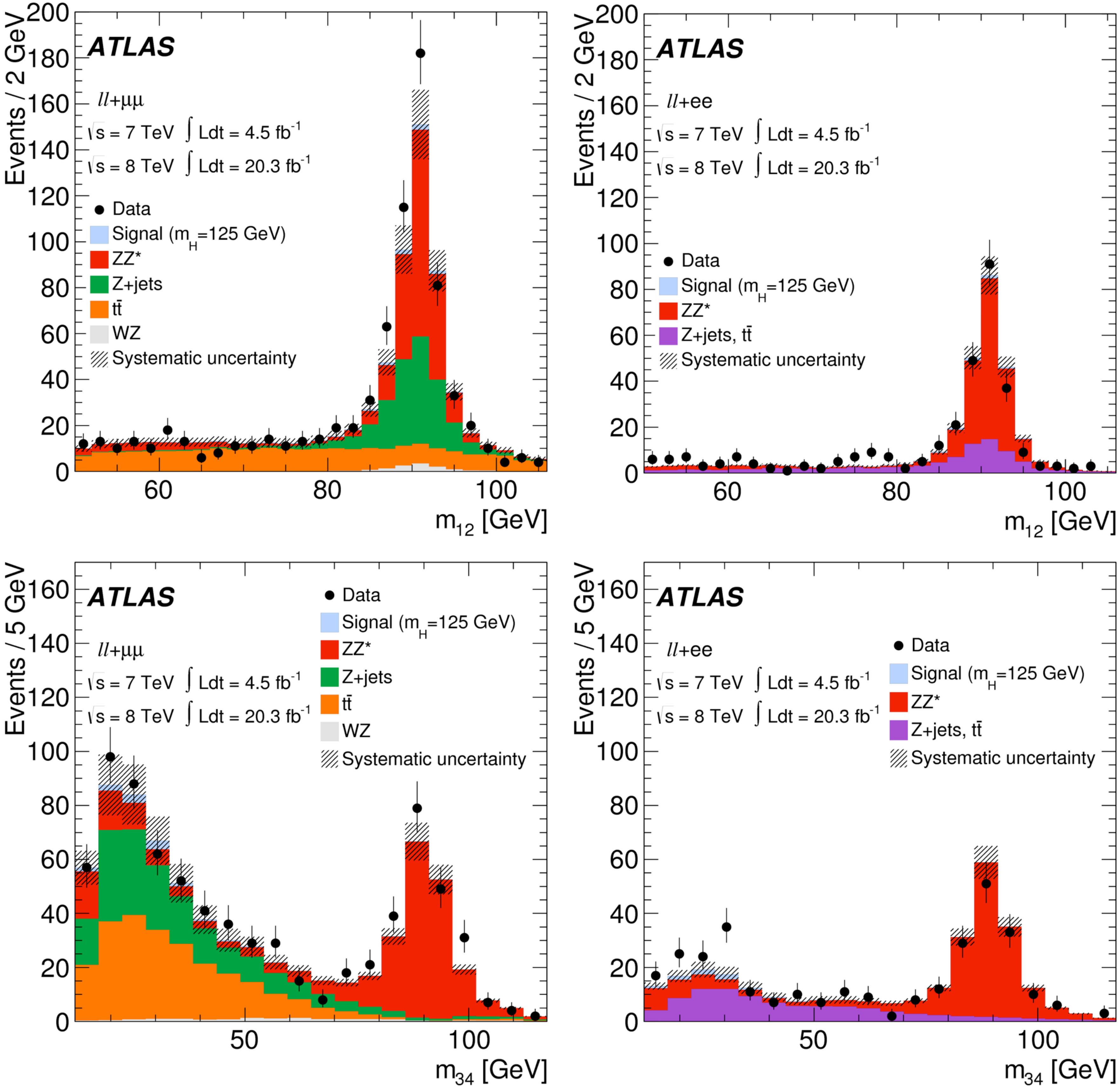
Backgrounds: $ZZ^{(*)} \to 4l$, Z+jets and ttbar

- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

- Two same-flavor opposite-sign di-leptons (e/μ)
- $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

50 GeV < m_{12} < 106 GeV,
$m_{thr}(m_{4l}) < m_{34} < 115$GeV m_{thr}=12-50GeV (140-190 GeV)
→ same-flavour opposite-sign pairs m_{ll}>5 GeV
→ $\Delta R_{l,l'}$>0.10(0.20) for (not-)same-flavour
→ Recover Final State Radiation photons
(~3% improvement in resolution)
→ m_Z constraint to improve resolution
(~15% improvement in resolution)

H→ZZ(*)→4l: Backgrounds



ZZ background estimated using MC simulation and NLO cross section

Backgrounds with fake/non-prompt leptons (ttbar, Z+heavy flavour, Z+jet, WZ) estimated from data:

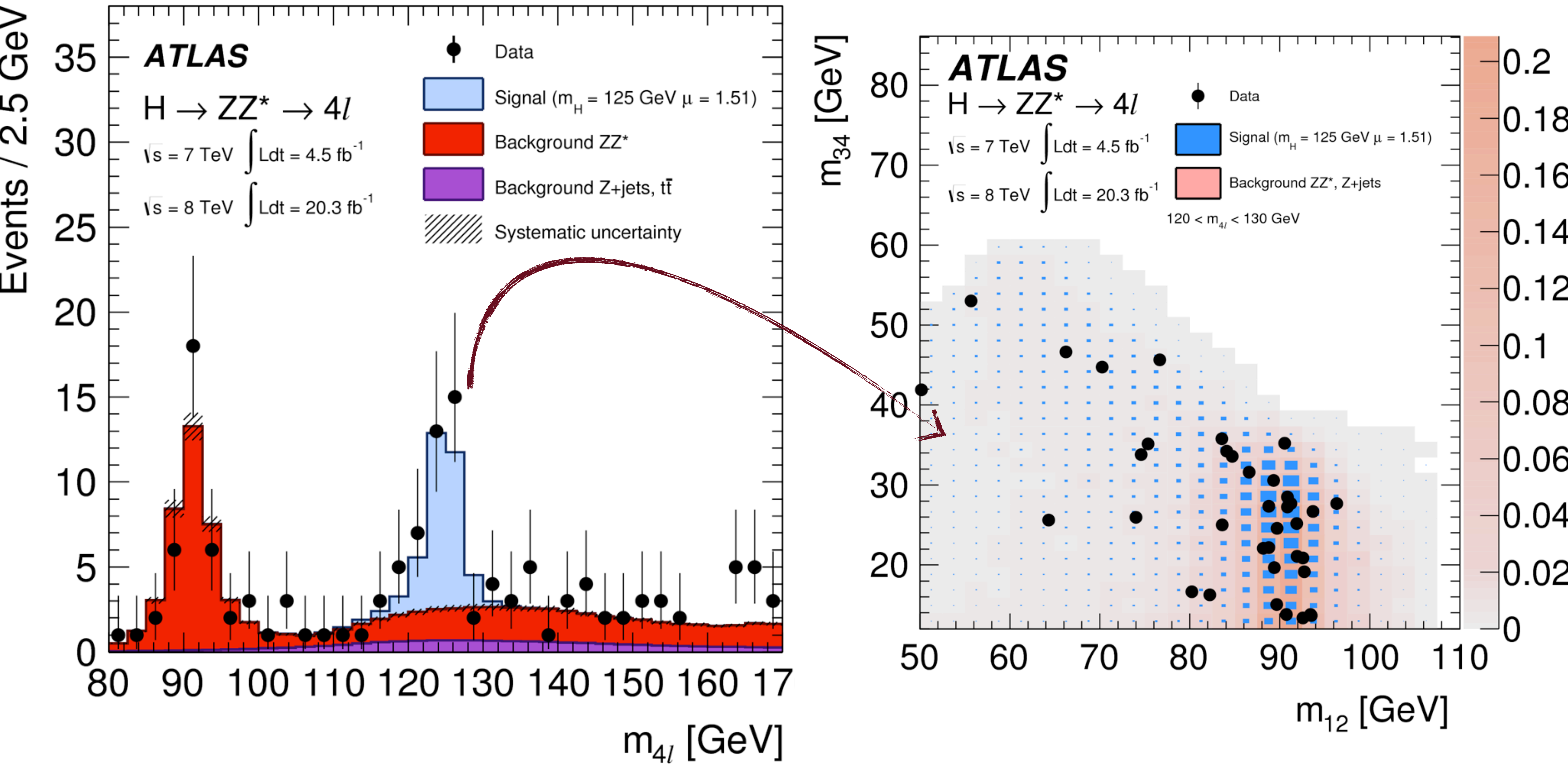
ll+μμ : Simultaneous fit using 4 exclusive Control Regions
- inverted d_0 significance
- inverted isolation
- eμ+μμ
- Same-sign sub-leading

ll+ee : 3 data-driven methods
- 3l+X
- transfer factors
- truth/reco categories

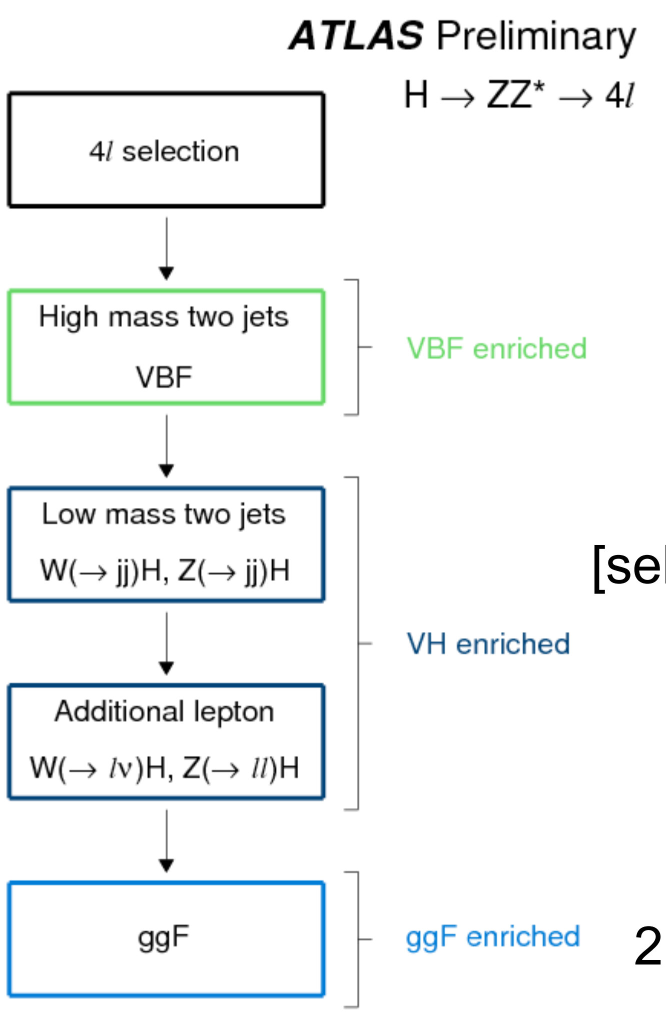
Overall uncertainties ~20%

Background-dominated Control Region
[Remove isolation/impact parameter requirements on sub-leading di-lepton]

H→ZZ$^{(*)}$→4l: Selected Events



$H \to ZZ^{(*)} \to 4l$: Event Categorization



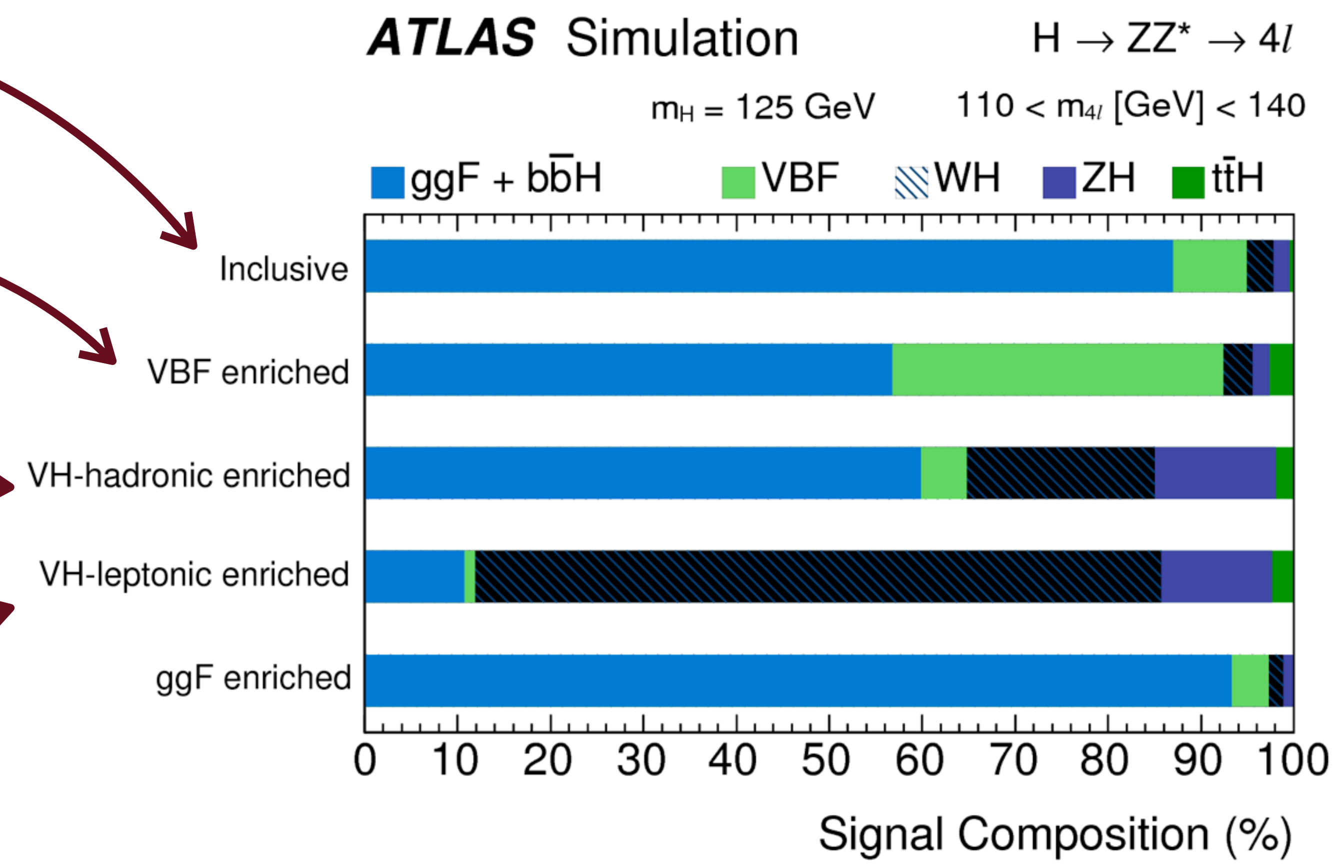
2D fit: (m_{4l}, BDT_{VBF})

1D fit: m_{4l}
[selection using BDT_{VH}]

1D fit: m_{4l}

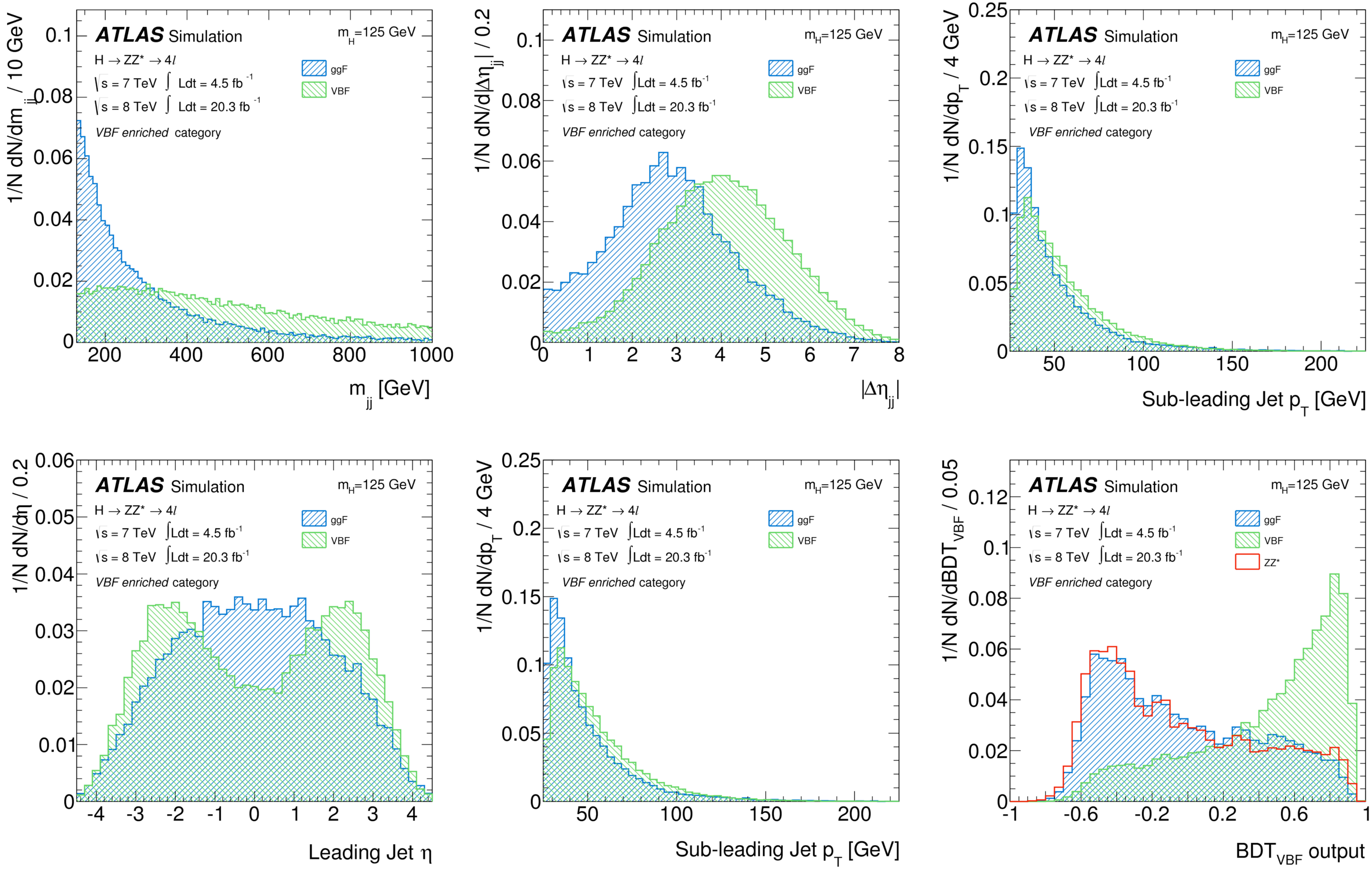
2D fit: (m_{4l}, BDT_{ZZ})

Event Categorization
→ probe production mechanisms



Category	$gg \to H,\ q\bar{q}/gg \to b\bar{b}H/t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$
	$\sqrt{s} = 8$ TeV		
ggF enriched	12.0 ± 1.4	0.52 ± 0.02	0.37 ± 0.02
VBF enriched	1.2 ± 0.4	0.69 ± 0.05	0.10 ± 0.01
VH-hadronic enriched	0.41 ± 0.14	0.030 ± 0.004	0.21 ± 0.01
VH-leptonic enriched	0.021 ± 0.003	0.0009 ± 0.0002	0.13 ± 0.01

H→ZZ(*)→4l: BDT category

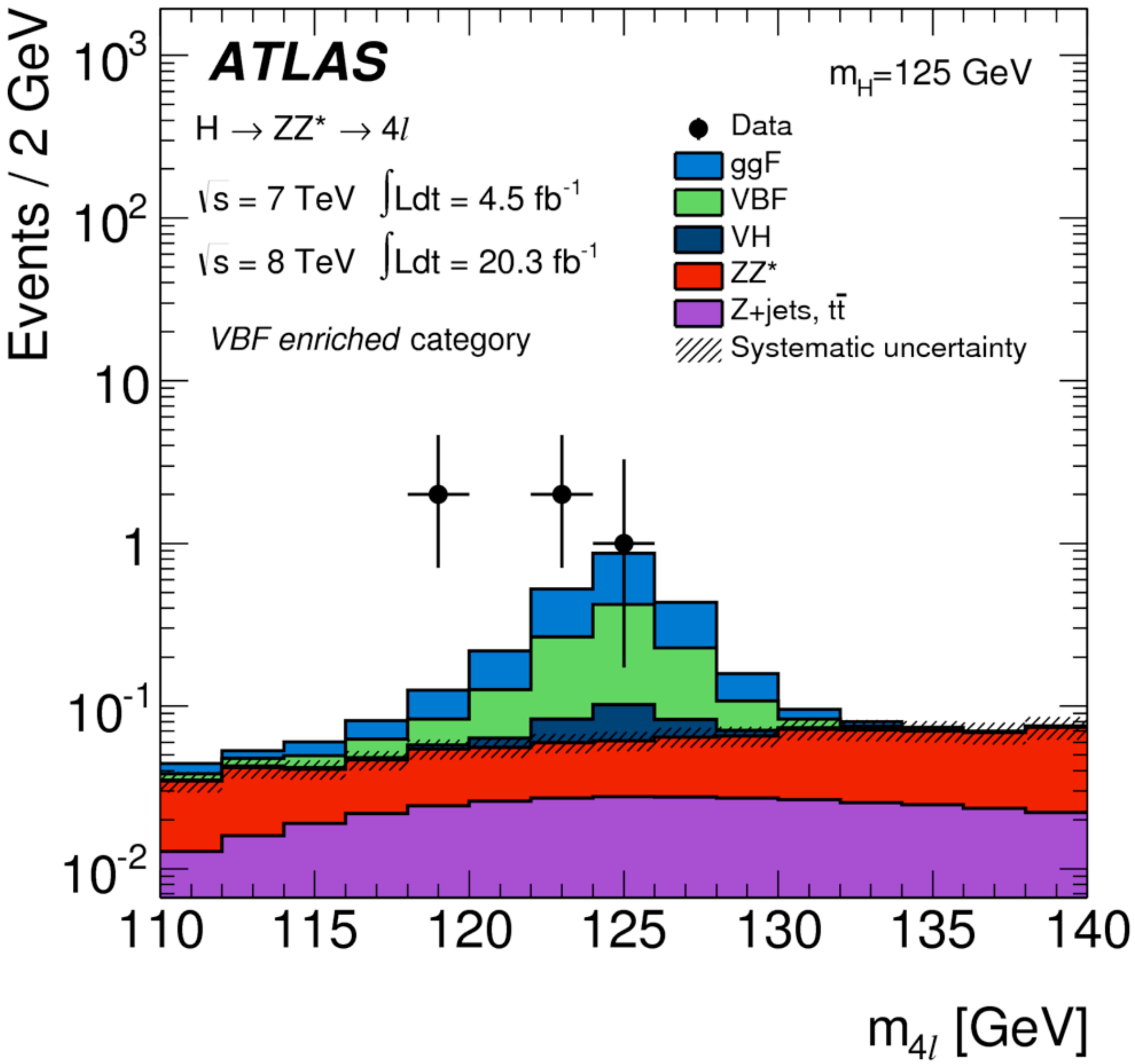


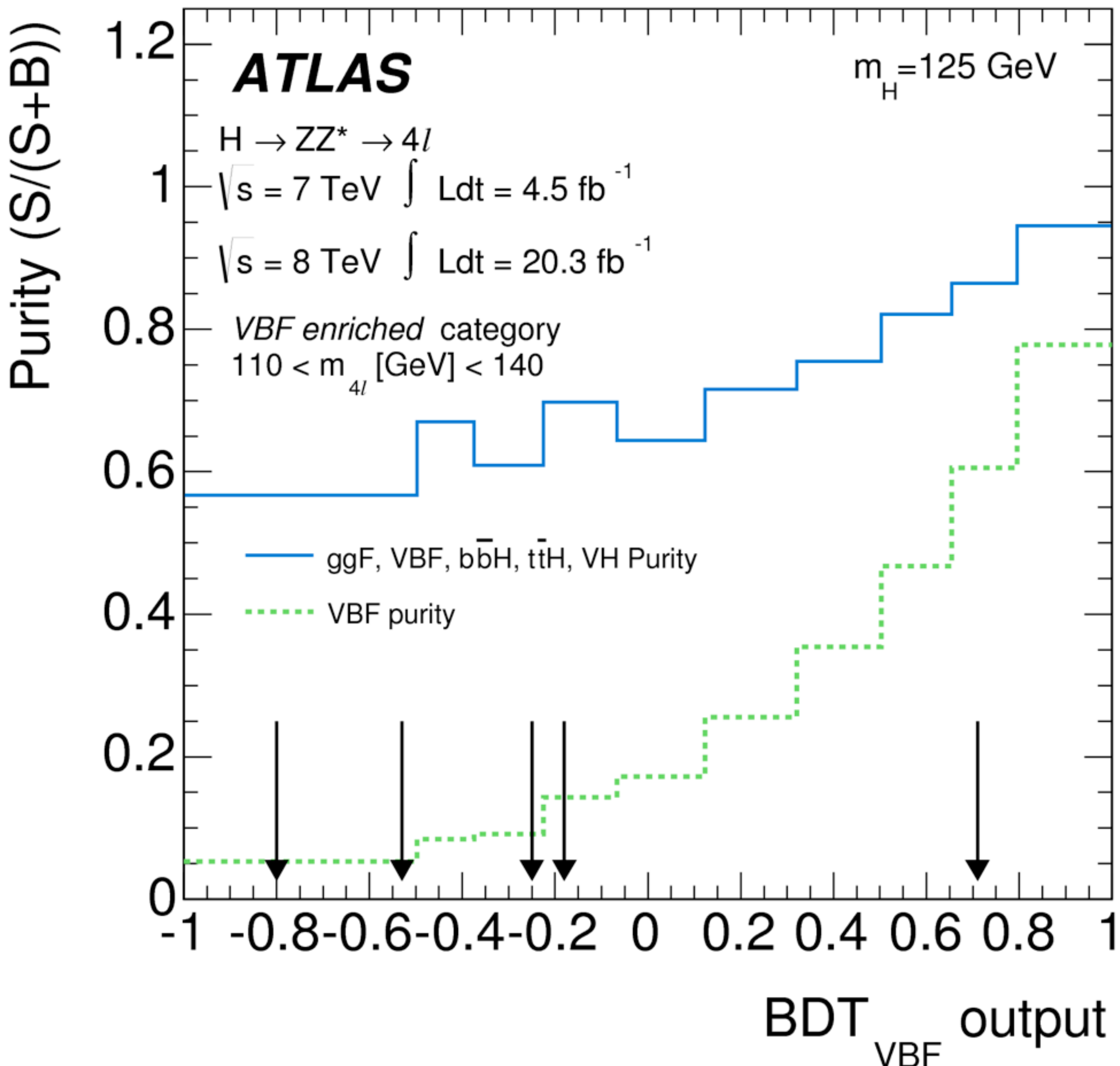
Need to be careful to select variables that are reasonably described by simulation

$H \to ZZ^{(*)} \to 4l$: Systematic Uncertainties in categorisation

Process	$gg \to H, q\bar{q}/gg \to b\bar{b}H/t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	ZZ^*
	VBF enriched category			
Theoretical cross section	20.4%	4%	4%	8%
Underlying event	6.6%	1.4%	–	–
Jet energy scale	9.6%	4.8%	7.8%	9.6%
Jet energy resolution	0.9%	0.2%	1.0%	1.4%
Total	23.5%	6.4%	8.8%	12.6%
	VH-hadronic enriched category			
Theoretical cross section	20.4%	4%	4%	2%
Underlying event	7.5%	3.1%	–	–
Jet energy scale	9.4%	9.3%	3.7%	12.6%
Jet energy resolution	1.0%	1.7%	0.6%	1.8%
Total	23.7%	10.7%	5.5%	12.9%
	VH-leptonic enriched category			
Theoretical cross section	12%	4%	4%	5%
Leptonic VH-specific cuts	1%	1%	5%	–
Jet energy scale	8.8%	9.9%	1.7%	3.2%
Total	14.9%	10.7%	6.6%	5.9%
	ggF enriched category			
Theoretical cross section	12%	4%	4%	4%
Jet energy scale	2.2%	6.6%	4.0%	1.0%
Total	12.2%	7.7%	5.7%	4.1%

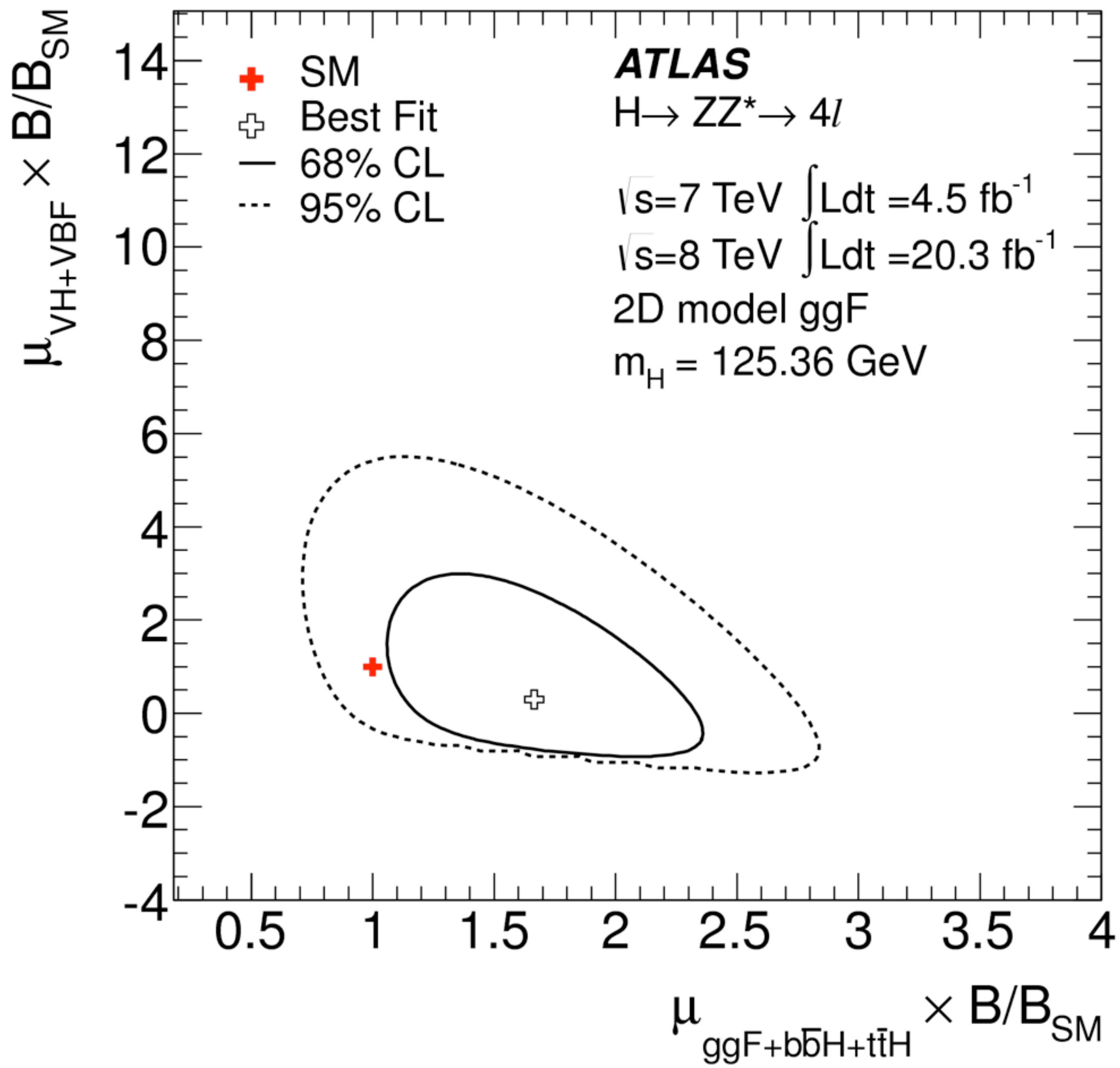
$H \to ZZ^{(*)} \to 4l$: Results

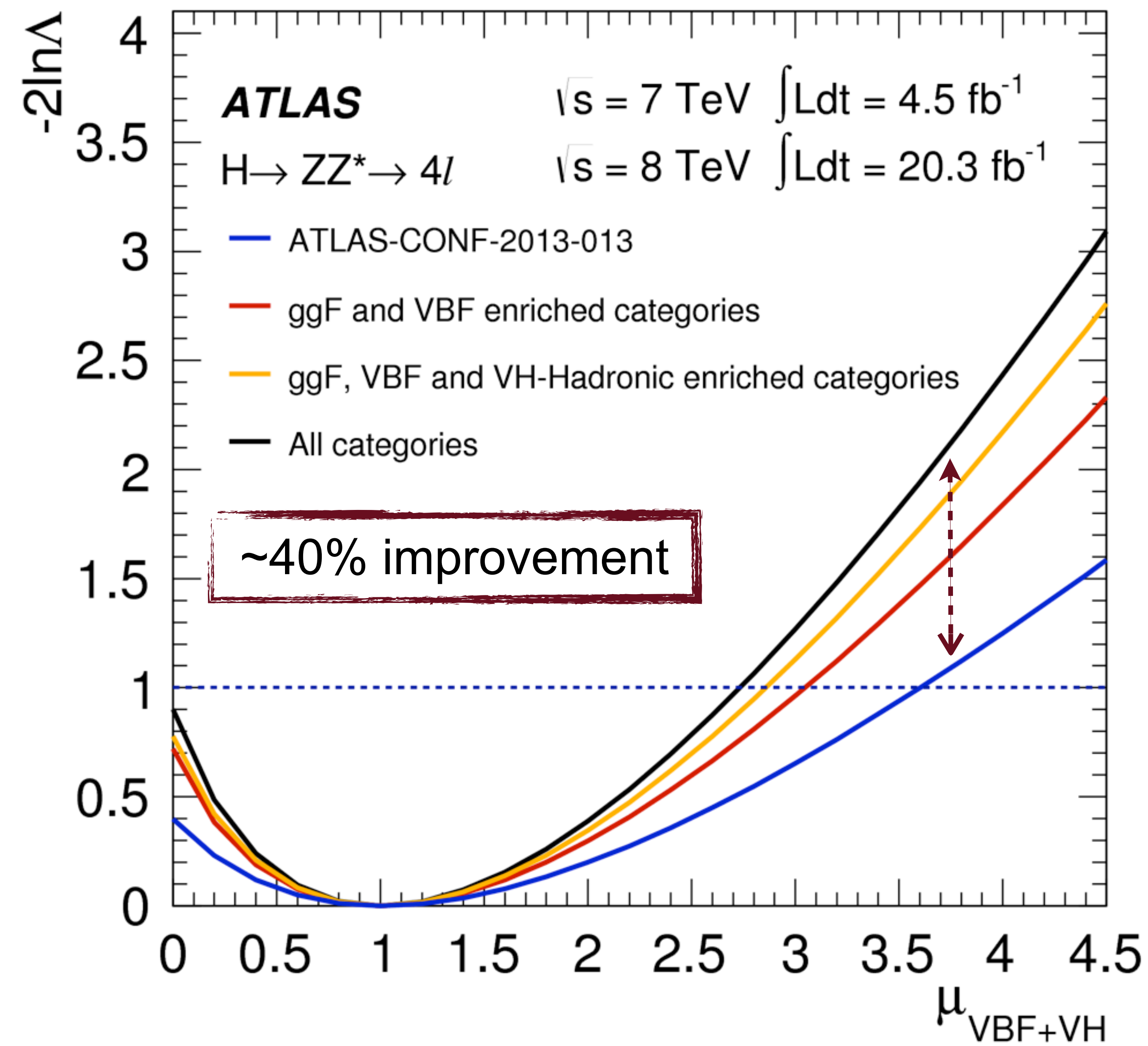




110 < m_{4l} < 140 GeV
event yields
VBF-enriched: 5
VH-hadronic: 0
VH-leptonic: 0

$H \to ZZ^{(*)} \to 4l$: Coupling Results



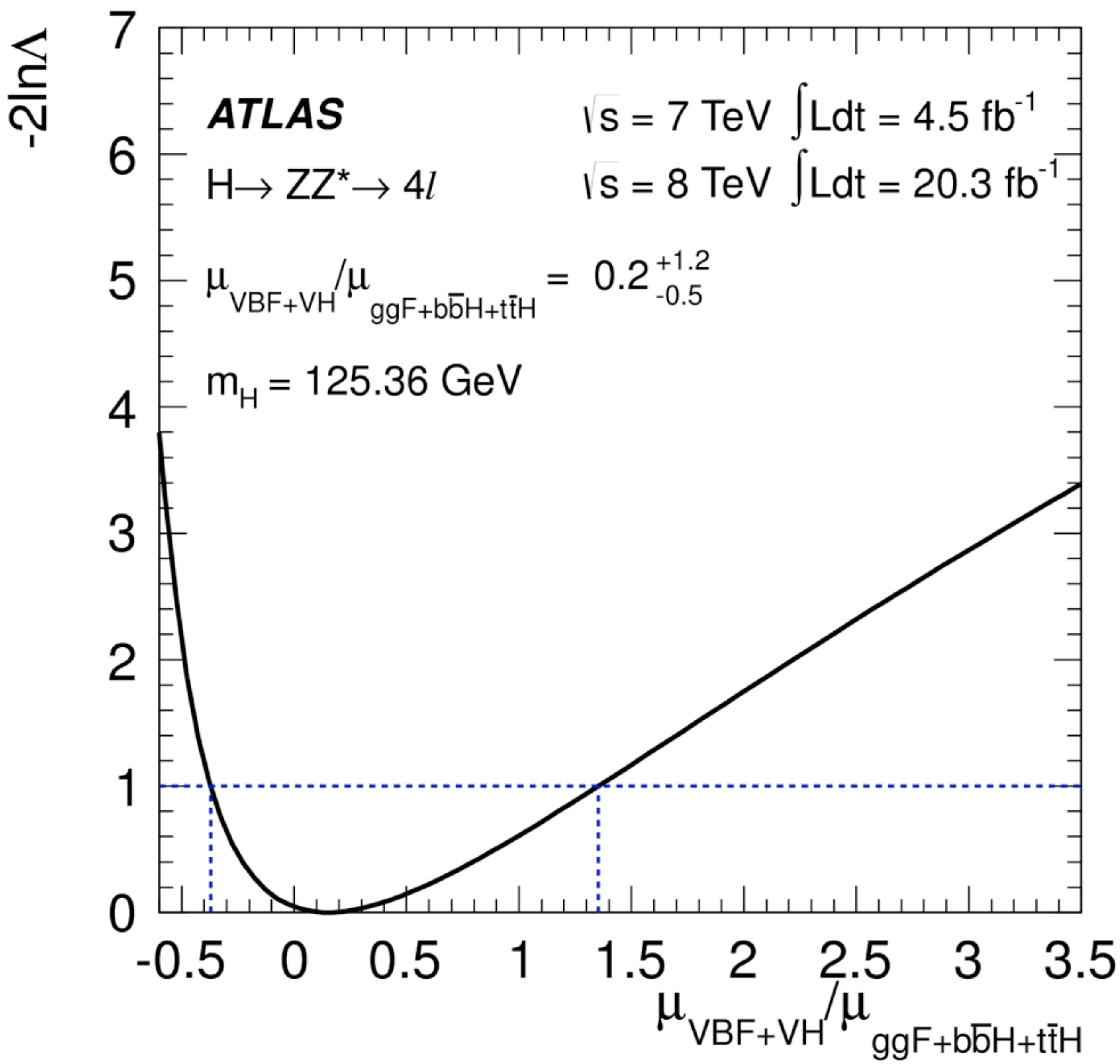


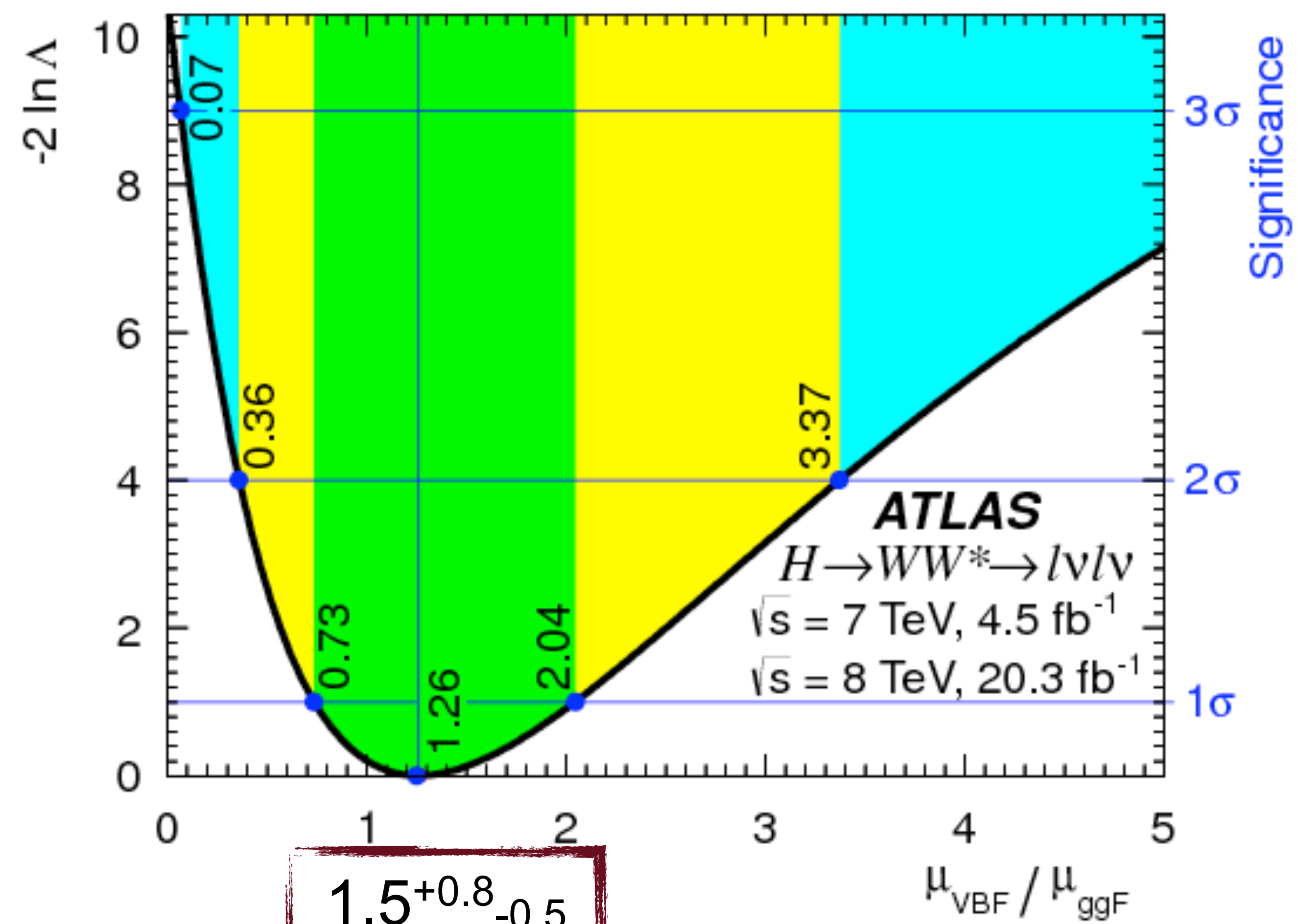
$\mu_{ggF+bbH+ttH} = 1.66^{+0.45}_{-0.41}(\text{stat})^{+0.25}_{-0.15}(\text{syst})$

$\mu_{VBF+VH} = 0.26^{+1.60}_{-0.91}(\text{stat})^{+0.36}_{-0.23}(\text{syst})$

$\mu_{VBF+VH}/\mu_{ggF+bbH+ttH} = 0.2^{+1.2}_{-0.5}$

H→ZZ(*)→4l: Coupling Results



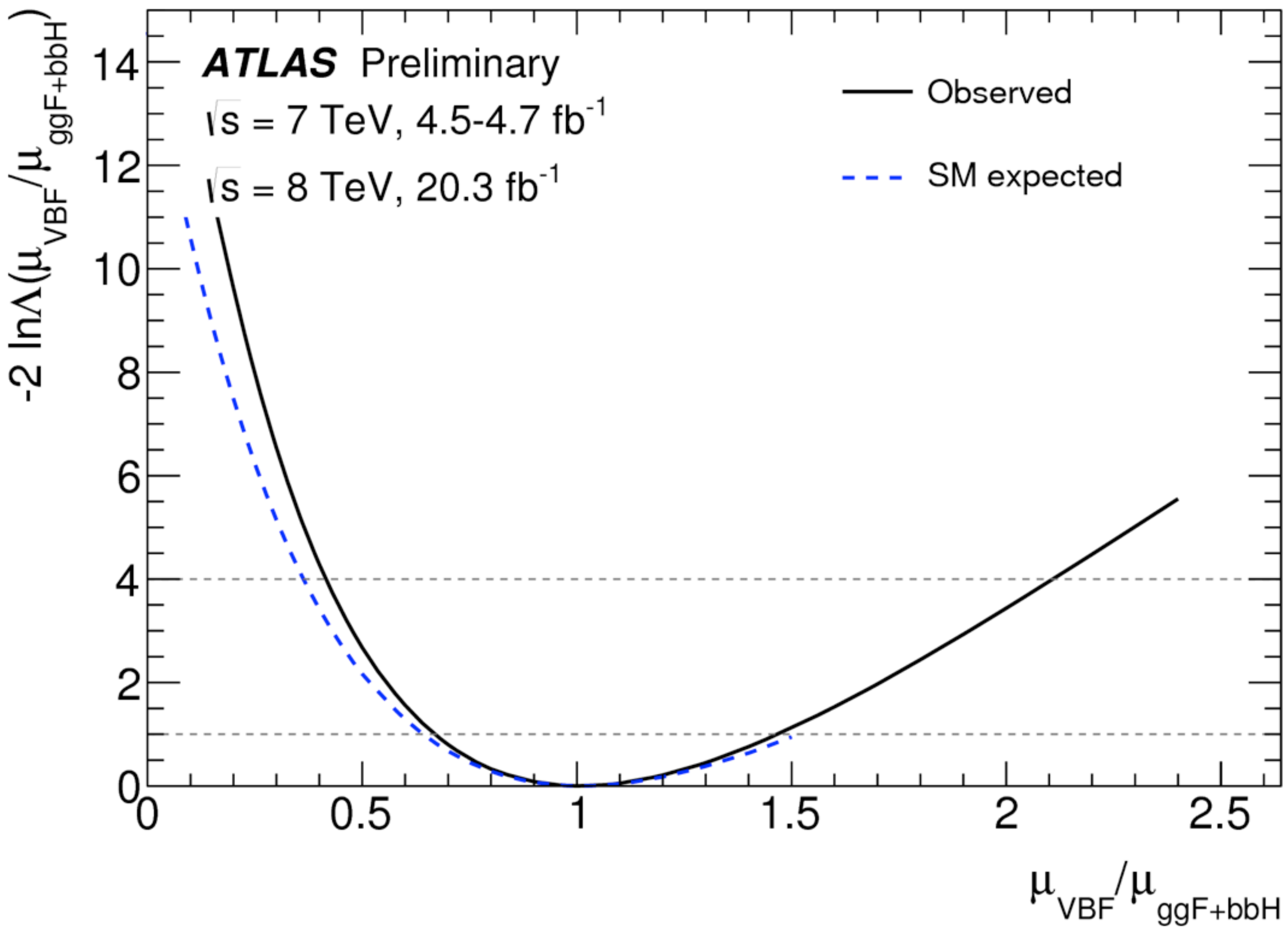


$1.5^{+0.8}_{-0.5}$

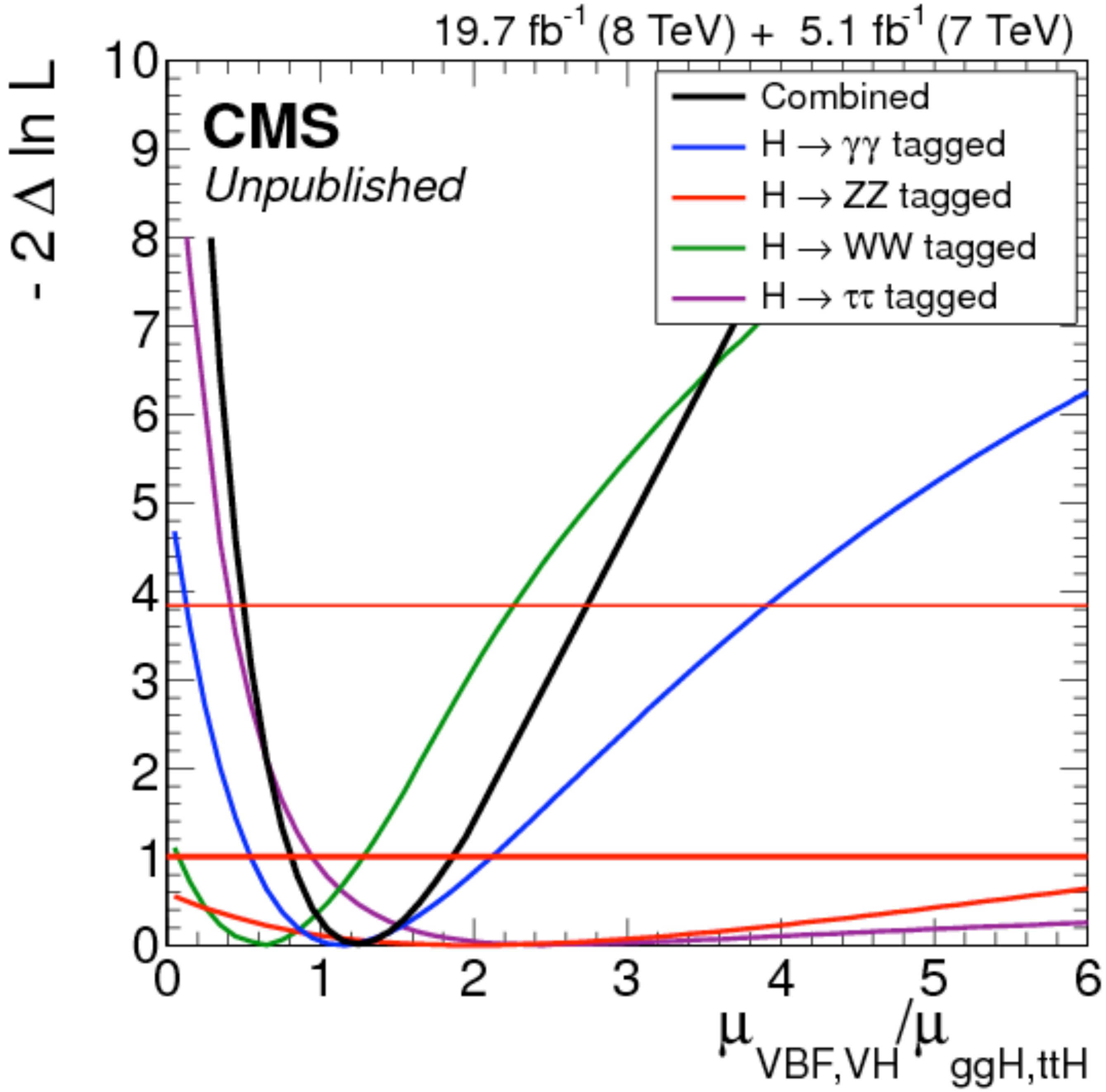
$\mu_{VBF+VH}/\mu_{ggF+bbH+ttH} = 0.2^{+1.2}_{-0.5}$

Some way to go still before observation...

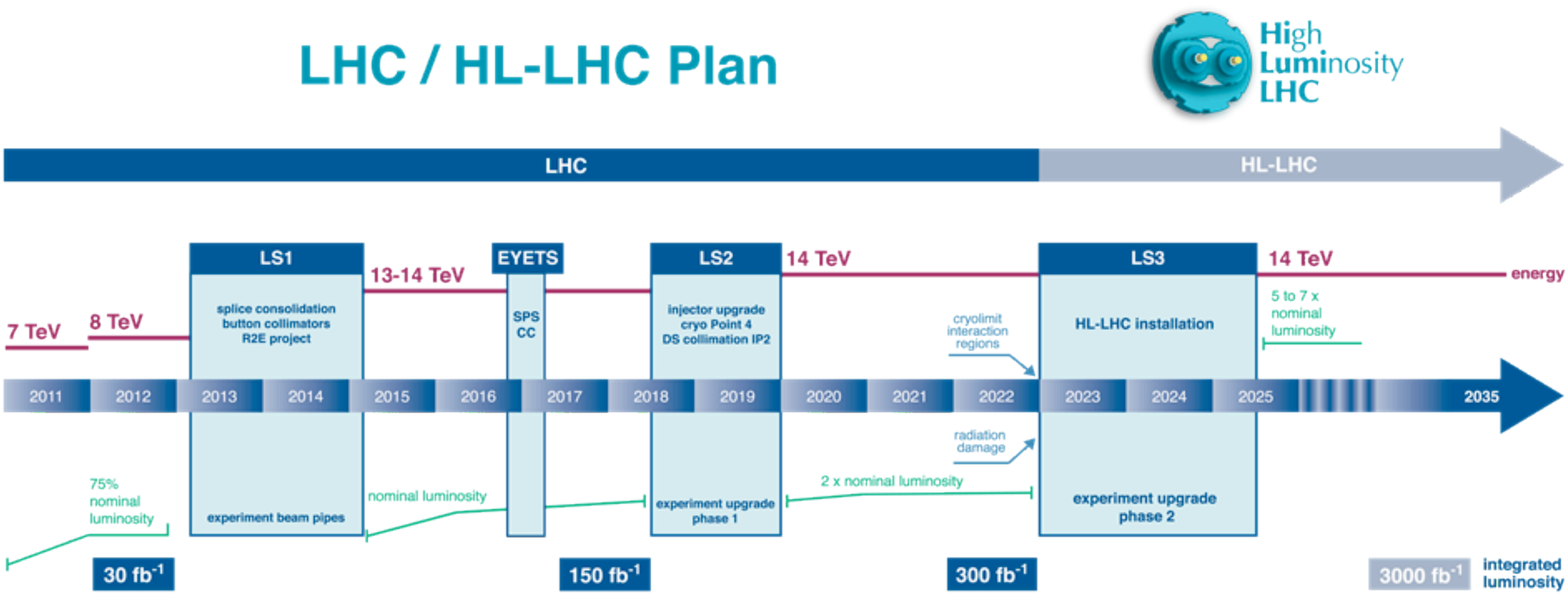
LHC Higgs boson: Combining all the channels



$\mu_{ggF}^{WW^*}$		$1.15^{+0.28}_{-0.24}$	
Ratio of cross sections	Best-fit value	Significance (σ) Observed	Expected
$R_{VBF/ggF}$	$1.00^{+0.46}_{-0.34}$	4.3	3.8
$R_{VH/ggF}$	$1.33^{+0.94}_{-0.68}$	2.6	3.1
$R_{ttH/ggF}$	$1.90^{+1.12}_{-0.86}$	2.4	1.5



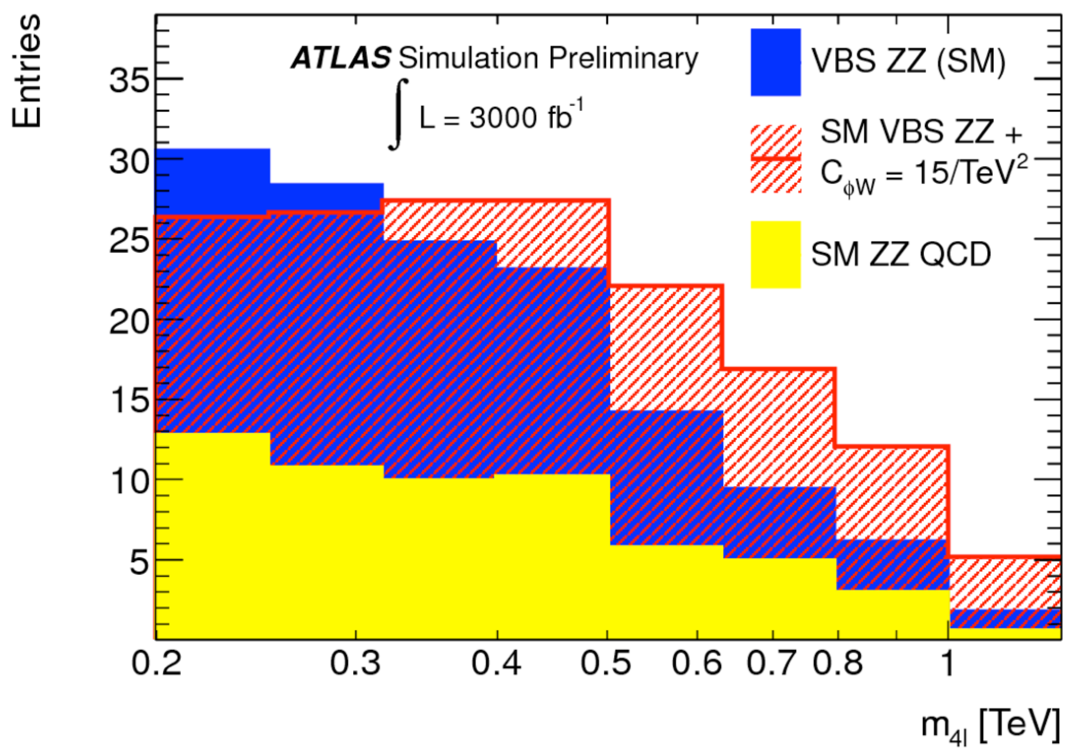
LHC/HL-LHC Plan



QGC in Run II and beyond

The increased energy and integrated luminosity at LHC Run II/III and beyond would allow access to various processes:
- VBS $ZZ \to 4l$, $WZ \to l\nu ll$, $W^{\pm}W^{\pm} \to l^{\pm}\nu l^{\pm}\nu$,...
- Tri-bosons $Z\gamma\gamma \to ll\gamma\gamma$,...

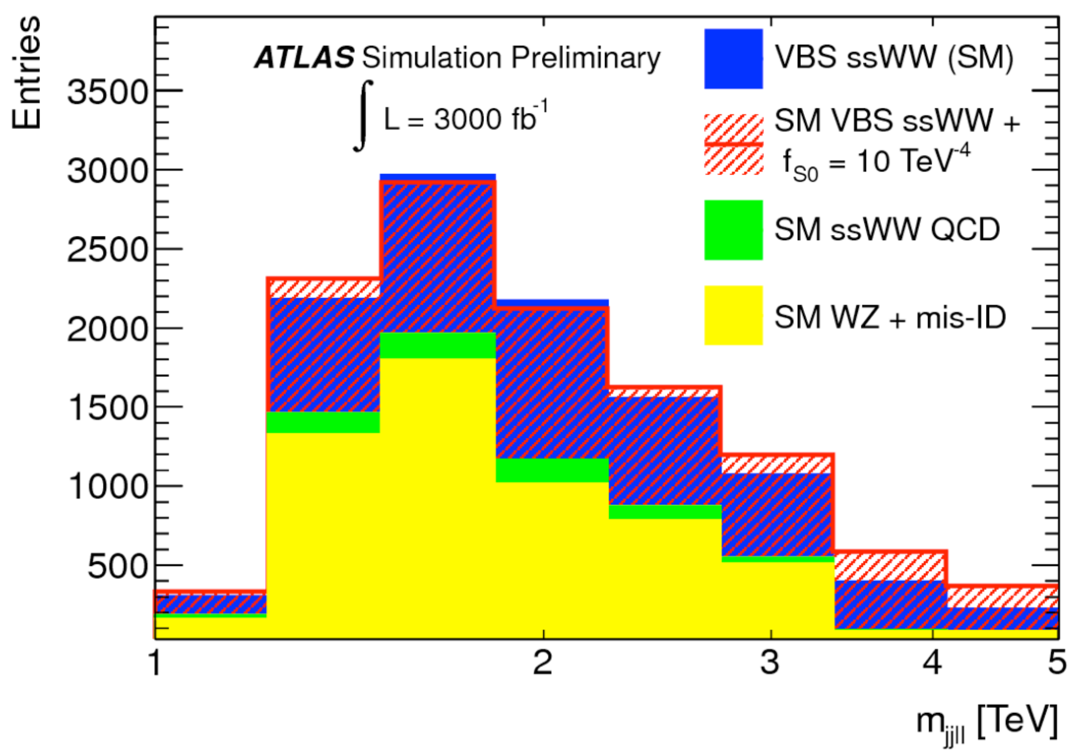
Each of them sensitive to different operators in the Effective Field Theory approach.



$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$

affects H→VV couplings
(i.e. triboson and VBS studies)
but not di-boson production

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^{\pm}W^{\pm}$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

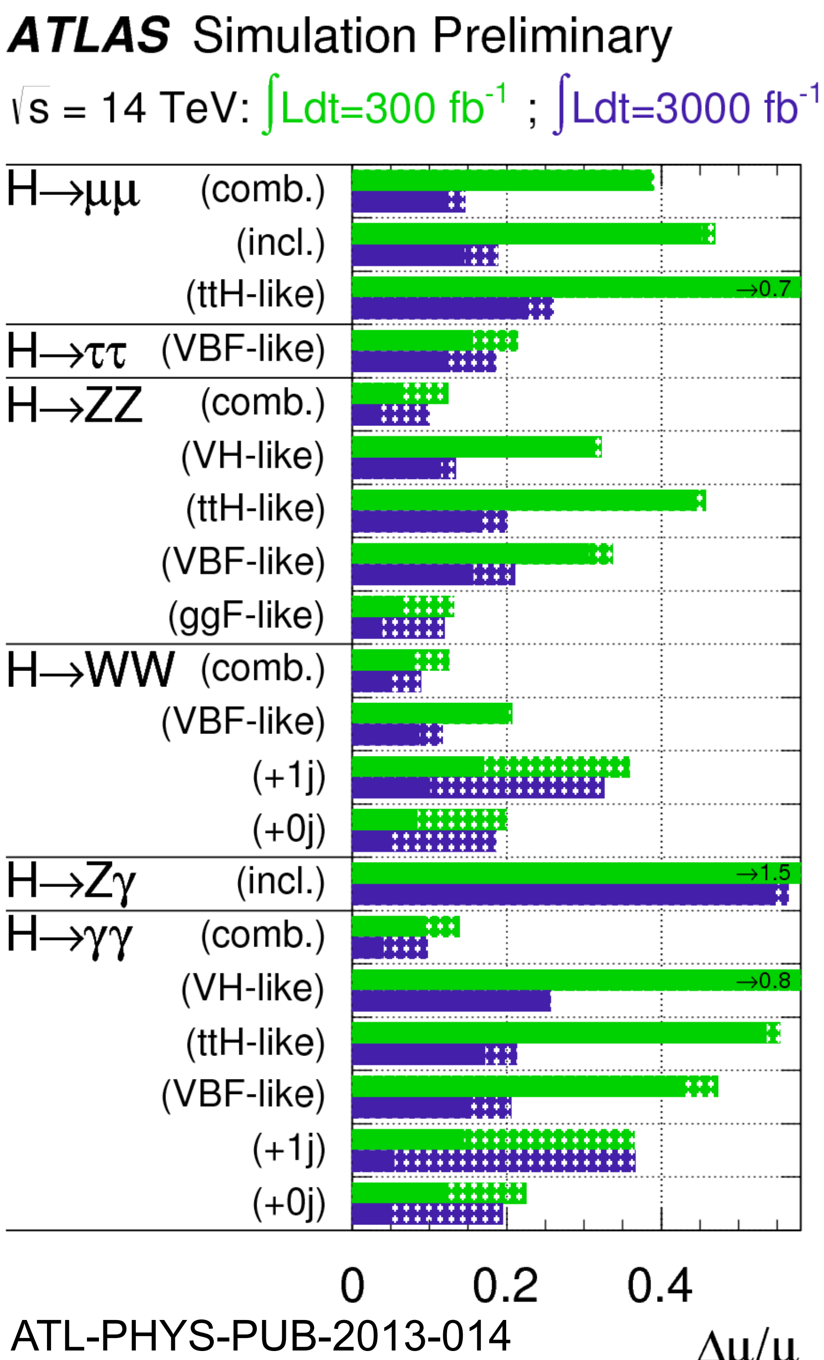


Higgs in Run II and beyond

The LHC is a Higgs Factory

- Run II ×5-6 more integrated luminosity compared to Run I
- ×2.3 - 3.9 increase in Higgs production cross section from 8TeV to 13TeV
- ×3.4-5 improvement in statistical sensitivity

In Run II several Higgs analysis may become systematics limited
need to work on reducing those



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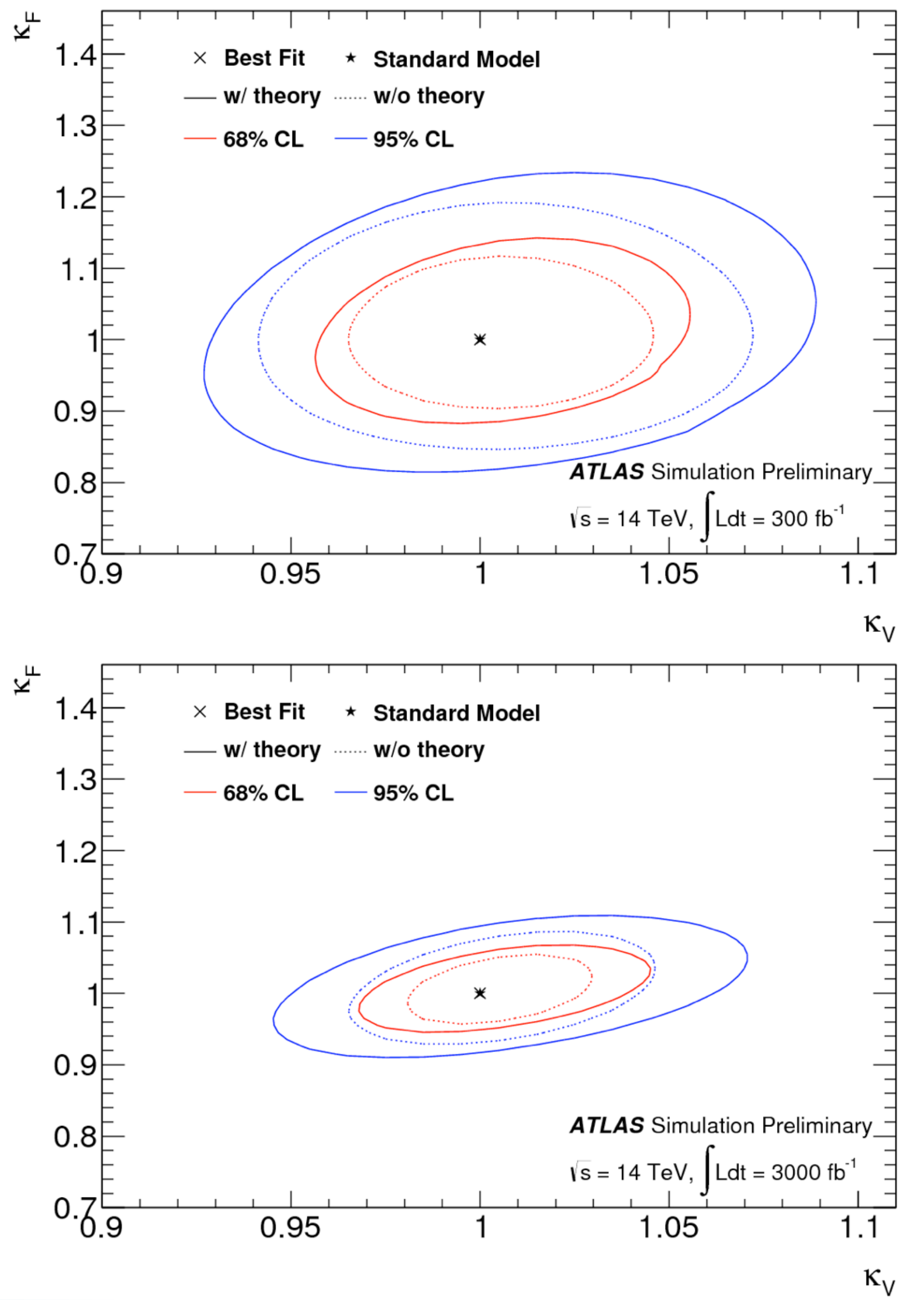
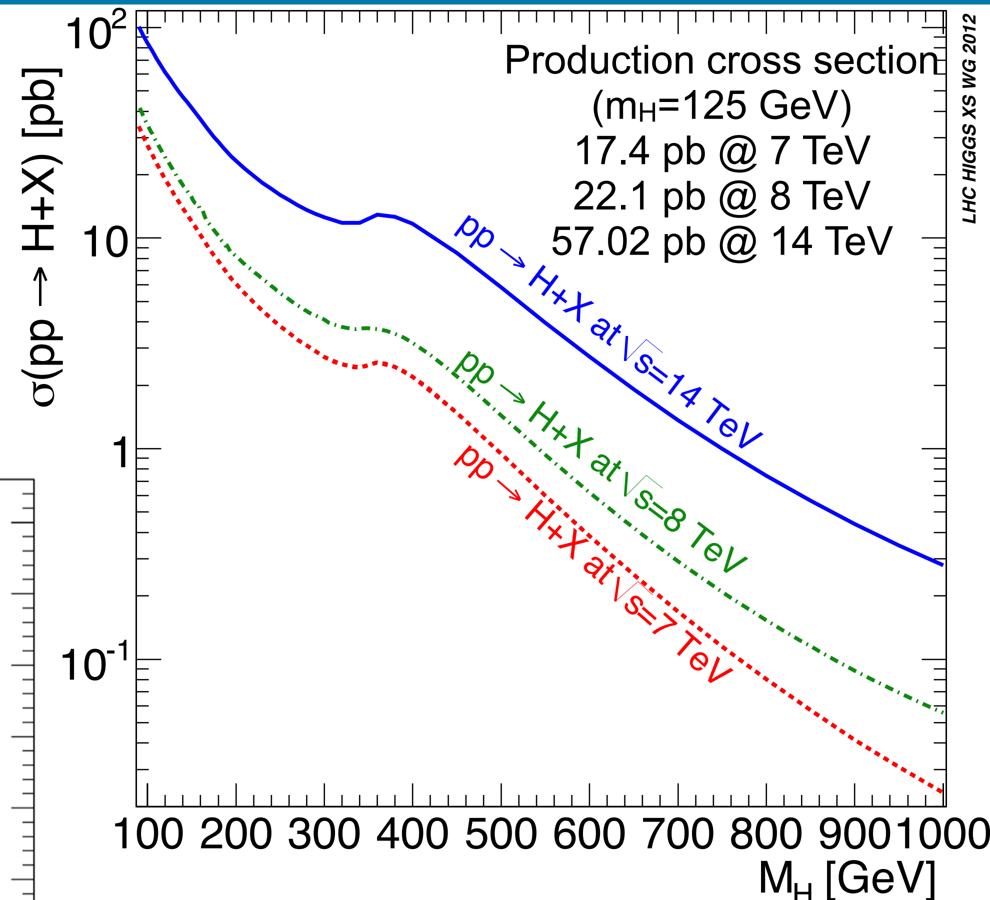
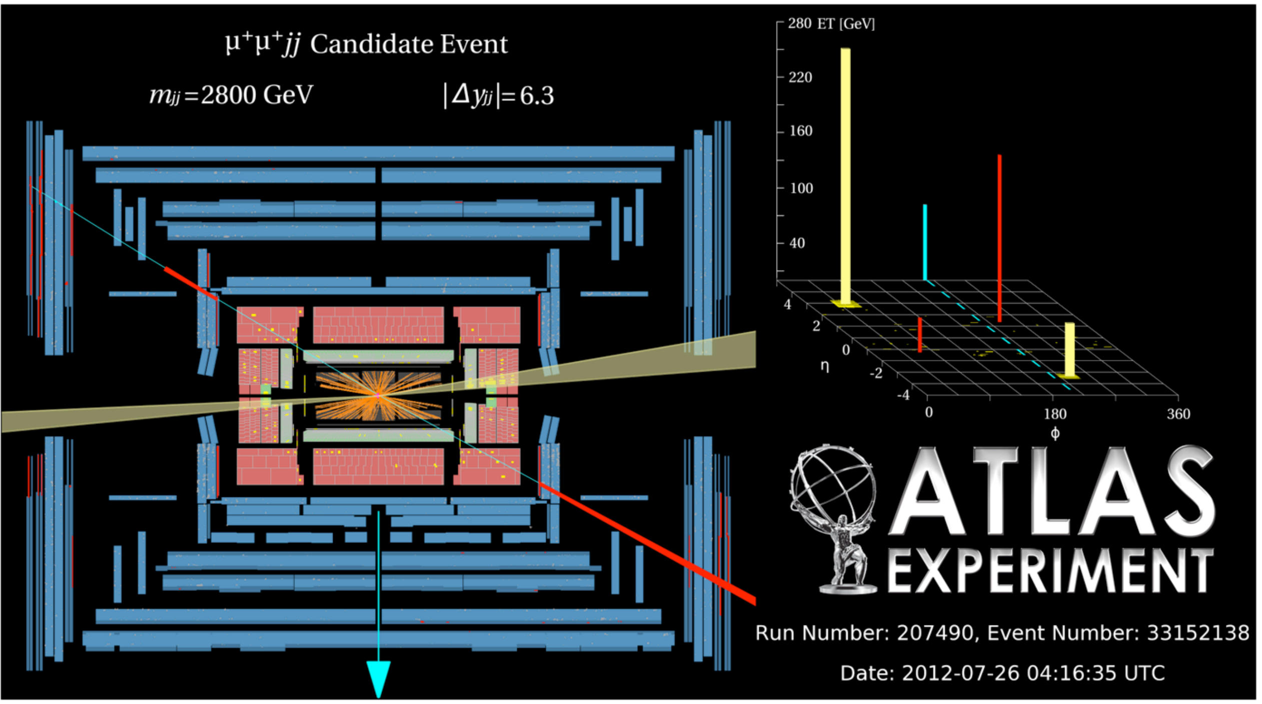




Several open topics in the Higgs sector for future studies:

- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production

Summary



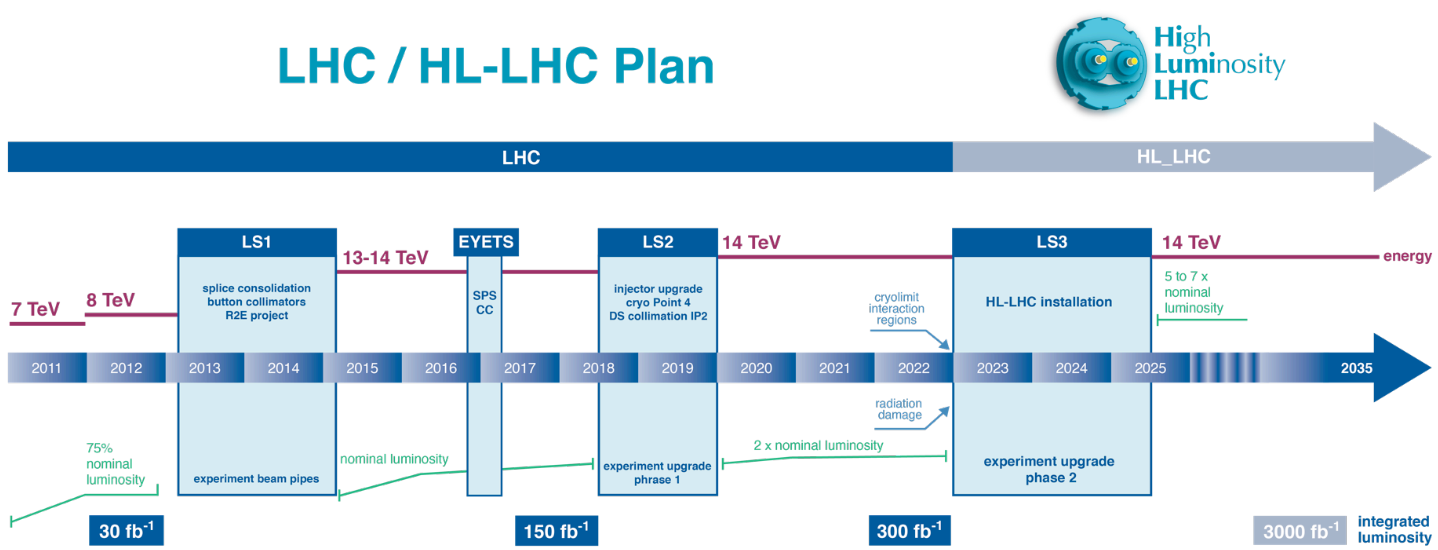
We just begin to explore the dynamics of Electro-Weak Symmetry Breaking

Within the Standard Model this is purely due to the Higgs non-zero vacuum expectation value.
But new physics could contribute,
without contradicting current experimental limits!

New physics may be lurking there!

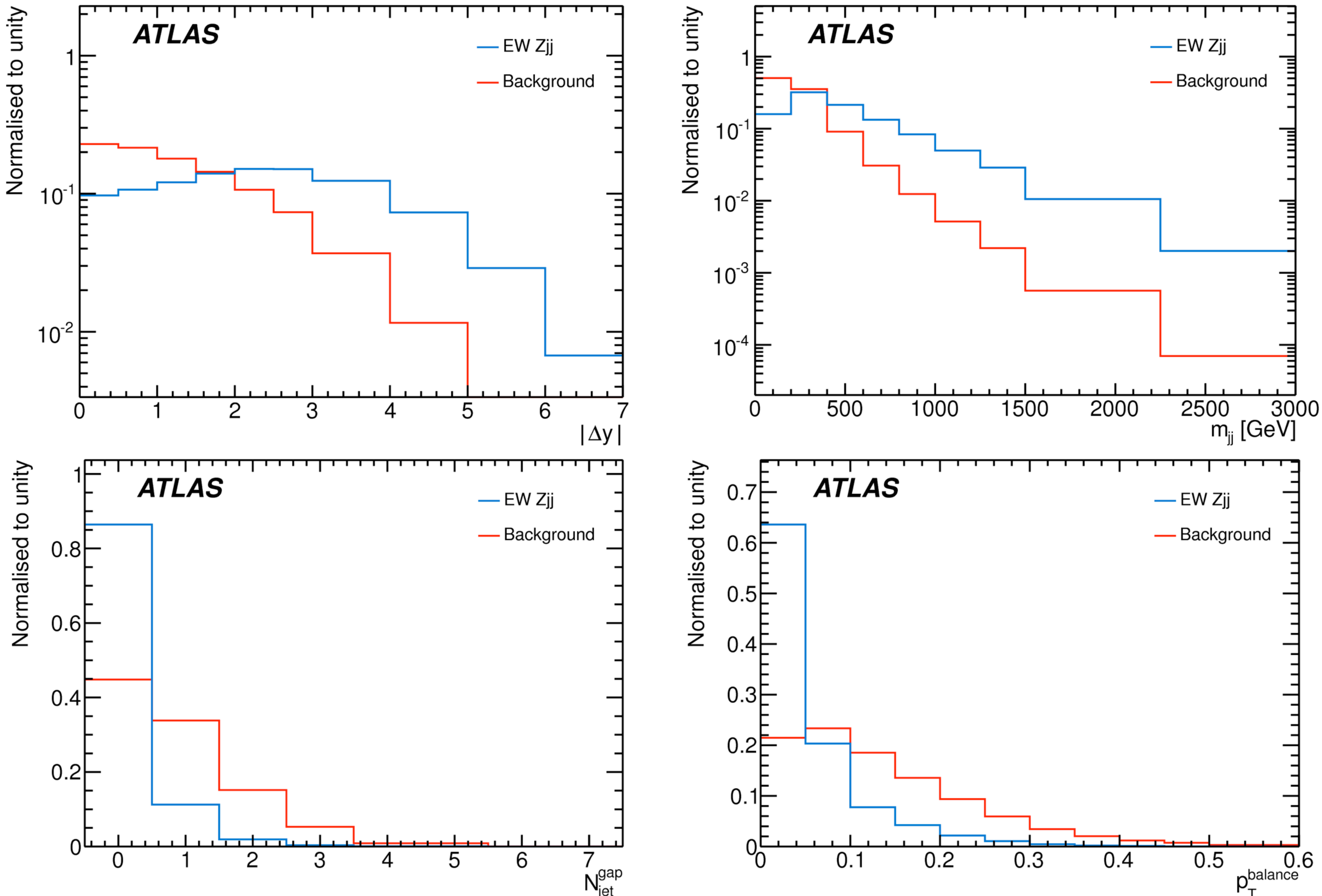
With the LHC Run II/III and beyond, these are major questions to be answered!

Intensive dialogue/collaboration between theory and experiment is needed to reduce modeling uncertainties and to optimally benefit from the wealth of information



Additional Slides

EW Zjj vs strong Zjj



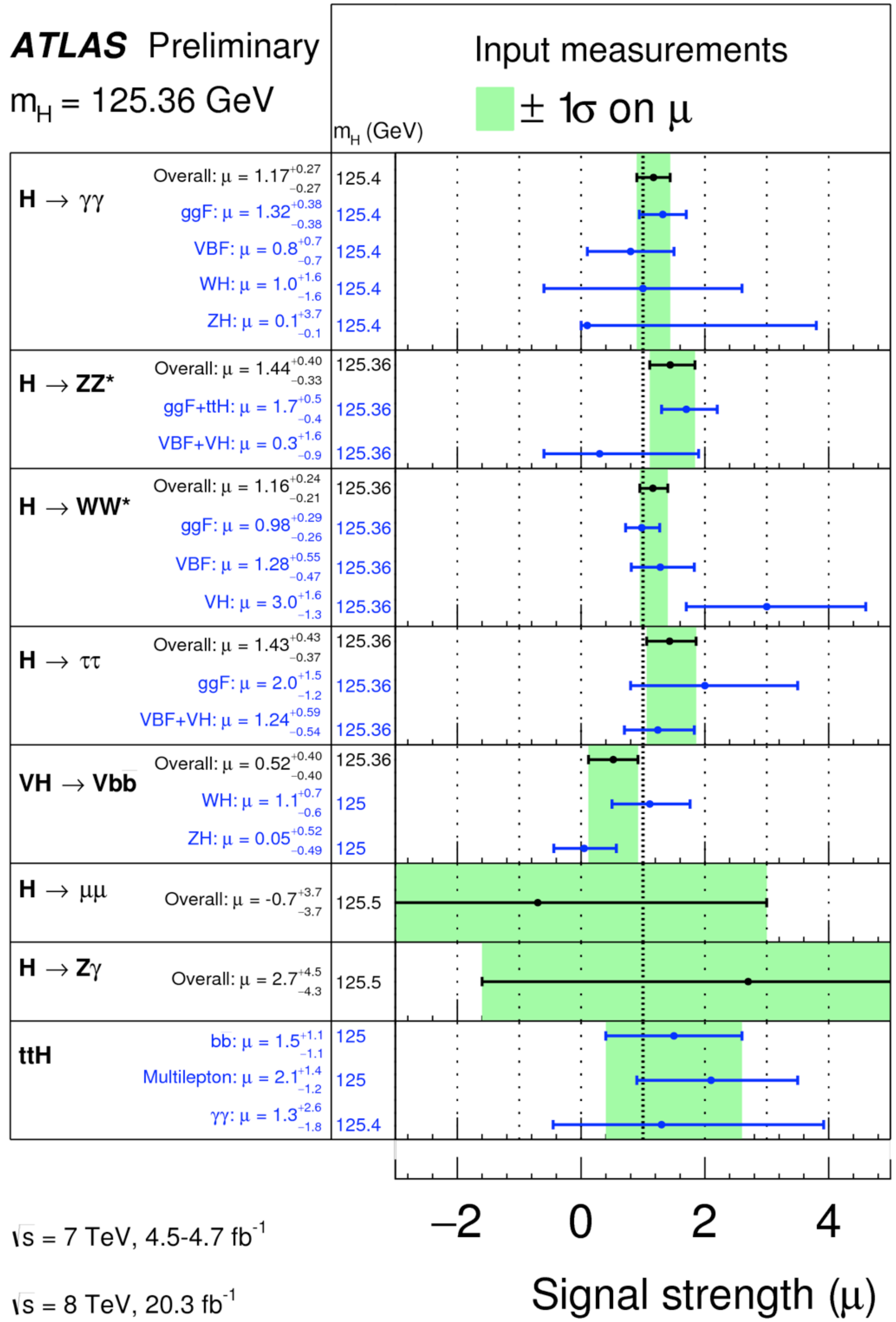
Jet activity both in terms of kinematics of the events, and as additional hadronic activity are crucial to separate EW and strong production

$W^\pm W^\pm jj \to l^\pm \nu l^\pm \nu jj$: Systematic Uncertainties

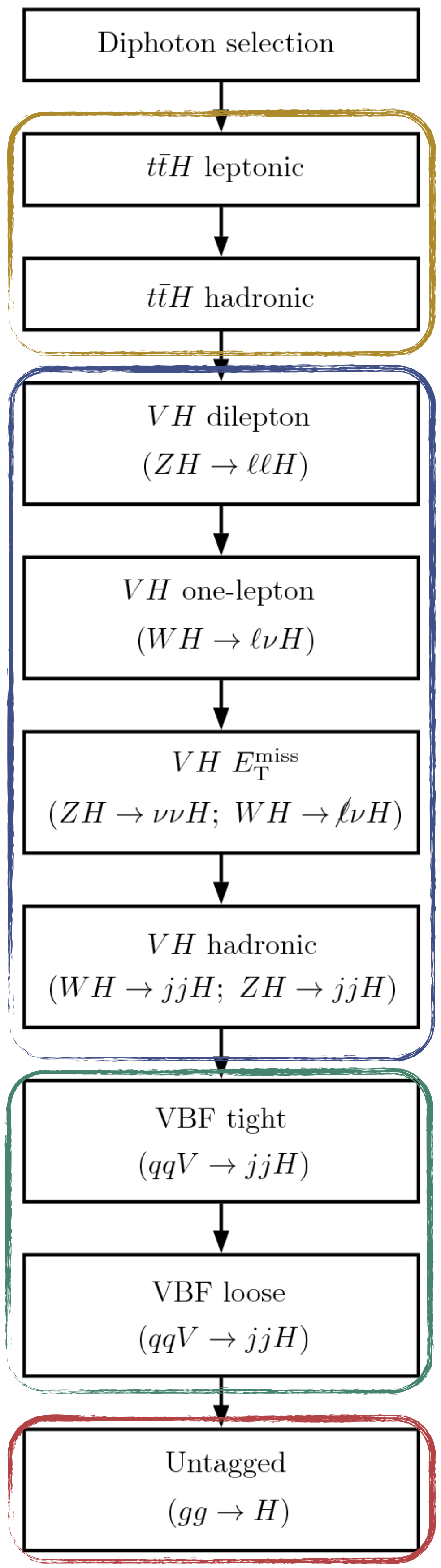
Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background		Signal	
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^\pm W^\pm jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^\pm W^\pm jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^\pm W^\pm jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^\pm W^\pm jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

Overview of rate measurements



H→γγ: Couplings



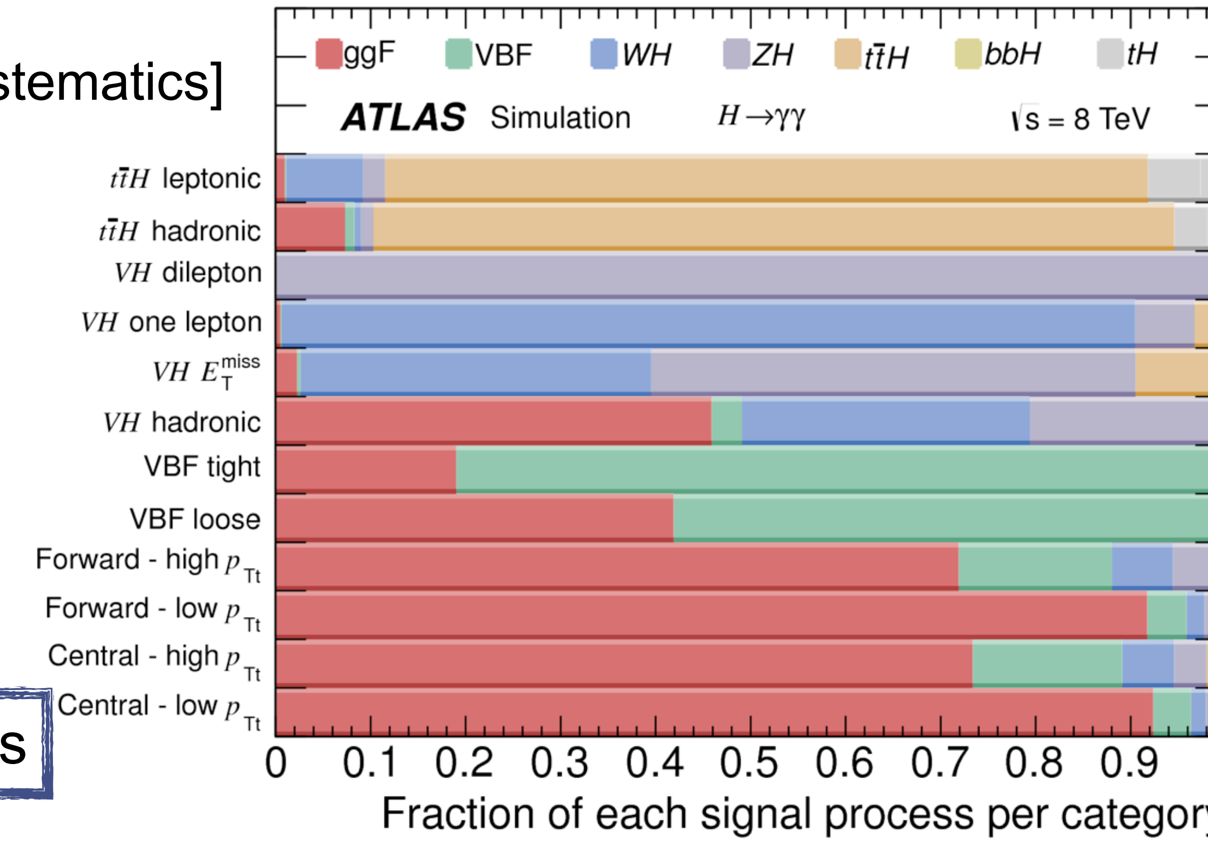
couplings optimized categories
[min expected $\delta\mu_{prod}$ for SM Higgs inc. systematics]

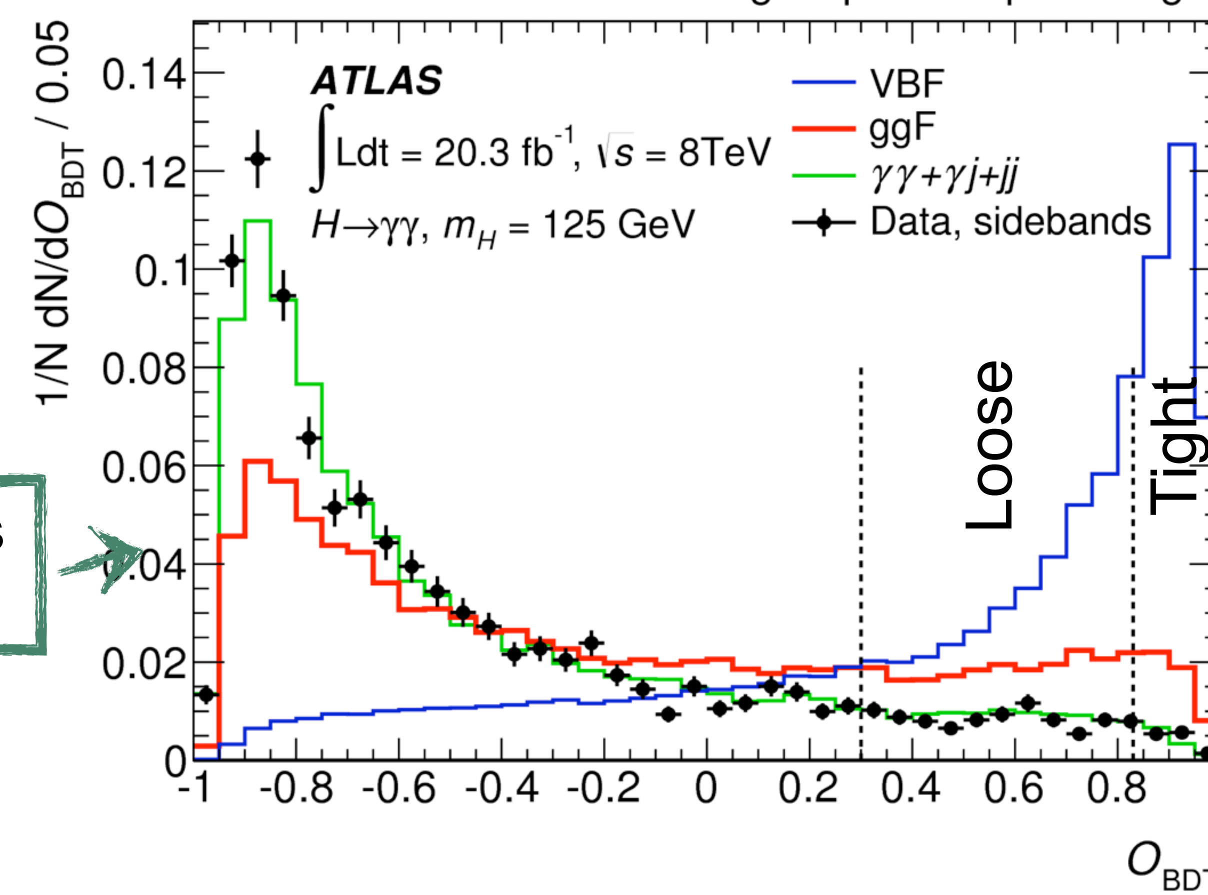
2 × ttH enriched categories

4 × WH/ZH enriched categories

2 × VBF enriched categories
Employing a BDT selection

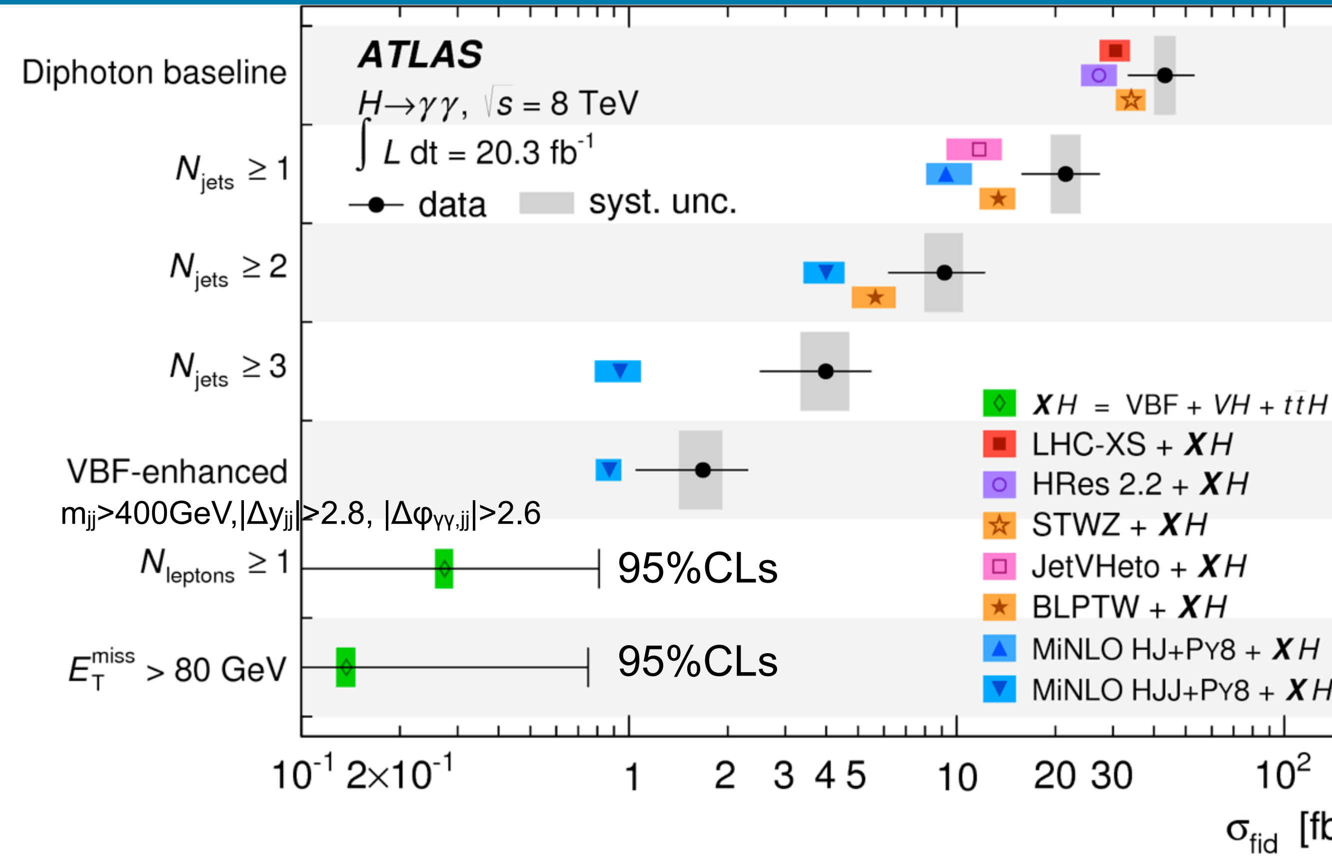
4 × untagged (pT and η)





H→γγ: Fiducial/Differential cross sections

5 measurements + 2 upper limits on fiducial cross sections



12 differential cross sections

a) kinematics ($pT_{\gamma\gamma}$,$|y_{\gamma\gamma}|$)

b) associated jet activity (Nj, $|y_j|$, ...)

c) spin-CP-sensitive (|cosθ*|, ...)

d) VBF-sensitive ($|\Delta y_{jj}|$,...)

Extraction procedure

γγ dataset binned in variable of interest

Simultaneous unbinned maximum likelihood fit of $m_{\gamma\gamma}$ in each bin

Bin-by-bin acceptance, efficiency and resolution correction("unfolding")