ATLAS-Heidelberg Meeting @ Trifels 2022

$Z\gamma\gamma$ – What it Tells us about EW Interactions

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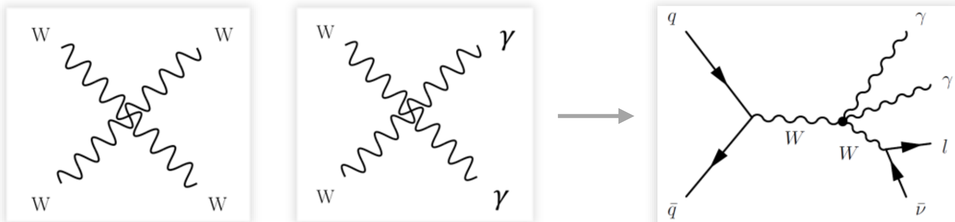
- Electromagnetic and weak (EW) interactions: γ, W, Z
- EW theory predicts gauge self-interactions

  $\Rightarrow$ $WWZ, WW\gamma$ (TGC) and $WWWW, WW\gamma\gamma$, .. (QGC)



- Coupling between 3,4 neutral EWK gauge bosons forbidden in SM

- Verify predictions of EW theory for *rare* processes ($Z\gamma\gamma$)

  + sensitivity for new physics

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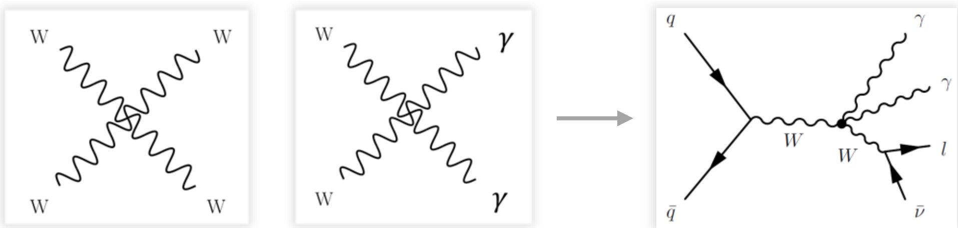

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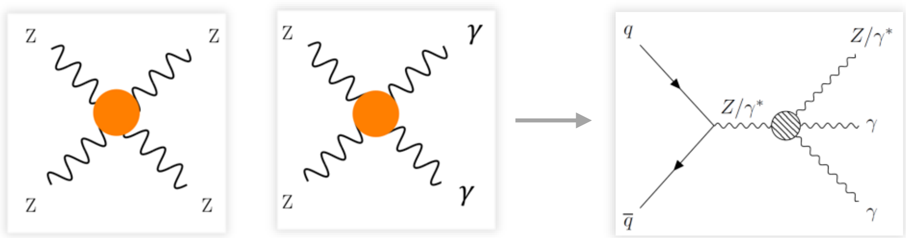

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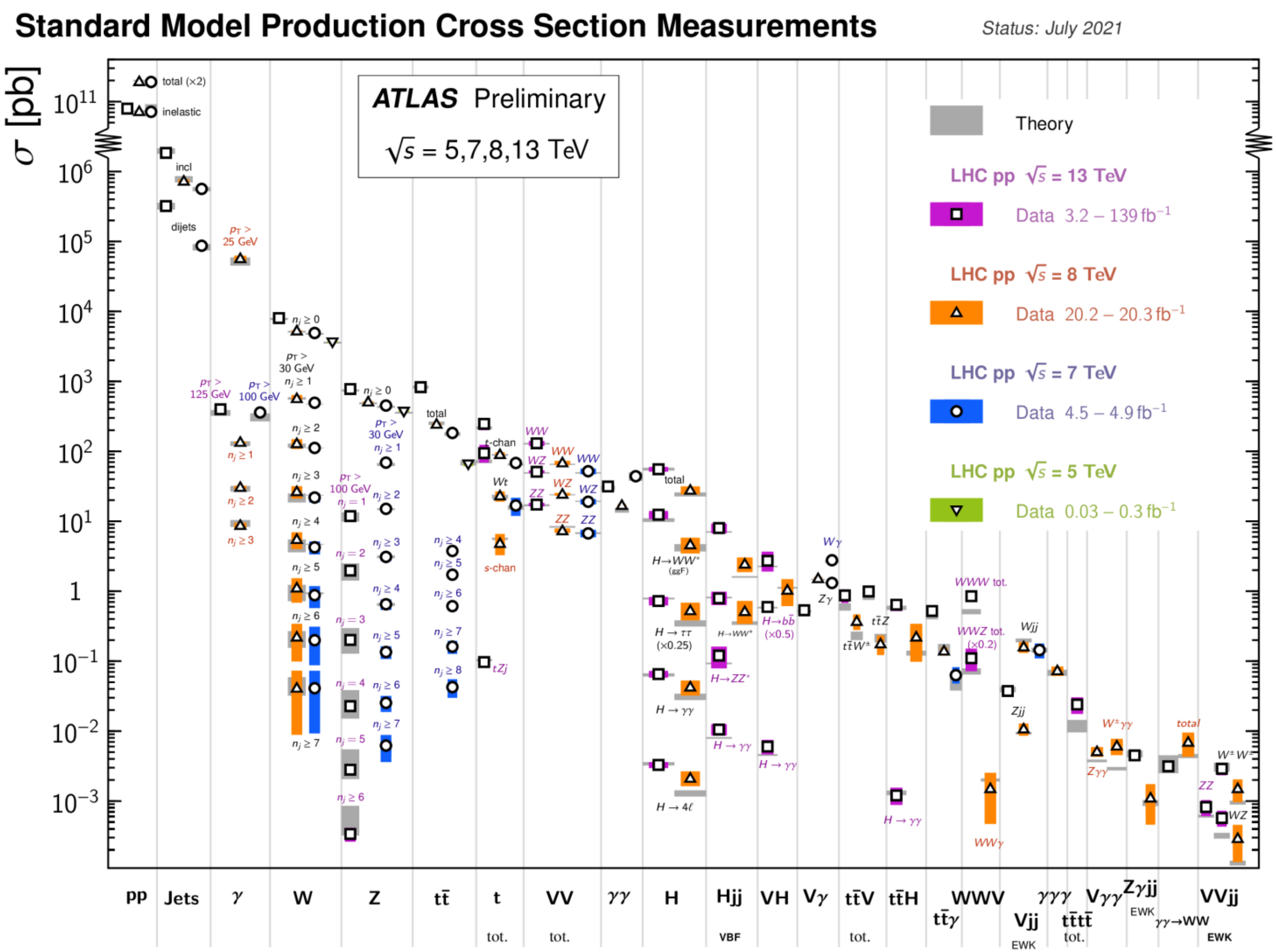
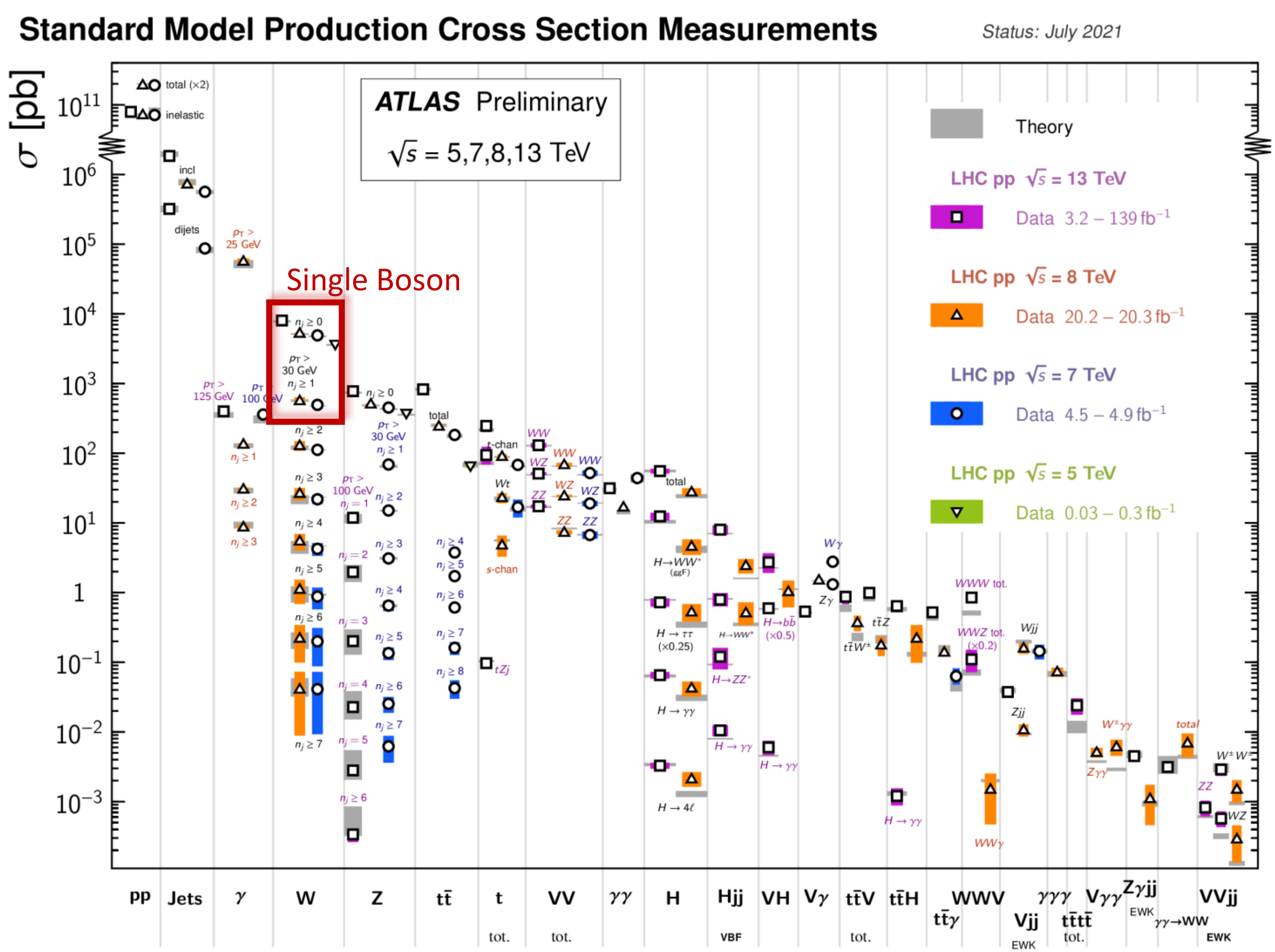

Standard Model Production Cross Section Measurements
Status: July 2021
ATLAS Preliminary
√s = 5,7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 5 TeV
Data 0.03 – 0.3 fb⁻¹
σ [pb]
total (x2)
inelastic
incl
dijets
pp
Jets
γ
W
Z
tt̄
t
tot.
VV
tot.
γγ
H
Hjj
VBF
VH
Vγ
tt̄V
tot.
tt̄H
tt̄γ
WWV
Vjj
EWK
γγγ
tt̄tt̄
tot.
Vγγ
Zγjj
EWK
γγ→WW
VVjj
EWK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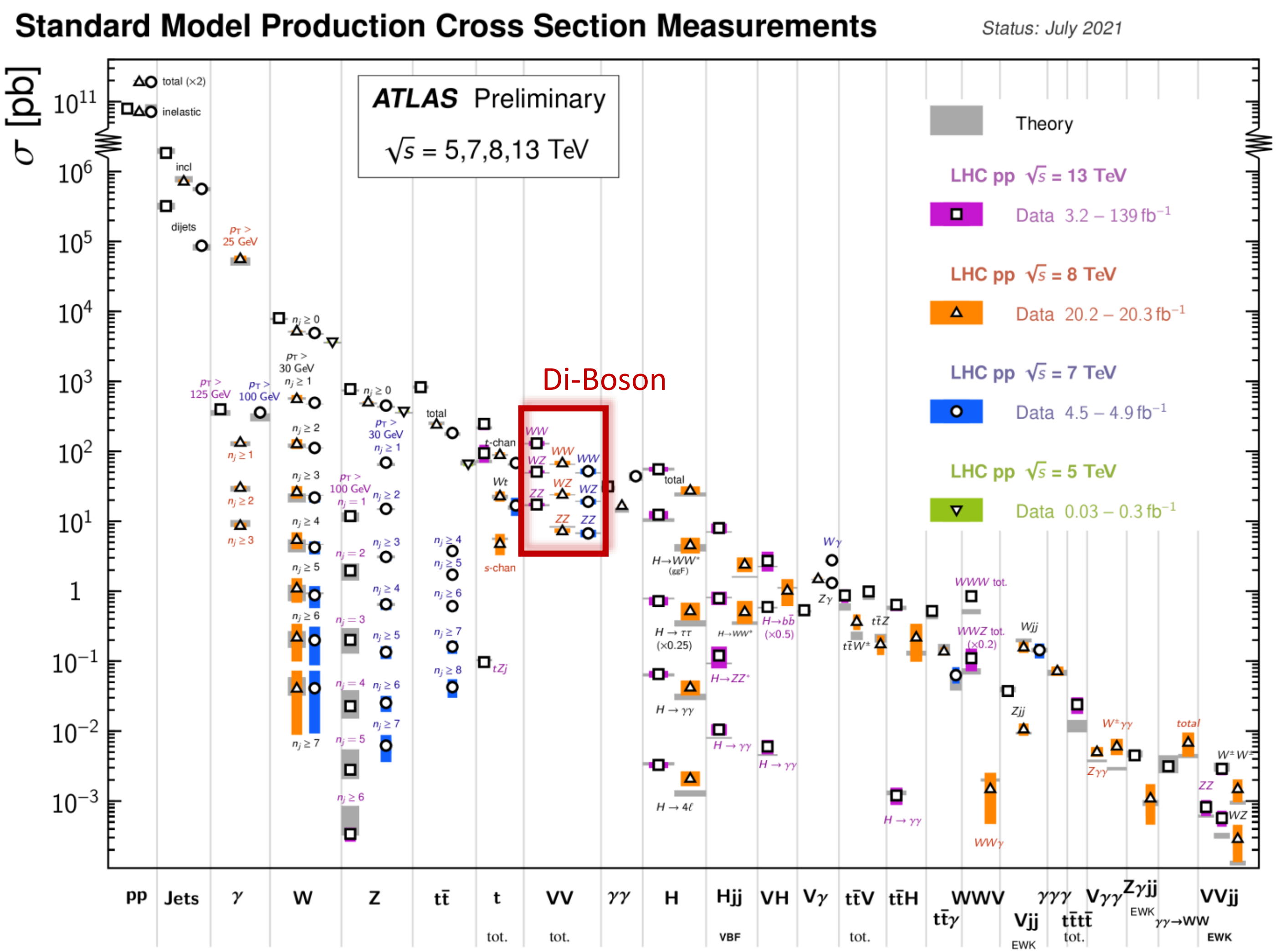
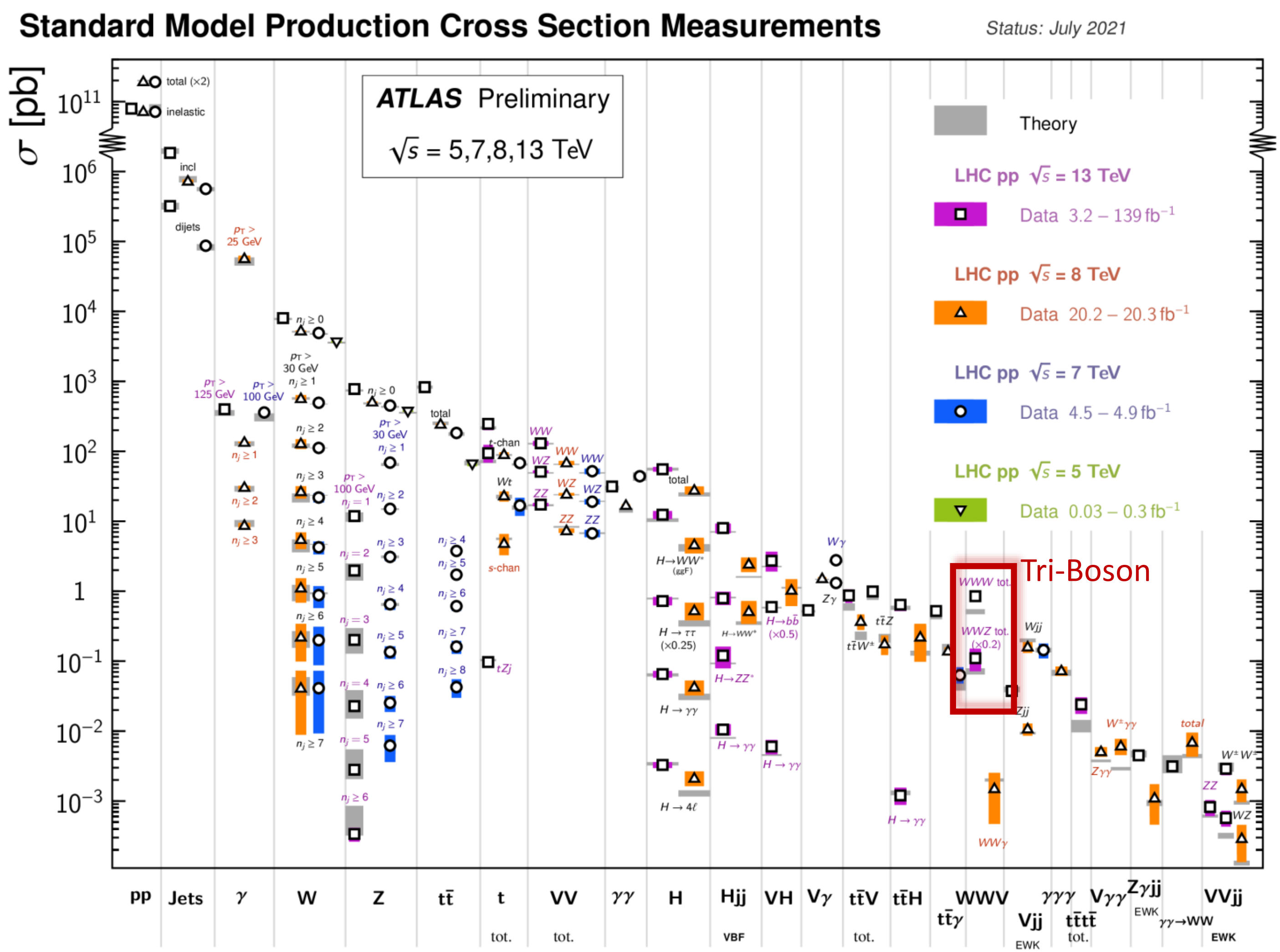
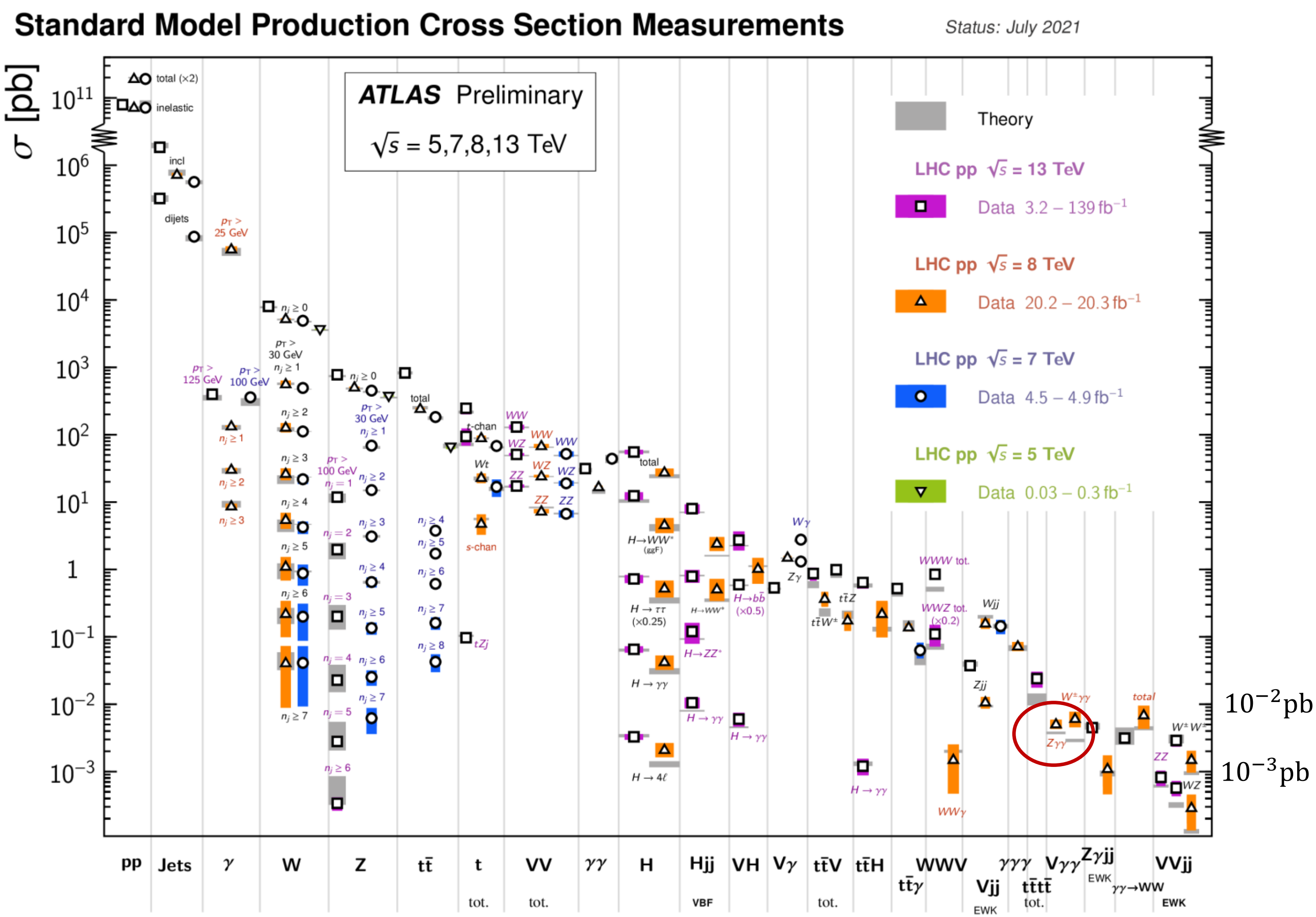
Single Boson
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
tt̄γ
WWV
Vjj
γγγ
tt̄tt̄
Vγγ
Zγjj
γγ→WW
VVjj

ATLAS σ Measurements



ATLAS σ Measurements

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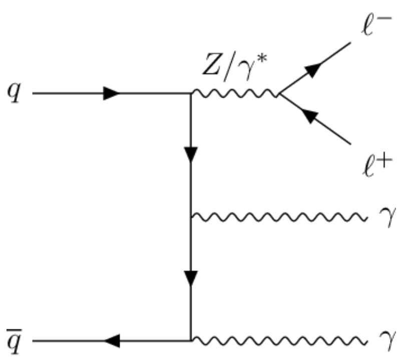
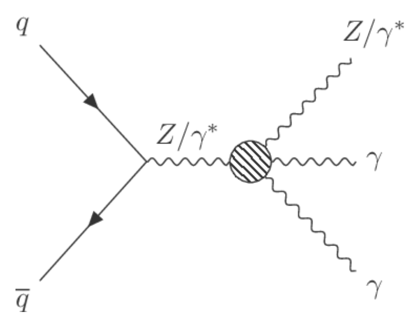
σ [pb]
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Hjj
VH
Vγ
tt̄V
tt̄H
WWV
tt̄γ
Vjj
γγγ
tt̄tt̄
Vγγ
Zγjj
γγ→WW
VVjj
10⁻²pb
10⁻³pb

Overview

- Run2 dataset (2015-2018), fully leptonic $Z(\rightarrow ee, \mu\mu) + \gamma\gamma$
- 2 isolated photons + 1 OSSF lepton pair
- Integrated + differential cross section @ particle level



SM $Z\gamma\gamma$ production



New physics contribution

Background Contamination

Background contamination in the signal region

- Any process with photons and charged same-flavour leptons
- Limited performance of particle identification algorithms

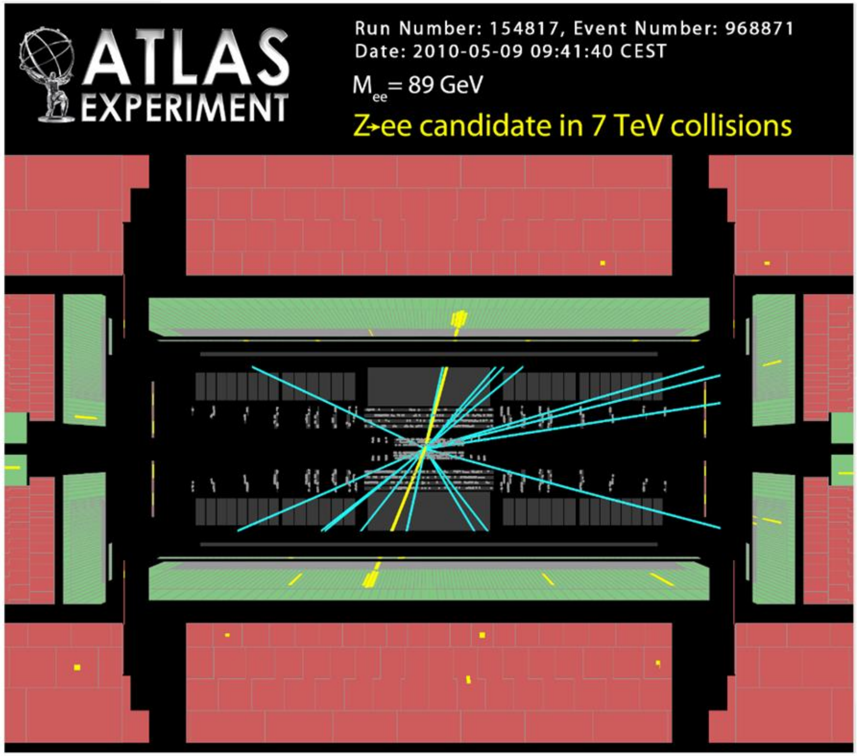
Minor backgrounds

- $t\bar{t}\gamma\gamma$ process, 2 leptons from $t \to Wb$ chain
- $ZZ \to llll$ ($e \to \gamma$ fakes)

Dominant background

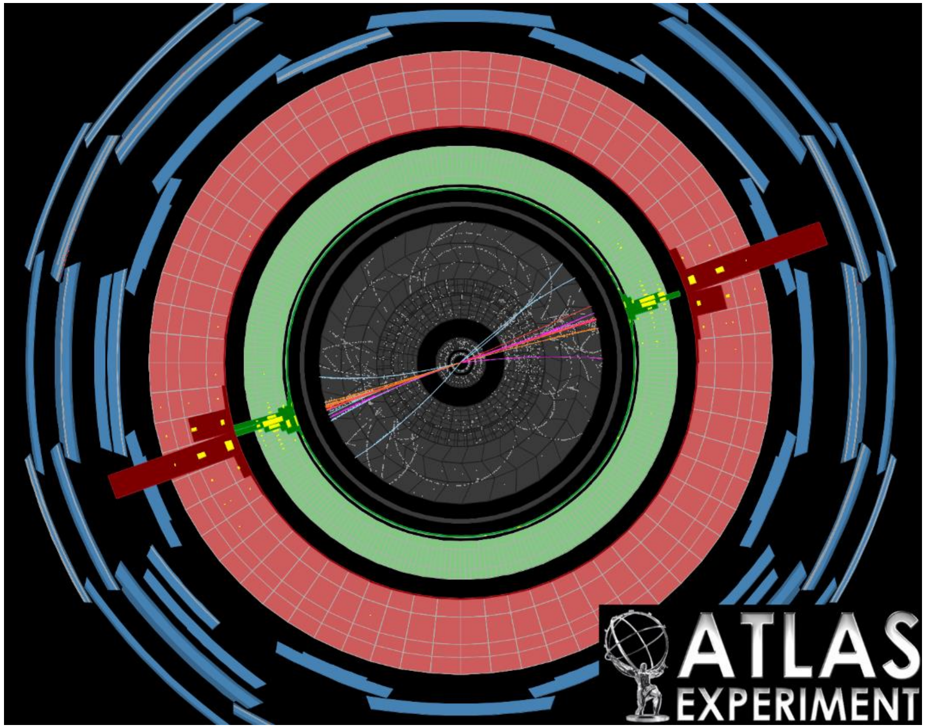
- Non-prompt photon production in jets

Electrons

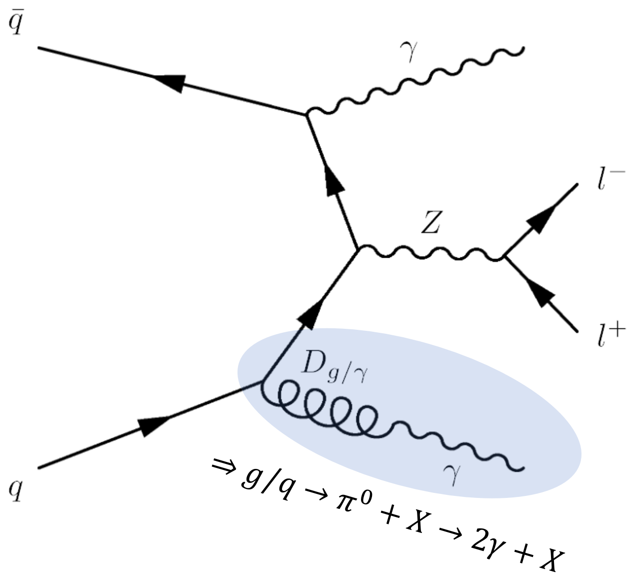


(Missing track in ID → fake photon)
Contamination of $ZZ \to llll$

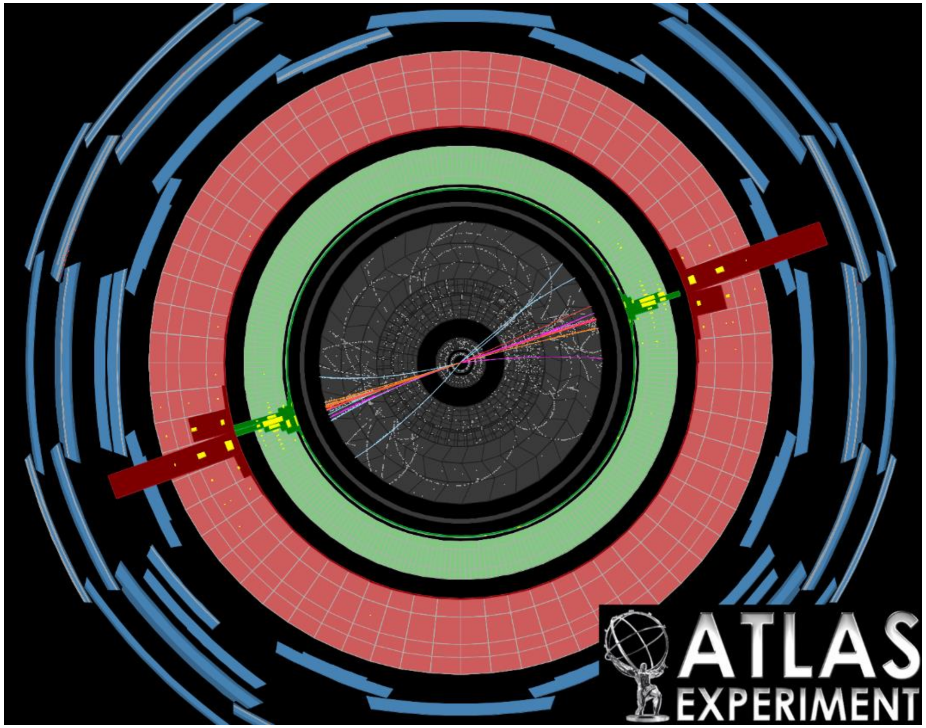
Jets



(Non-prompt γ production within jets)



Jets



(Non-prompt γ production within jets)

Fake Photons from jets

- Non-prompt photons surrounded by jet remnants

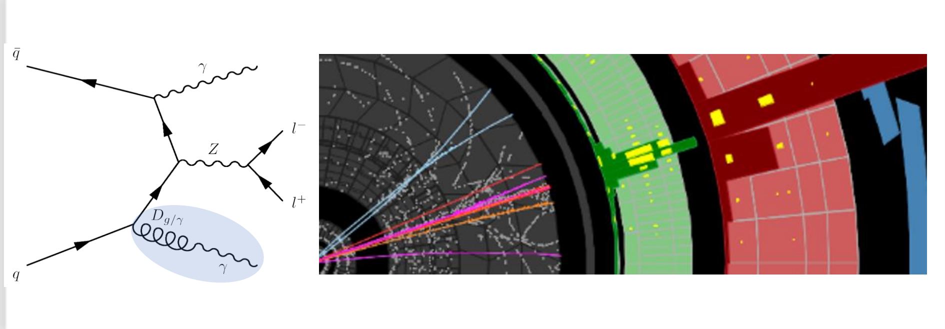
  $\Rightarrow$ Large isolation energy, hadronic activity

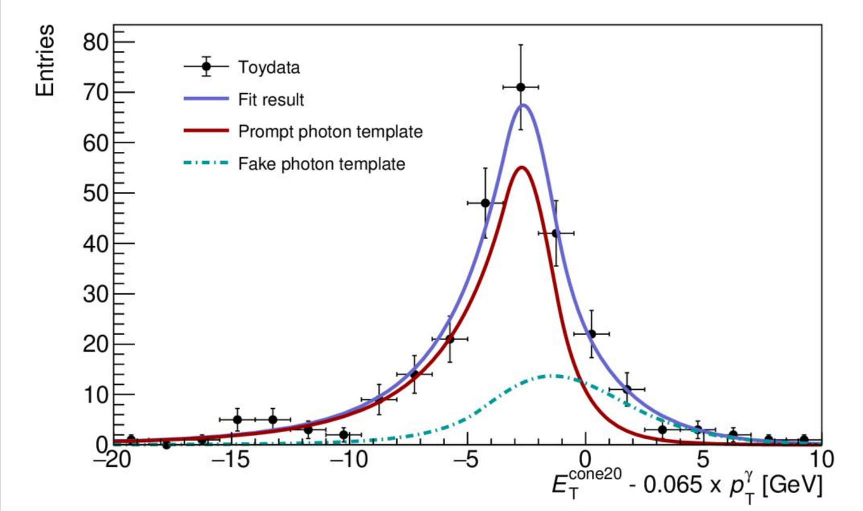
- Derive templates for prompt/non-prompt γ

  $\Rightarrow Z\gamma\gamma$ signal, $Z\gamma j + Zj\gamma + Zjj$ backgrounds

- Fit templates to measured isolation energy in data

  $\Rightarrow$ *2D Template Fit*





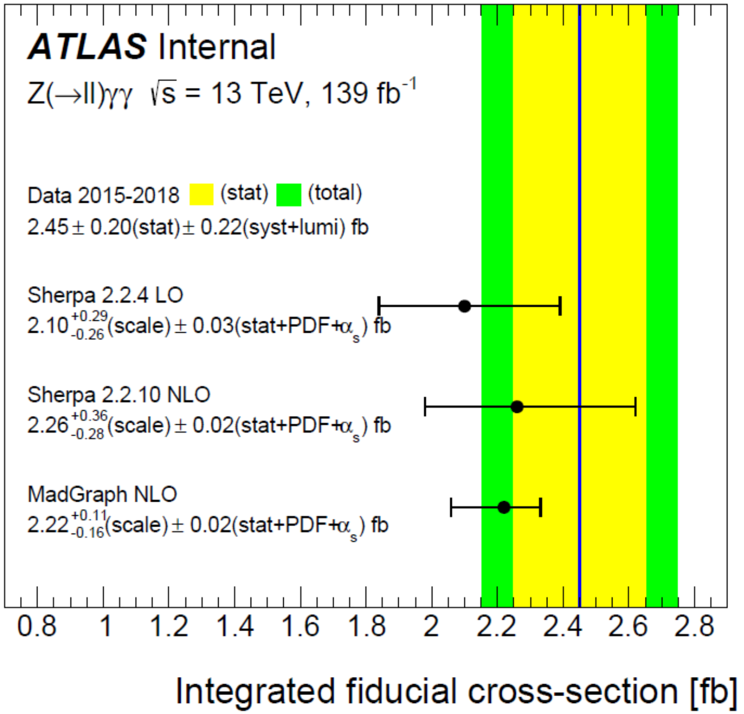
	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
N^{obs}	148	171
$N_{j\to\gamma\, fakes}$	$29.8 \pm 5.7\ (stat.) \pm 5.5\ (sys.)$	$34.4 \pm 6.6\ (stat.) \pm 6.3\ (sys.)$
$N_{t\bar{t}\gamma\gamma}$	$6.4 \pm 0.4\ (stat.) \pm 1.4\ (sys.)$	$8.4 \pm 0.5\ (stat.) \pm 1.8\ (sys.)$
$N_{\ell\ell\ell\ell}$	$1.03 \pm 0.10\ (stat.) \pm 0.51\ (sys.)$	$1.2 \pm 0.11\ (stat.) \pm 0.6\ (sys.)$
$N_{WZ\gamma}$	$0.69 \pm 0.06\ (stat.) \pm 0.35\ (sys.)$	$0.52 \pm 0.05\ (stat.) \pm 0.26\ (sys.)$
N_{ZH}	$1.08 \pm 0.01\ (stat.) \pm 0.22\ (sys.)$	$1.38 \pm 0.01\ (stat.) \pm 0.28\ (sys.)$
$N_{Z\gamma+\gamma}$	$2.07 \pm 0.16\ (stat.) \pm 0.72\ (sys.)$	$2.74 \pm 0.21\ (stat.) \pm 0.96\ (sys.)$
$N_{Z+\gamma\gamma}$	$1.44 \pm 0.04\ (stat.) \pm 0.39\ (sys.)$	$1.90 \pm 0.05\ (stat.) \pm 0.51\ (sys.)$
N_{sig}^{data}	$105.5 \pm 12.2\ (stat.) \pm 8.1\ (sys.)$	$120.4 \pm 13.1\ (stat.) \pm 9.4\ (sys.)$
$N_{sig}^{\text{Sherpa LO}}$	$83.0 \pm 1.9\ (stat.)$	$112.2 \pm 2.2\ (stat.)$
$N_{sig}^{\text{Sherpa NLO}}$	$91.5 \pm 0.9\ (stat.)$	$119.5 \pm 1.0\ (stat.)$
$N_{sig}^{\text{MadGraph5\_aMC@NLO}}$	$91.0 \pm 1.0\ (stat.)$	$118.1 \pm 1.2\ (stat.)$

Total event composition

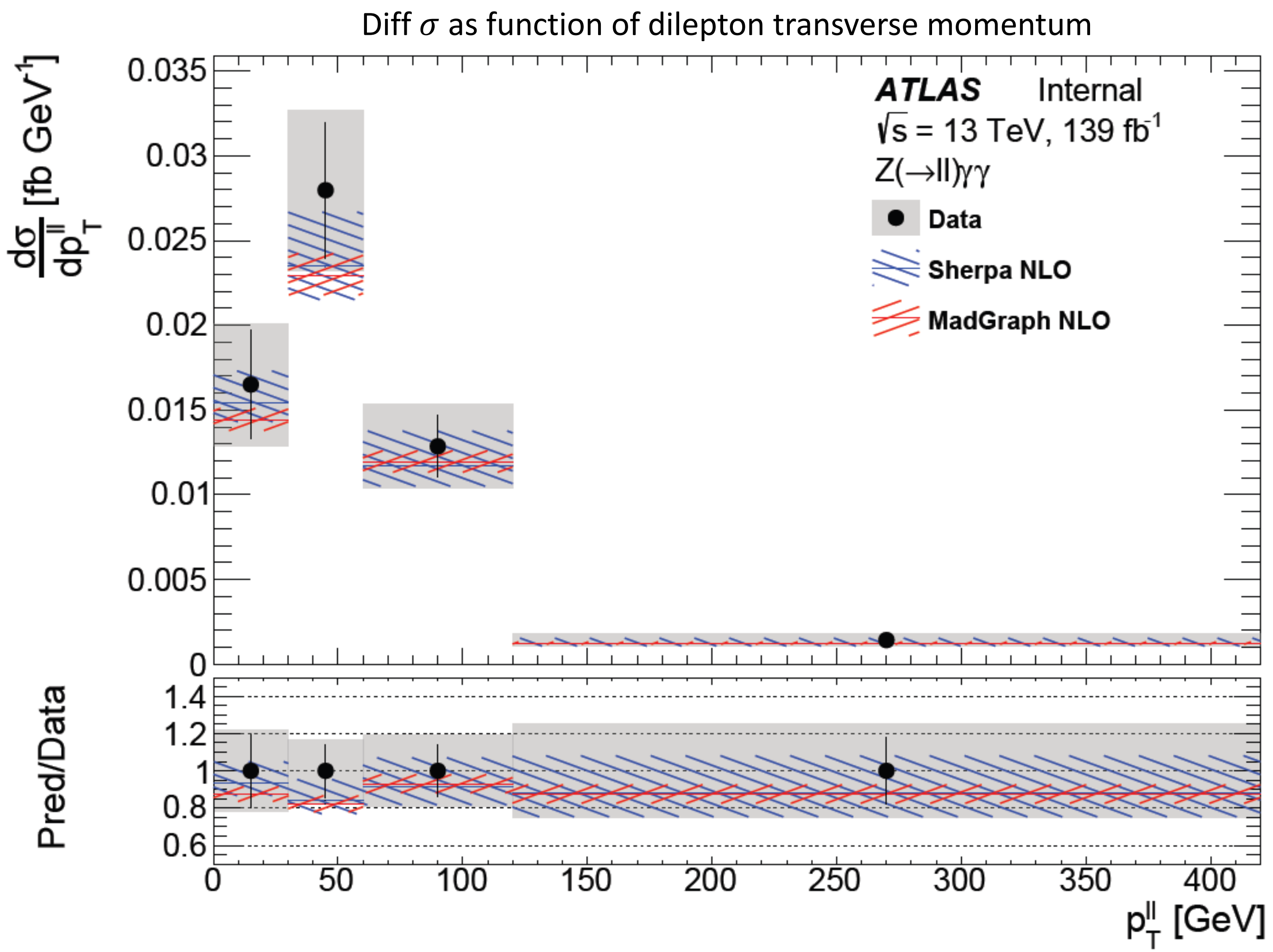
- Background contamination
    - Fakes from jets: 64 events (20%)
    - $t\bar{t}\gamma\gamma$: 15 events (5%)
    - $e \to \gamma$ fakes: 2 events (<1%)
- Dominant $Z\gamma\gamma$ signal process: 226 events (71%)

Integrated cross section

- σ measured @ particle level
  - ⇒ Correct for detector effects
  - (inefficiency of particle reconstruction, ..)
- $\sigma^{ll\gamma\gamma} = 2.45 \pm 0.20(\text{stat}) \pm 0.22(\text{syst})$ fb
- *Good agreement* between measurement and EW predictions

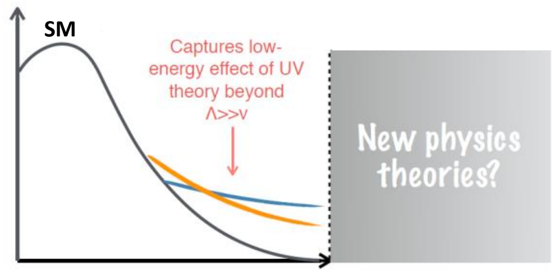


Measured Cross Section



Good agreement with EW predictions also differentially

- **E**ffective **F**ield **T**heory
- Direct search for new physics (@ large scales) not always feasible
  - LHC upper boundary $(13 \times \hat{x})$ TeV



- *Use current SM measurements to constrain NP parameters*

- Starting point: SM Lagrangian of dimension $d \leq 4$
- Add higher dimension terms that fulfill SM symmetries

SM / NP

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \ldots$$

Λ: scale of NP

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

Reduces to L_{SM} for $\Lambda \to \infty$

O_i^d: Operator of dimension d + coefficient f_i^d

Constructing the Lagrangian

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{f_i^d}{\Lambda^{d-4}} O_i^d$$

- Which dimension do we need?
- Uneven dimension (5,7,..) operators violating baryon/lepton conservation
- Dimension 6? Introduces TGC and QGC, can not give rise to neutral QGC

⇒ Dimension 8? Only QGC, also valid for neutral bosons

⇒ Suppression by Λ^4, SM contribution expected to dominate

Procedure of generating new samples

- MadGraph5 for matrix element, Pythia8 for parton shower
  - *generate p p > l+ l- a a*
- Add contributions of dimension-8 operators (*transverse operators* O_{T0-T9})
- How to combine SM + NP in matrix element?

$$\left|A_{SM} + \sum_i c_i A_i\right|^2 = \underbrace{|A_{SM}|^2}_{\text{SM}} + \sum_i \underbrace{c_i 2Re(A_{SM} A_i)}_{\text{interference term (lin)}} + \sum_i \underbrace{{c_i}^2 |A_i|^2}_{\text{quadratic term (quad)}} + \sum_{ij, i \neq j} \underbrace{c_i c_j 2Re(A_i A_j)}_{\text{cross term (neglected)}}$$

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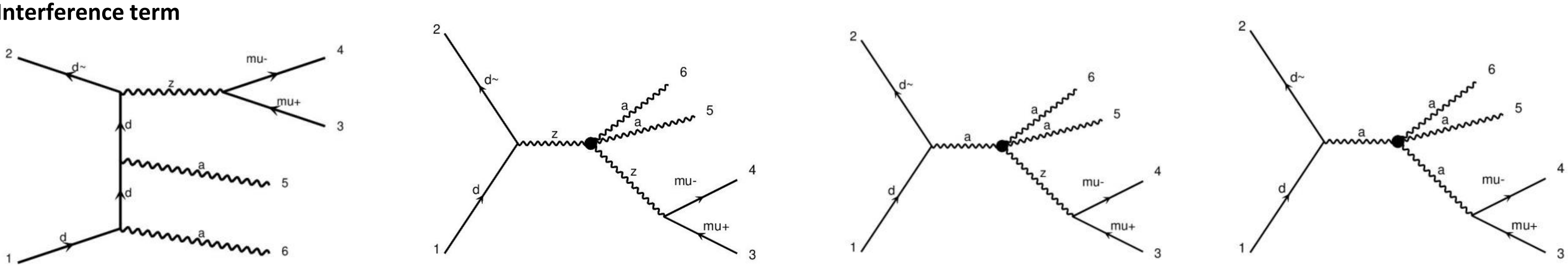
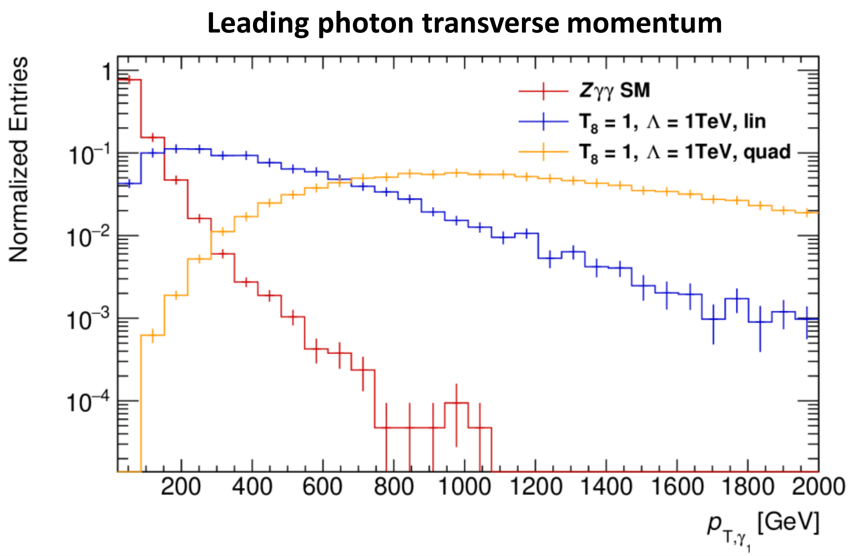
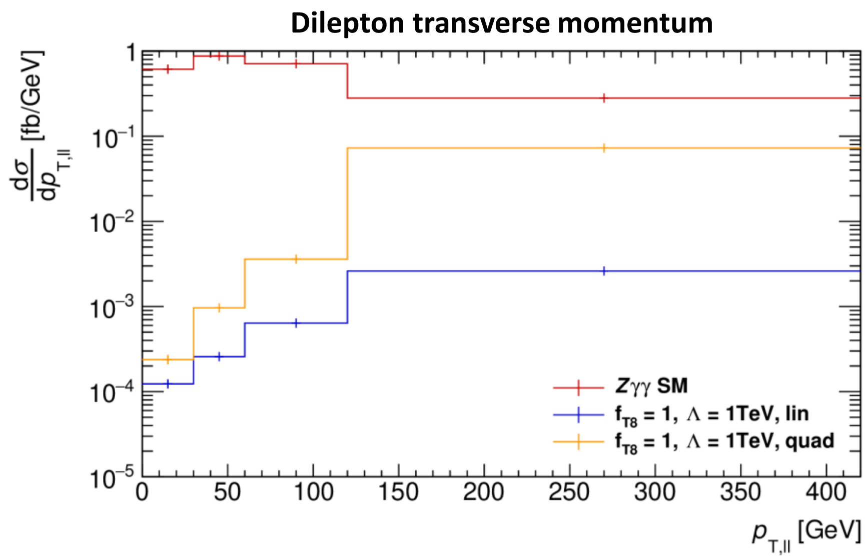
Interference term





- Int: dominates at low energies
- Quad: dominates at large energies

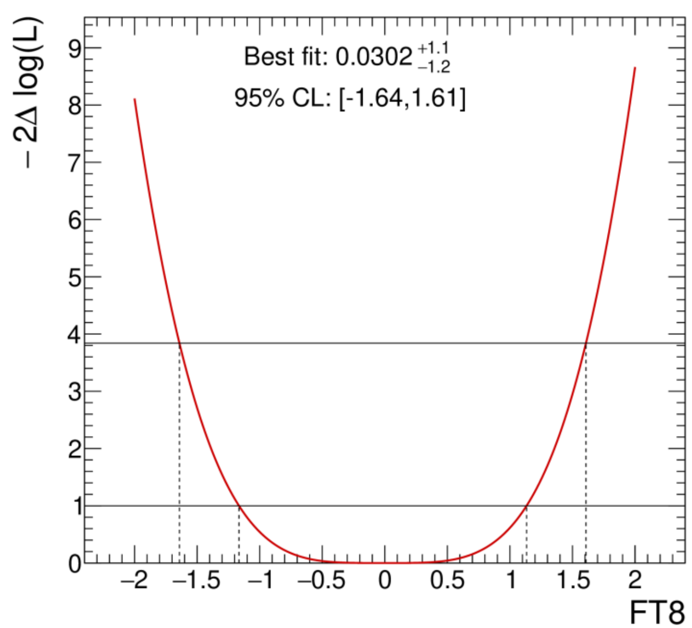


- $p_{\mathrm{T},ll}$ offers largest sensitivity for O_{T0-T8}
- Small EFT contribution in fiducial region

Limit Setting

- Observable p_T^{ll}, what else is needed?
  1. SM $Z\gamma\gamma$ production or data
  2. EFT contribution (lin + quad)
  3. Uncertainties (experimental + theory)

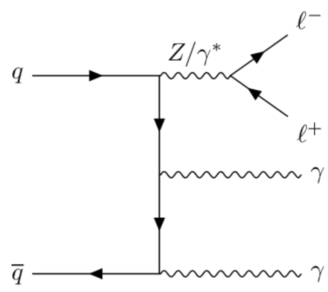
⇒ Profile likelihood ratio allows to extract limits @ 95% CL

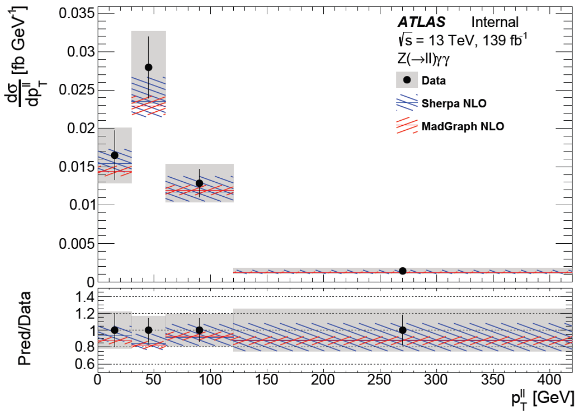


Coefficient	Expected limit [TeV^{-4}]	Observed limit [TeV^{-4}]
$f_{T,0}$	[−8.91, 8.35]	[−9.87, 9.33]
$f_{T,1}$	[−8.92, 8.35]	[−9.88, 9.34]
$f_{T,2}$	[−18.39, 16.68]	[−20.31, 18.68]
$f_{T,5}$	[−4.18, 4.07]	[−4.64, 4.54]
$f_{T,6}$	[−6.33, 6.23]	[−7.04, 6.94]
$f_{T,7}$	[−14.02, 13.48]	[−15.55, 15.04]
$f_{T,8}$	[−1.48, 1.44]	[−1.64, 1.61]
$f_{T,9}$	[−3.03, 2.92]	[−3.36, 3.26]

First T_1, T_2, T_6, T_7 limits in

ATLAS @ 13 TeV





- Triboson production of $Z\gamma\gamma$
- Test SM predictions at small σ + gauge self-interaction

  $\Rightarrow$ Successful prediction of EW interactions

- Sensitivity for dim-8 operators in context of EFT interpretation

Thanks for your attention!

Coefficient	Expected limit [TeV^{-4}]	Observed limit [TeV^{-4}]
$f_{T,0}$	$[-8.91, 8.35]$	$[-9.87, 9.33]$
$f_{T,1}$	$[-8.92, 8.35]$	$[-9.88, 9.34]$
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Backup Slides

Constructing the Lagrangian

- Generate new dim-8 electroweak fields via

  ⇒ Covariant derivative D_μ of Higgs field ϕ

  ⇒ Field strength tensor W_μ^i of *SU(2)* and B_μ of *U(1)*

Transverse, 4 field strength tensors
(no mass limitation)
⇒ 8 Operators

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right] \quad , \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right] \quad , \quad \mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad , \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad , \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \; .$$

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

Longitudinal, 4 Higgs derivatives
(exactly 4 massive bosons)
⇒ 3 Operators

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad , \quad \mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} \quad , \quad \mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} + \mathrm{h.c.}$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right] \quad .$$

Mixed, 2 Higgs derivatives + 2 field strength tensors
(at least 2 massive bosons)
⇒ 7 Operators

Constructing the Lagrangian

- Generate new dim-8 electroweak fields via
  - ⇒ Covariant derivative D_μ of Higgs field ϕ
  - ⇒ Field strength tensor W_μ^i of *SU(2)* and B_μ of *U(1)*

Transverse, 4 field strength tensors
(no mass limitation)
⇒ 8 Operators

most promising

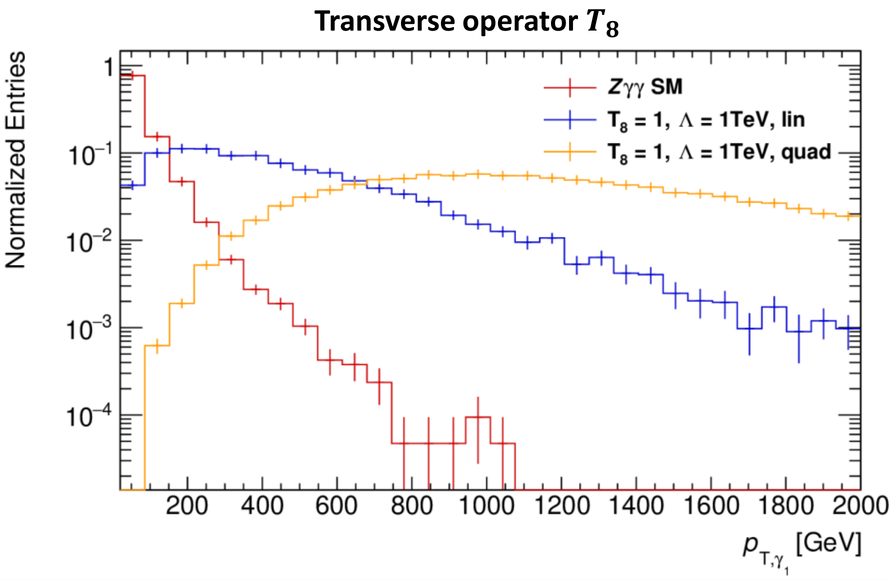
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

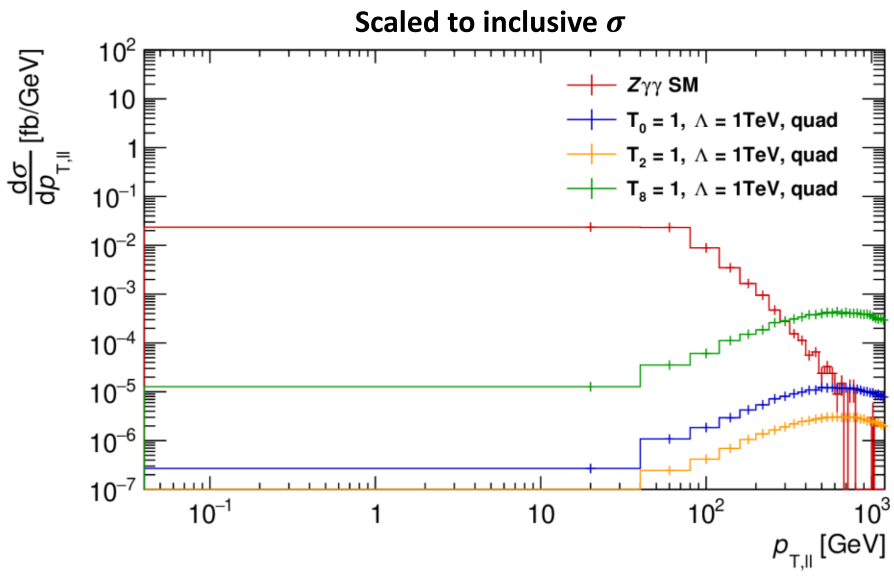
Longitudinal, 4 Higgs derivatives
(exactly 4 massive bosons)
⇒ 3 Operators

Mixed, 2 Higgs derivatives + 2 field strength tensors
(at least 2 massive bosons)
⇒ 7 Operators

Rivet routine

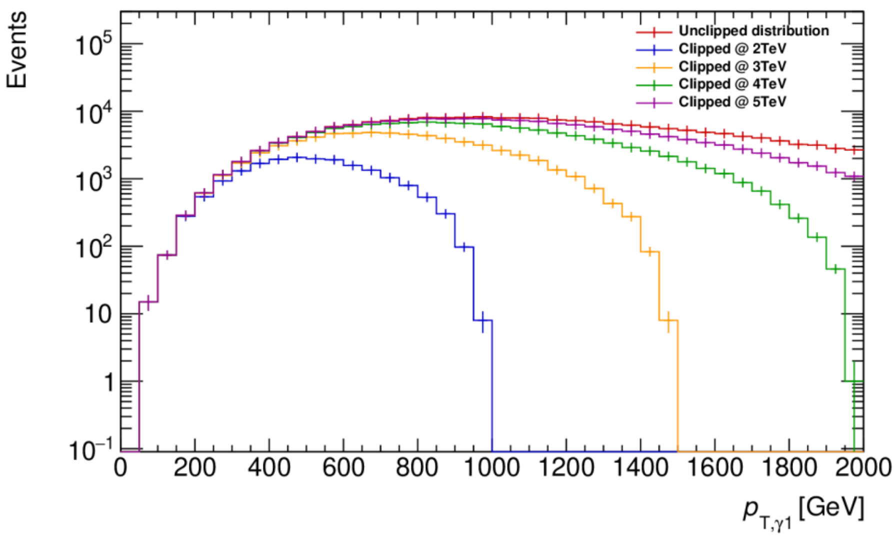
- Goal: measure inclusive + differential cross section @ fiducial phase space
- Read HepMC (SM, lin, quad) data in Rivet and apply fiducial selection
  - ⇒ Mimics detector-level selection
  - ⇒ Rivet provides final state particles, easy to apply selection

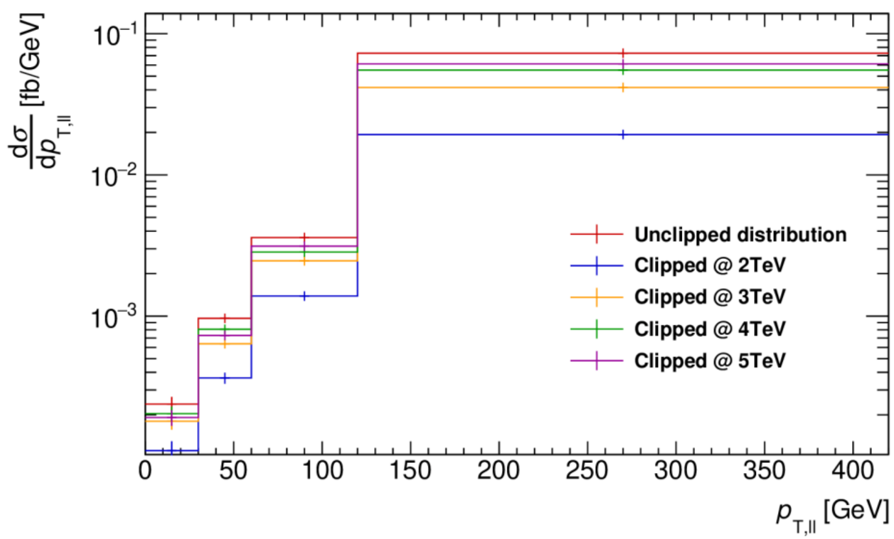




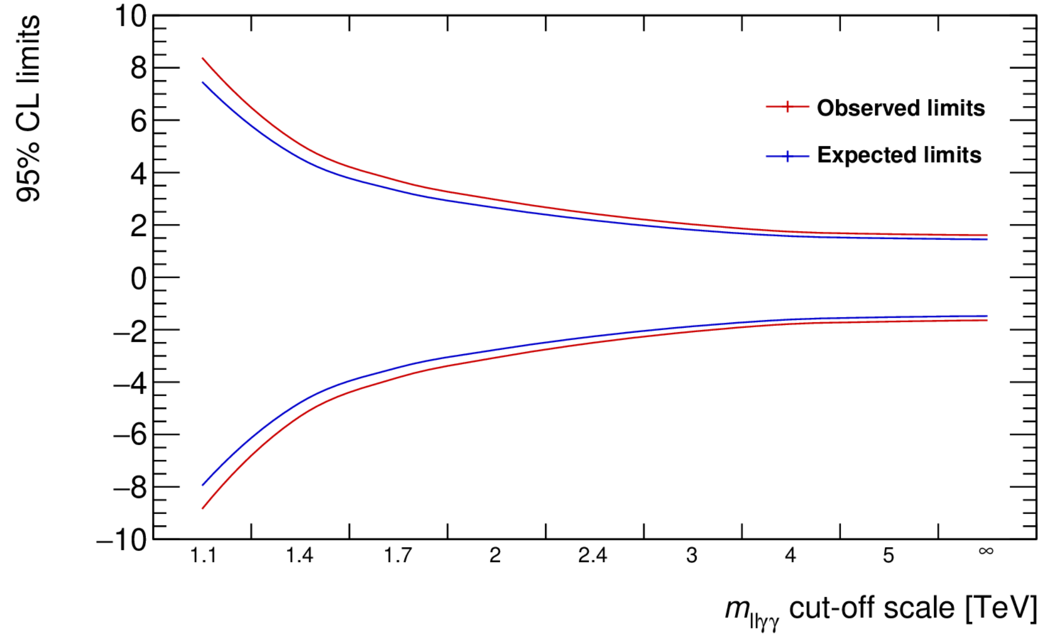
Restoring Unitarity

- EFT violates unitarity at large energy scales
- EFT contributions *clipped* for energies exceeding scale E_c
  - Scale choice: $m_{ll\gamma\gamma}$
- Clipping is done at parton level, *before* parton shower
  - $m_{ll\gamma\gamma}$ formed per event using LHE file and *lhe_parser.py*





Evolution of limits for O_{T_8}



Observed limits for all clipping thresholds

Coefficient	E_c = 1.1 TeV	E_c = 1.4 TeV	E_c = 1.7 TeV	E_c = 2.0 TeV	E_c = 2.4 TeV	E_c = 3 TeV	E_c = 4 TeV	E_c = 5 TeV	$E_c = \infty$
$f_{T,0}/\Lambda^4$	[−47.03, 41.06]	[−29.62, 26.38]	[−21.61, 19.56]	[−17.36, 15.90]	[−14.24, 13.19]	[−11.91, 11.15]	[−10.49, 9.88]	[−10.05, 9.48]	[−9.87, 9.33]
$f_{T,1}/\Lambda^4$	[−47.03, 41.06]	[−29.62, 26.38]	[−21.61, 19.56]	[−17.36, 15.90]	[−14.24, 13.20]	[−11.91, 11.14]	[−10.50, 9.89]	[−10.05, 9.49]	[−9.88, 9.34]
$f_{T,2}/\Lambda^4$	[−97.67, 80.00]	[−60.73, 51.23]	[−44.42, 38.33]	[−35.51, 31.27]	[−29.16, 26.07]	[−24.55, 22.27]	[−21.51, 19.71]	[−20.67, 18.99]	[−20.31, 18.68]
$f_{T,5}/\Lambda^4$	[−23.80, 22.94]	[−14.18, 13.68]	[−10.47, 10.12]	[−8.28, 8.02]	[−6.83, 6.65]	[−5.67, 5.54]	[−4.95, 4.84]	[−4.72, 4.62]	[−4.64, 4.54]
$f_{T,6}/\Lambda^4$	[−34.83, 33.44]	[−21.56, 20.88]	[−15.76, 15.35]	[−12.67, 12.37]	[−10.31, 10.11]	[−8.67, 8.52]	[−7.52, 7.41]	[−7.19, 7.08]	[−7.04, 6.94]
$f_{T,7}/\Lambda^4$	[−81.59, 75.19]	[−49.88, 46.50]	[−35.44, 33.43]	[−28.46, 26.99]	[−23.19, 22.15]	[−19.30, 18.55]	[−16.73, 16.14]	[−15.85, 15.33]	[−15.55, 15.04]
$f_{T,8}/\Lambda^4$	[−8.83, 8.37]	[−5.29, 5.07]	[−3.81, 3.67]	[−3.05, 2.95]	[−2.49, 2.42]	[−2.07, 2.01]	[−1.78, 1.74]	[−1.69, 1.65]	[−1.64, 1.61]
$f_{T,9}/\Lambda^4$	[−17.71, 16.36]	[−10.45, 9.80]	[−7.78, 7.35]	[−6.25, 5.94]	[−5.06, 4.85]	[−4.18, 4.03]	[−3.62, 3.51]	[−3.44, 3.33]	[−3.36, 3.26]

EFT Interpretation – ATLAS Limits

Strength of limits

- Few 8 TeV + one 13 TeV measurement (Closure)
- First T_1, T_2, T_6, T_7 limits in ATLAS @ 13 TeV

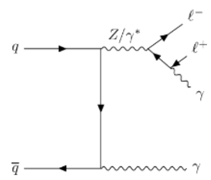
Coefficient	Limit $[\mathrm{TeV}^{-4}]$
f_{T0} (13TeV)	[-0.095,0.085]
f_{T1} (8TeV)	[-200,200] → [-9.88,9.34]
f_{T2} (8TeV)	[-400,400] → [-20.31,18.68]
f_{T5} (13TeV)	[-0.09,0.10]
f_{T6} (8TeV)	[-1900,1900] → [-7.04,6.94]
f_{T7} (8TeV)	[-4300,4300] → [-15.55,15.04]
f_{T8} (13TeV)	[-0.06,0.06]
f_{T9} (13TeV)	[-0.13,0.13]

Limits from $WV\gamma$, $Z\gamma$ dijet, $Z\gamma\gamma$, $W\gamma\gamma$

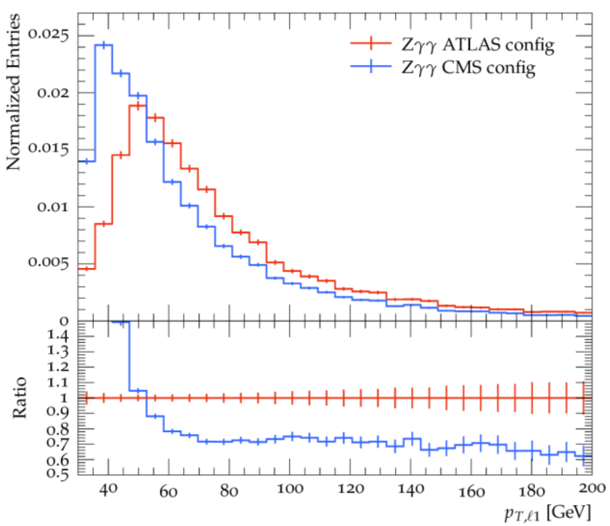
Coefficient	Expected limit $[\mathrm{TeV}^{-4}]$	Observed limit $[\mathrm{TeV}^{-4}]$
$f_{T,0}$	$[-8.91, 8.35]$	$[-9.87, 9.33]$
$f_{T,1}$	$[-8.92, 8.35]$	$[-9.88, 9.34]$
$f_{T,2}$	$[-18.39, 16.68]$	$[-20.31, 18.68]$
$f_{T,5}$	$[-4.18, 4.07]$	$[-4.64, 4.54]$
$f_{T,6}$	$[-6.33, 6.23]$	$[-7.04, 6.94]$
$f_{T,7}$	$[-14.02, 13.48]$	$[-15.55, 15.04]$
$f_{T,8}$	$[-1.48, 1.44]$	$[-1.64, 1.61]$
$f_{T,9}$	$[-3.03, 2.92]$	$[-3.36, 3.26]$

CMS $Z\gamma\gamma$ analysis

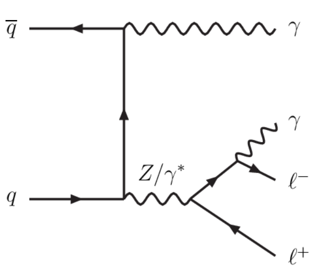
- Paper published May 28th, 2021
- Significance of 4.8σ
- Different phase space selection
  - Most notably: FSR included

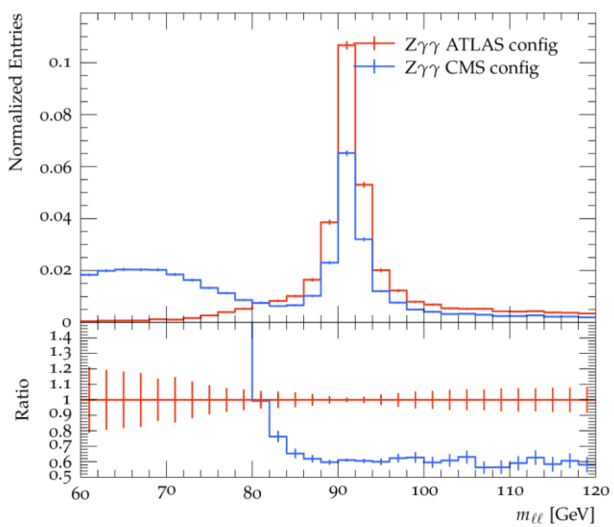


Parameter	$Z\gamma\gamma$ (TeV^{-4}) Expected	Observed
f_{M2}/Λ^4	—	—
f_{M3}/Λ^4	—	—
f_{T0}/Λ^4	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	[−1.54, 1.54]	[−1.82, 1.82]

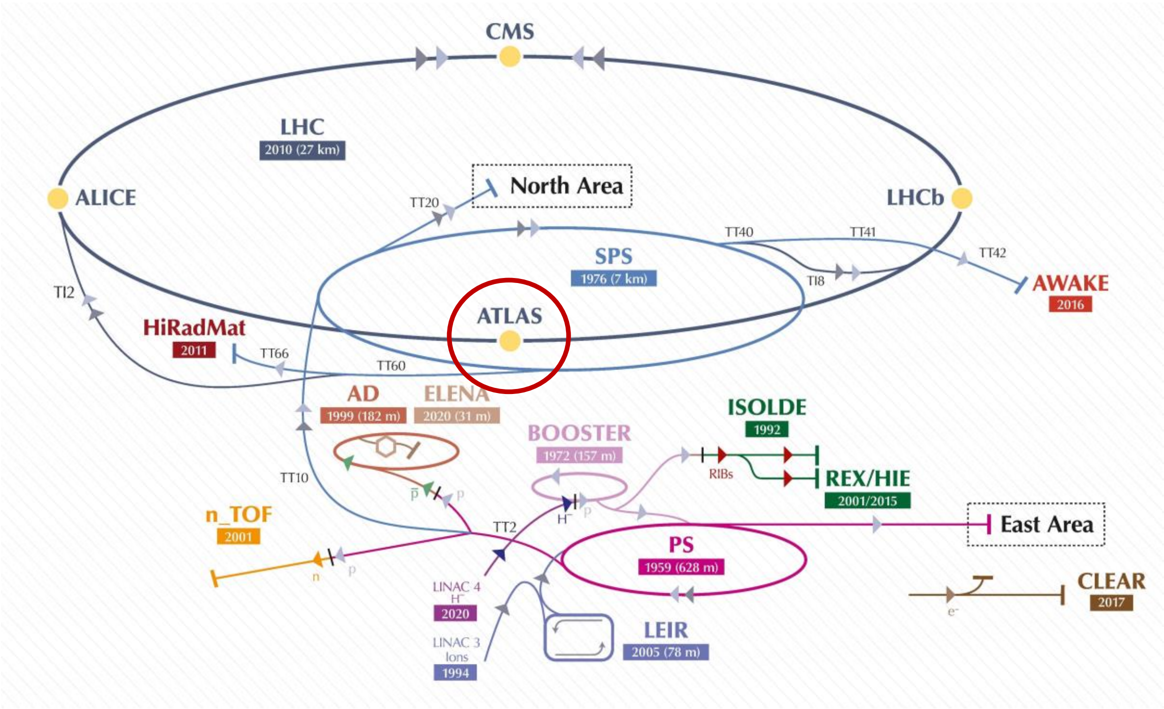


CMS Lepton kinematics affected by FSR





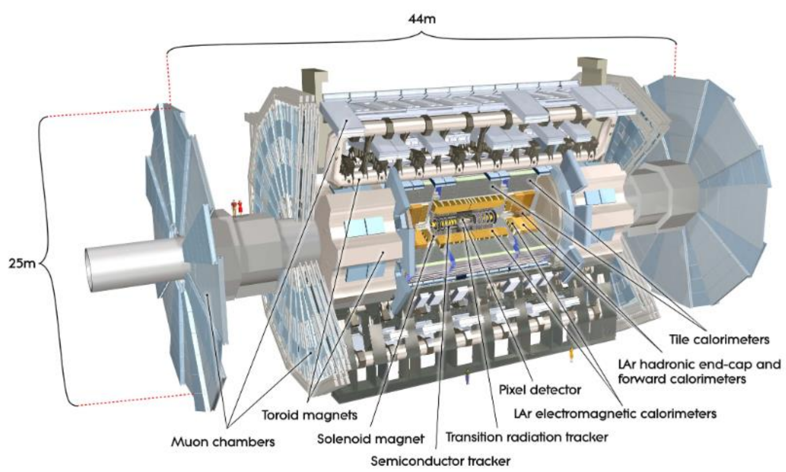
- World's largest/most-powerful particle collider
- Located close to Geneva (Border of France-Switzerland)
- LHC accelerates p-p, Pb-Pb, Xe-Xe ions at energies up to $\sqrt{s} = 13$ TeV
  - ⇒ Two beam pipes guiding beams in opposite direction
  - ⇒ Beam consists of >2000 bunches with 10^{11} protons
- Major data-taking periods: Run-2 (2015-2018), Run-3 (2022-2025)

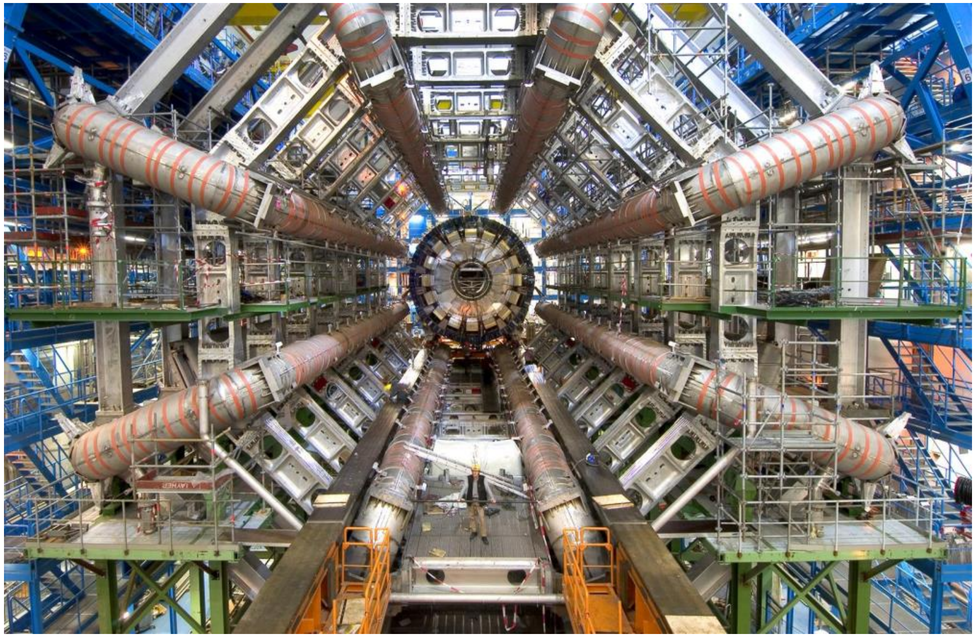


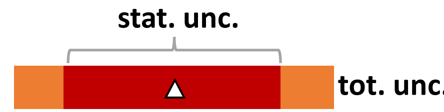
A Toroidal LHC ApparatuS

- General-purpose detector with $\sim 4\pi$ coverage
- $44\mathrm{m}$ long, diameter of $25\mathrm{m}$
- $25\mathrm{ns}$ bunch spacing $\rightarrow$ collisions @ $40\mathrm{MHz}$ $\rightarrow$ $1\mathrm{kHz}$ (trigger system)
- Consists of multiple sub-detectors + magnetic system surrounding interaction point
  - ⇒ Inner Detector: track reconstruction of charged particles
  - ⇒ Calorimeter: electromagnetic (e,γ,jets), hadronic (jets)
  - ⇒ Muon Spectrometer (μ)

innermost to outermost





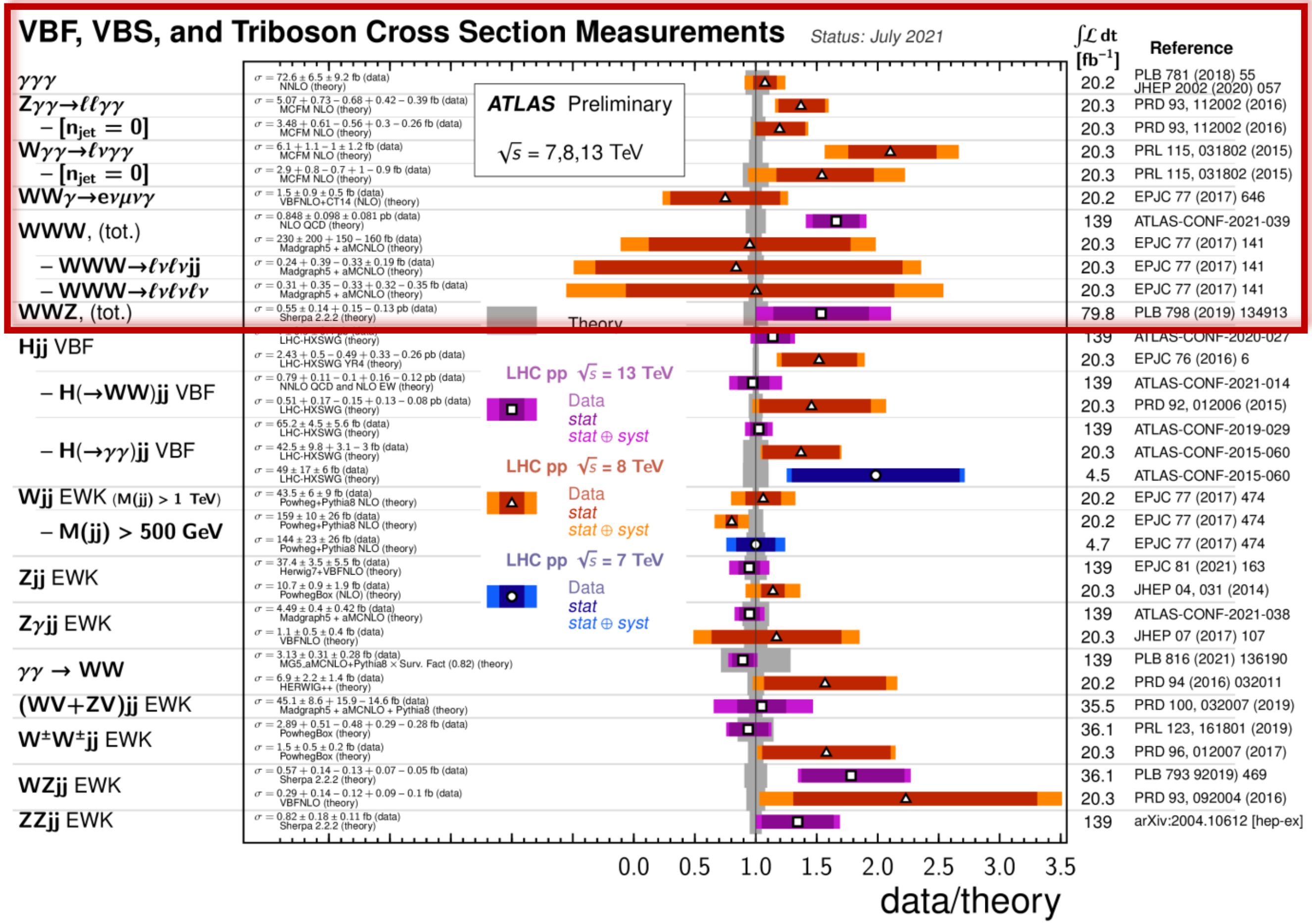


2012 $Z\gamma\gamma$ analysis: 20.3 fb^{-1}

Run 2: 139 fb^{-1}

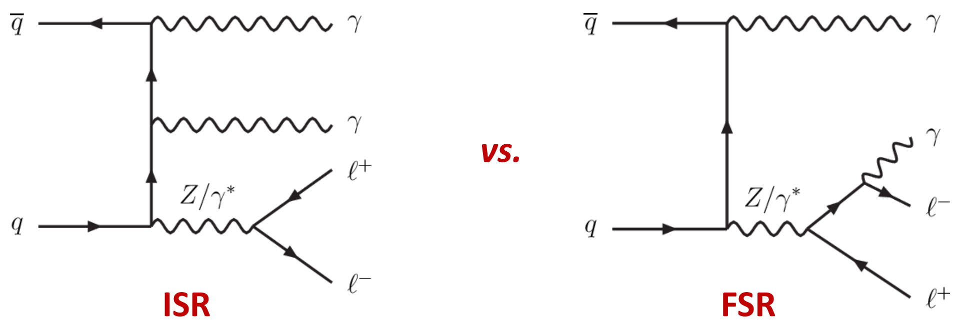
$N = \sigma \times L_{\text{int}}$

$7\times$ luminosity



Rejection of Final State Radiation

- Photons emitted from initial quark lines (ISR) *or* charged leptons (FSR)

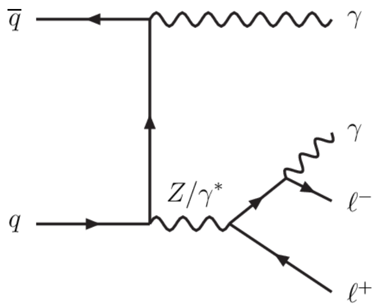


- 8 TeV $Z\gamma\gamma$ analysis included FSR

⇒ Rejection of FSR selects prompt/pure TGP

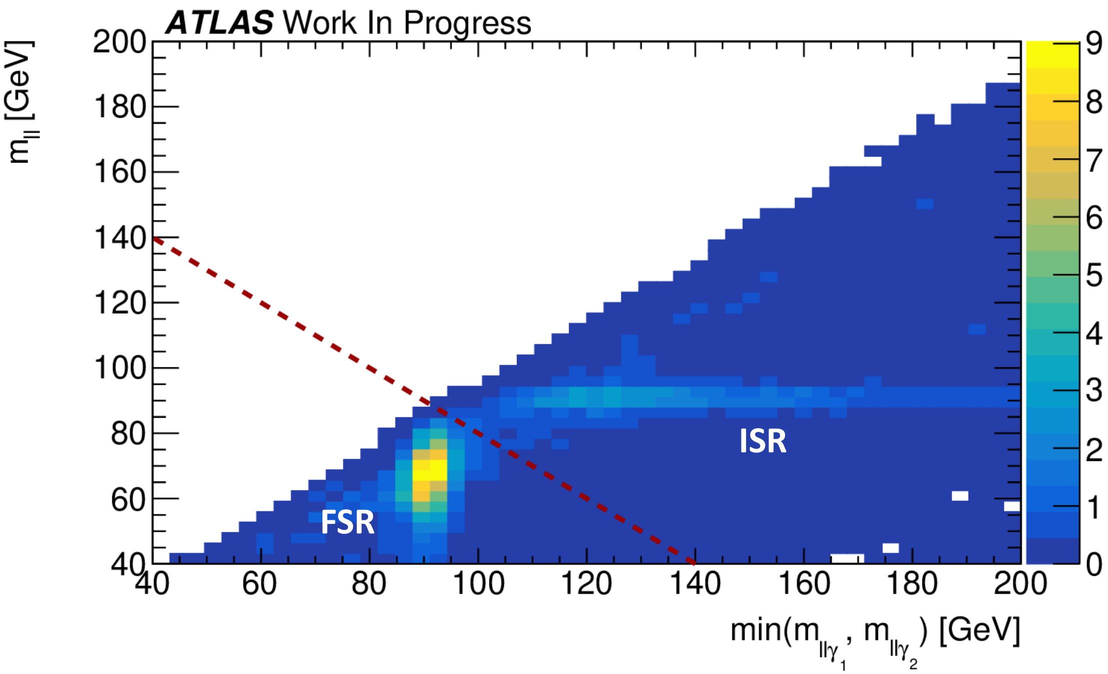
FSR Rejection

- (Invariant mass $m_{ll} > 40$ GeV)
- $m_{ll} + \min(m_{ll,\gamma_1}, m_{ll,\gamma_2}) > 2 \times m_{Z,\text{PDG}}$
  - $m_{ll} < Z$ boson mass
  - $m_{ll,\gamma_{1,2}} \sim Z$ boson mass

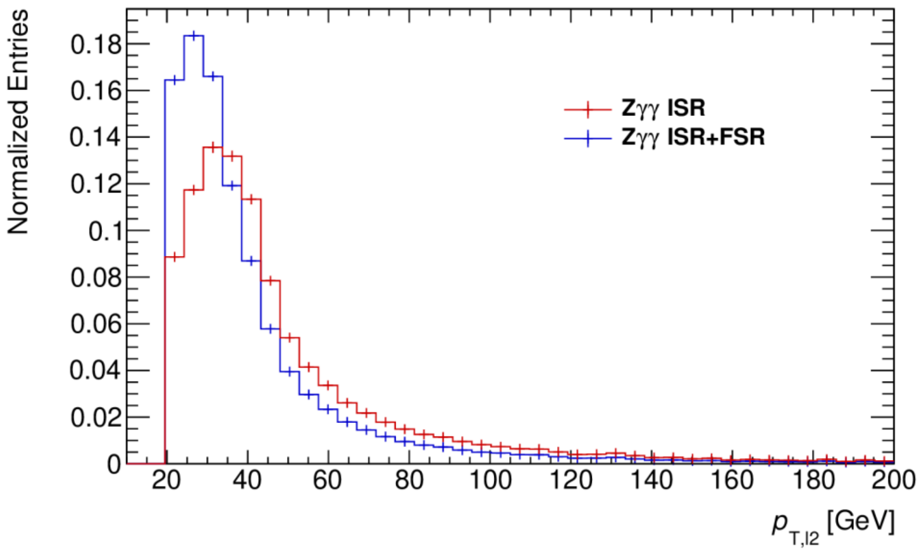


$Z\gamma\gamma$ signal MC sample (NLO in QCD)

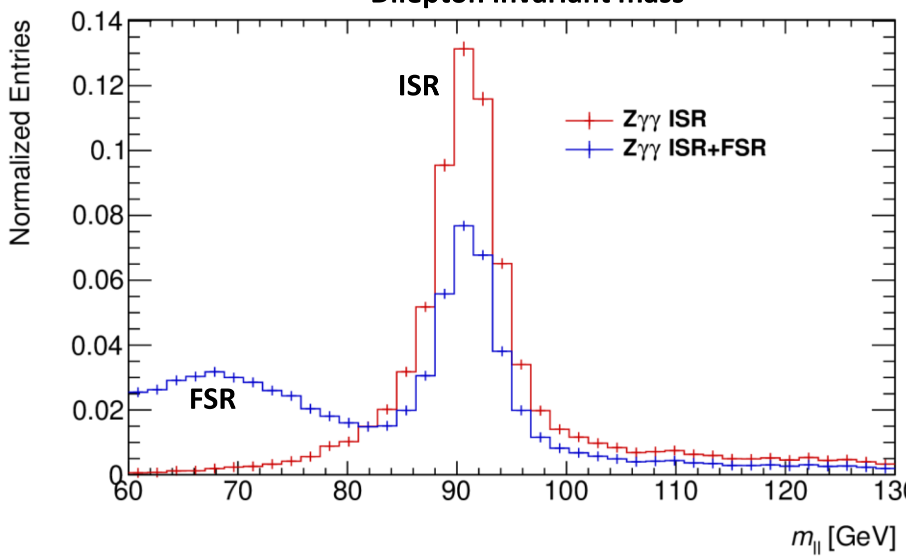
Scaled to $L_{\text{int}} = 139\ \text{fb}^{-1}$



Subleading lepton p_T

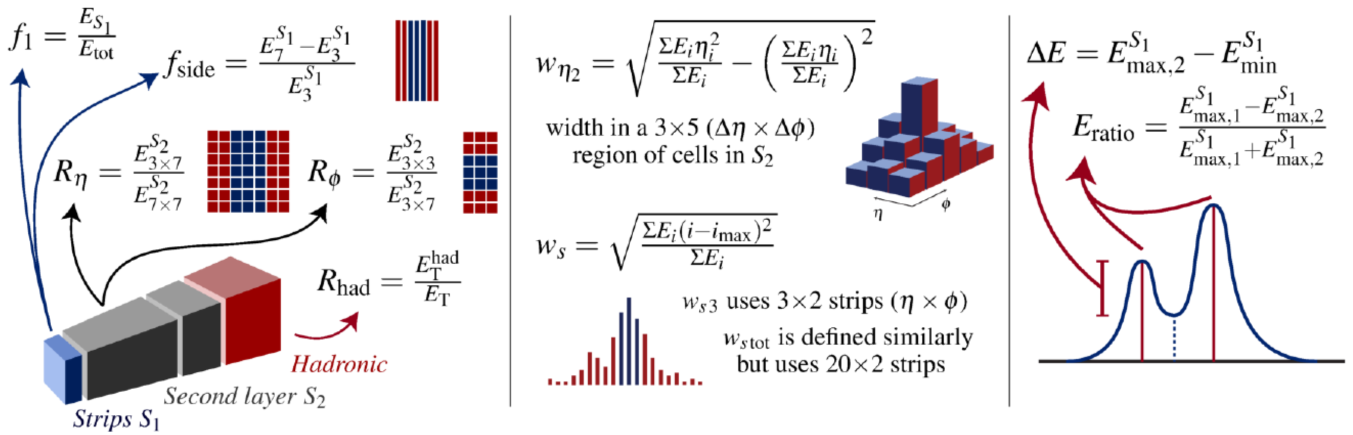


Dilepton invariant mass



FSR: loss of lepton energy

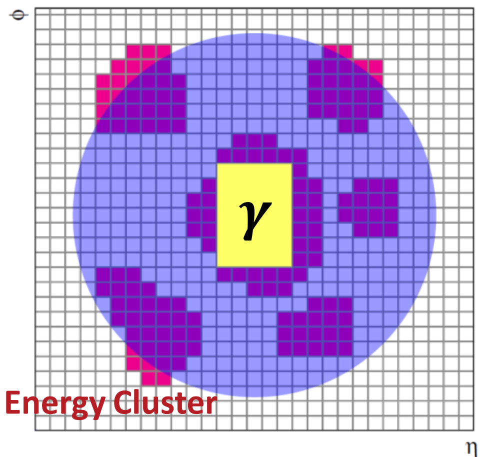
FSR: second, broad peak below m_Z

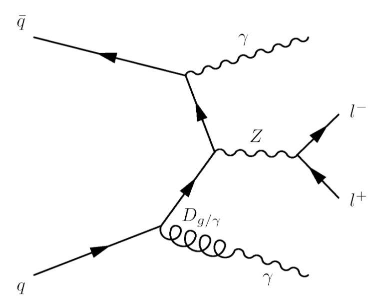


Photon Identification

- Define fake-enriched CR using *dedicated identification*
  - ⇒ Select electromagnetic component (genuine non-prompt photon)
    - *pass* e.g. R_{had}: energy ratio between HCAL-ECAL
  - ⇒ Select hadronic component (jet remnant)
    - *fail* e.g. w_{s3}: lateral shower width

- **Photon Isolation Energy**
  - ⇒ Measure for hadronic activity around photon
  - ⇒ Cone of radius 0.2

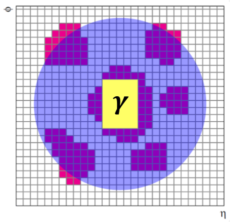


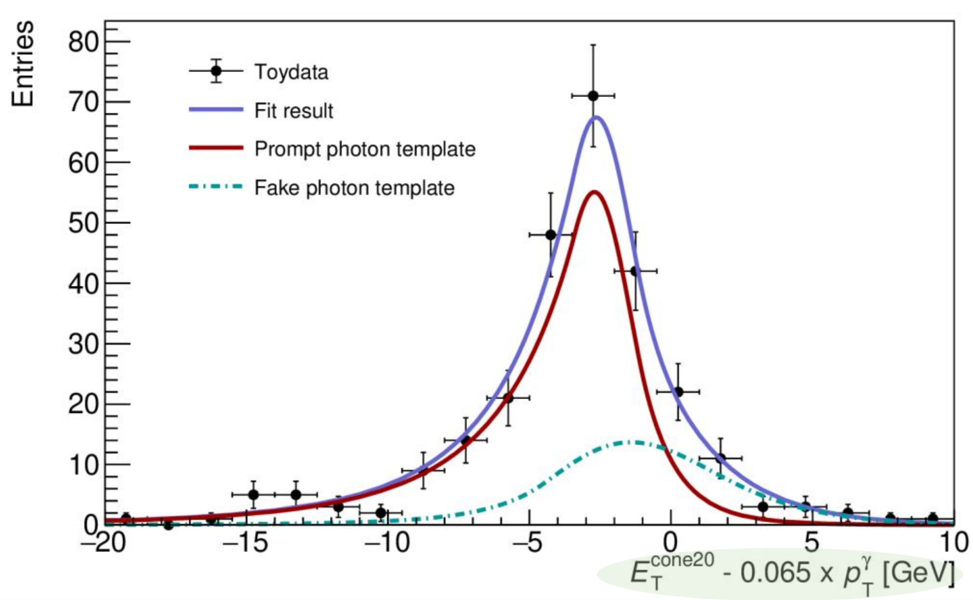


$\Rightarrow g/q \rightarrow \pi^0 + X \rightarrow 2\gamma + X$

Isolation energy E_T^{cone20}

- Observable in 2D Template Fit
- Derive templates, probability density, for E_T^{cone20}
  - ⇒ Prompt photons: $Z\gamma\gamma$ signal
  - ⇒ Fake photons: $Z\gamma j$, $Zj\gamma$, Zjj backgrounds
- Fit templates to observed isolation energy in data
  - ⇒ Fix shape of templates, determine normalization for each process





Fake photon contamination w.r.t *loose isolation*

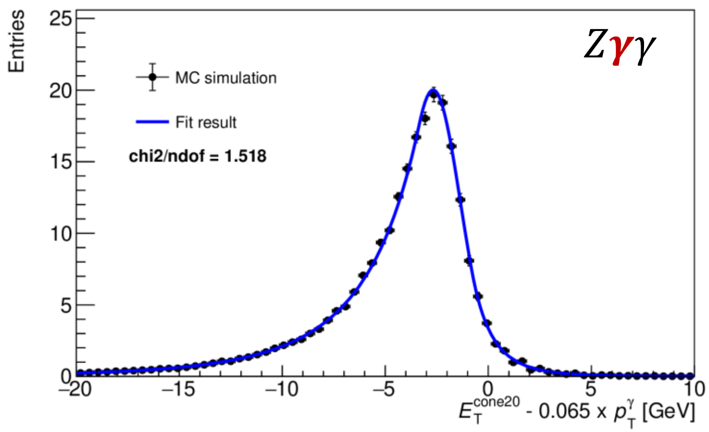
⇒ $E_T^{\text{cone20}} - 0.065 \times p_T < 0$

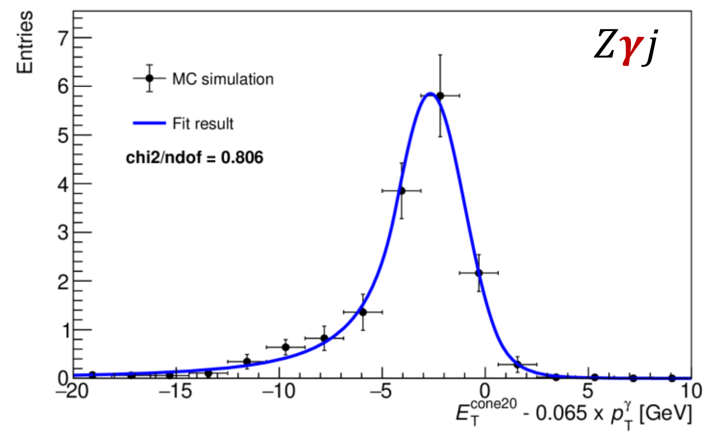
⇒ $E_T^{\text{cone20}} / p_T < 0.065$

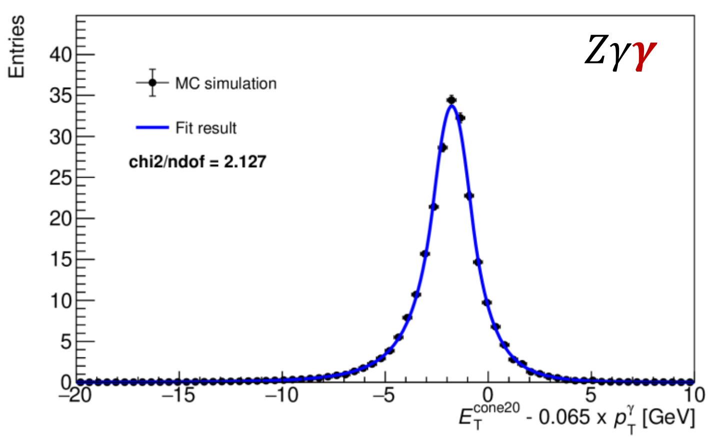
2D Template Fit - Templates

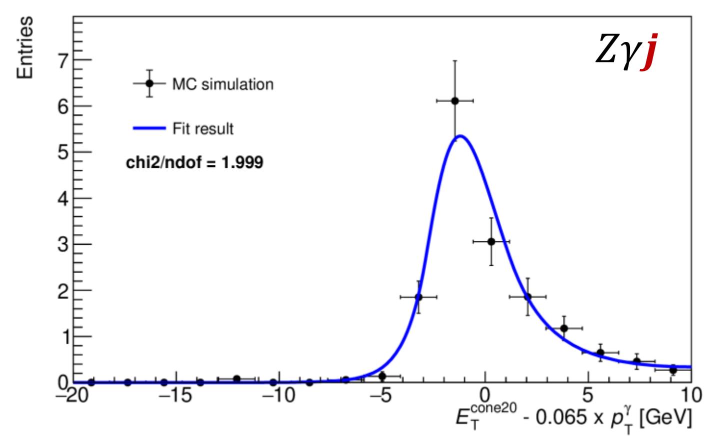
Template Extraction

- 2D: leading/subleading photon templates
- Extracted in MC simulation or fake-enriched data CRs
  - ⇒ Gaussian core + power-law/exp tails
  - ⇒ Superposition of Gaussian kernels









Template Extraction

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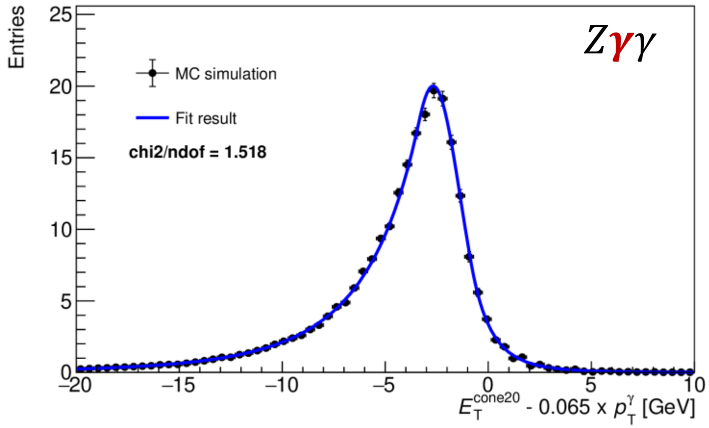
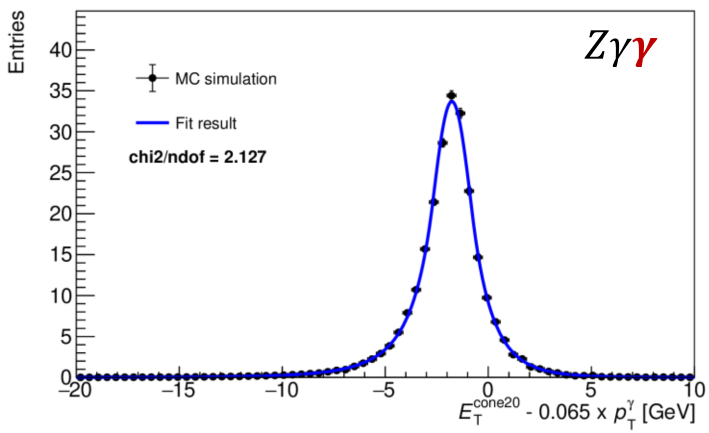
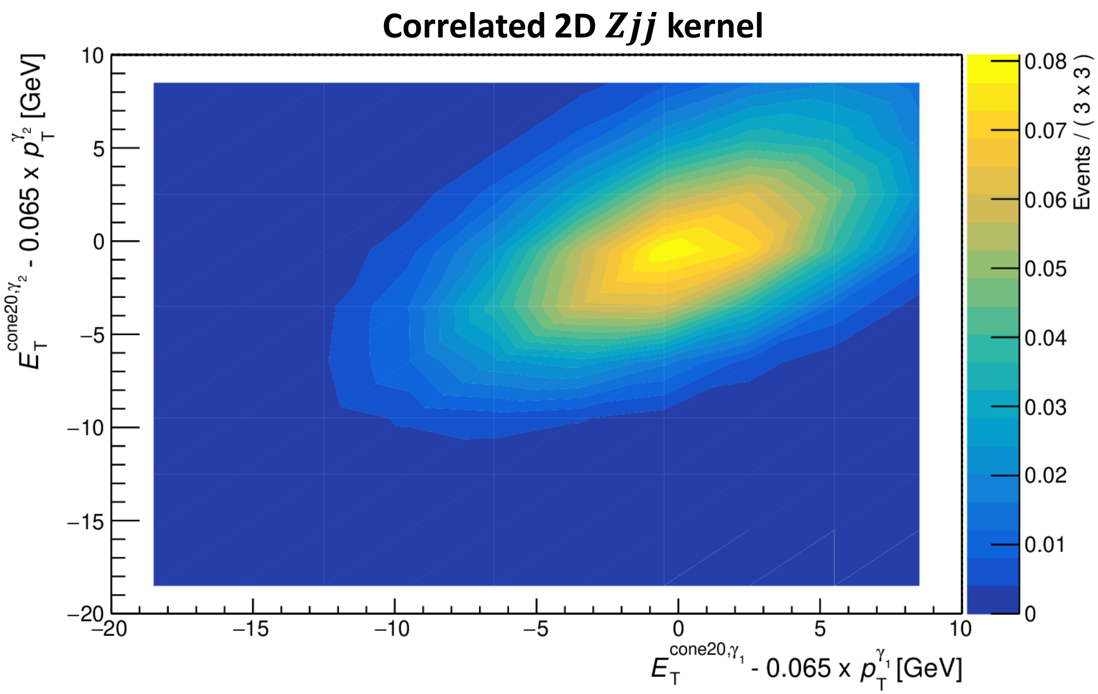


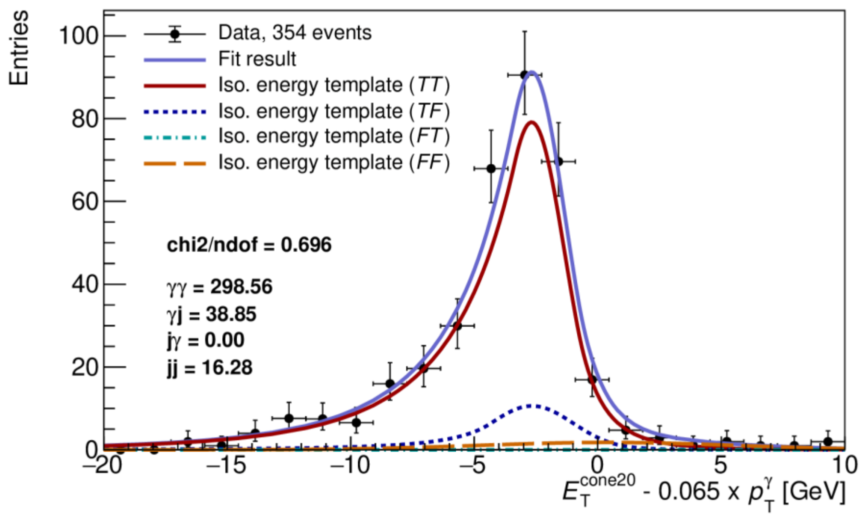




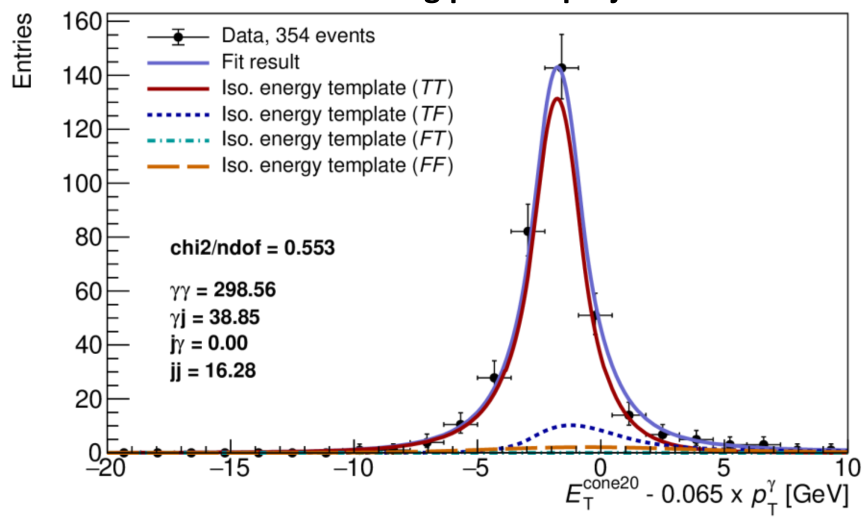
Final 2D Fit

- Shape of templates fixed
- Sum of templates fitted to observed 2D isolation energy in Run-2

Leading photon projection



Subleading photon projection

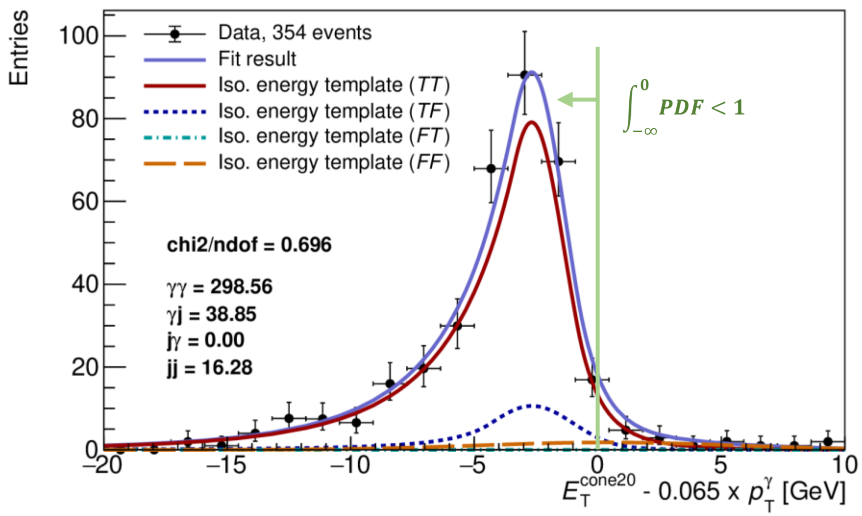


Final 2D Fit

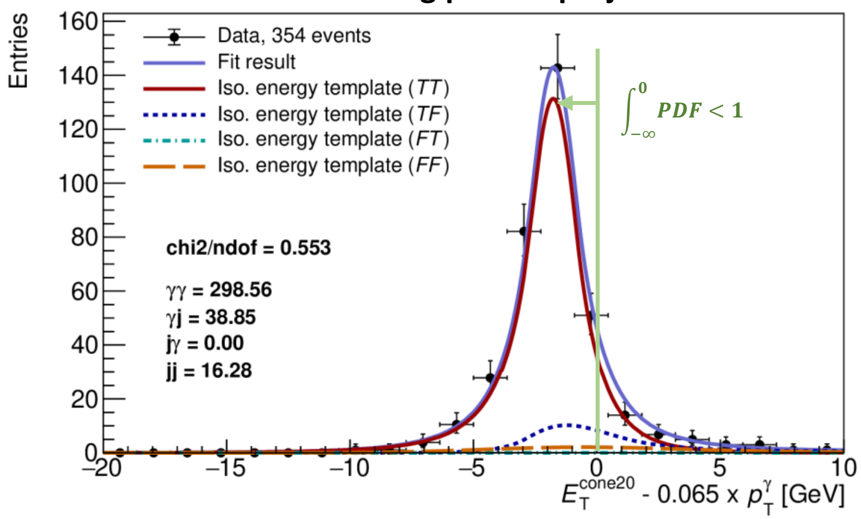
- Shape of templates fixed
- Sum of templates fitted to observed 2D isolation energy in Run-2

$E_T^{\text{cone20}} - 0.065 \times p_T < 0$

Leading photon projection



Subleading photon projection



	2D Template
$Z\gamma\gamma$ SR yield	249.5±21.0 (stat.)±19.1 (sys.)
$Z\gamma j$ SR yield	21.5±9.5 (stat.)±11.0 (sys.)
$Zj\gamma$ SR yield	0.0±7.8 (stat.)±11.2 (sys.)
Zjj SR yield	5.5±2.5 (stat.)±2.7 (sys.)
Total fakes	27.0±11.0 (stat.)±15.9 (sys.)