IMPRS for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

ATLAS EXPERIMENT

FSP ATLAS
Erforschung von Universum und Materie

KIRCHHOFF-INSTITUT FÜR PHYSIK

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

# The journey to 5σ


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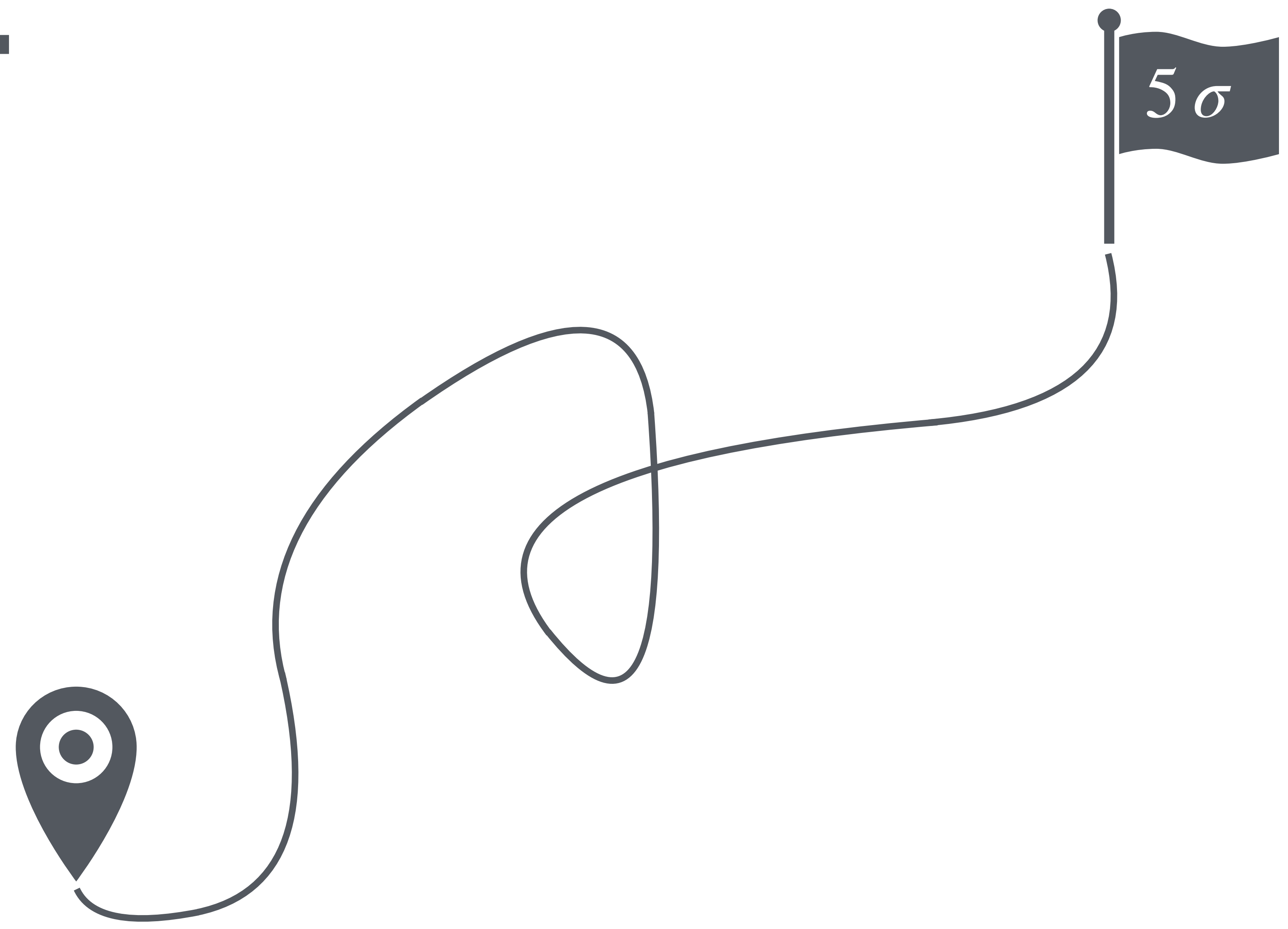


Annweiler am Trifels, July 2024

# How to make an observation

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| | | | |
|---|---|---|---|
| Pick an appropriate final state | Apply an event selection to maximise your S/B | Estimate the irreducible backgrounds | Check if you are above 5σ |

# Pick an appropriate final state

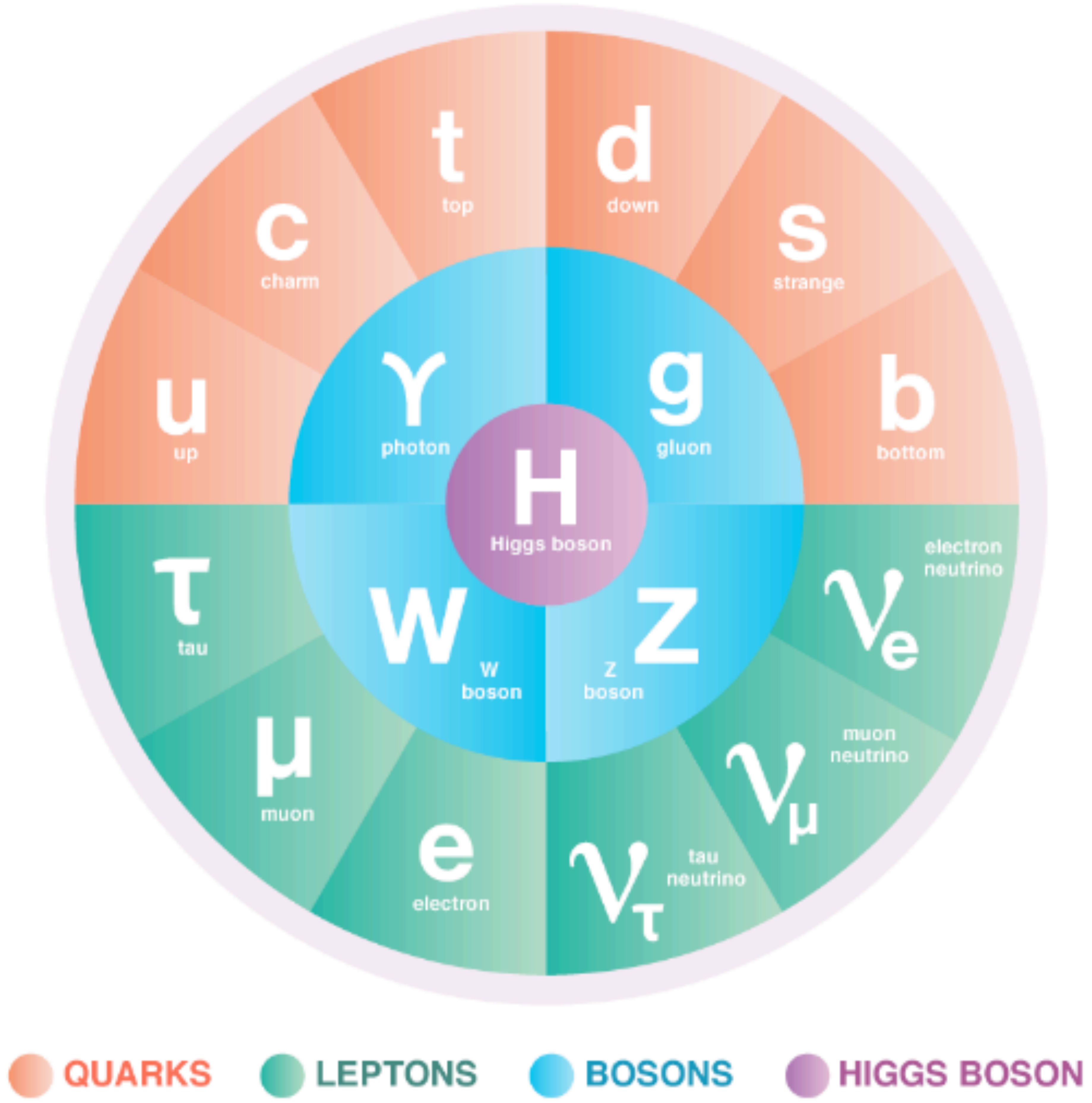
pp

$q\bar{q}$

gg

…

→




[1]

→

photons

electrons

muons

jets

neutrinos/
MET

# Pick an appropriate final state, but …

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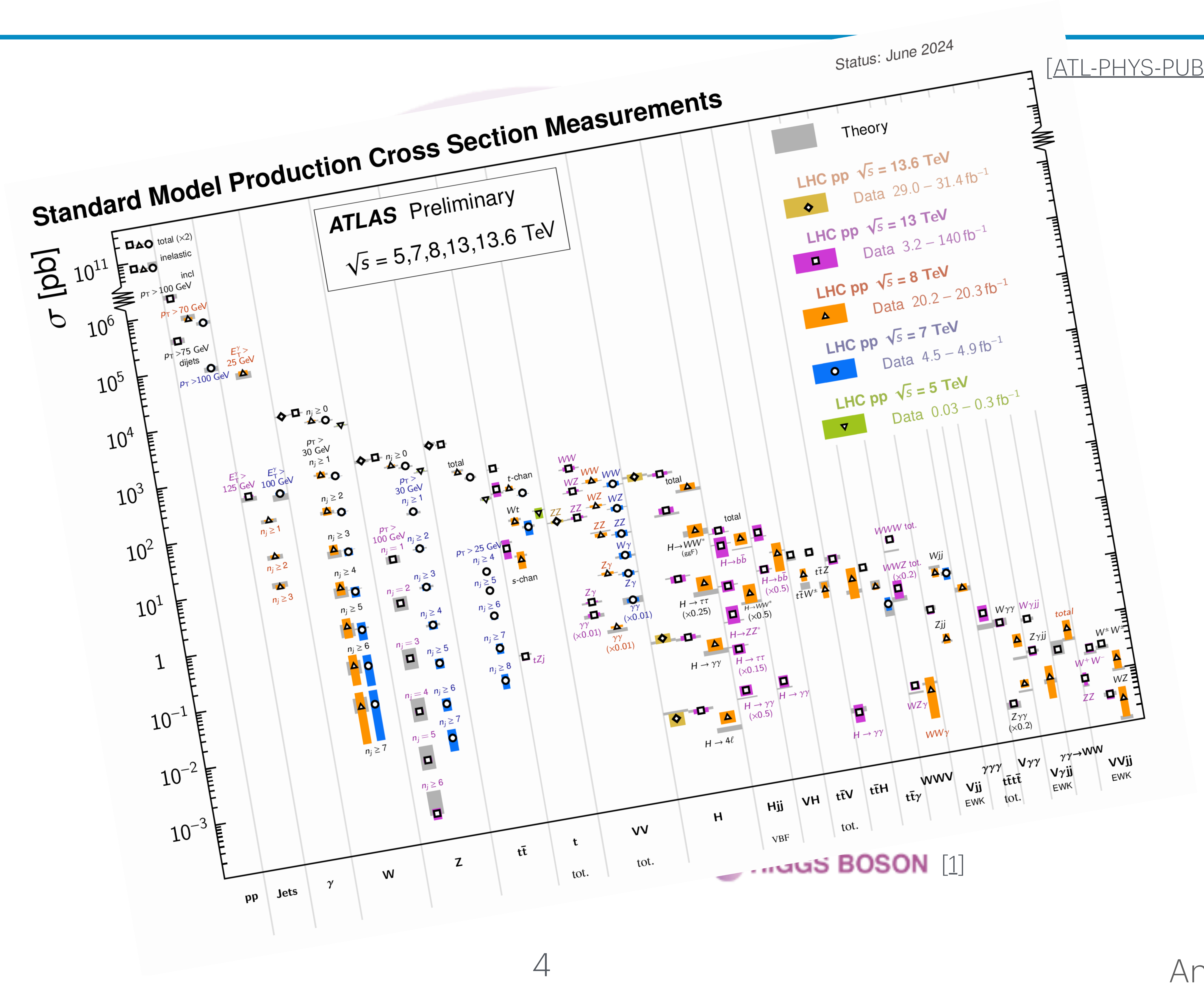
[ATL-PHYS-PUB-2024-011]

pp

$q\bar{q}$

gg

…




photons

electrons

muons

jets

neutrinos/
MET

# Pick an appropriate final state, but …

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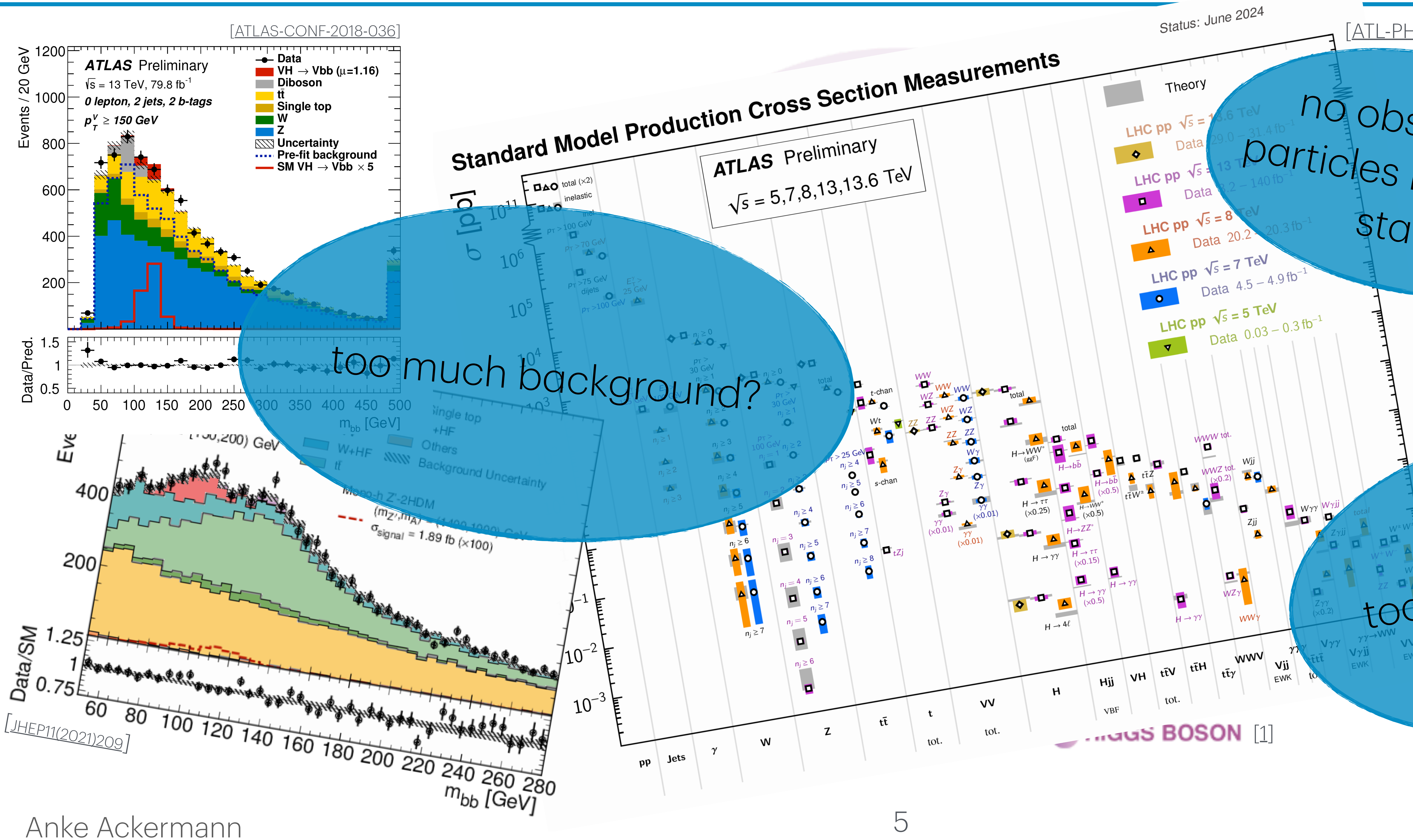



too much background?

no observable particles in the final state?

too low cross section?

photons

electrons

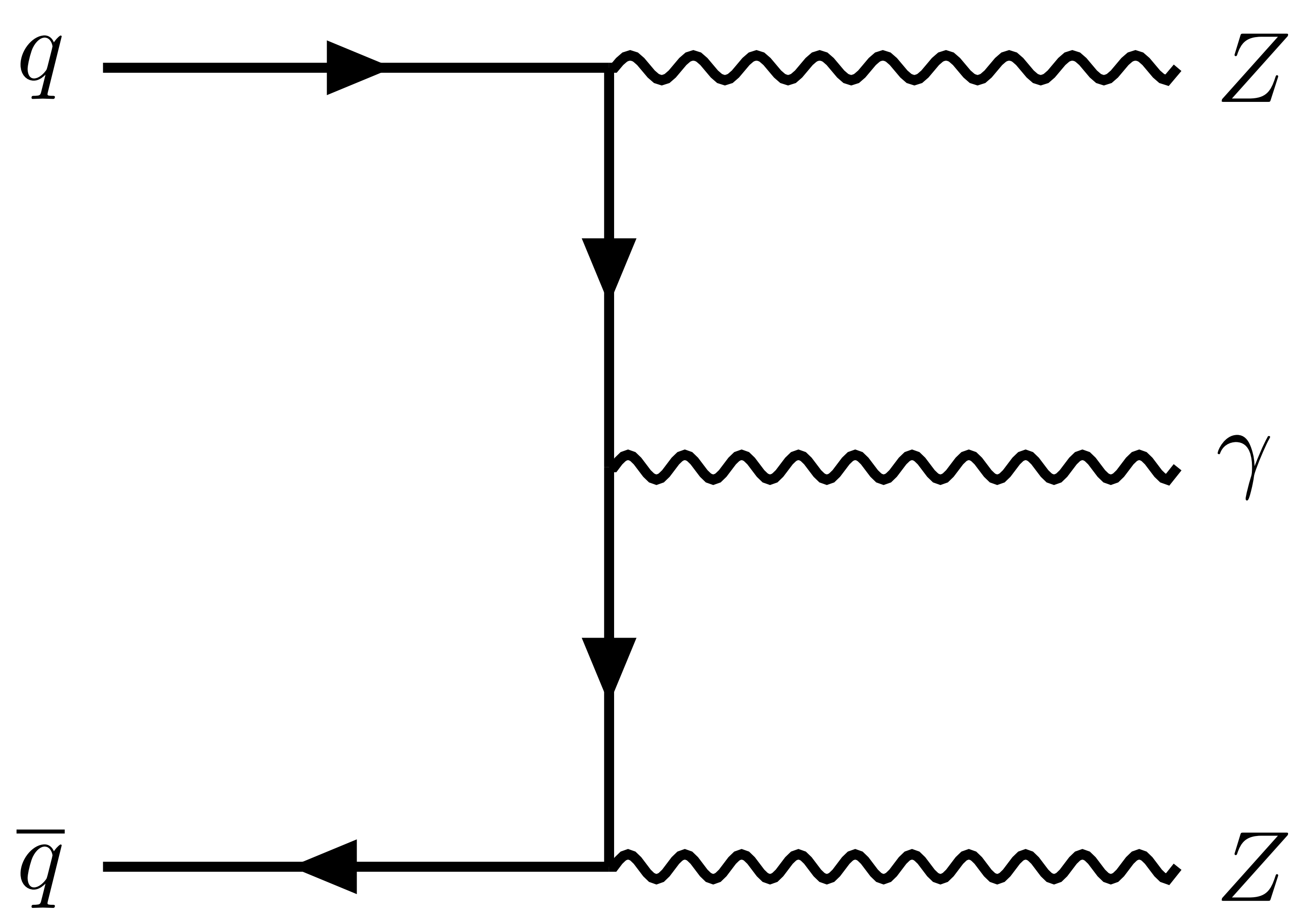
muons

jets

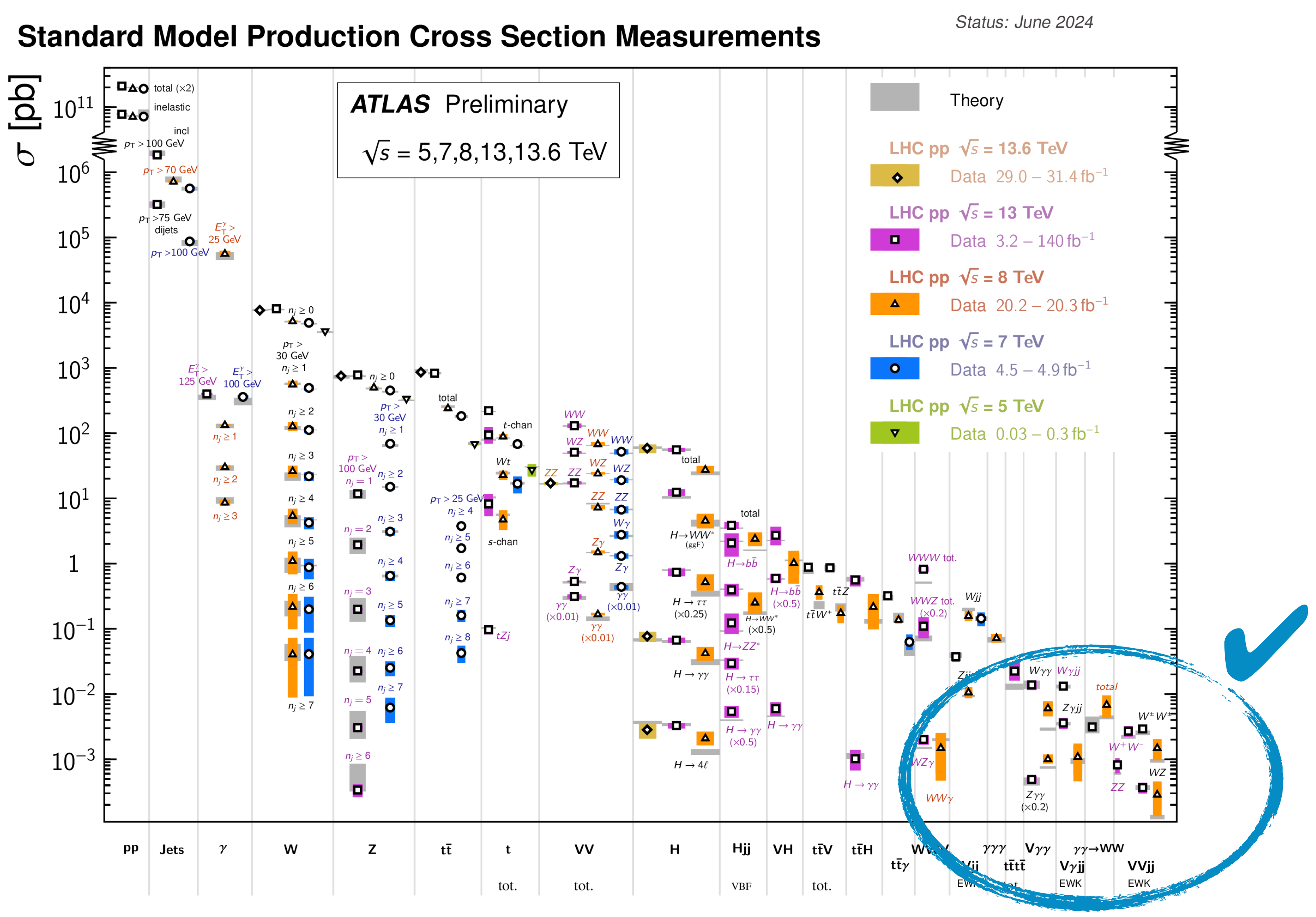
neutrinos/ MET

# An appropriate final state

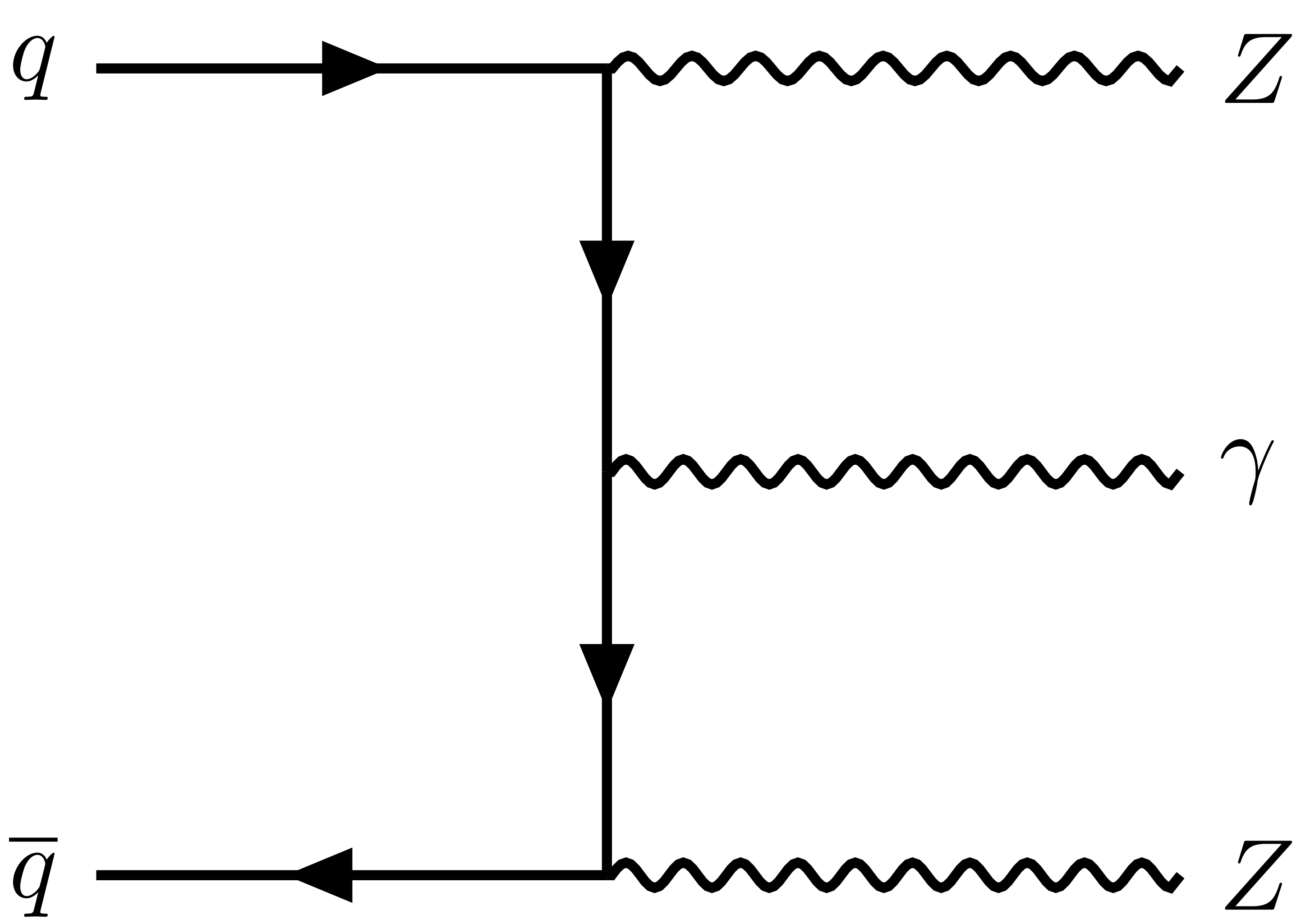
$$q\bar{q} \to ZZ\gamma$$



# An appropriate final state

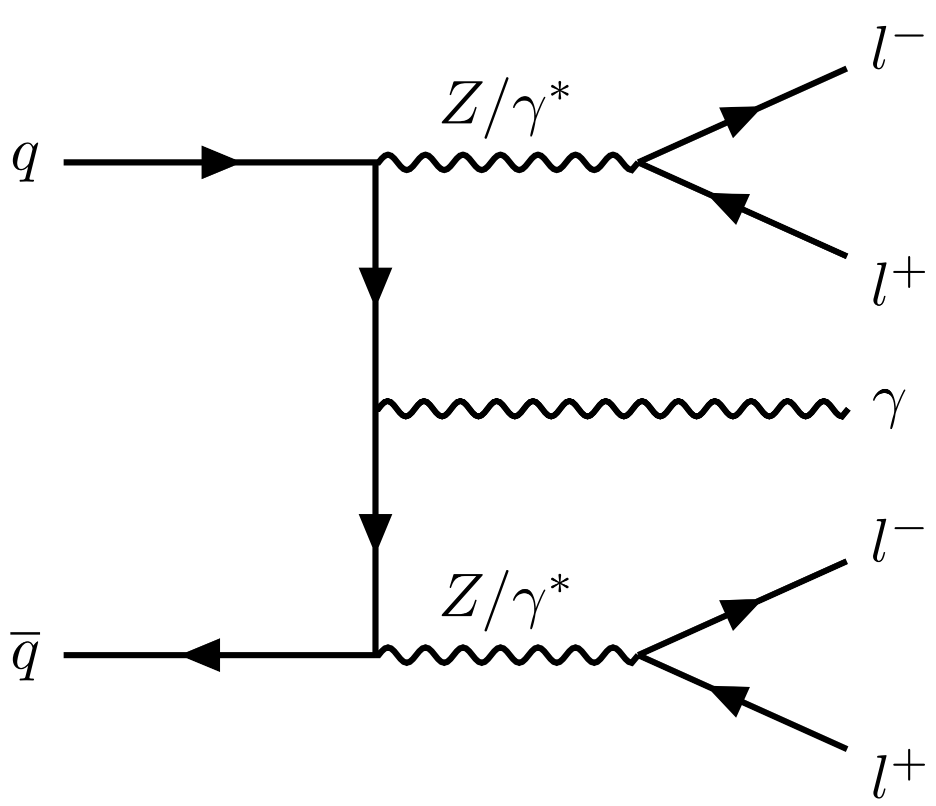


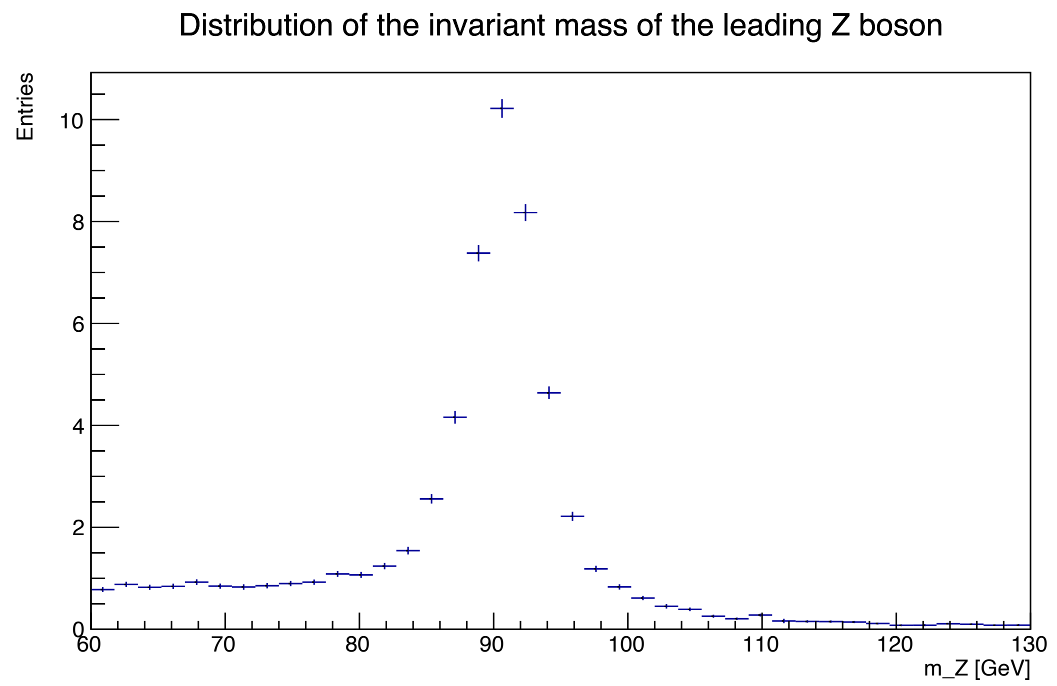

$$q\bar{q} \rightarrow ZZ\gamma$$




background? ✔

Final state particles ✔



# How to make an observation

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| Pick an appropriate final state ✔ | Apply an event selection to maximise your S/B | Estimate the irreducible backgrounds | Check if you are above 5σ |
|---|---|---|---|

# Apply a good event selection

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1.

Select the final state particles

2.

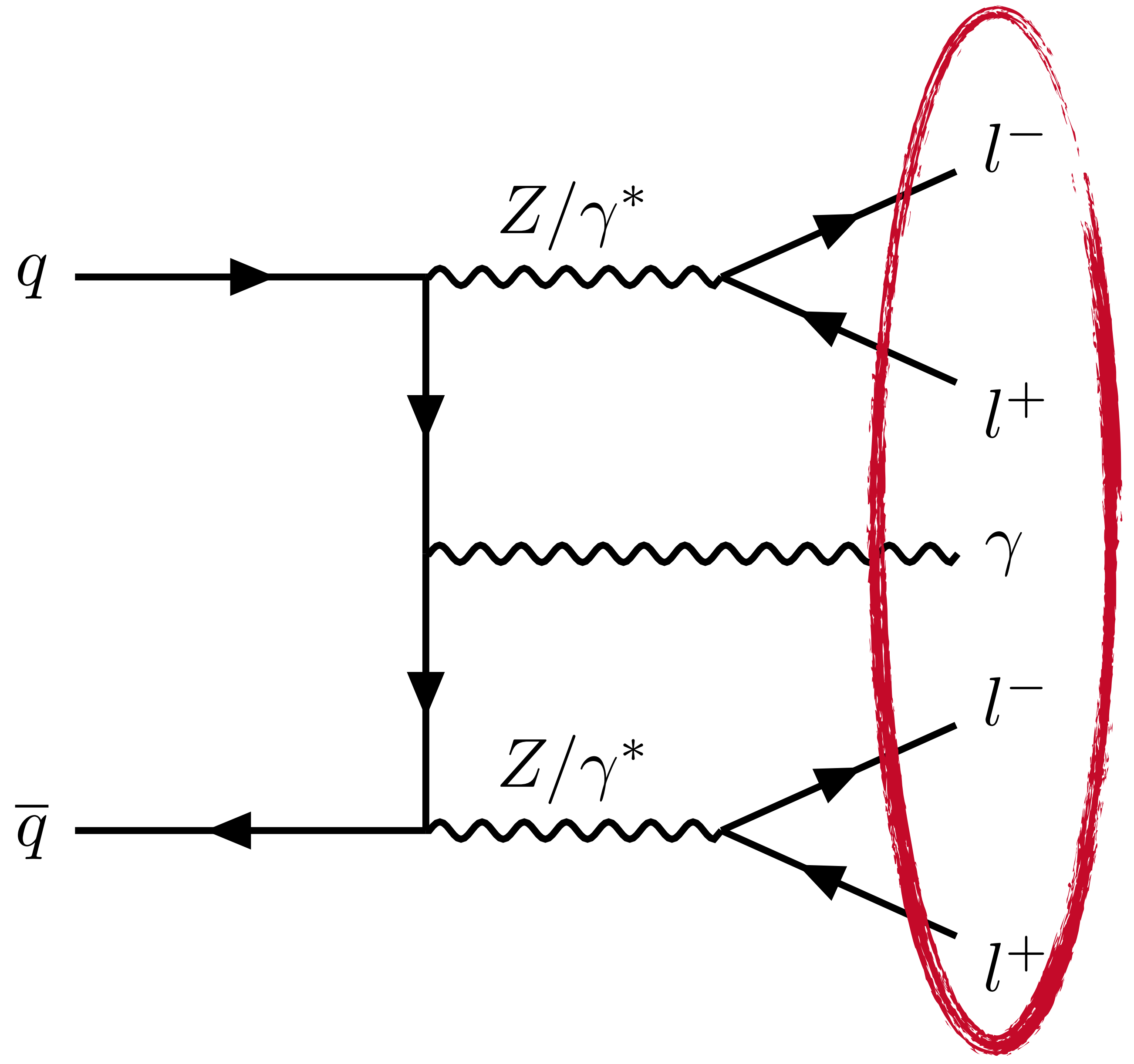
Use properties of the production channel

3.

Remove as much background as possible

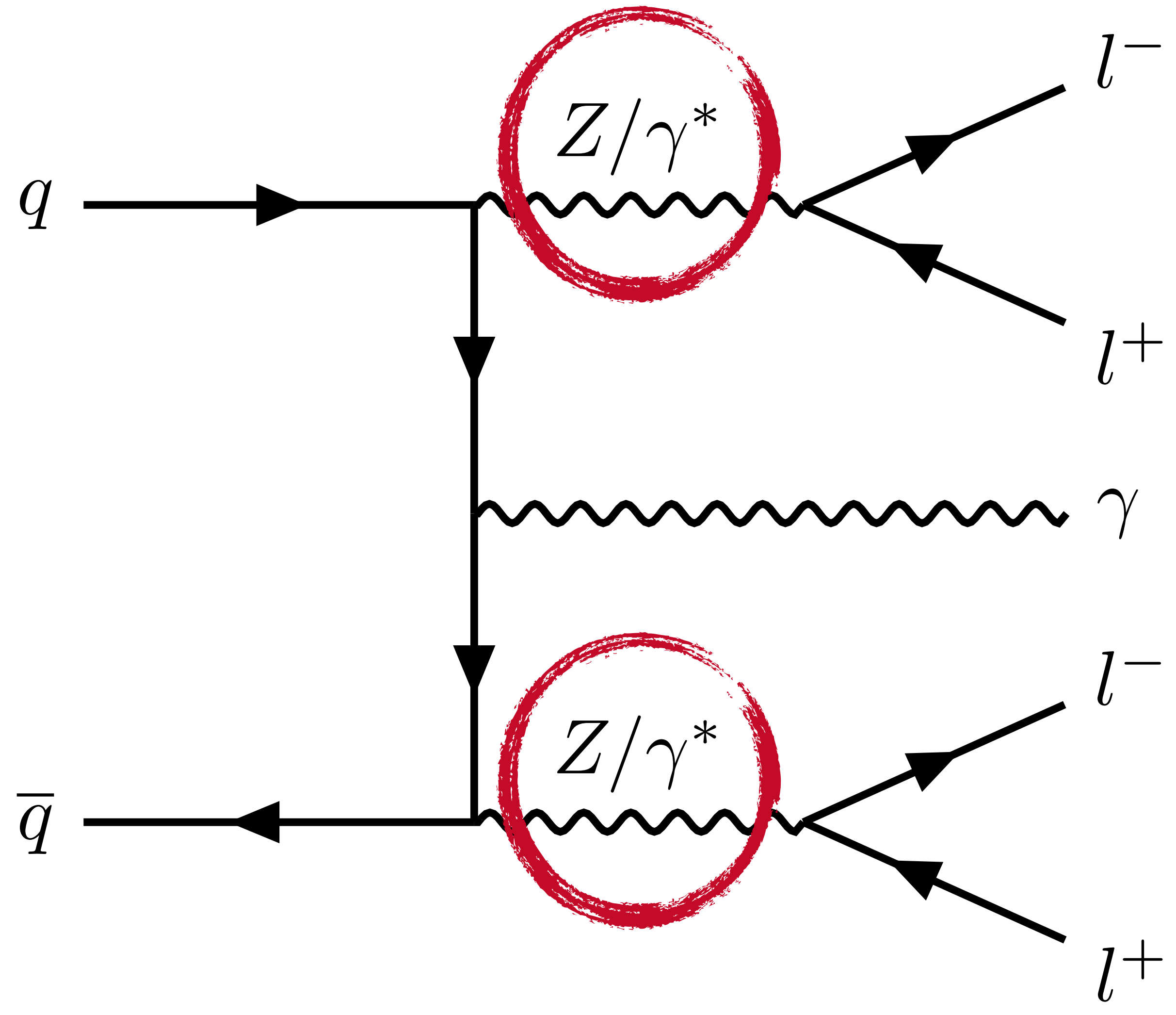
# Select the final state particles

- 2 pairs of 2 opposite-sign same-flavour (OSSF) leptons → 4e, 4μ, 2e2μ
- 1 photon, $p_T > 20$ GeV
- invariant mass $m_{\ell\ell} > 40$ GeV
- $\min(|m_{\ell\ell,1} - m_Z| + |m_{\ell\ell,2} - m_Z|)$
- FSR rejection



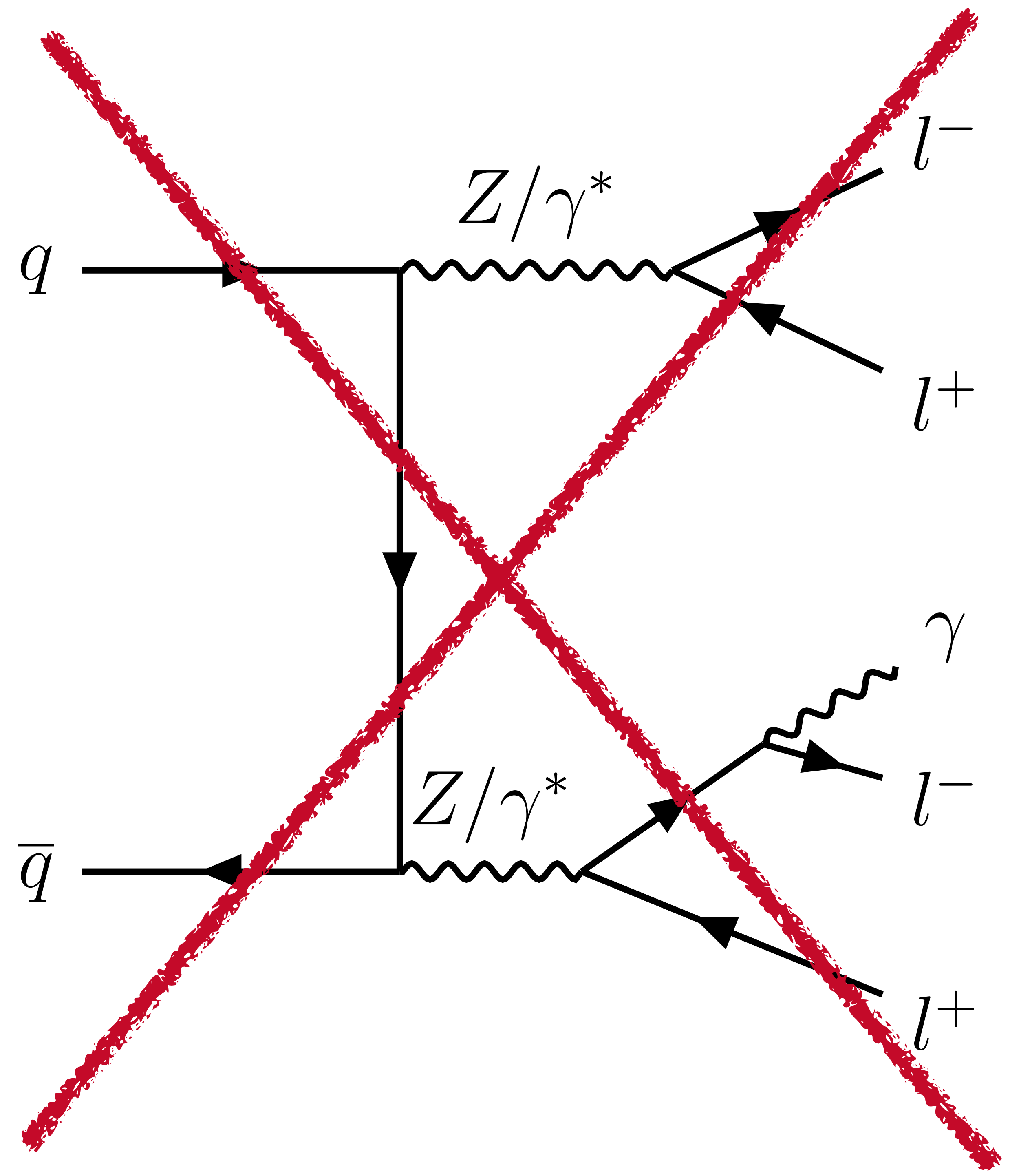
# Use properties of the Z boson

- 2 pairs of 2 opposite-sign same-flavour (OSSF) leptons → 4e, 4μ, 2e2μ
- 1 photon, $p_T > 20$ GeV
- invariant mass $m_{\ell\ell} > 40$ GeV
- $\min(\,|\,m_{\ell\ell,1} - m_Z\,| + |\,m_{\ell\ell,2} - m_Z\,|\,)$
- FSR rejection



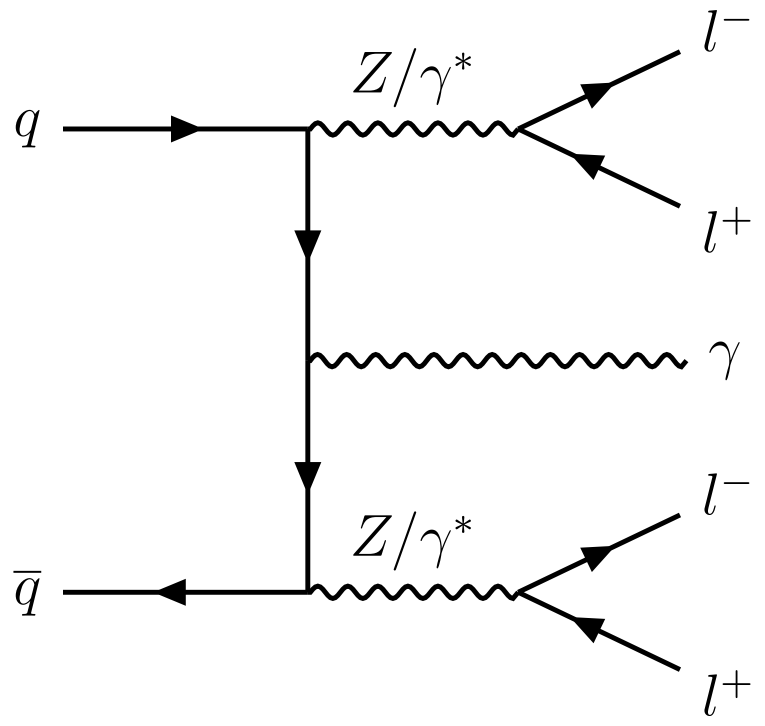
# Remove background

- 2 pairs of 2 opposite-sign same-flavour (OSSF) leptons → 4e, 4μ, 2e2μ
- 1 photon, $p_T > 20$ GeV
- invariant mass $m_{\ell\ell} > 40$ GeV
- $\min(|m_{\ell\ell,1} - m_Z| + |m_{\ell\ell,2} - m_Z|)$
- FSR rejection

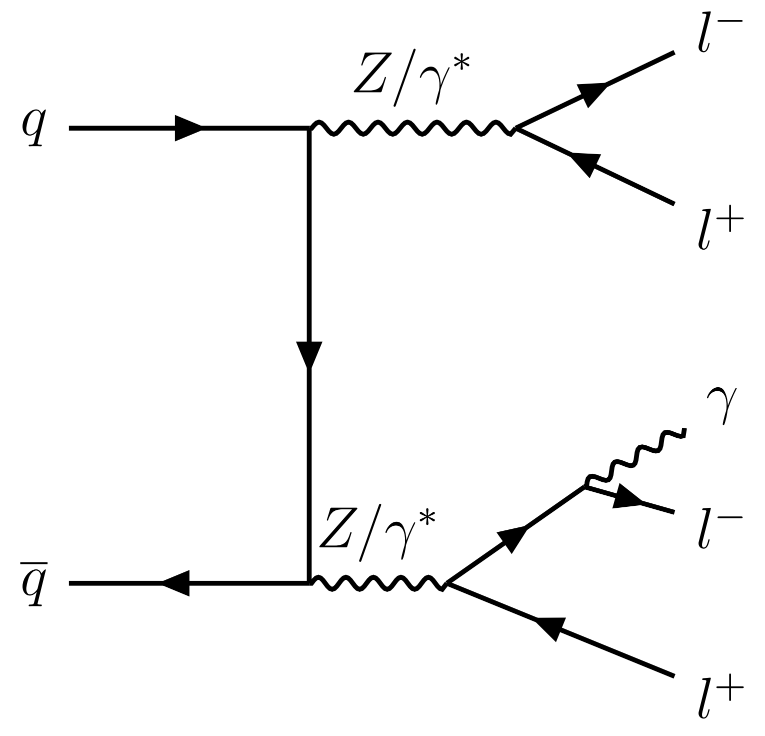


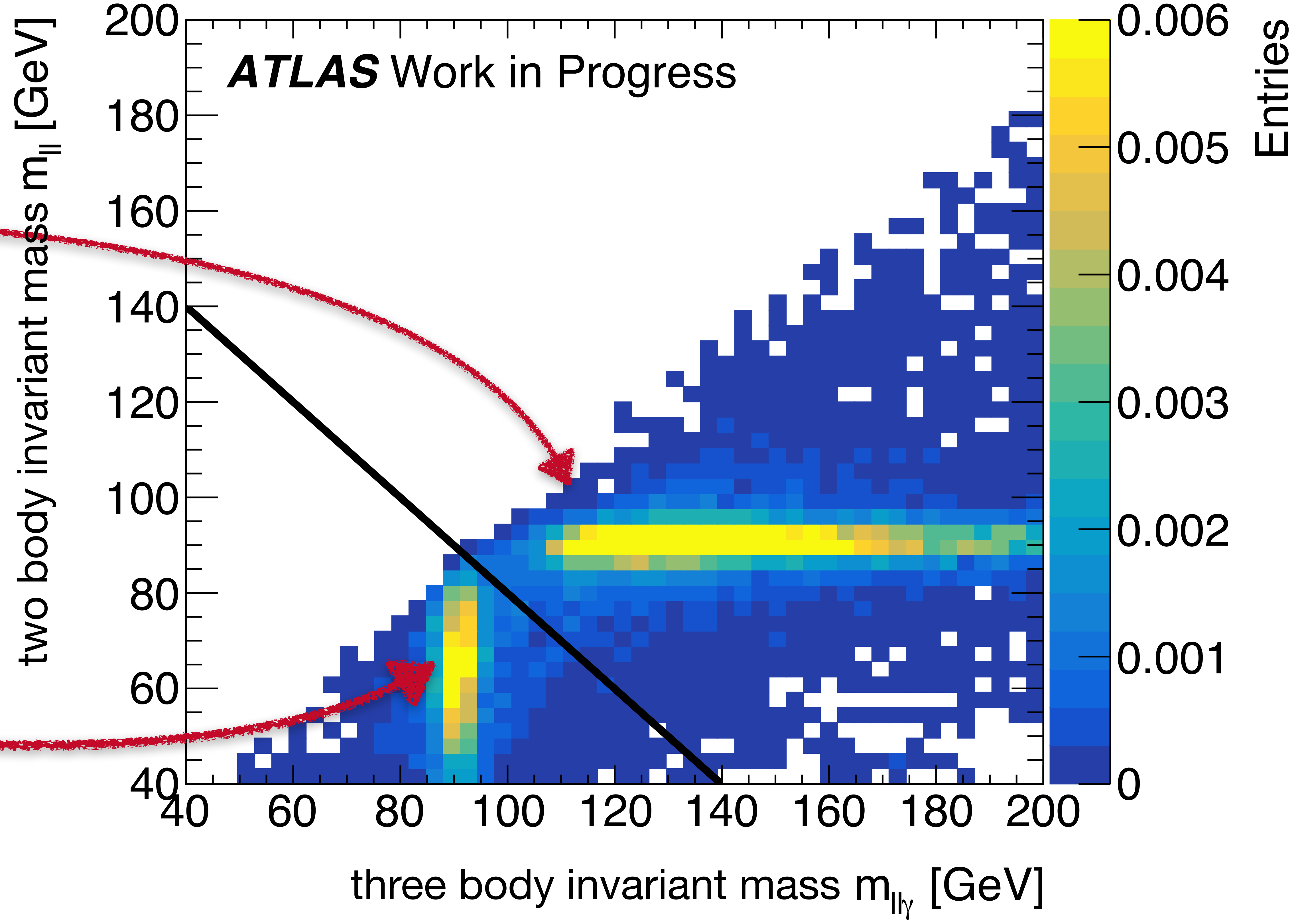
# Remove background

Signal




FSR




FSR rejection: ( $m_{\ell\ell\gamma} + m_{\ell\ell}$ ) < 2 $m_Z$

# How to make an observation

Pick an appropriate final state ✔

Apply an event selection to maximise your S/B ✔

Estimate the irreducible backgrounds

Check if you are above 5σ

# Estimate the irreducible background

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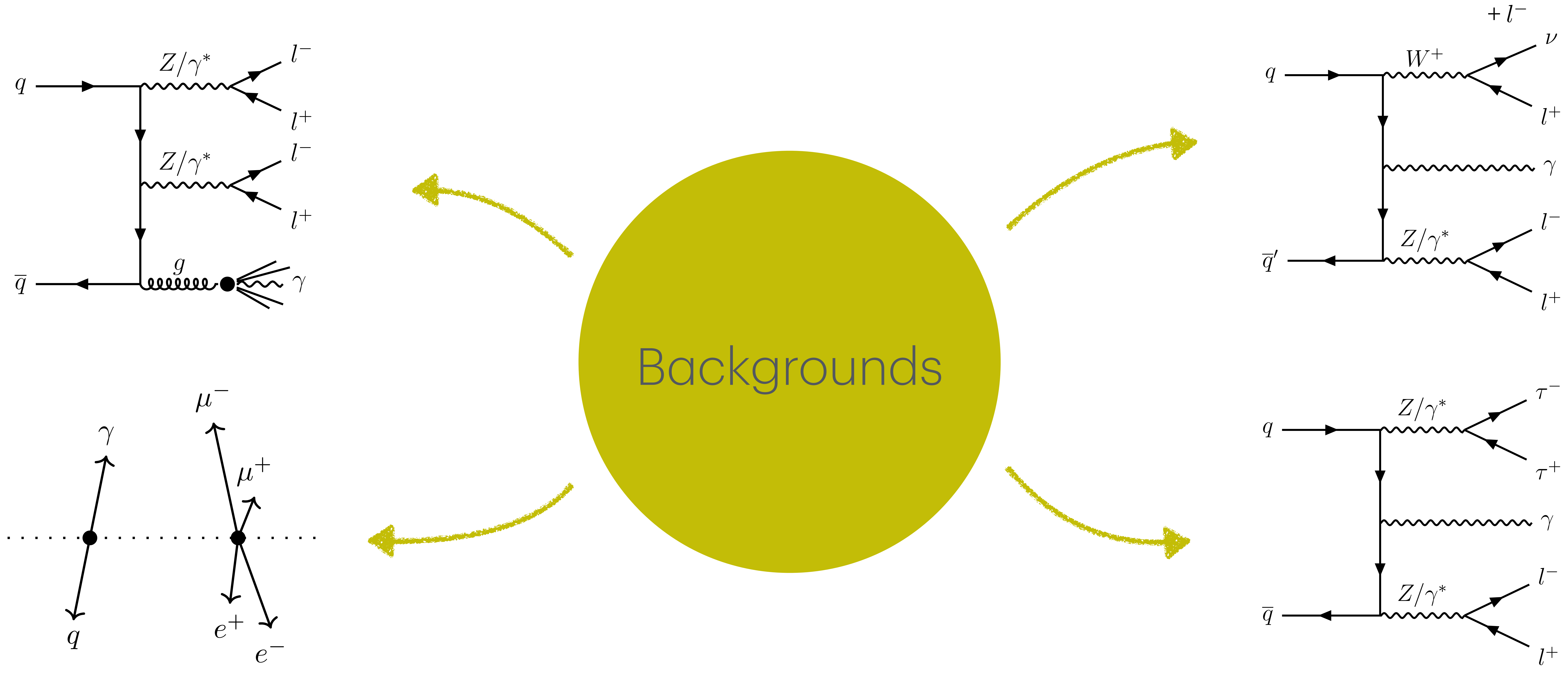
1. Determine potential backgrounds

2. Estimate the potential backgrounds

3. Keep the uncertainties low

# Potential backgrounds



# Potential backgrounds

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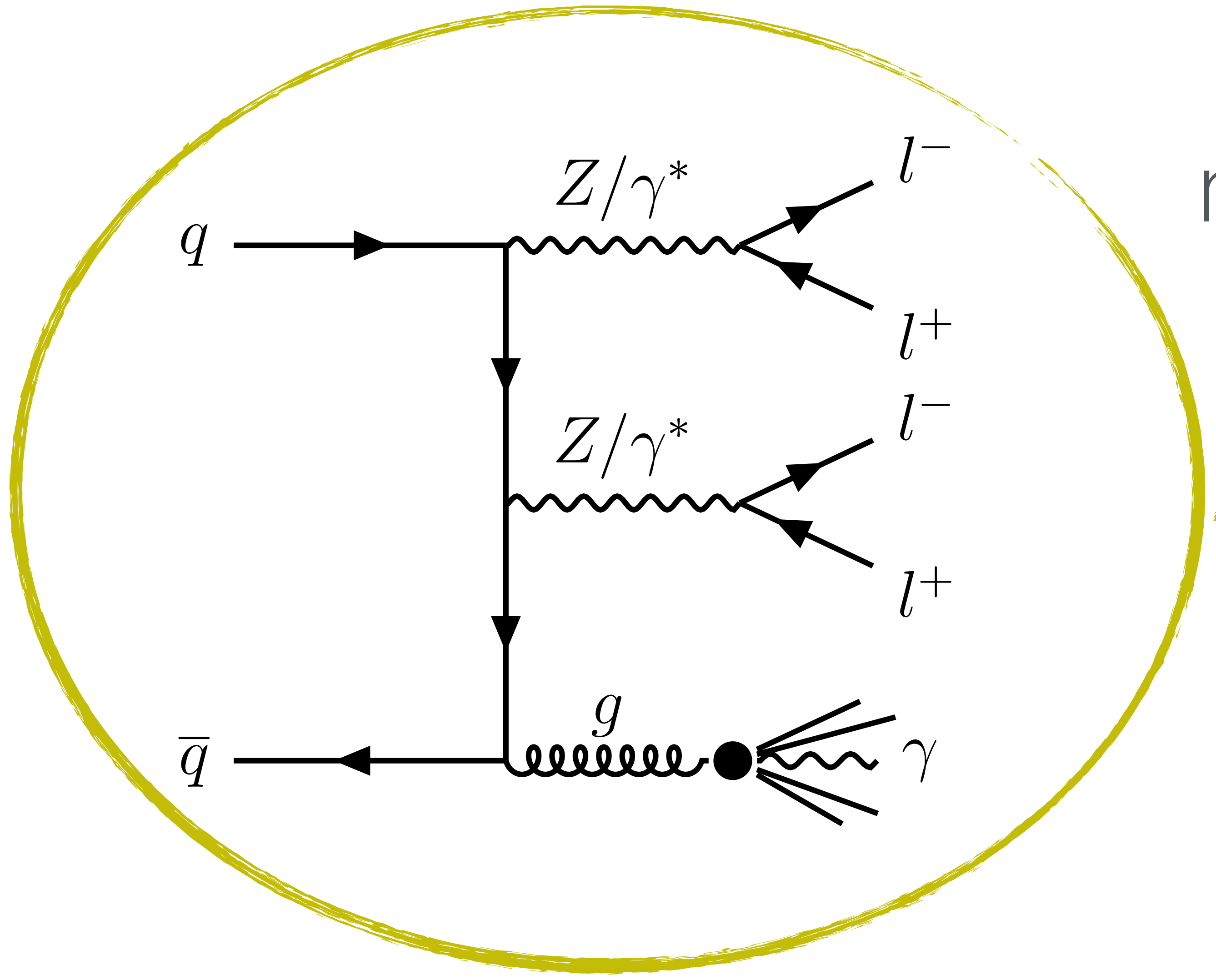
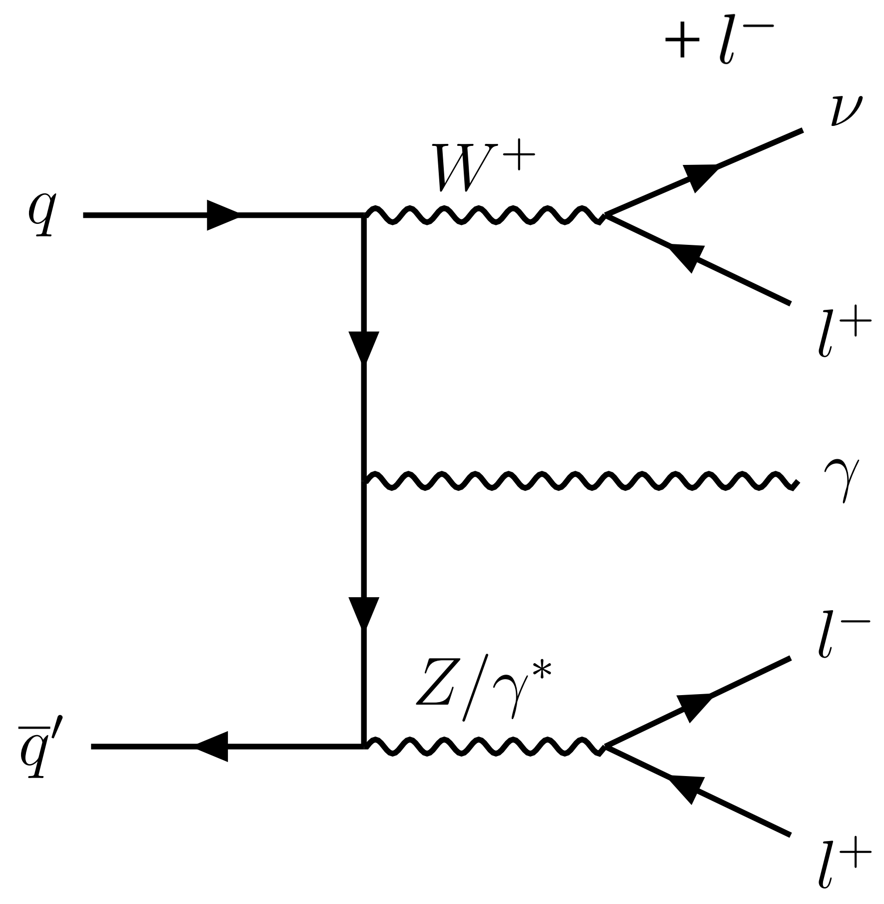
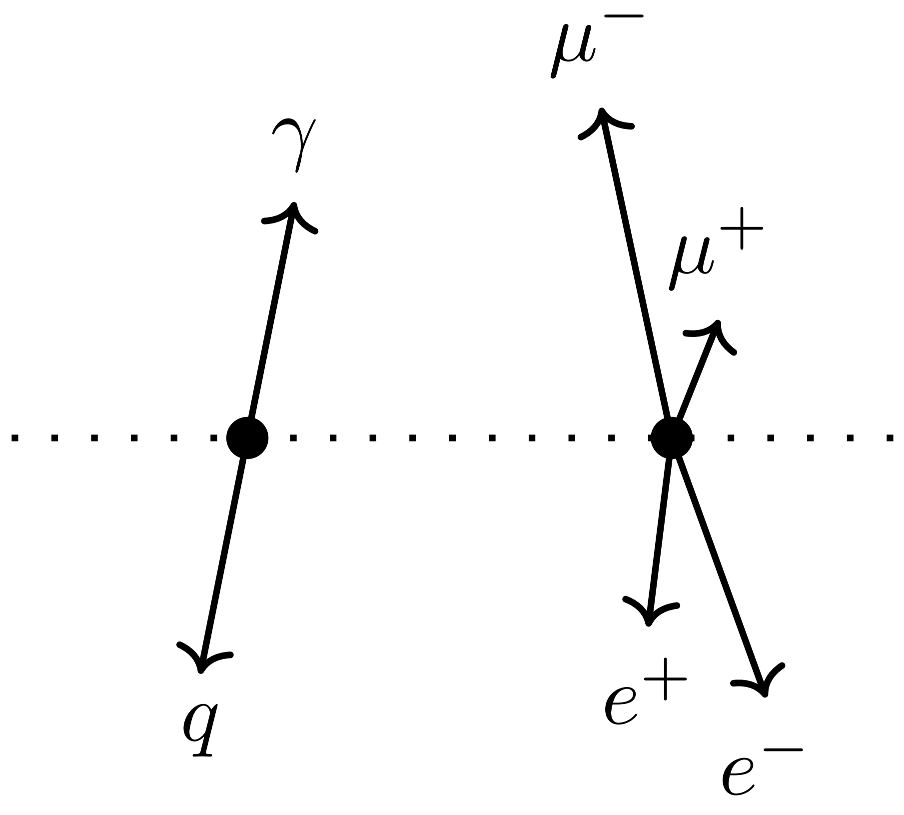
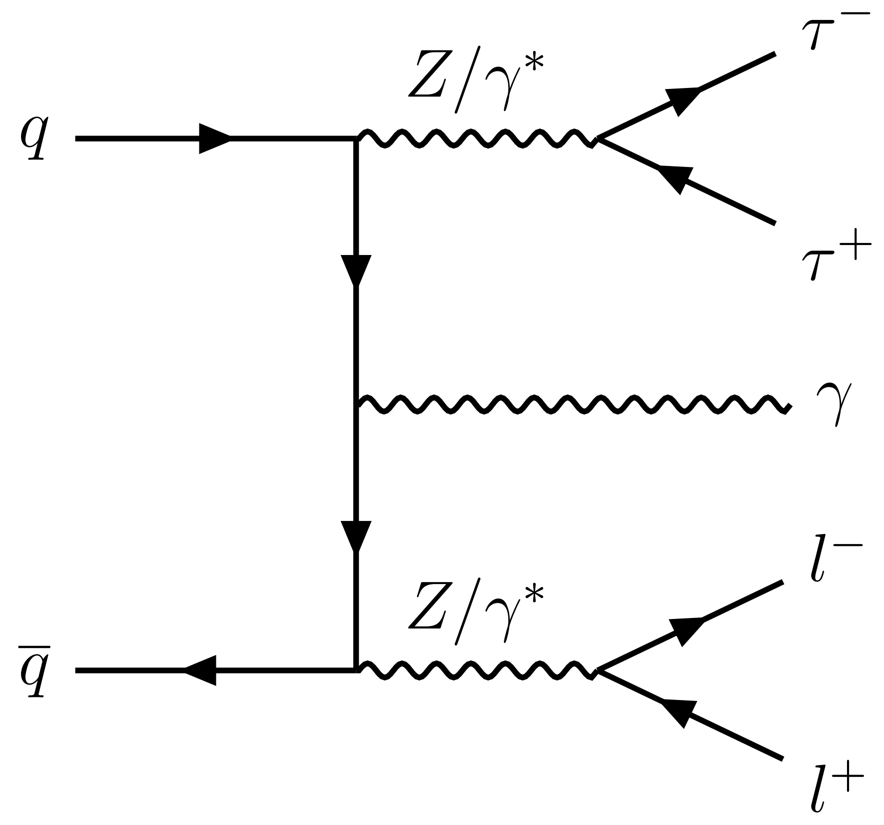



non-prompt photon background




Backgrounds



# Potential backgrounds

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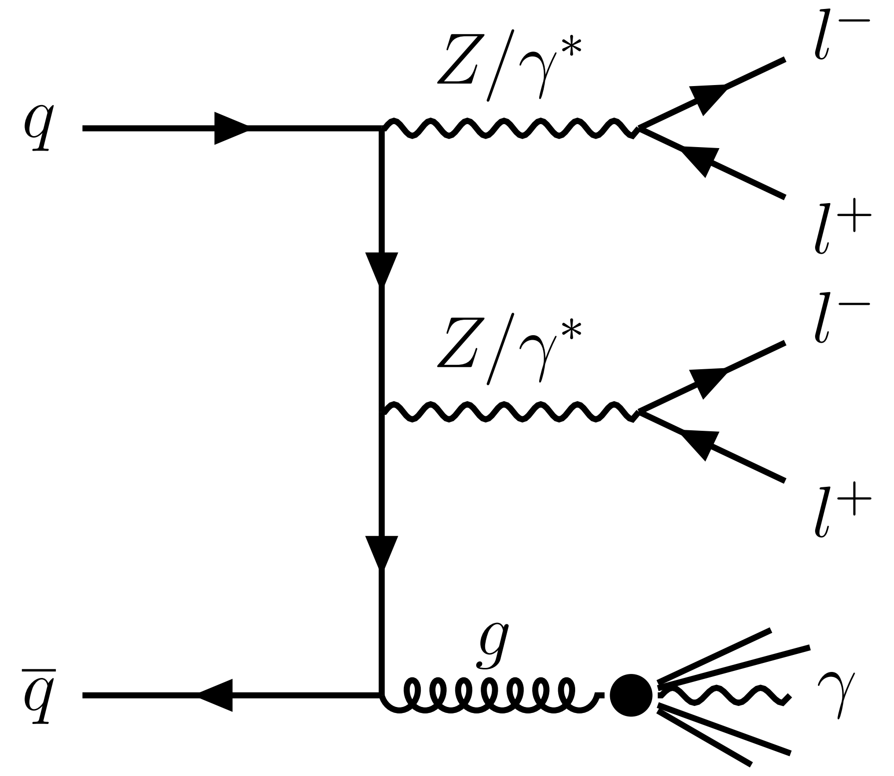
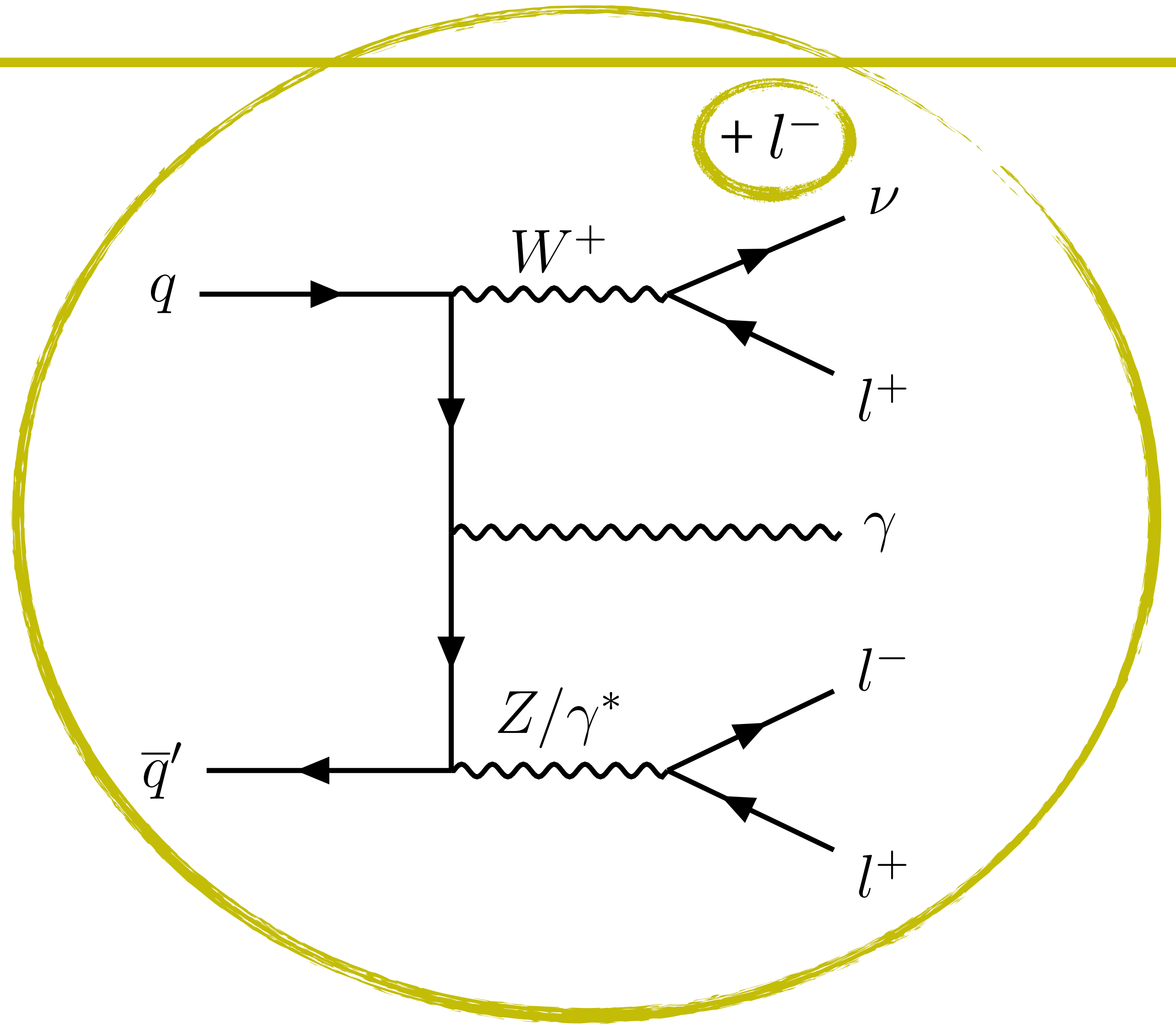
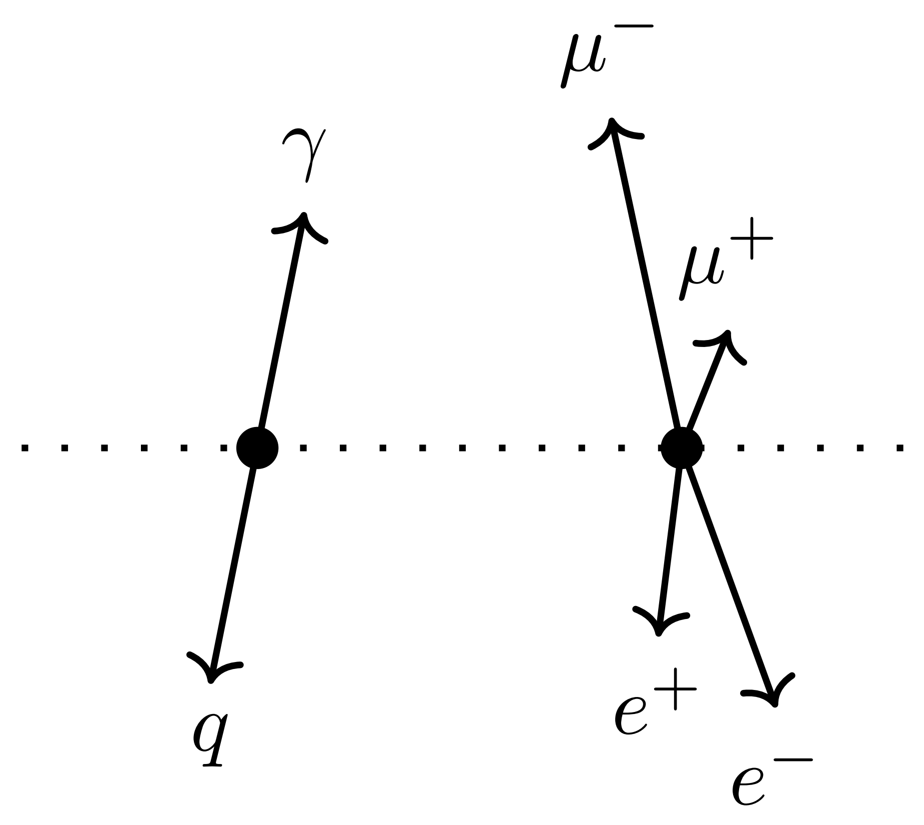
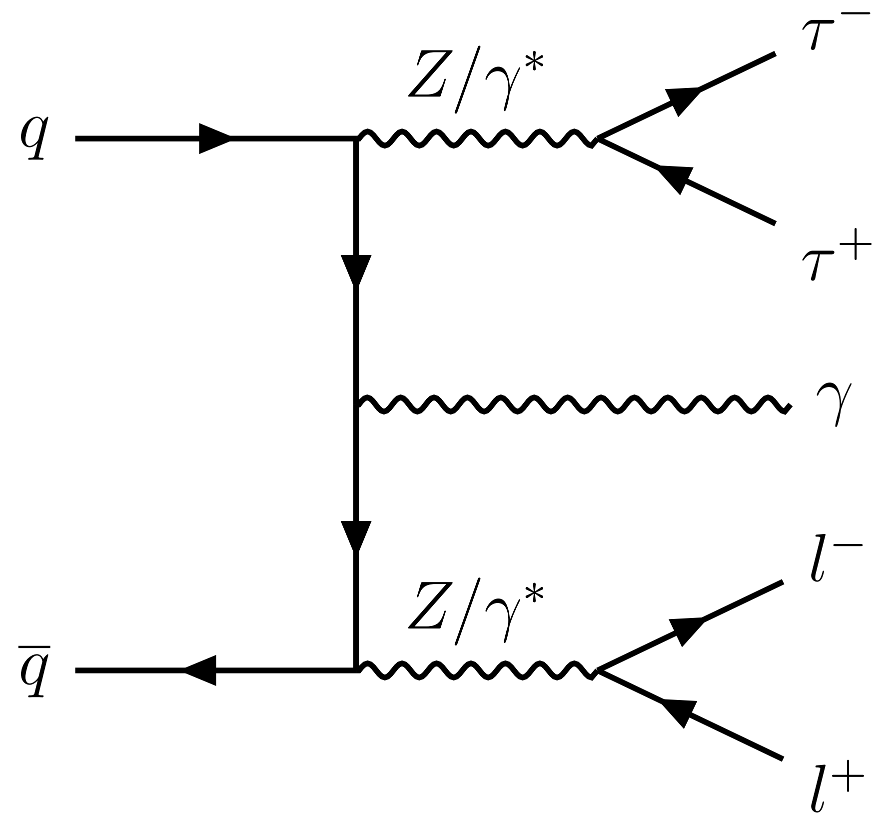



misidentified lepton background

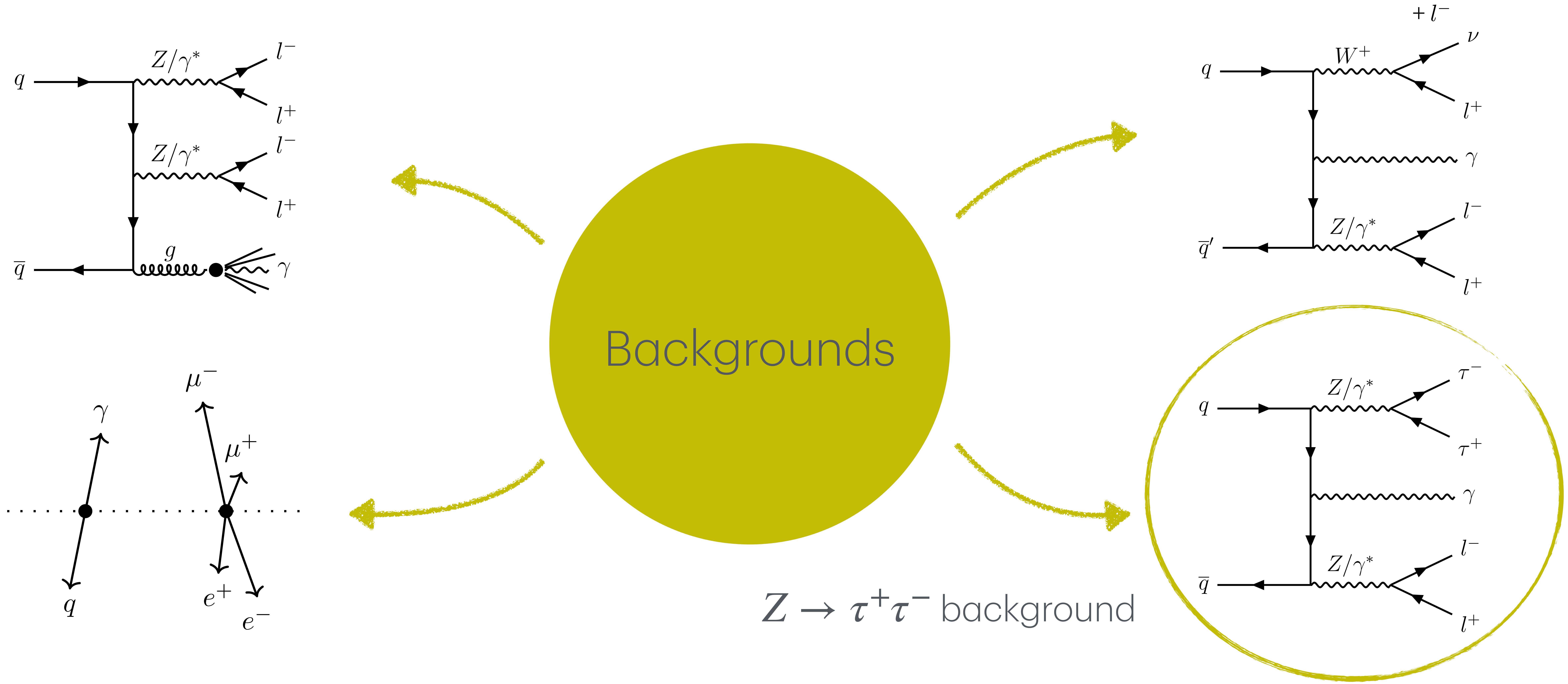






# Potential backgrounds




$Z \rightarrow \tau^+\tau^-$ background

# Potential backgrounds

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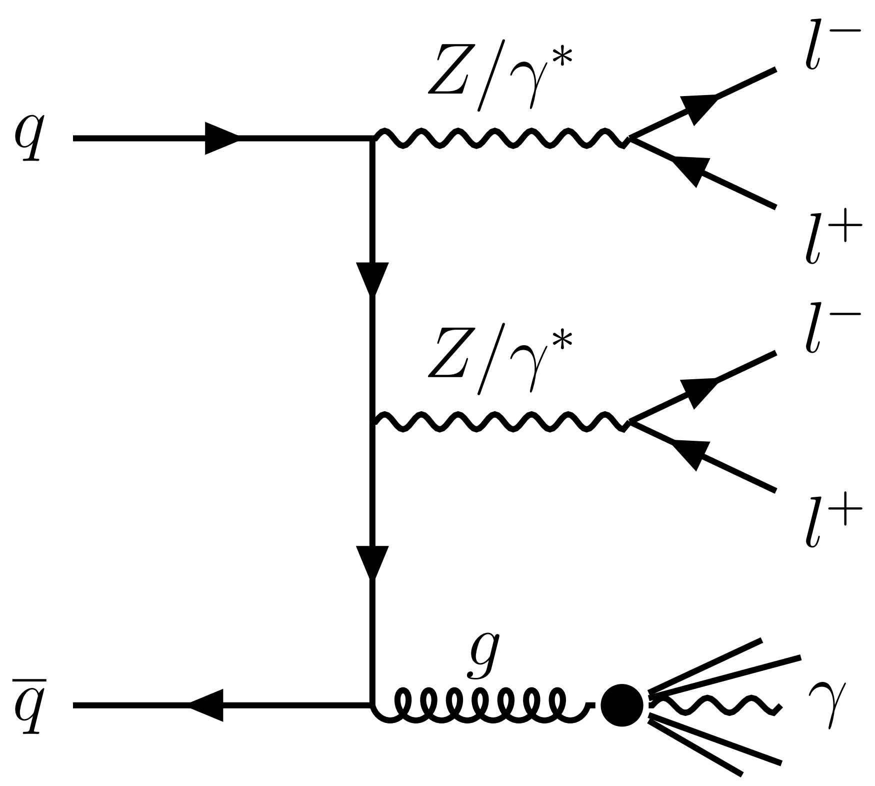
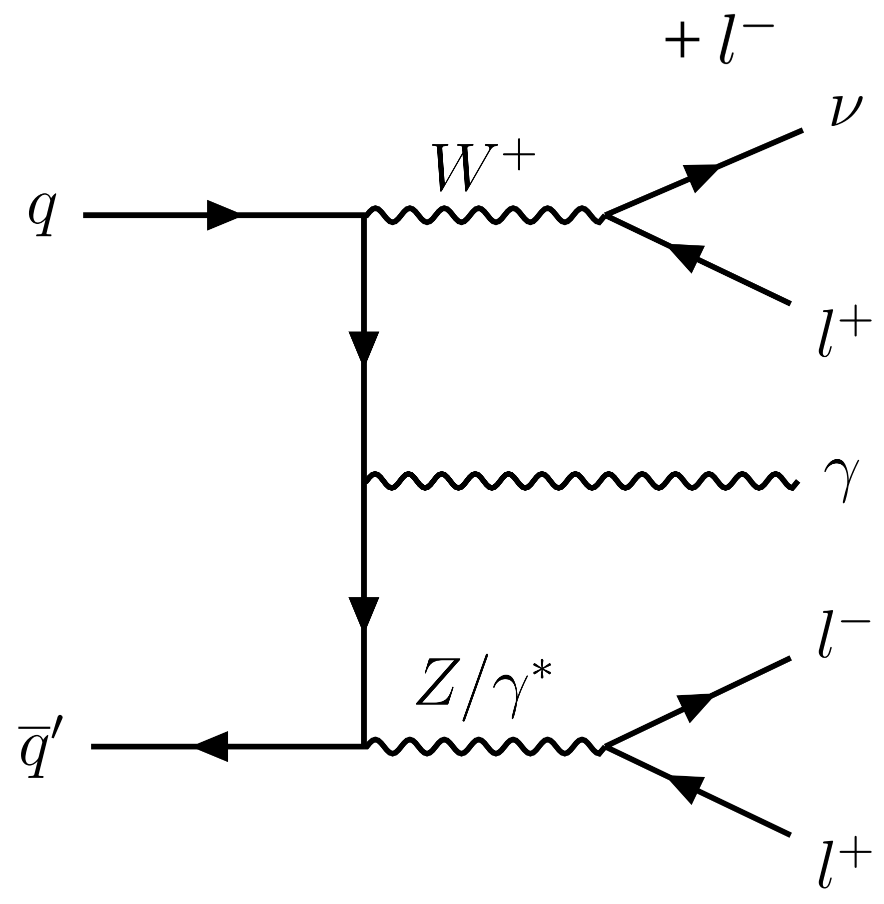
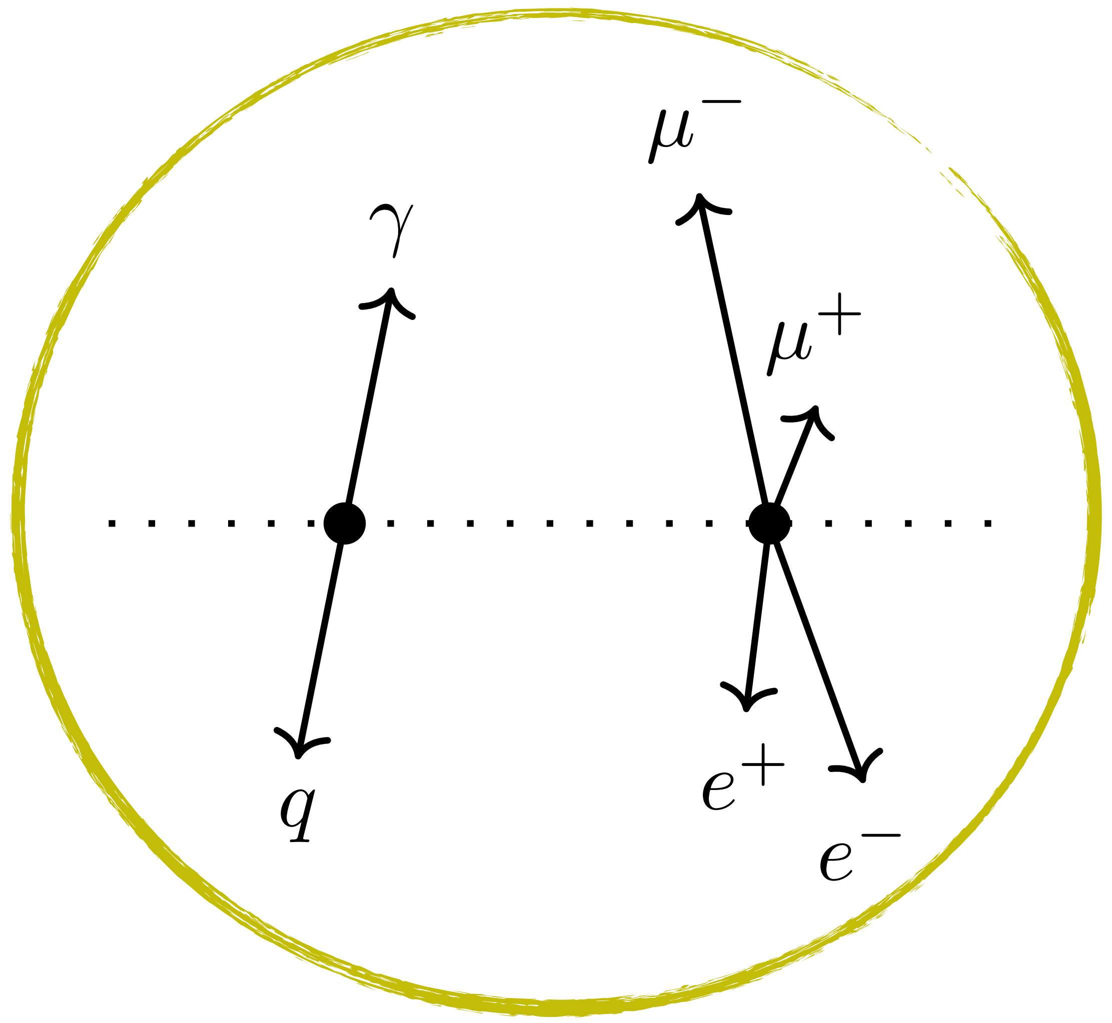
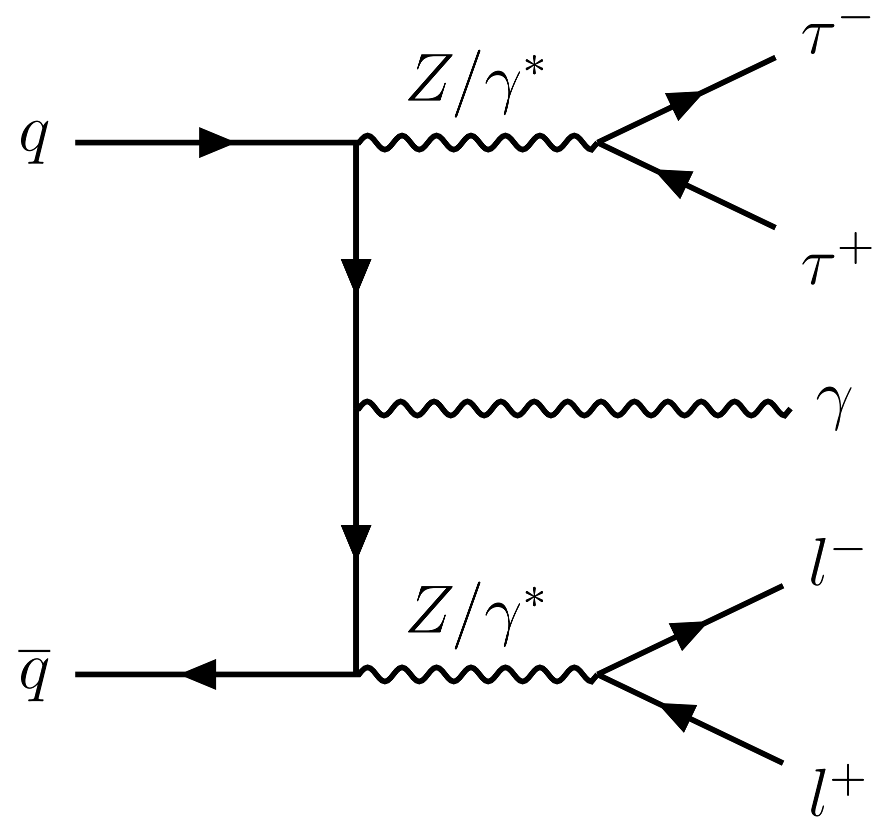



Backgrounds




pileup background



# Potential backgrounds

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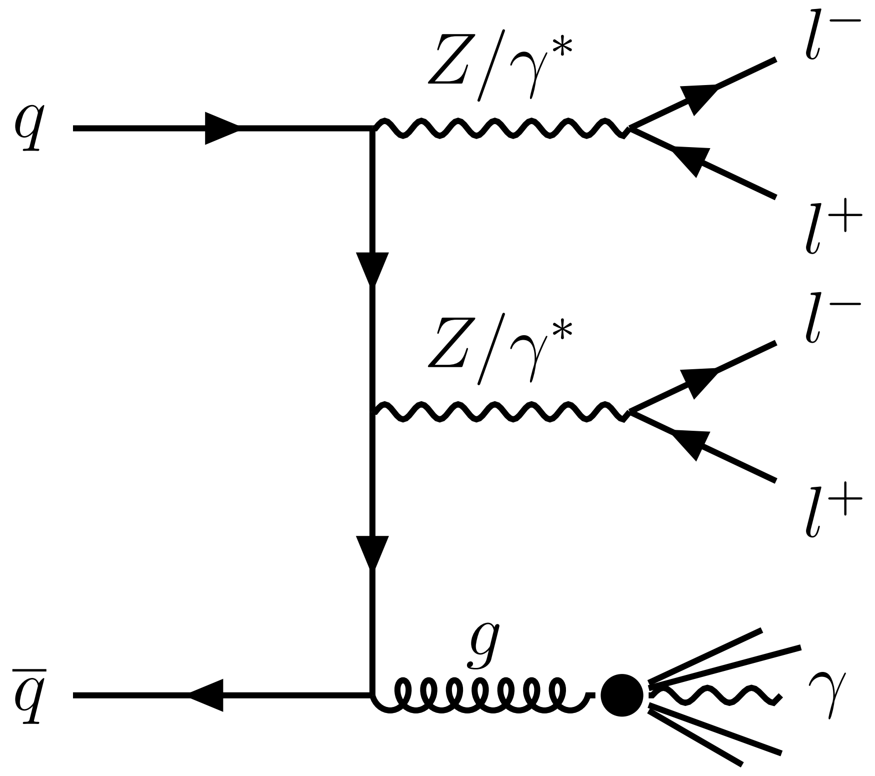
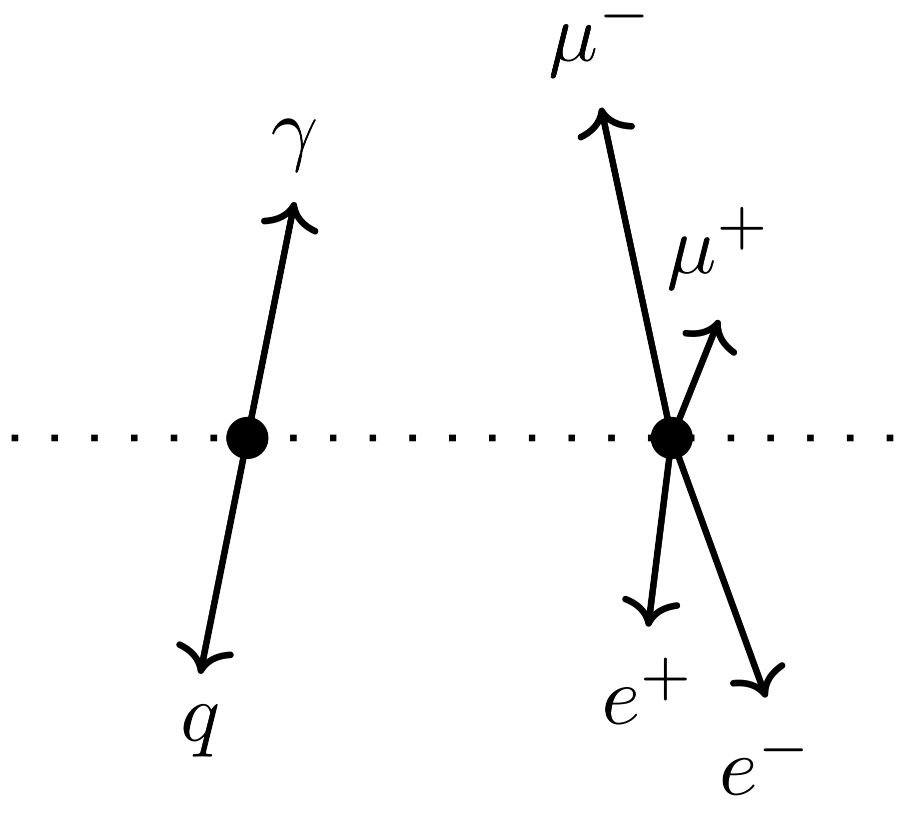
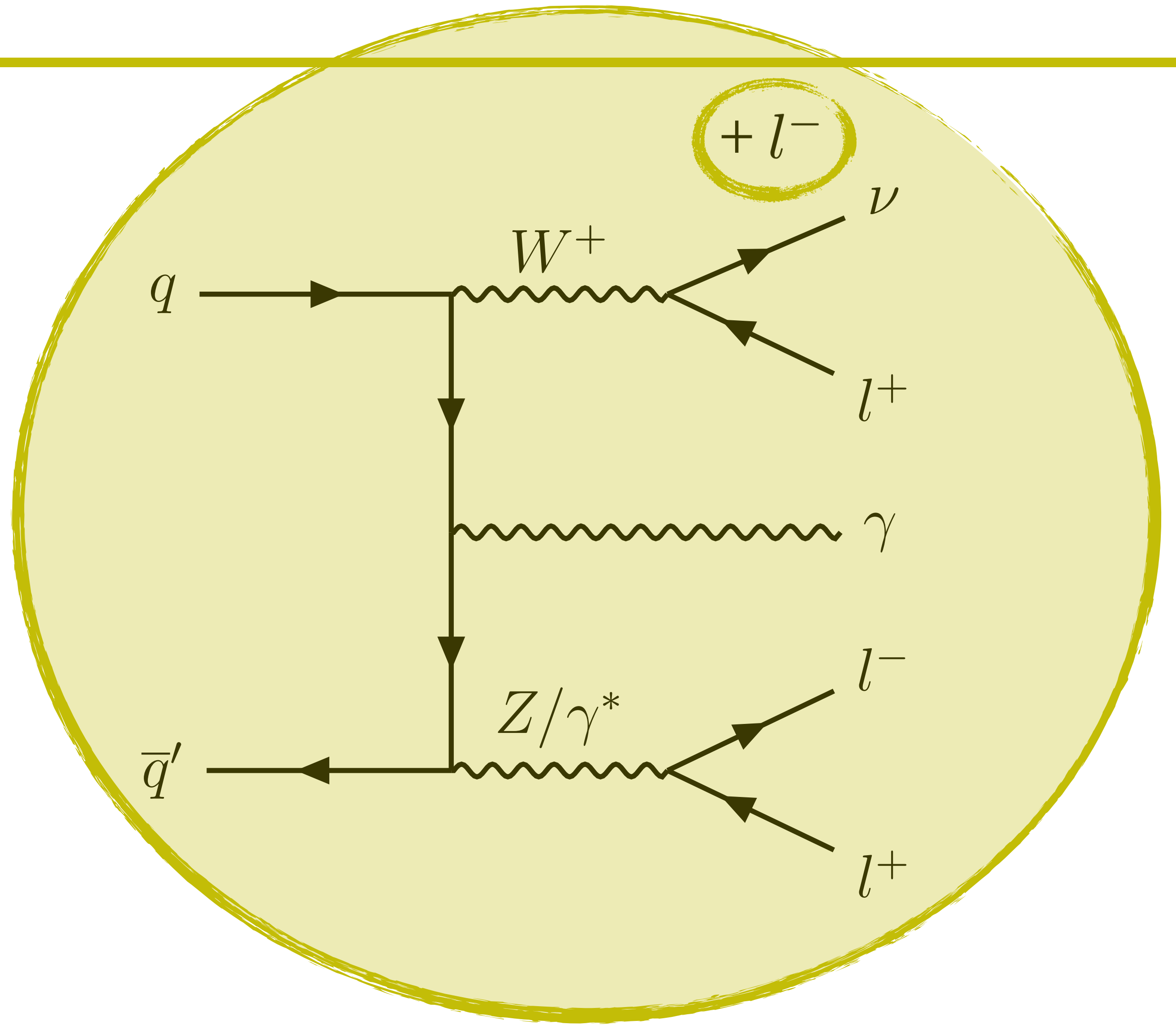
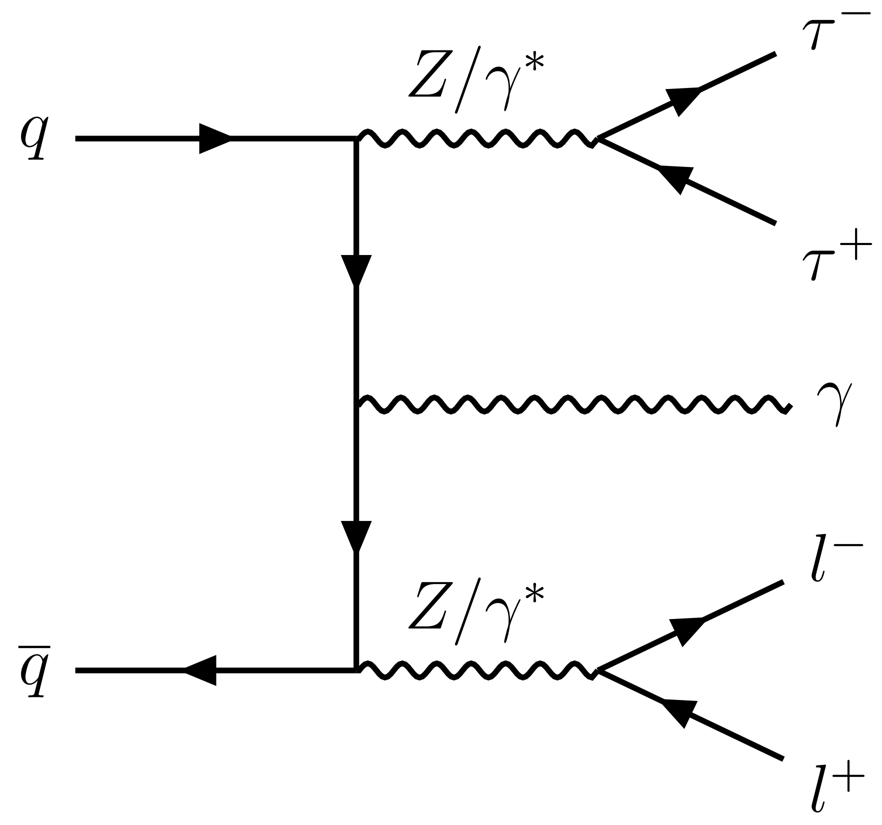



misidentified lepton background

Backgrounds



# Estimate the background

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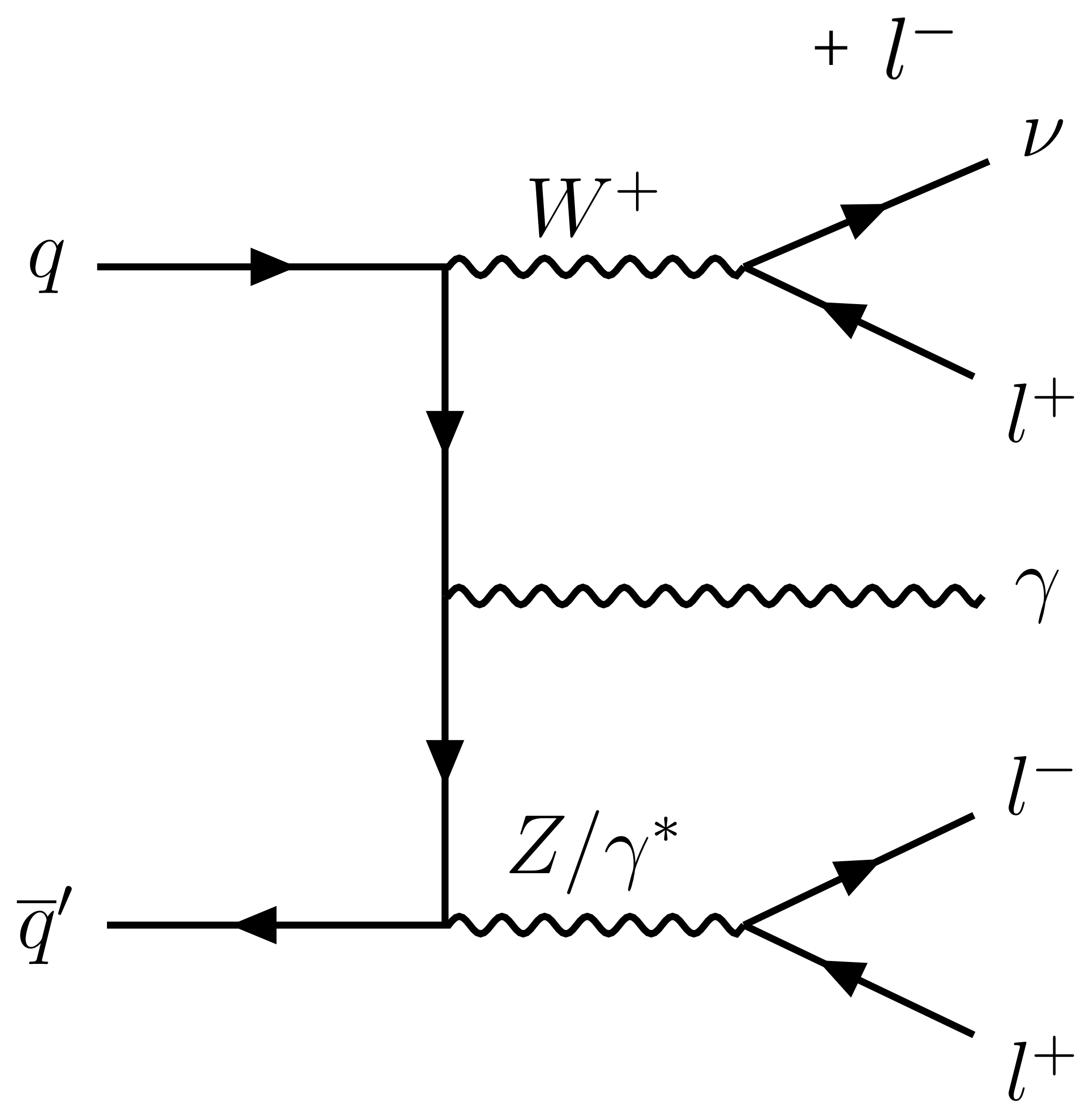
Overview - misidentified leptons:

- non-prompt leptons mainly from jets
- main backgrounds: $WZ\gamma$, $t\bar{t}\gamma$
- method: matrix method + fake factor
  - real efficiencies from MC
  - fake efficiencies from data (Z CR)



# Estimate the background

measurable quantities

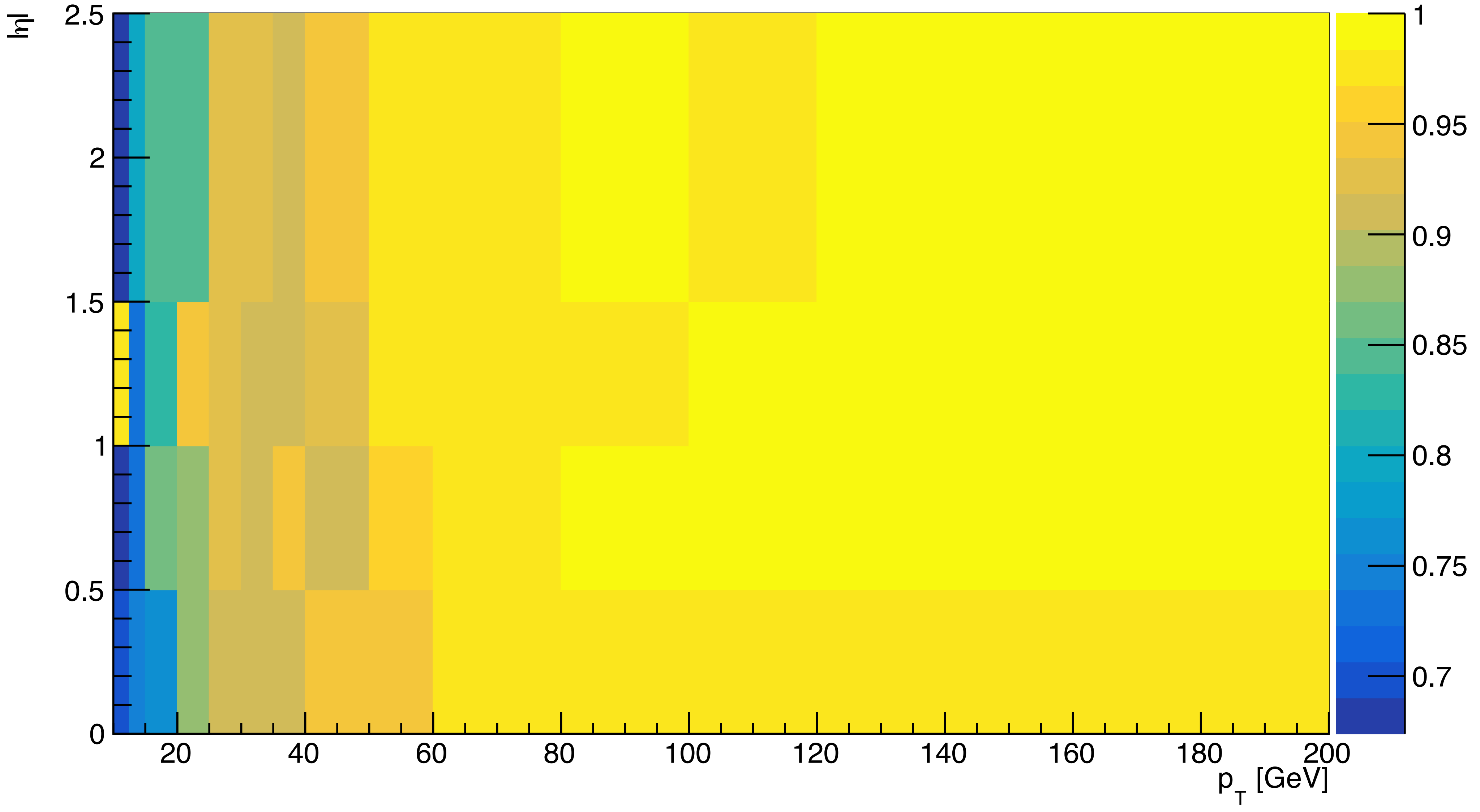
$$\begin{pmatrix} N^t \\ N^l \end{pmatrix} = \begin{pmatrix} r & f \\ 1-r & 1-f \end{pmatrix} \begin{pmatrix} N_r \\ N_f \end{pmatrix}$$

properties

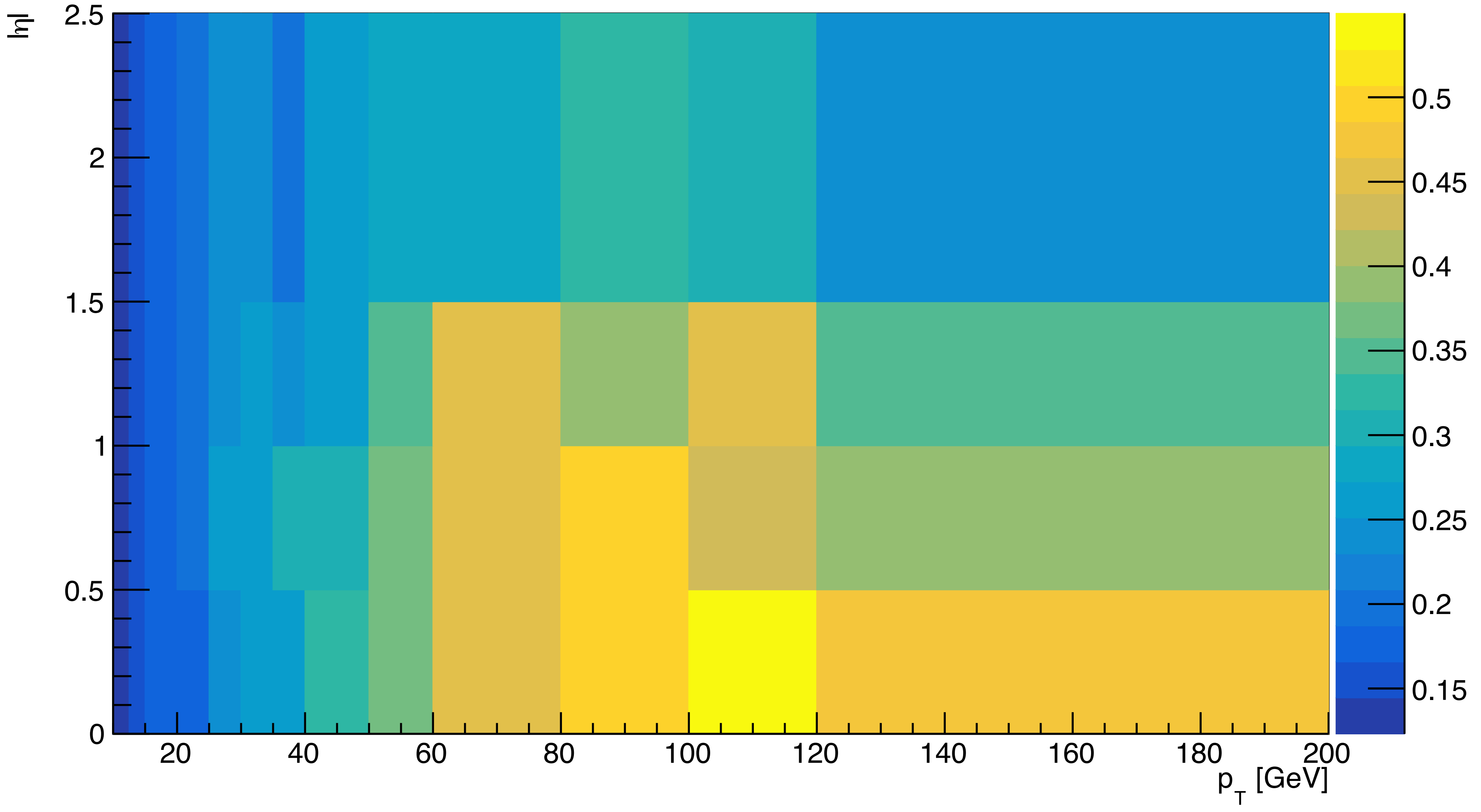
tight leptons
loose leptons

real leptons
fake leptons

Real efficiencies of the electrons




Fake efficiencies of the electrons



# Estimate the background

CR1

CR2

$$\begin{pmatrix} N^{tt} \\ N^{tl} \\ N^{lt} \\ N^{ll} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 \bar{r}_2 & r_1 \bar{f}_2 & f_1 \bar{r}_2 & f_1 \bar{f}_2 \\ \bar{r}_1 r_2 & \bar{r}_1 f_2 & \bar{f}_1 r_2 & \bar{f}_1 f_2 \\ \bar{r}_1 \bar{r}_2 & \bar{r}_1 \bar{f}_2 & \bar{f}_1 \bar{r}_2 & \bar{f}_1 \bar{f}_2 \end{pmatrix} \begin{pmatrix} N^{rr} \\ N^{rf} \\ N^{fr} \\ N^{ff} \end{pmatrix}$$

$$N_{\mathrm{SR}}^{\text{fake lepton}} = r_1 f_2 N^{rf} + f_1 r_2 N^{fr} + f_1 f_2 N^{ff}$$

# Estimate the background

CR1

CR2

$$\begin{pmatrix} N^{tt} \\ N^{tl} \\ N^{lt} \\ N^{ll} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 \bar{r}_2 & r_1 \bar{f}_2 & f_1 \bar{r}_2 & f_1 \bar{f}_2 \\ \bar{r}_1 r_2 & \bar{r}_1 f_2 & \bar{f}_1 r_2 & \bar{f}_1 f_2 \\ \bar{r}_1 \bar{r}_2 & \bar{r}_1 \bar{f}_2 & \bar{f}_1 \bar{r}_2 & \bar{f}_1 \bar{f}_2 \end{pmatrix} \begin{pmatrix} N^{rr} \\ N^{rf} \\ N^{fr} \\ N^{ff} \end{pmatrix}$$

$$N_{\mathrm{SR}}^{\text{fake lepton}} = \sum_{i,j} \frac{r_i f_i}{ri - fi} \frac{r_j(1-f_j)}{r_j - f_j} N_{\mathrm{CR1},i,j} - \sum_{i,j} \frac{r_i f_i}{r_i - f_i} \frac{r_j f_j}{r_j - f_j} N_{\mathrm{CR2},i,j}$$

$$N_{\mathrm{CR1},i,j}^{\mathrm{data}} - N_{\mathrm{CR1},i,j}^{ZZ\gamma}$$

# Estimate the background

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- CR1: SR with 1 lepton loose & !tight
  - data: 1 ± 1
  - 4ℓ+γ signal sample: 0.436 ± 0.024
- CR2: SR with 2 lepton loose & !tight
  - data: 1 ± 1
  - 4ℓ+γ signal sample: 0.0121 ± 0.00

→

| electrons | matrix method |
|---|---|
| $p_T$ | $-0.012 \pm 0.002$ |
| $\eta$ | $-0.009 \pm 0.001$ |
| $p_T,\, \eta$ | $-0.012 \pm 0.002$ |
| muons | |
| $p_T$ | $0.17 \pm 0.18$ |
| $\eta$ | $0.05 \pm 0.07$ |
| $p_T,\, \eta$ | $0.15 \pm 0.16$ |

# Estimate the background

- CR1: SR with 1 lepton loose & !tight
  - data: 1 ± 1
  - 4ℓ+γ signal sample: 0.436 ± 0.024
- CR2: SR with 2 lepton loose & !tight
  - data: 1 ± 1
  - 4ℓ+γ signal sample: 0.0121 ± 0.00

| electrons | matrix method |
|---|---|
| $p_T$ | $-0.012 \pm 0.0$[illegible] |
| $\eta$ | $-0.00$[illegible] |
| $p_T,\ \eta$ | [illegible] $\pm 0.002$ |
| muons | |
| $p_T$ | [illegible]$17 \pm 0.18$ |
| $\eta$ | [illegible]$0.07$ |
| $p_T,\ \eta$ | $0.1$[illegible] |

unphysical results

too large uncertainties

# Estimate the background

- CR1: SR with 1 lepton loose & !tight
  - data: 1 ± 1
  - 4ℓ+γ signal sample: 0.436 ± 0.024
- CR1′: SR with 1 lepton loose & !tight, no photon
  - data: 553 ± 24
  - 4ℓ MC sample: 233.6 ± 2.0

$$\frac{N^{\ell\,\text{fake}}_{ZZ\gamma}}{N_{ZZ\gamma}} = \frac{N^{\ell\,\text{fake}}_{ZZ}}{N_{ZZ}}$$

$$\frac{N^{CR_1}_{ZZ\gamma}}{N_{ZZ\gamma}} = \frac{0.436 \pm 0.004}{5.83 \pm 0.08} = 0.0748 \pm 0.0042$$

$$\frac{N^{CR_1'}_{ZZ}}{N_{ZZ}} = \frac{233.6 \pm 2.0}{3112.6 \pm 7.2} = 0.0750 \pm 0.0007$$

$\Big\}$ $0.06\,\sigma$

# Estimate the background

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Misidentified leptons in ZZ:

| electrons | fake estimate |
|---|---|
| $p_T$ | $27.2 \pm 6.2 \pm 2.5$ |
| $\eta$ | $18.0 \pm 4.5 \pm 1.5$ |
| $p_T, \eta$ | $26.5 \pm 6.6 \pm 2.6$ |
| muons | |
| $p_T$ | $6.9 \pm 1.3 \pm 1.1$ |
| $\eta$ | $6.6 \pm 1.1 \pm 1.2$ |
| $p_T, \eta$ | $6.8 \pm 1.5 \pm 1.3$ |

Systematic uncertainties

- stat. uncertainty from efficiencies propagated
- syst. uncertainty through binning (one bin $\eta$, 3 bins $p_T$)
- variations of prompt MC background ±10%
- difference to fake factor method

# Estimate the background

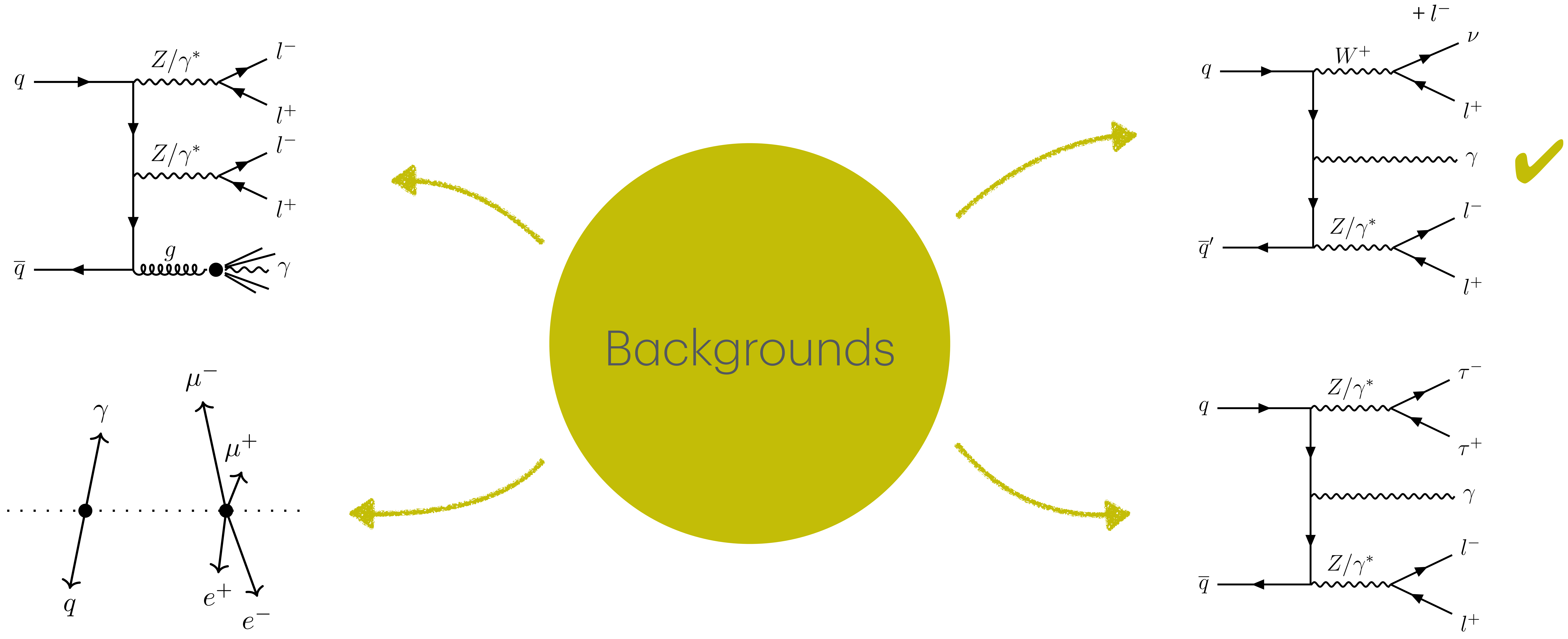
$$N^{\ell\,\text{fake}}_{ZZ\gamma} = \frac{N^{\ell\,\text{fake}}_{ZZ}}{N_{ZZ}} N_{ZZ\gamma}$$

$$N^{\ell\,\text{fake}}_{ZZ\gamma} = 0.062 \pm 0.014$$

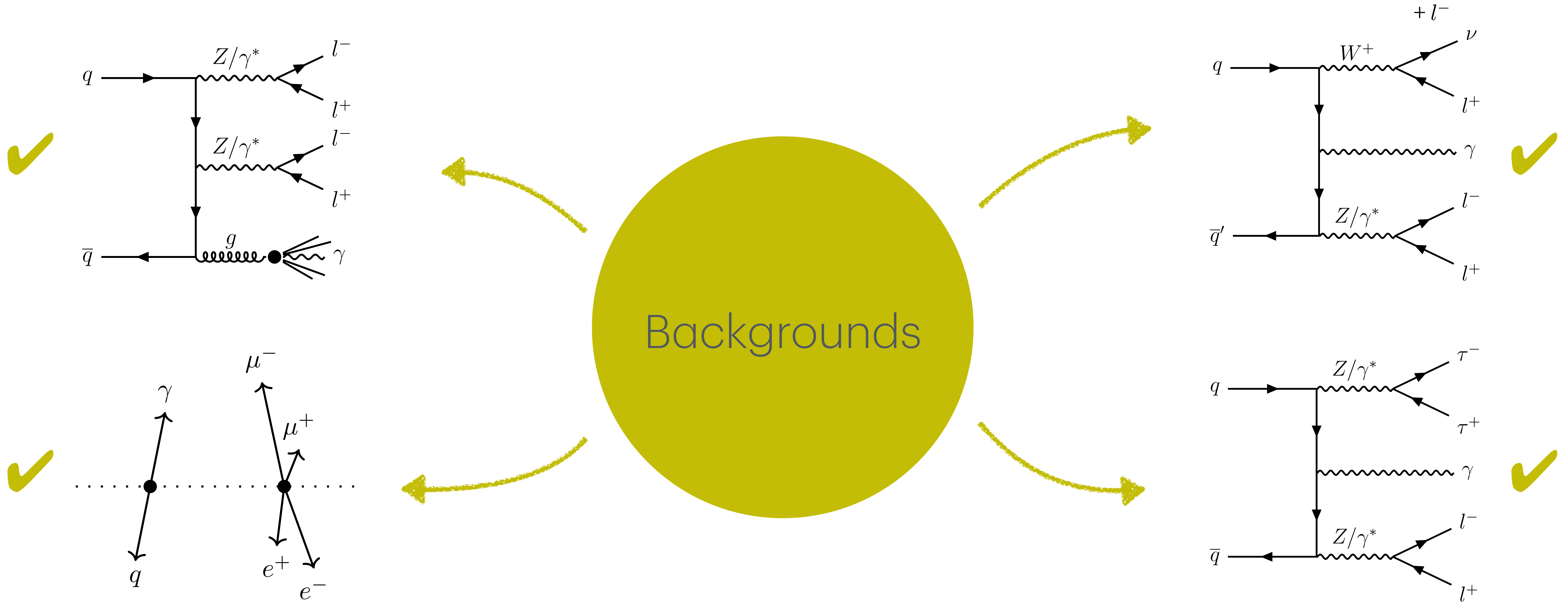
Misidentified leptons in ZZγ:

| electrons | fake estimate |
|---|---|
| $p_T$ | $0.051 \pm 0.013$ |
| $\eta$ | $0.034 \pm 0.009$ |
| $p_T, \eta$ | $0.050 \pm 0.013$ |
| muons | |
| $p_T$ | $0.013 \pm 0.003$ |
| $\eta$ | $0.012 \pm 0.003$ |
| $p_T, \eta$ | $0.013 \pm 0.004$ |

# Potential backgrounds



# Potential backgrounds



# How to make an observation

| Pick an appropriate final state ✔ | Apply an event selection to maximise your S/B ✔ | Estimate the irreducible backgrounds ✔ | Check if you are above 5$\sigma$ |
|---|---|---|---|

# Derive the signal significance



1.

Combine all backgrounds

2.

Get the right formula

3.

Above 5σ?

# Overview - expected events

| | Number of Events |
|---|---|
| SHERPA 2.2.11 $\ell\ell\ell\ell\gamma$ | $5.83 \pm 0.21$ |
| POWEGPYTHIA8 $ZH(\rightarrow Z\gamma)$ | $0.74 \pm 0.03$ |
| **Signal** | $6.57 \pm 0.21$ |
| Non-prompt Photons | $0.49 \pm 0.09$ |
| Misidentified Leptons | $0.062 \pm 0.014$ |
| Pile up | $0.056 \pm 0.014$ |
| $Z \rightarrow \tau\tau$ contribution | $0.035 \pm 0.006$ |
| **Total Background** | $0.64 \pm 0.09$ |
| $N_{\text{tot}}$ | $7.21 \pm 0.23$ |

# Overview - expected events

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| | Number of Events |
| --- | --- |
| SHERPA 2.2.11 $\ell\ell\ell\ell\gamma$ | $5.83 \pm 0.21$ |
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| Pile up | $0.056 \pm 0.014$ |
| $Z \rightarrow \tau\tau$ contribution | $0.035 \pm 0.006$ |
| **Total Background** | $0.64 \pm 0.09$ |
| $N_{\text{tot}}$ | $7.21 \pm 0.23$ |

# What formula?

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$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

$$Z = \frac{s}{b}$$

$Z$: significance

$n$: number of events

$s$: number of signal events

$b$: number of background events

$\sigma$: total background uncertainty

$$Z = \frac{s}{\sqrt{b+\sigma^2}}$$

$$Z = \frac{s}{\sqrt{s+b}}$$

$$Z = \frac{s}{\sqrt{b}}$$

$$Z = \sqrt{2\left(n \ln\left[\frac{n}{b}\right] - (n-b)\right)}$$

# What formula?

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Poisson-Poisson model with asymptotic formulae

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

$$Z = \frac{s}{b}$$

Signal to noise/ background ratio

$Z$: significance
$n$: number of events
$s$: number of signal events
$b$: number of background events
$\sigma$: total background uncertainty

Gaussian approximation w/ uncertainty

$$Z = \frac{s}{\sqrt{b+\sigma^2}}$$

$$Z = \frac{s}{\sqrt{s+b}}$$

Signal significance used by TMVA

$$Z = \frac{s}{\sqrt{b}}$$

Gaussian approximation w/o uncertainty

Poisson-Poisson model with asymptotic formulae w/o uncertainty

$$Z = \sqrt{2\left(n \ln\left[\frac{n}{b}\right] - (n-b)\right)}$$

[ATL-COM-GEN-2018-026]

# What formula?

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Gaussian approximation w/o uncertainty

[ATL-COM-GEN-2018-026]

# Above 5σ?

| | Number of Events |
|---|---|
| Sherpa 2.2.11 $\ell\ell\ell\ell\gamma$ | $5.83 \pm 0.21$ |
| PowegPythia8 $ZH(\to Z\gamma)$ | $0.74 \pm 0.03$ |
| **Signal** | $6.57 \pm 0.21$ |
| Non-prompt Photons | $0.49 \pm 0.09$ |
| Misidentified Leptons | $0.062 \pm 0.014$ |
| Pile up | $0.056 \pm 0.014$ |
| $Z \to \tau\tau$ contribution | $0.035 \pm 0.006$ |
| **Total Background** | $0.64 \pm 0.09$ |
| $N_{\text{tot}}$ | $7.21 \pm 0.23$ |

$$Z = \sqrt{2\left(n \ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)}$$

$$Z = 4.58\,\sigma$$

# How to make an observation

Pick an appropriate final state ✔

Optimise the event selection

Estimate the irreducible backgrounds

Check if you are above 5σ

Repeat 🔁

# Above 5σ?

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# Above 5σ?

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$$Z = 5\,\sigma$$

# Backup

# Analysis strategy

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- fully leptonic decay: Z→ee, μμ
- signal: 4ℓ+γ
- pp → ZZγ → 4ℓ+γ (incl. pp → ZH(→Zγ) → 4ℓ+γ)
- analysis of full Run 2 data (140 $fb^{-1}$)

| ***ATLAS*** Work in Progress | Number of Events |
|---|---|
| SHERPA 2.2.11 $\ell\ell\ell\ell\gamma$ | $5.83 \pm 0.21$ |
| POWEGPYTHIA8 $ZH(\to Z\gamma)$ | $0.74 \pm 0.03$ |
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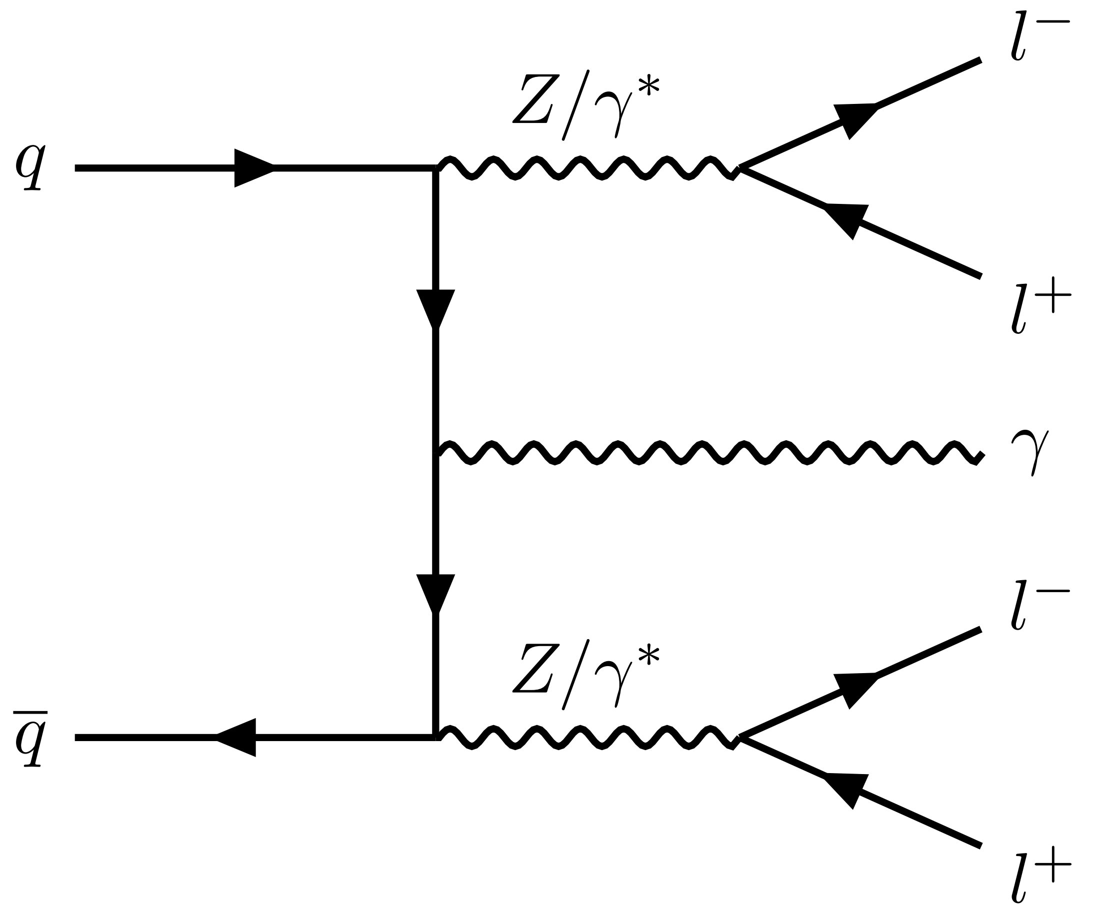
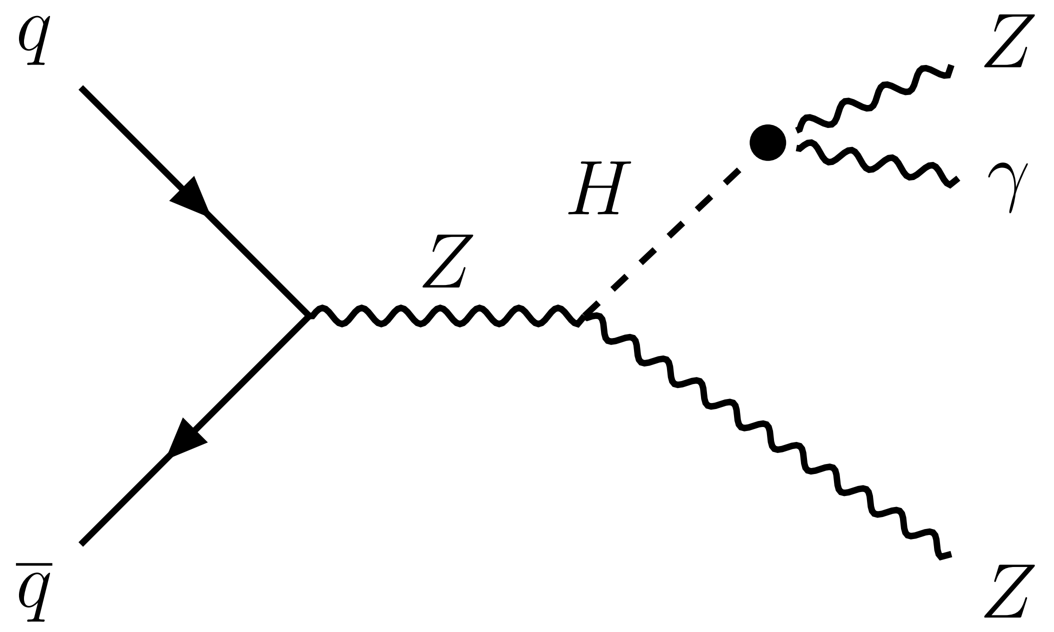
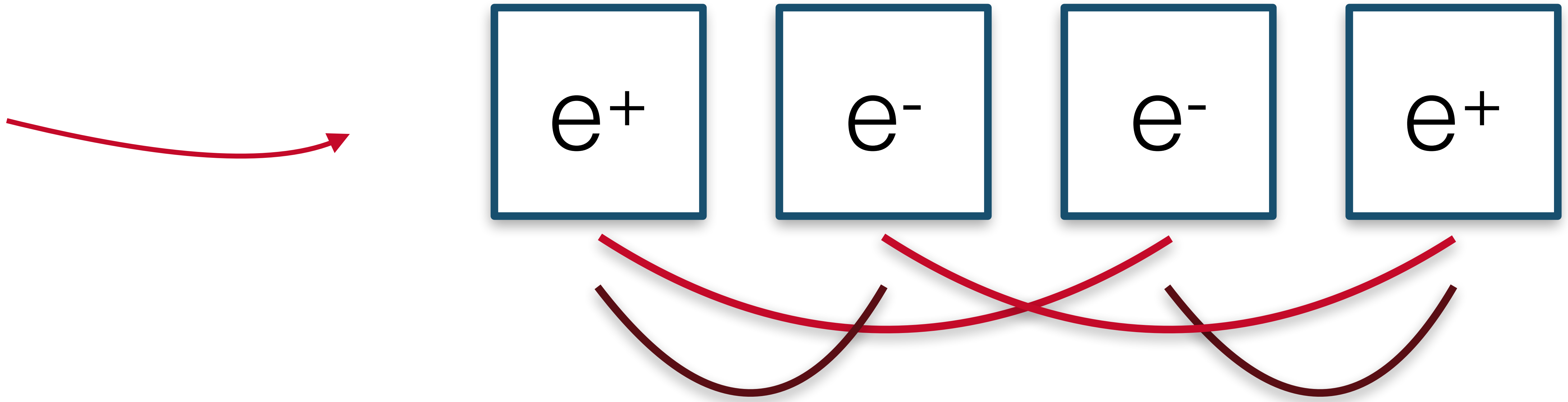


# Event selection

- 2 pairs of 2 opposite-sign same-flavour (OSSF) leptons → 4e, 4μ, 2e2μ
- invariant mass $m_{\ell\ell}$ > 40 GeV
- min( | $m_{\ell\ell,1}$ - $m_Z$ | + | $m_{\ell\ell,2}$ - $m_Z$ | )
- 1 photon, $p_T$ > 20 GeV
- FSR rejection



# Event selection

| | Electrons | Muons | Photon |
| --- | --- | --- | --- |
| Kinematics | $p_T > 30, 25, 10, 10\text{GeV}$ | | $p_T > 20\text{GeV}$ |
| | $\mid \eta \mid < 2.47$ | $\mid \eta \mid < 2.5$ | $\mid \eta \mid < 2.37$ |
| | excl. $1.37 < \mid \eta \mid < 1.52$ | | excl. $1.37 < \mid \eta \mid < 1.52$ |
| Identification | tight ($l_1$), medium | medium | tight |
| Isolation | Loose | PflowTightFixedRad ($l_1$), | FixedCutLoose |
| | | PflowLooseFixedRad | $\Delta R(l, \gamma) > 0.4$ |
| Multiplicity | $\geq 2$ OSSF pairs | | $\geq 1$ photon |
| Mass | $m_{ll} > 40$ GeV, $(m_{ll\gamma} + m_{ll}) > 2 \cdot m_Z$ | | |
| Trigger | single lepton triggers | | |

# Signal Systematics

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| Source | Relative uncertainty [%] |
|---|---|
| Photon identification efficiency | 1.2 |
| Photon isolation efficiency | 1.0 |
| Electron-Photon energy resolution | $-0.19/+0.14$ |
| Electron-Photon energy scale | 0.4 |
| Electron identification efficiency | 2.1 |
| Electron isolation efficiency | 0.11 |
| Electron reconstruction efficiency | 0.5 |
| Muon isolation efficiency | 0.6 |
| Muon reconstruction efficiency | 0.5 |
| Muon trigger efficiency | 0.15 |
| Pile-up reweighting | -1.4/+1.6 |
| Monte Carlo signal statistics | 1.3 |
| Theoretical uncertainties | x.xx |
| Integrated luminosity | 0.83 |
| Total systematic uncertainty signal | 3.6 |

Table 1: Systematic uncertainty sources that contribute less than 0.1% are not shown. Theoretical uncertainties are not yet included.

# Non-prompt photon estimation

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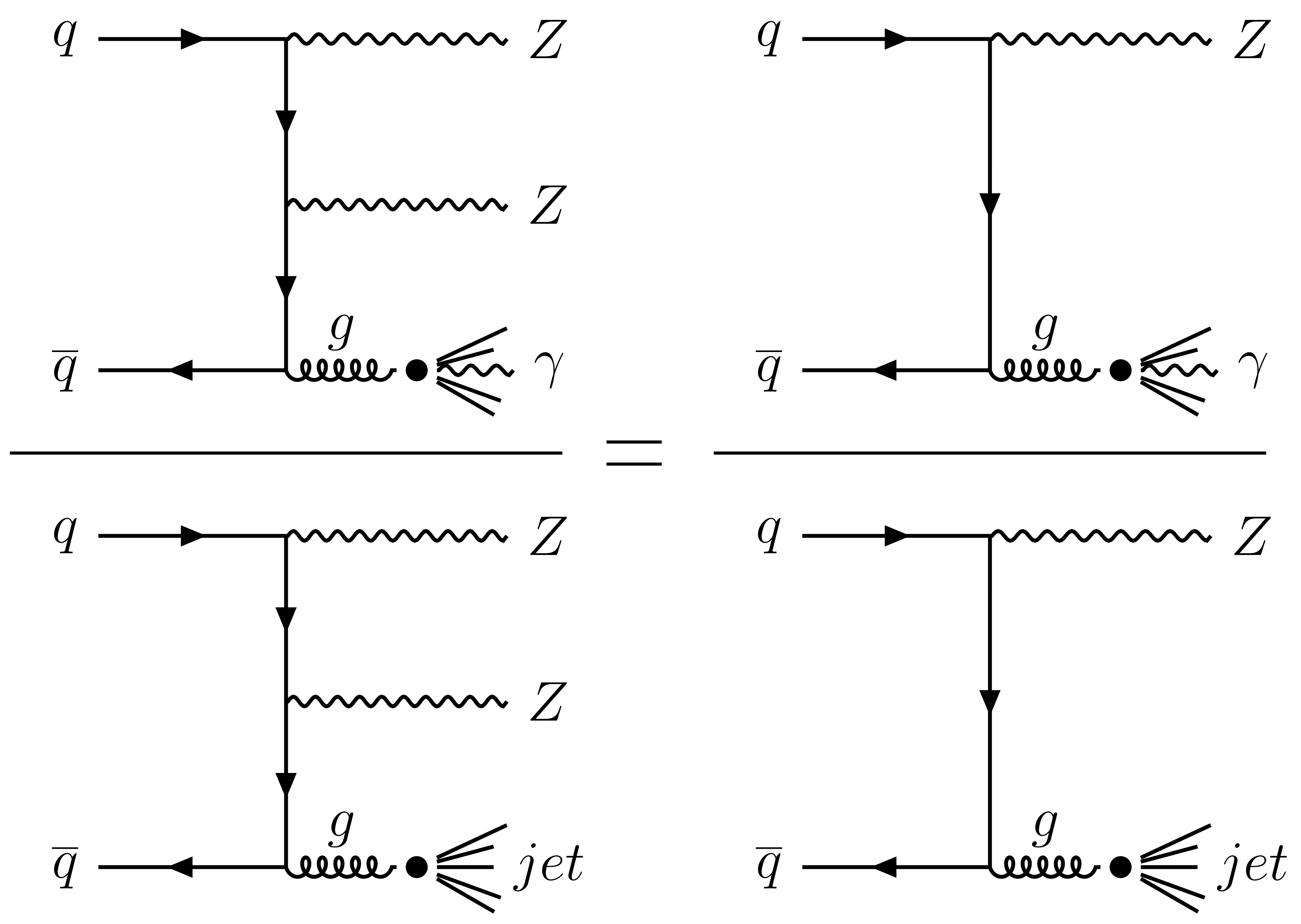
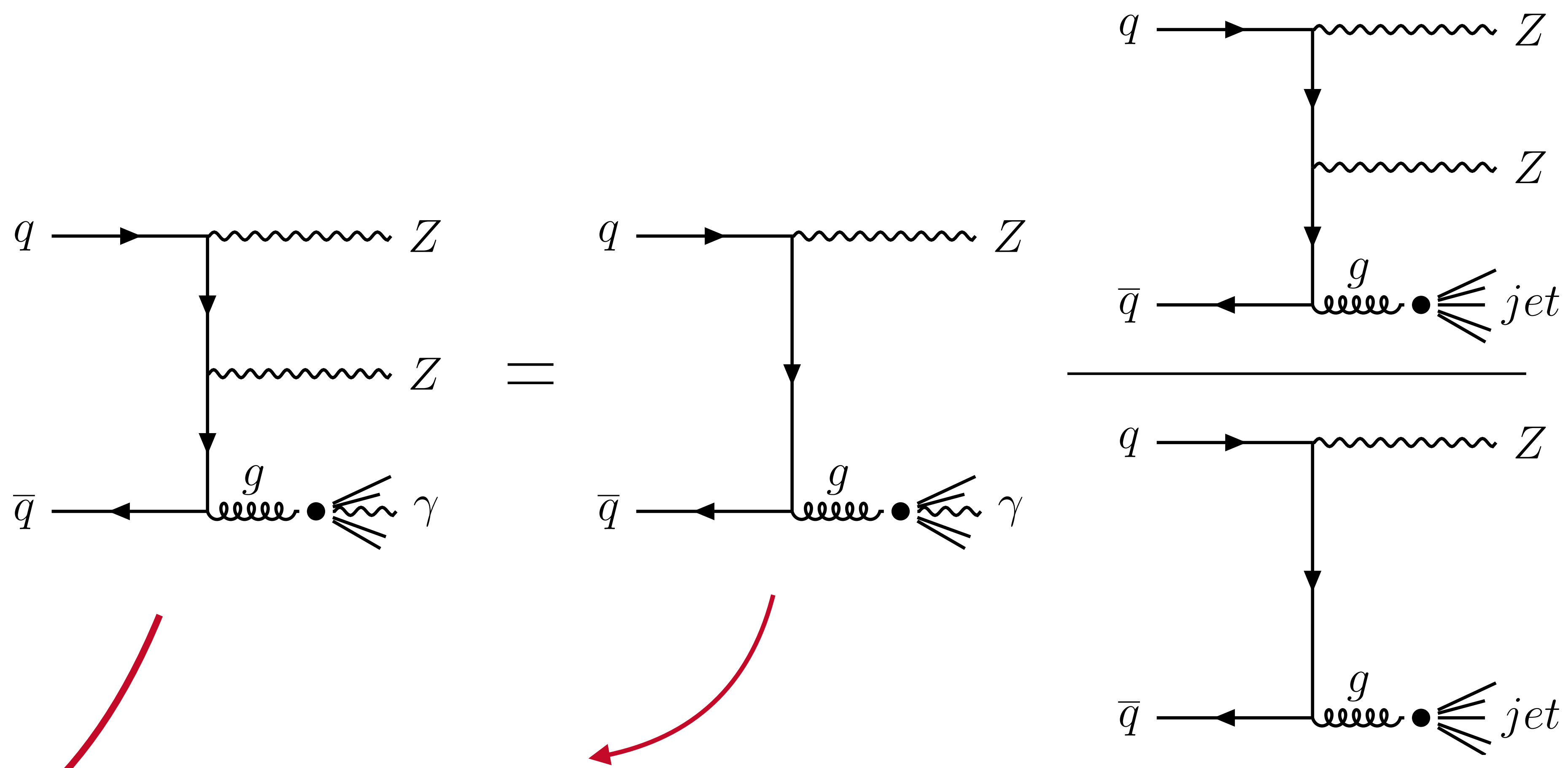
Ansatz:

The ratio of non-prompt photons produced in jets is independent of the simultaneous produced particles.

$$\frac{N_{ZZ\gamma}^{\gamma \text{non-prompt}}}{N_{ZZ}^{\text{jets}}} = \frac{N_{Z\gamma}^{\gamma \text{non-prompt}}}{N_{Z}^{\text{jets}}}$$

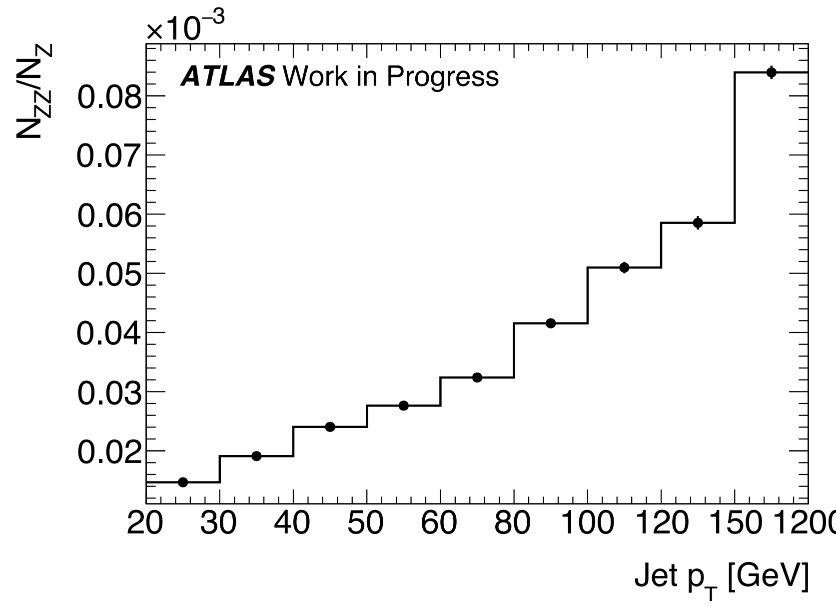


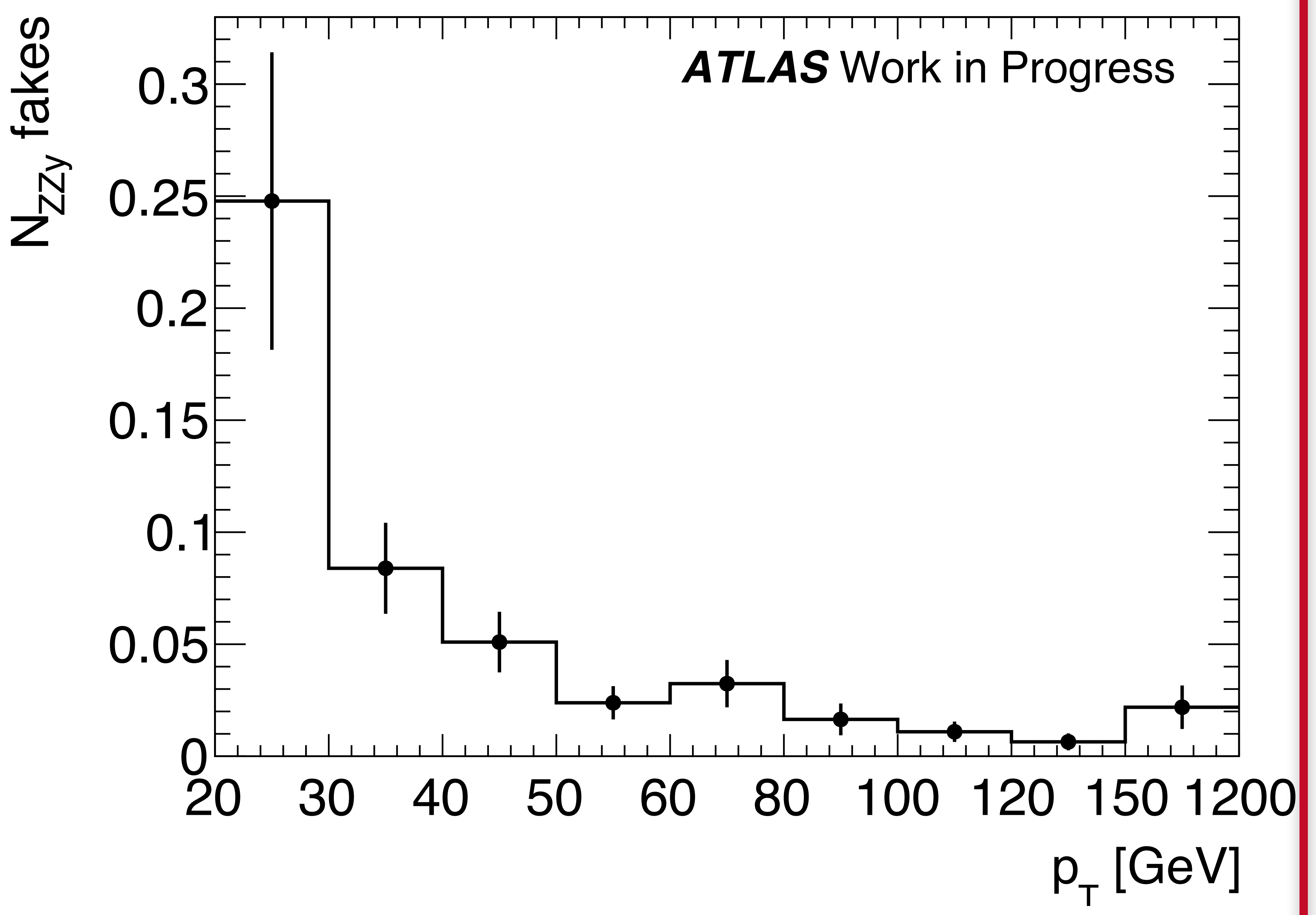
# Non-prompt photon estimation




Estimation from Zγ Analysis

MC ZZ+jets, Z+jets

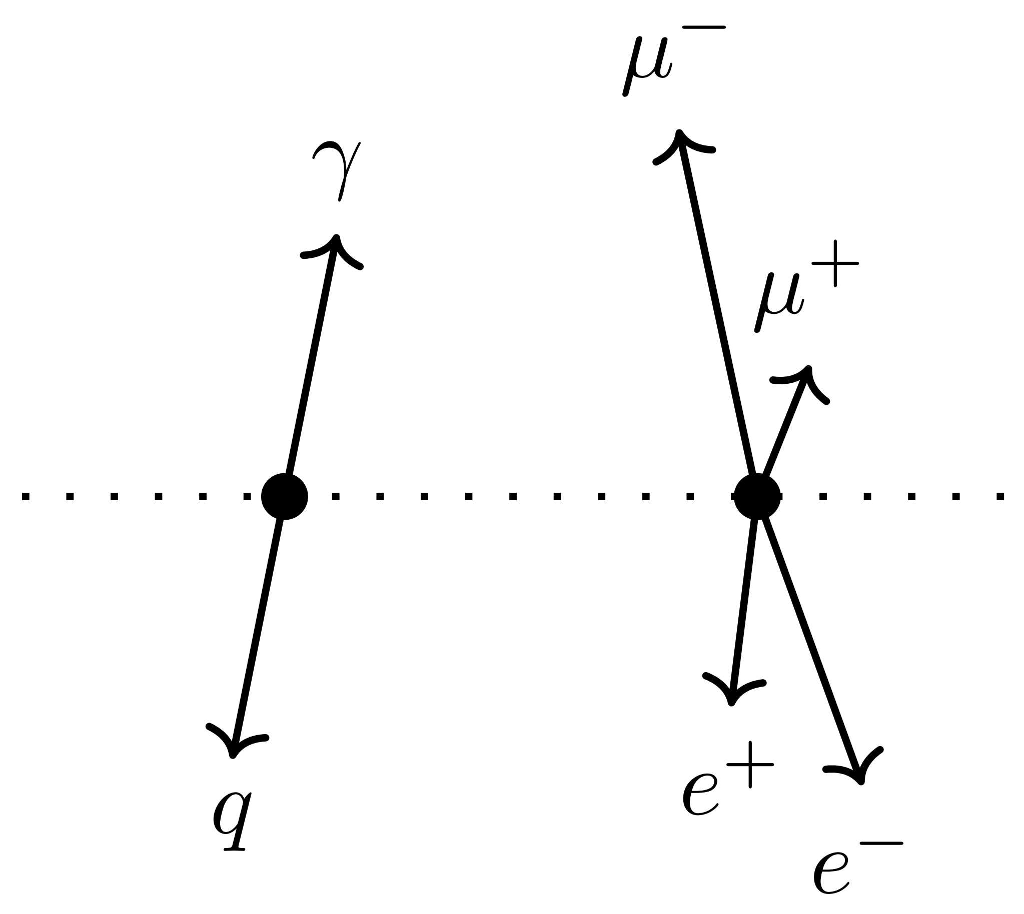



$$N^{\gamma\text{fake}}_{ZZ\gamma} = 0.49 \pm 0.003\ \text{(stat.)}\ \pm 0.09\ \text{(syst.)}$$

# Pile-up

Two independent interactions in the same bunch crossing




- Pile up contribution: ZZ + γ
  ↪ photon cannot be associated to any vertex
- Ansatz: $N_{ZZ+\gamma} \sim P_{ZZ}\, P_{\gamma}$
- Determine pile up on particle level with MC overlay (ZZ+γ)
- Apply correction to derive estimate on reconstruction level

# Matrix method

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- baseline selection (loose) > signal selection (tight)
- real efficiency: $\frac{\text{prompt tight leptons}}{\text{prompt loose leptons}}$

  ↪ derive with MC
- fake efficiency: $\frac{\text{fake tight leptons}}{\text{fake loose leptons}}$

  ↪ derive in fake enriched CR with data (Z CR)


→ loose leptons:
electrons: loose ID, no iso
muons: fail tight d0 significance, no iso

→ tight leptons:
electrons: medium ID, loose iso
muons: tight d0 significance, loose iso

# Real efficiencies

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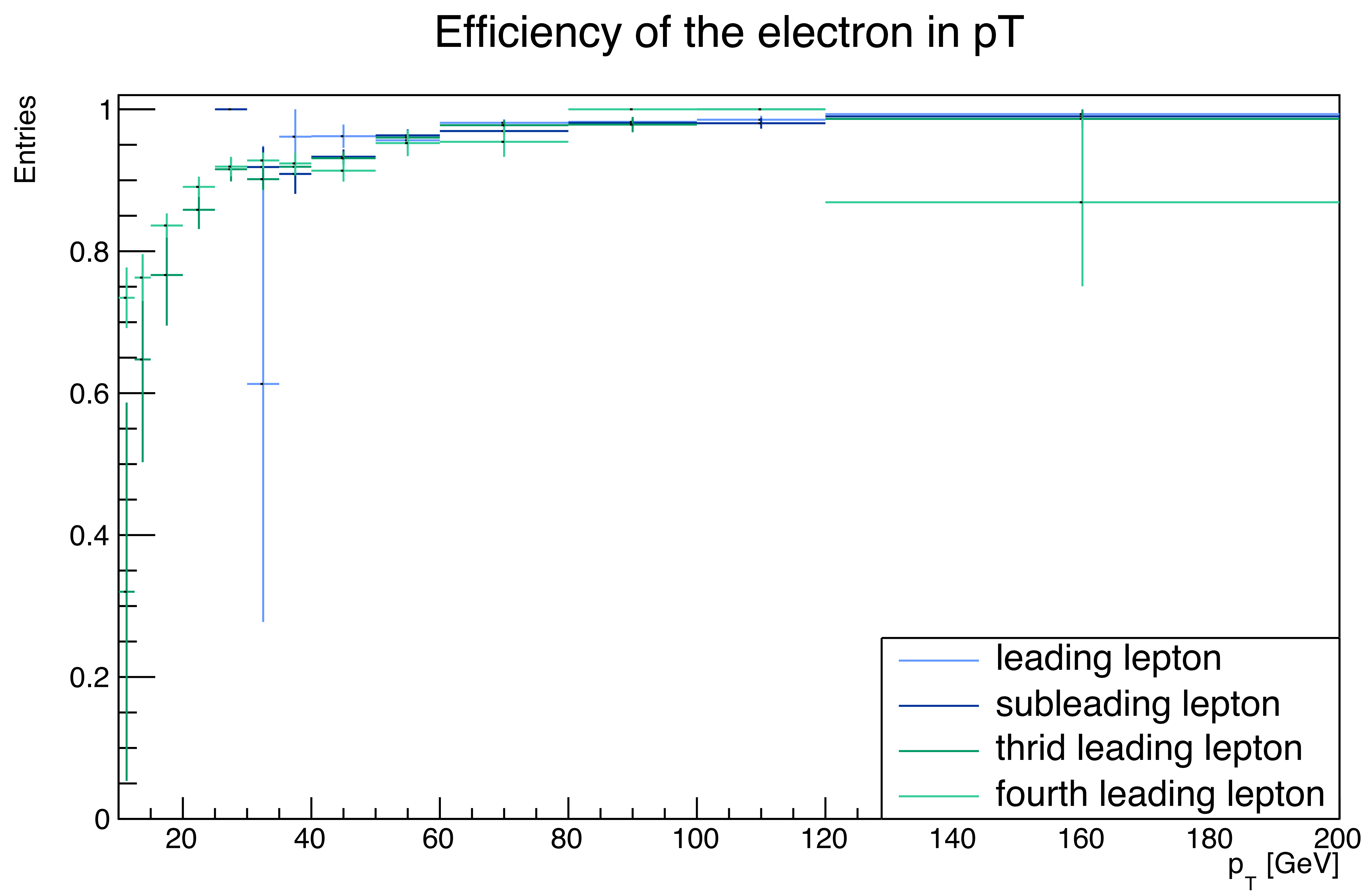
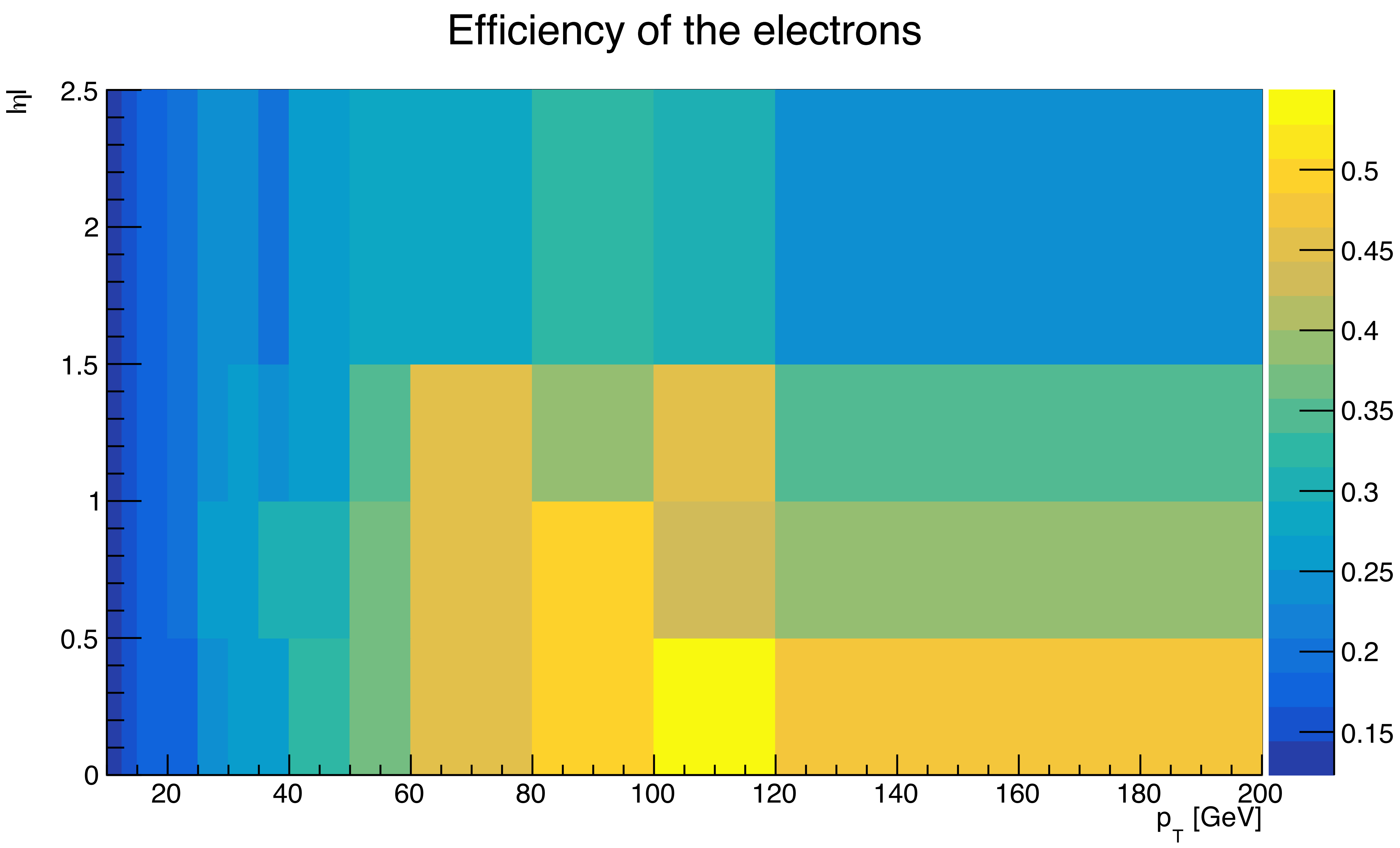
- ZZγ SR → MC
- ansatz: efficiency is independent of lepton (leading, subleading, etc.)
- comparison of lepton efficiencies in MC
- small differences → features of lepton pT distribution



# Fake efficiencies




# Misidentified leptons - validation

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$$N^{\ell\,\text{fake}}_{ZZ\gamma} = 0.062 \pm 0.014$$

$$N^{\ell\,\text{fake}}_{ZZ} = 33 \pm 7$$

- VR1: SR with 1 OSSF pair & 1SSSF pair
    - ZZy SR - data: 0 ± 0 ✅
    - ZZ SR - data: 29 ± 5 ✅
- VR2: SR with 1 OSSF pair & 1OSOF pair
    - ZZy SR - data: 0 ± 0 ✅ (w/o mass cut: 1 ± 1)
    - ZZ SR - data: 32 ± 6 ✅