UNIVERSITÉ DE GENÈVE

swiss physical society

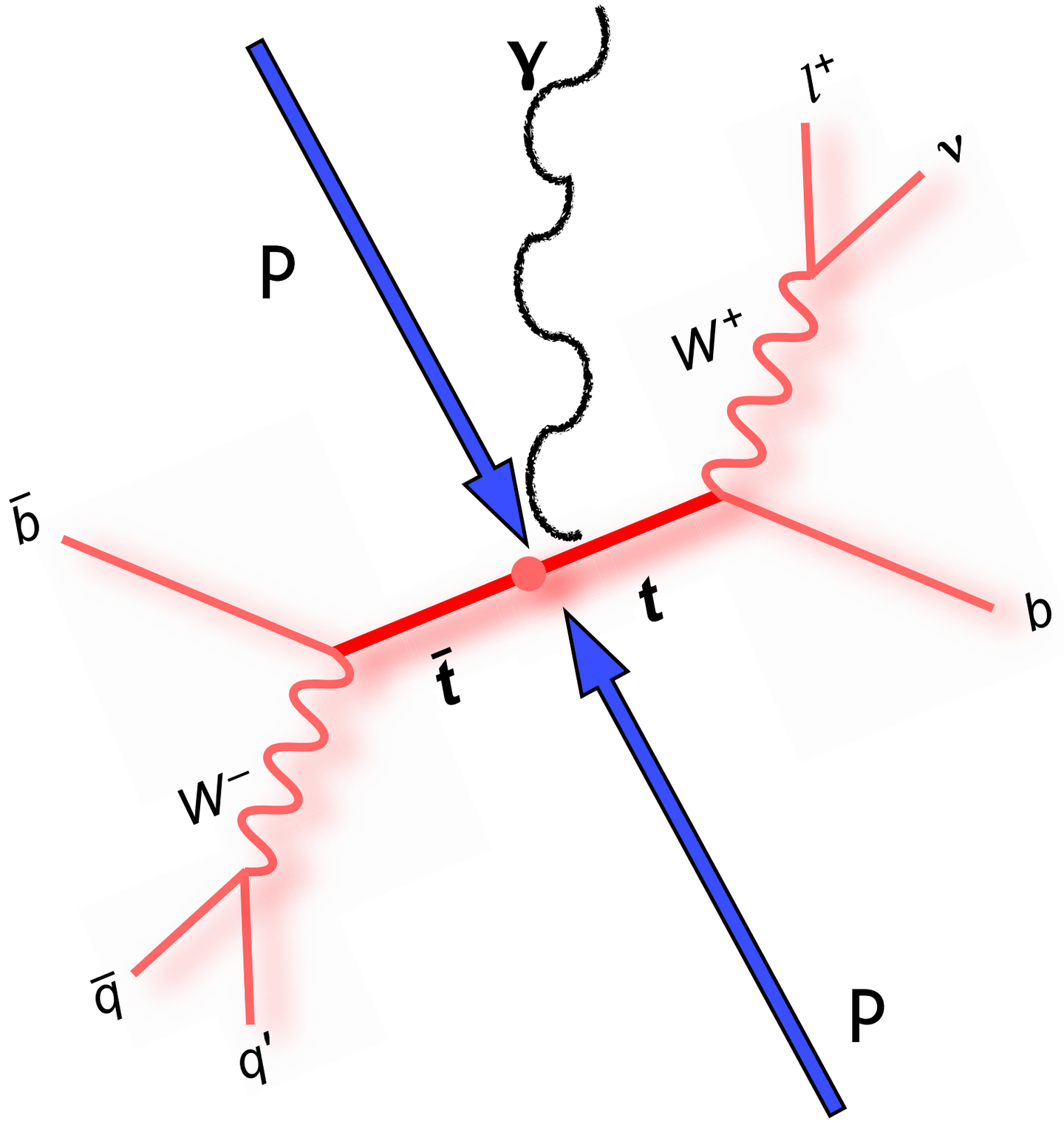
Measurement of the $t\bar{t}\gamma$ cross section at $\sqrt{s}$ = 7 TeV using the ATLAS detector

Gaetano Barone

DPNC, University of Geneva

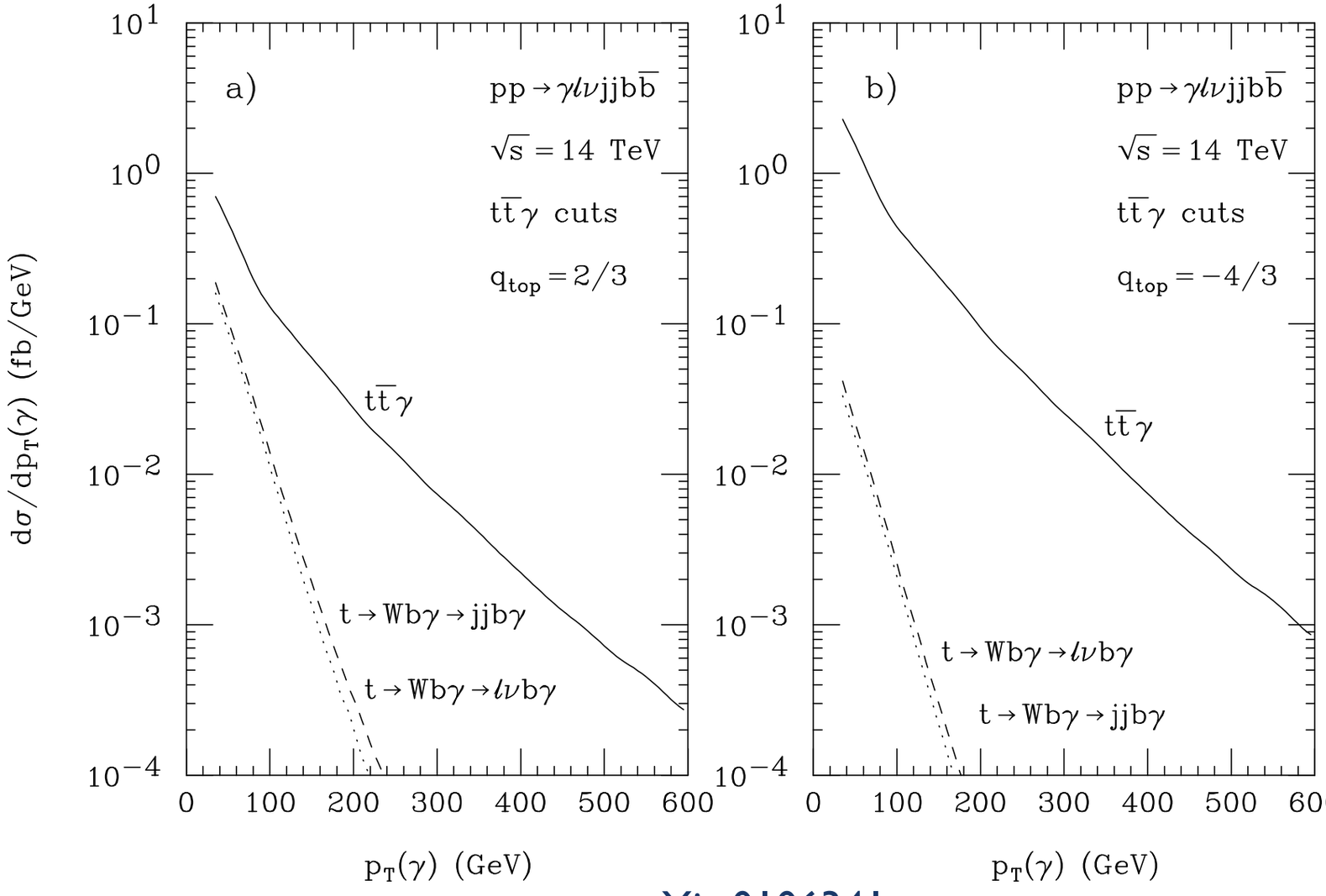
Outline

- Introduction
  - Probe top EM couplings
- Analysis Strategy
  - Selection
  - Irreducible backgrounds
  - Profile likelihood method
- Results
  - Fiducial Cross Section



Motivation

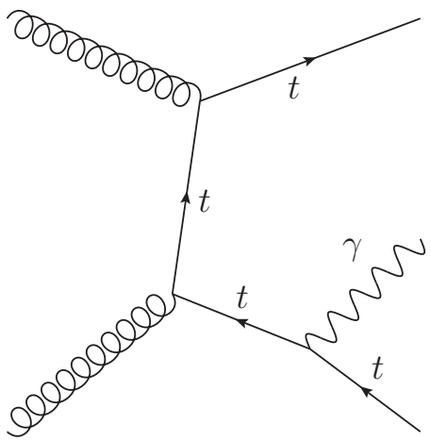
- Top is expected to play a crucial role in electroweak symmetry breaking
  - Manifestation new physics in top related precision measurements
- Electromagnetic (E.M.) couplings :
  - Extensive modifications in Standard Model (S.M.) extensions
    - ✦ composite quarks, etc ..
- Measurement of $t\bar{t}\gamma$ *(Z)* cross section
  - Direct probe of *VA*, and *A* couplings of the $t\bar{t}\gamma$ *(Z)* vertex
  - Direct probe of E.M. coupling (top charge)
  - Recent NLO calculation arXiv:1102.1967v2

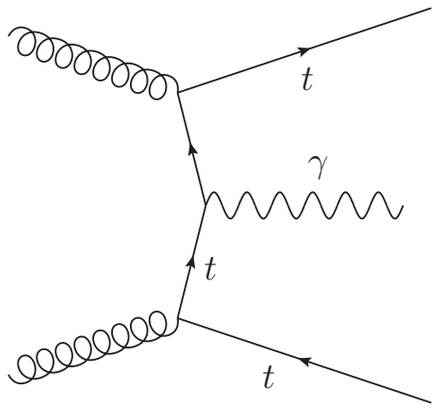


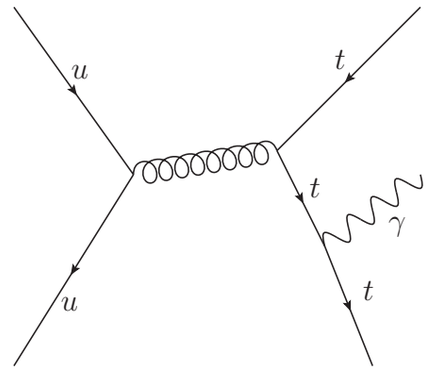
arXiv:0106341

The process

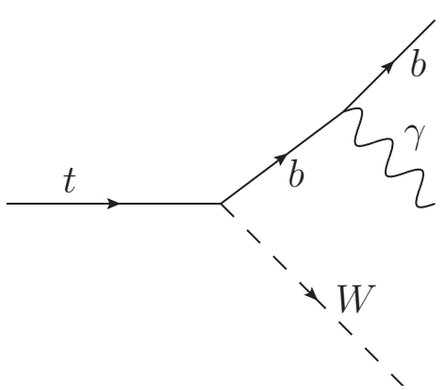
- Probe $t\gamma$ vertex
  - Direct probe via $q\bar{q} \rightarrow \gamma^* \rightarrow t\bar{t}$ impossible at LHC
  - Study γ production in association with $t\bar{t}$
- Classification of processes
  - Radiative production $pp \rightarrow t\bar{t}\gamma$, no γ radiation in top decay products ($t \rightarrow Wb$)

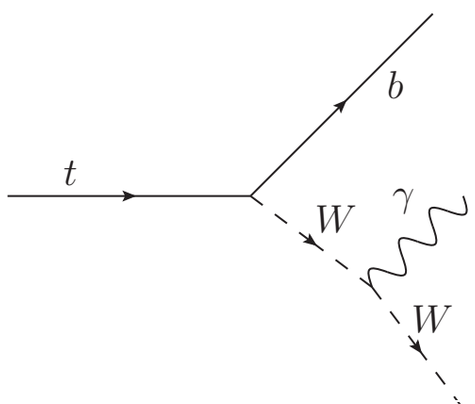


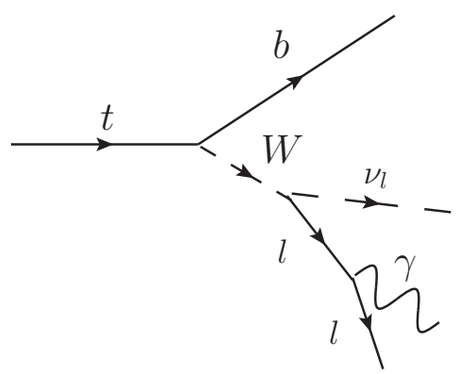




  - Radiative top decay: $t \rightarrow Wb\gamma$ (on-shell decay) or W decay chain



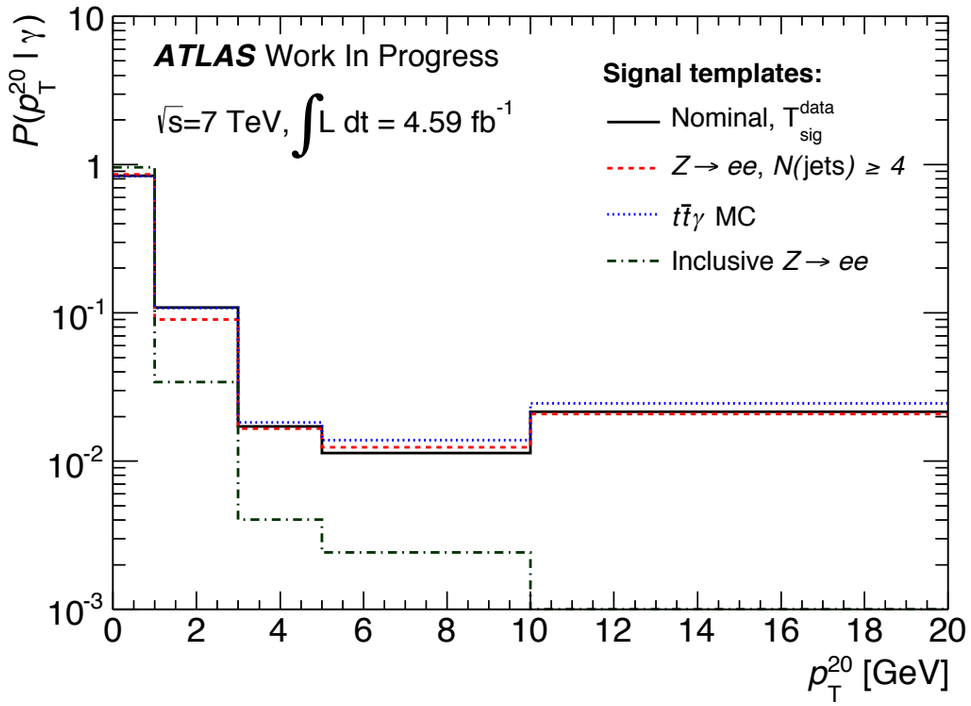


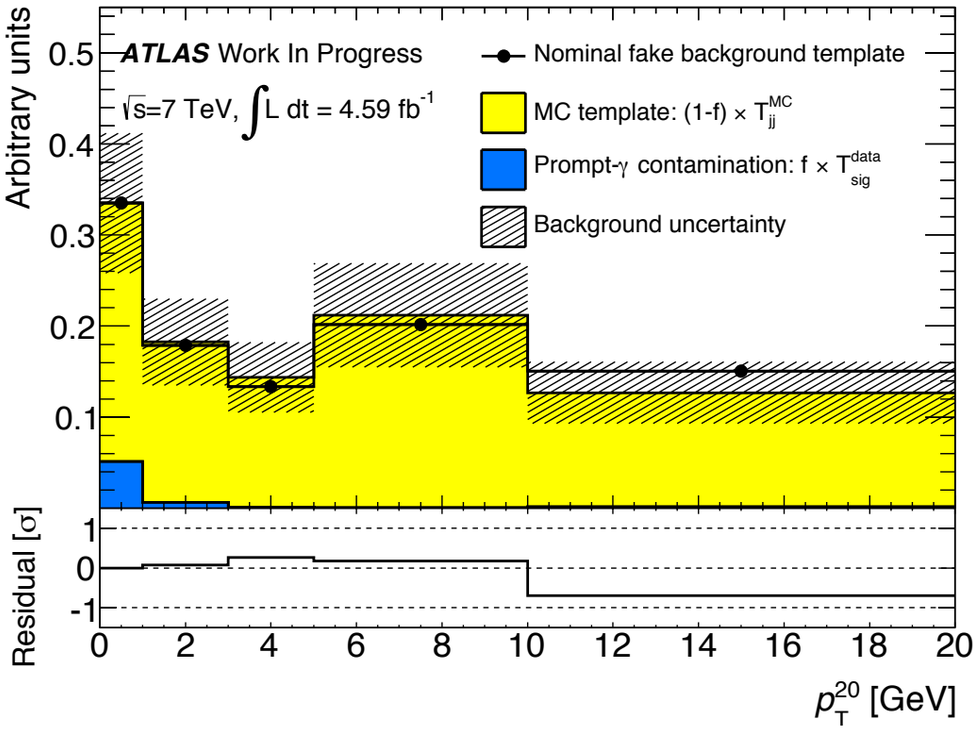


  - No distinction from above processes: non negligible interferences

Strategy

- Single lepton plus jets
  - Photon candidates from rectangular cuts on shower shapes
    - ✦ rejection of $\pi^0,\eta^0 \rightarrow \gamma\gamma$ (main background)
- Photon track isolation as discriminant: $p_T^{20}(\gamma)$
  - π^0,η^0 wider showers than prompt γ
  - Data driven templates
    - ✦ photon $Z \rightarrow ee$, 4jets
    - ✦ hadron control region (C.R.)
- Signal Extraction with profile likelihood on $p_T^{20}(\gamma)$





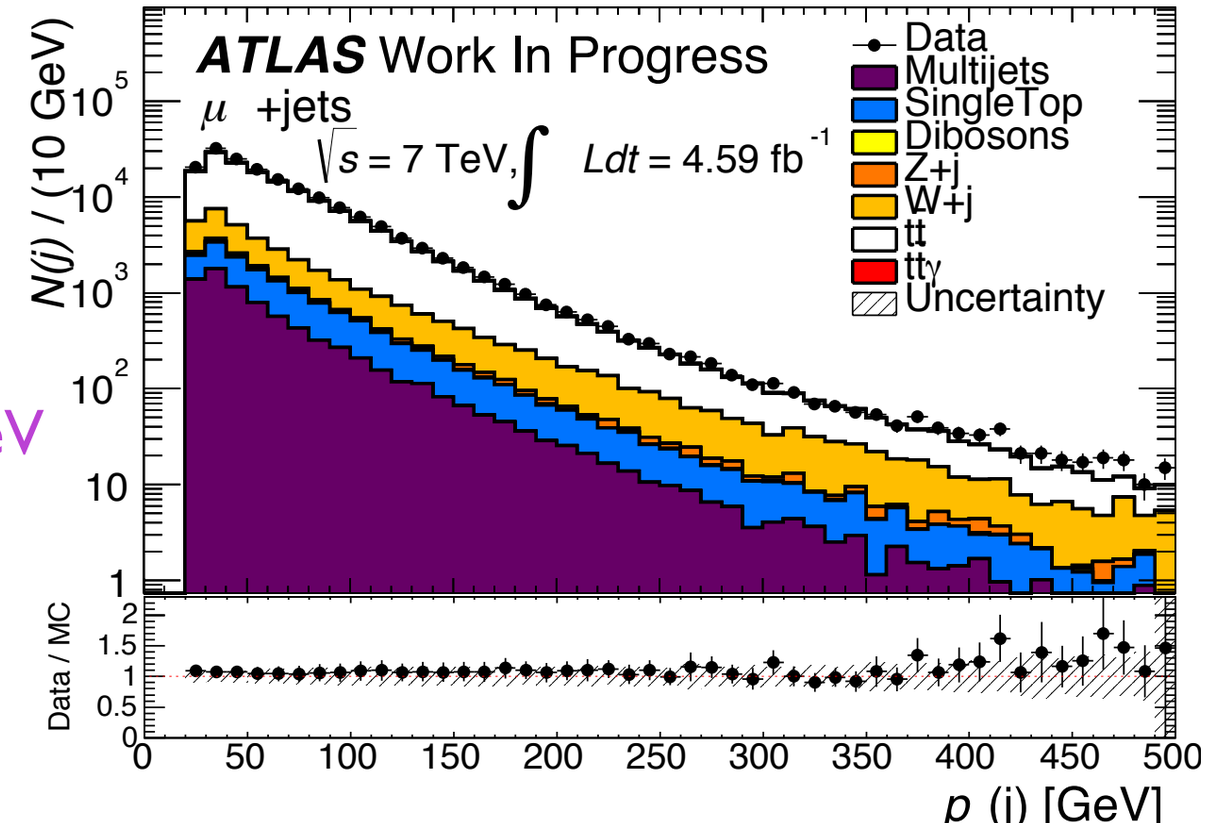
$$L\left(p_{\mathrm{T}}^{\mathrm{cone20}} \,|\, \sigma_{t\bar{t}\gamma},\, \mu(\varepsilon(\vec{\theta}), \mathcal{L}),\, N_b(\vec{\alpha})\right) =$$

$$\underbrace{\prod_{j=1}^{N_{\mathrm{bins}}} \frac{\nu_j^{N_j}}{N_j!} \cdot \exp(\nu_j)}_{\text{poisson expectation}} \times \underbrace{\prod_{i=1}^{\text{bck-systs}} \mathcal{N}(\alpha_i|\hat{\alpha}_i, \sigma_{\alpha_i})}_{\text{background uncertainties}} \times \underbrace{\prod_{i=1}^{\text{systs}} \mathcal{N}(\theta_i|\hat{\theta}_i, \sigma_{\theta_i})}_{\text{efficiency/acceptance uncertainties}} \times \underbrace{\mathcal{N}(\mathcal{L}, \hat{\mathcal{L}}|\sigma_{\mathcal{L}})}_{\text{luminosity uncertainty}}$$

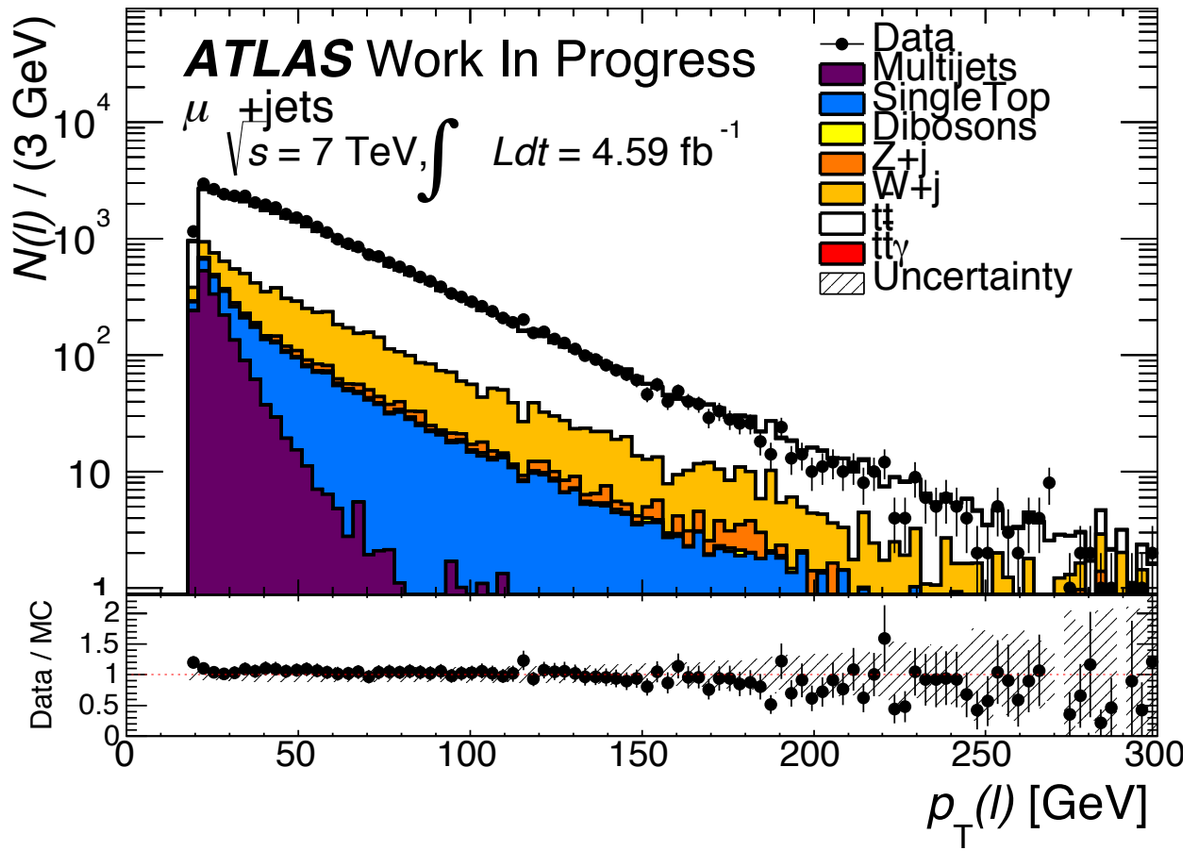
$$\nu_j = \nu_j(\sigma_{t\bar{t}\gamma}, \mu(\varepsilon(\vec{\theta})), N_b(\vec{\alpha})) = \mu\sigma_{t\bar{t}\gamma} \int dp_{\mathrm{T}}^{\mathrm{cone20}} F_S^j(p_{\mathrm{T}}^{\mathrm{cone20}}|\mu\sigma_{t\bar{t}\gamma}) + \sum_{i=1}^{n} N_b^i(\vec{\alpha}_i) \int dp_{\mathrm{T}}^{\mathrm{cone20}} F_{b^i}^j(p_{\mathrm{T}}^{\mathrm{cone20}}|N_b^i(\vec{\alpha}_i))$$

Selection

- Selection for $t\bar{t} \rightarrow$ *l*+jets (*l*=e,μ)
  - $N_j \geq 4$, 1lepton, N_j(b-tag) ≥ 1
  - Electron channel p_T(e)> 25 GeV :
    - ΔR(e,j)> 0.2, E_T^{miss} > 30 GeV m_T^W> 35 GeV
  - Muon channel p_T(μ)> 20 GeV:
    - ΔR(μ,j)> 0.4, E_T^{miss} > 20 GeV, $m_T^W + E_T^{miss}$ > 60GeV



- Tight photon rectangular cuts on shower shapes
  - γ kinematic cuts
    - $p_T(\gamma) > 20$ GeV
    - $\Delta R(\gamma, j) < 0.5$: event removal
    - $\Delta R(\gamma, l) < 0.7$: lepton FSR reduction
  - m(e,γ) > | m_Z ± 5 GeV | : e-fakes suppression from Z decays

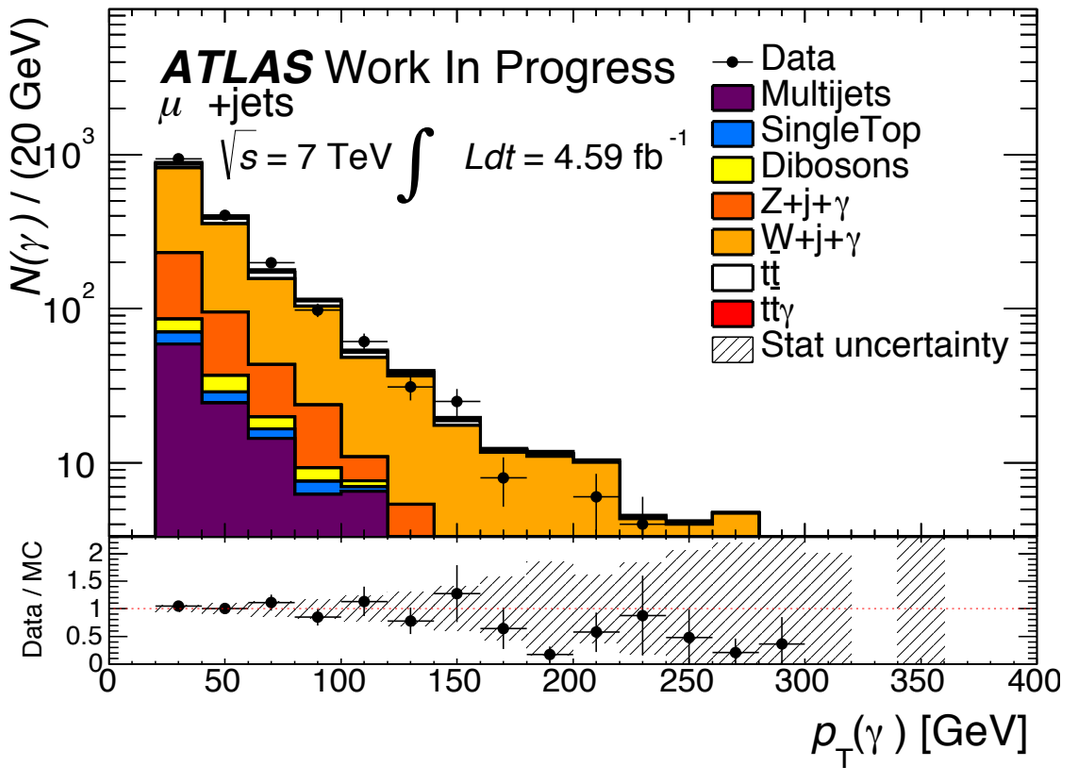


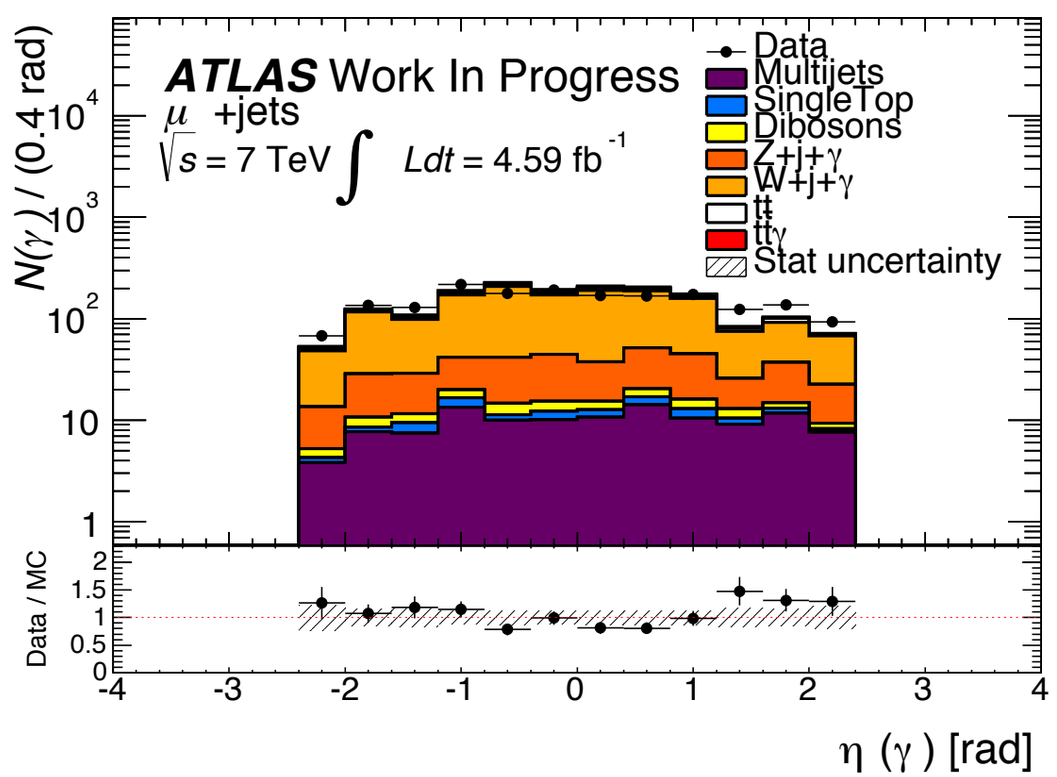
Irreducible Backgrounds SPS 2014

- Data driven:
  - W+jets+γ
    - Control (C.R) region $N_j < 4$ *b*-tag veto N(γ)> 0
  - Mulitjets
    - C.R. loose lepton requirements and tight γ
  - e faking γ:
    - Tag and probe Z→ee(γ)
    - extract scale factors

Contribution	e [events]	μ [events]
Z+j+γ	3.43 ± 2.35	2.682 ± 1.97
W+j+γ	5.38 ± 1.86	15.63 ± 4.41
Multijets	1.4 ± 1.24	1.92± 1.13
$WW/ZZ/WZ$	0.1 ± 0.12	0.20 ± 0.22
Single Top	2.74 ± 0.99	4.24 ± 1.50
$t\bar{t} \to le + \text{jets}$	12.72 ± 2.61	19.53 ± 3.83
Non Fiducial	35.9 ± 2.12	38.8 ± 1.5

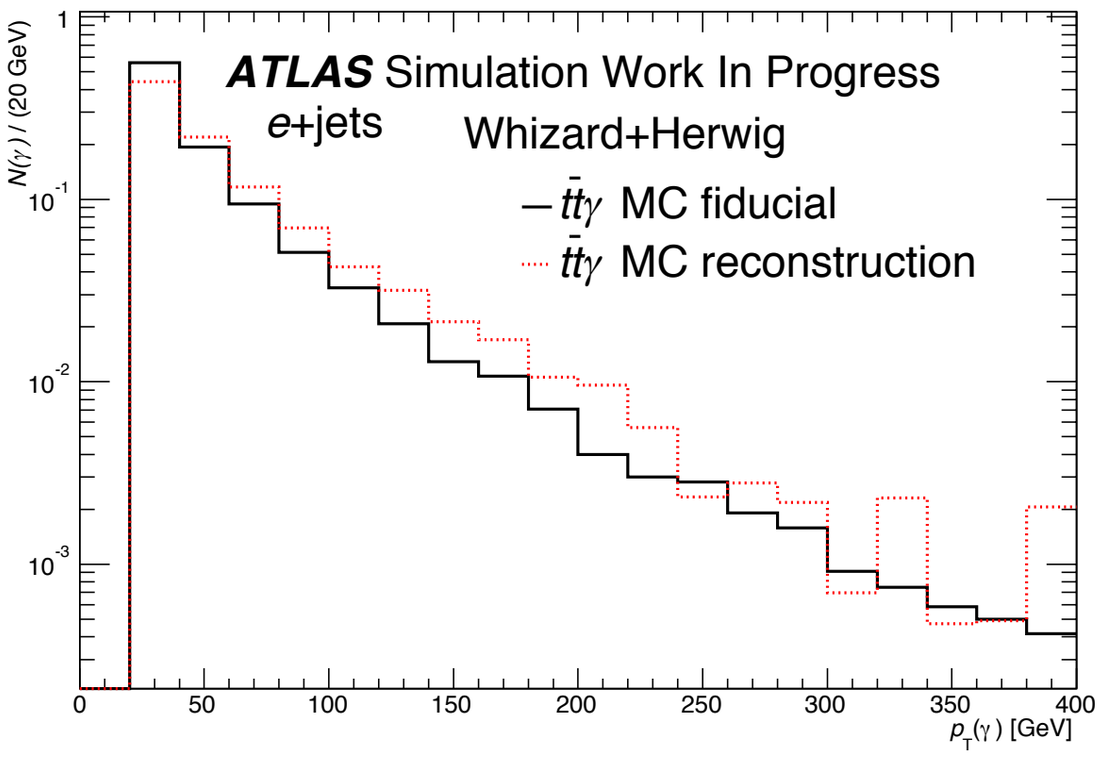
- Monte Carlo based :
  - Single Top, *WW/ZZ/WZ*, *Zj* (minor backgrounds)

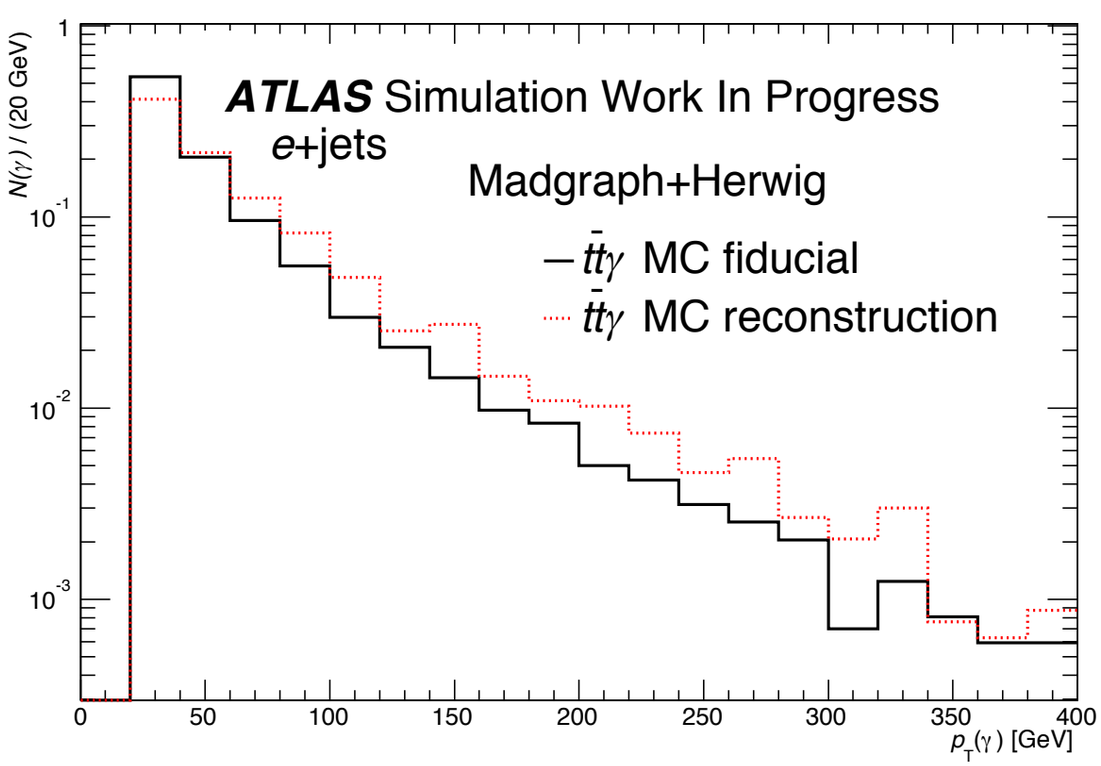




$\sigma_{t\bar{t}\gamma}$: Definition

- Fiducial phase space:
  - Avoid extrapolation to region with large theoretical uncertainties
  - Restrict to measured volume in detector acceptance
- Definition (summary):
  - Leptons:
    - Dressed $p_T(l) > 20$ GeV, $|\eta| < 2.5$
  - Jets:
    - Anti k-T $R=0.4$, $p_T(j) > 25$ GeV, $|\eta| < 2.5$
  - Photons:
    - $E_T(\gamma) > 20$ GeV, $|\eta| < 2.37$
  - Angular separation (consistent with data selection):
    - $\Delta R(e,j) > 0.2$ $\Delta R(j,\gamma) > 0.5$ $\Delta R(\mu,j) > 0.4$, $\Delta R(l,\gamma) > 0.7$





Uncertainties

- Breakdown:
  - profile likelihood procedure
- Signal:
  - Direct comparisons generators and different settings
    - ✦ scale variations, PYTHIA/ Herwig, QED FSR
- Signal template:
  - Modelling in likelihood by linear combinations of templates
  - e→γ extrapolation
    - ✦ comparison of MC templates w.r.t nominal (data driven)
  - Topology:
    - ✦ comparison of nominal w.r.t templates from Z→ee, 4 jets
- Hadron template:

$$T_{\mathrm{bkg}}^{\mathrm{corr}} = \left(\frac{1}{1-\alpha_{\mathrm{fake}}\cdot f}\right)\left[T_{\mathrm{bkg}}^{\mathrm{data,\ nom}} - \alpha_{\mathrm{fake}}\cdot f \times T_{\mathrm{sig}}^{\mathrm{data},\gamma}\right]$$

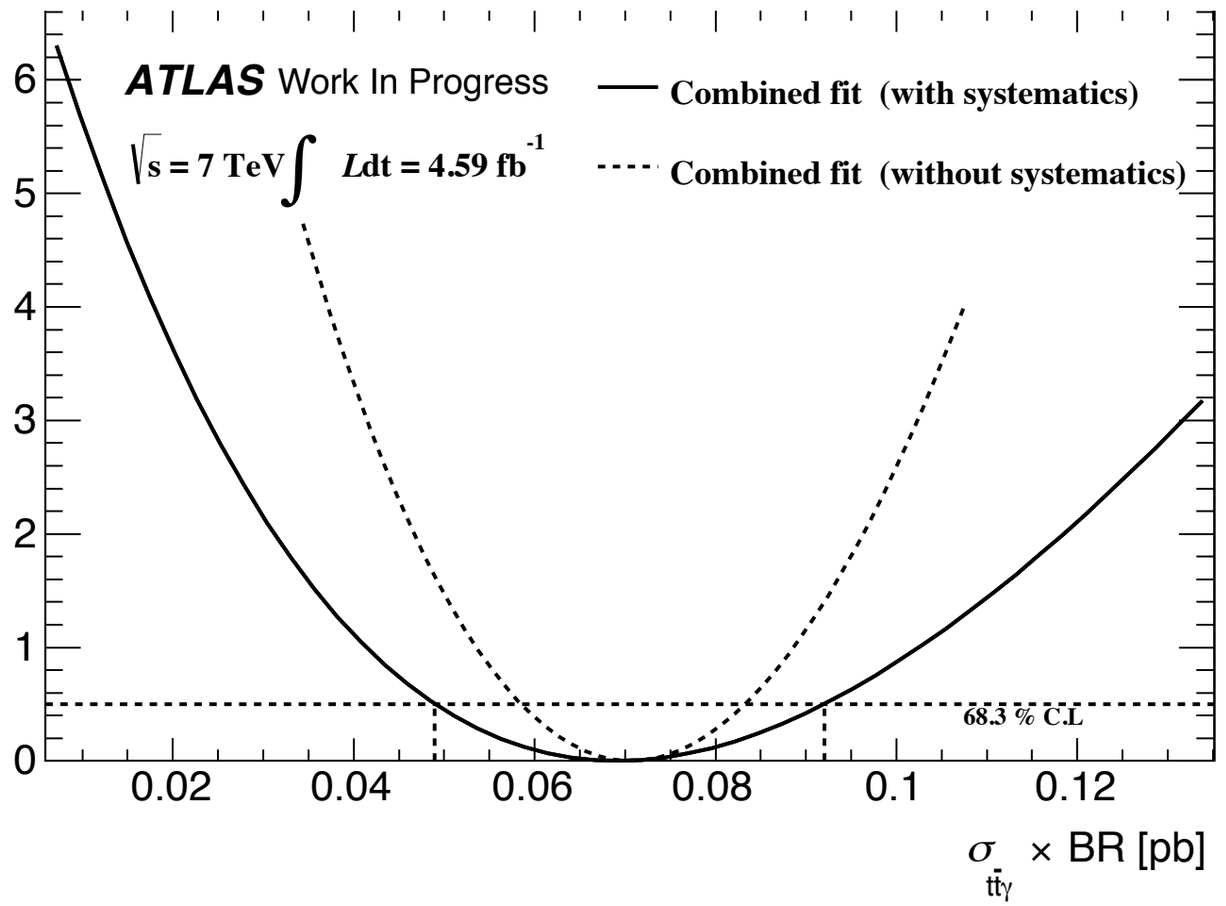
  - Expressed as combination of templates with/with out the correction for γ leakage

Source	Uncertainty [%]
Signal modelling	9.8
Lepton modelling	2.6
Jet Modelling	12.5
E_{T}^{miss} modelling	0.3
b-tag/Misstag	5.8
γ modelling	6.1
Irreducible backgrounds	5.5
Signal template	3.3
Hadron template	8.0

Combined Fit

- Simultaneous estimation on e and μ channels
  - complete modelling of uncertainties in likelihood

contribution	el + jets	μ + jets	total
signal	38 ± 11	70 ± 22	109 ± 33
background	95 ± 12	142 ± 15	238 ± 21
expectation Whizard × k-fact	36.1 ± 1.0	66.9 ± 1.3	137.1 ± 2.3
expectation Madgraph × k-fact	36 ± 0.9	66.4 ± 1.1	137.65 ± 2.0
total	-	-	347 ± 39
candidates	140	222	362



- Theoretical prediction

$$\sigma_{t\bar{t}\gamma}^{\mathrm{WHIZARD}} = 0.0645 \pm 0.00134\ (\mathrm{stat}) 0.0129\ (\mathrm{theor}) \mathrm{pb}$$

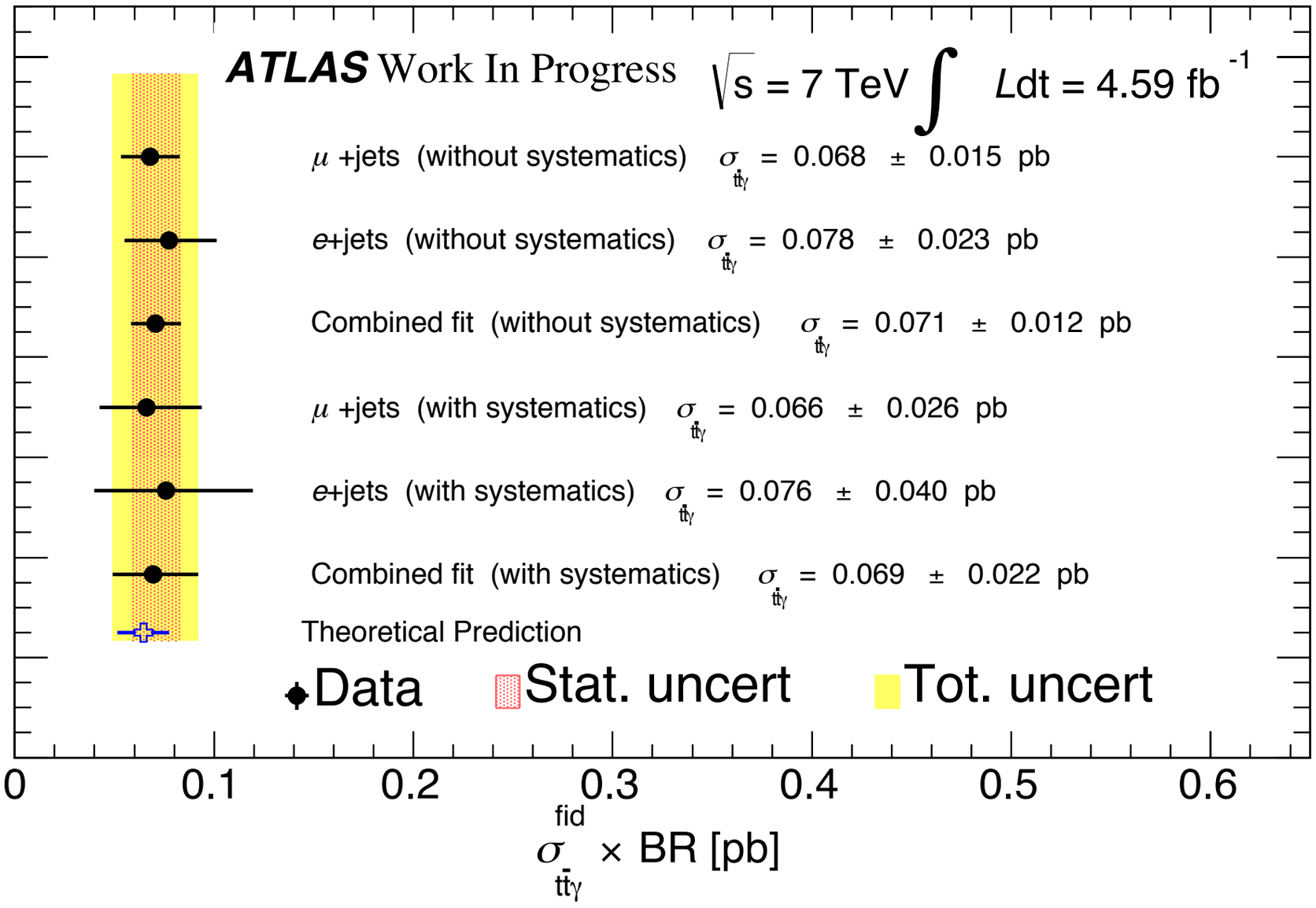
$$\sigma_{t\bar{t}\gamma}^{\mathrm{MadGraph}} = 0.0621 \pm 0.0010\ (\mathrm{stat}) 0.0124\ (\mathrm{theor}) \mathrm{pb}$$

- Measured cross section:

$$\sigma_{t\bar{t}\gamma}^{\mathrm{fid}} = 0.0692^{+0.013}_{-0.012}(\mathrm{stat})^{+0.019}_{-0.016}(\mathrm{syst}) \pm 0.0012(\mathrm{lumi})\ [\mathrm{pb}]$$

Sub Channels Estimation

- Sub channel independent results:
  - e/μ agreement within statistical uncertainty
- Sub channel theoretical prediction:
  - *LO* generator calculation in e/μ
  - *k*-factor Melnikov et Al in μ only
  - Good agreement for both Whizard and Madgraph.
  - Theoretical uncertainty
    - ✦ ~20 % k-factor
    - ✦ scale variations



Generator	$\sigma_{t\bar{t}\gamma}^{e,\mathrm{fid}}$ [pb]	$\sigma_{t\bar{t}\gamma}^{\mu,\mathrm{fid}}$ [pb]
Whizard+Herwig	0.0668 ± 0.00191 (stat) ± 0.033 (theor) pb	0.0645 ± 0.00135 (stat)0.0129 (theor) pb
Madgraph+Herwig	0.0624 ± 0.0014 (stat) ± 0.0125 (theor)pb	0.0621 ± 0.00104 (stat)0.0124 (theor) pb

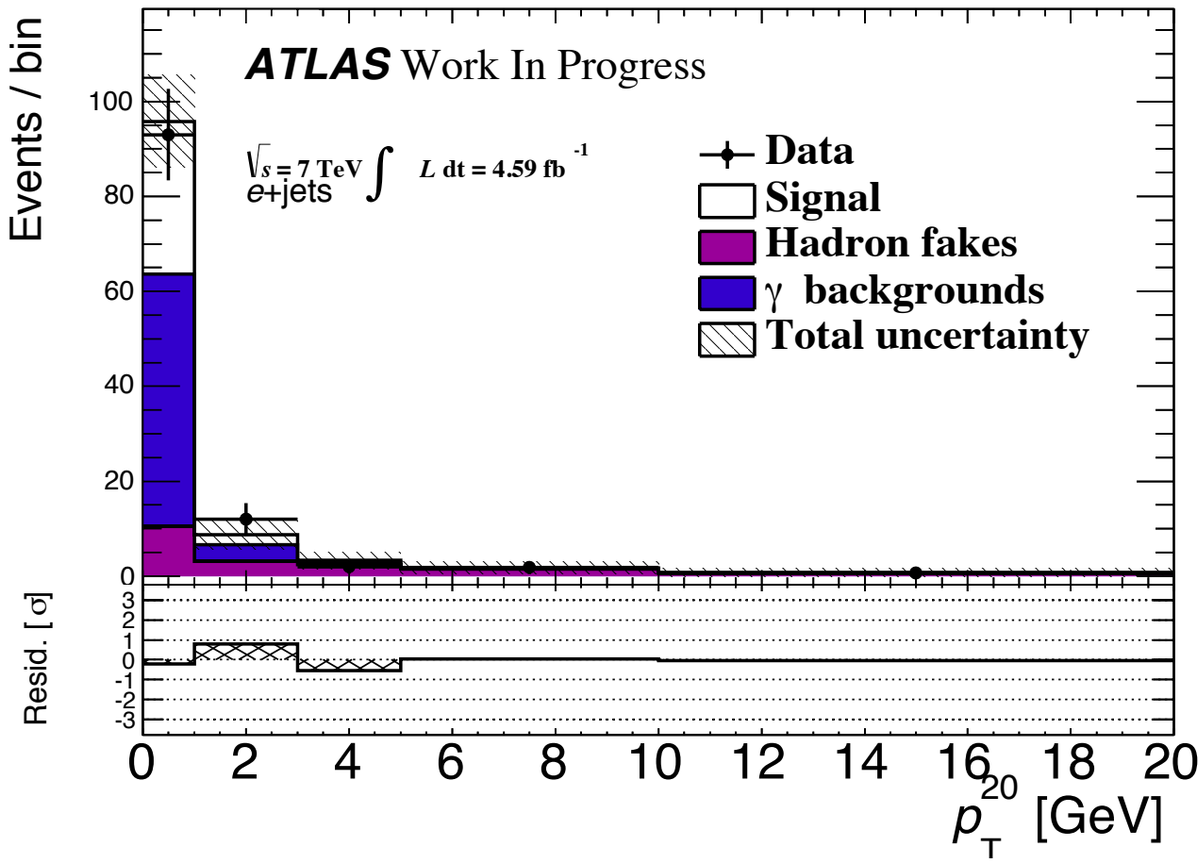
Conclusions

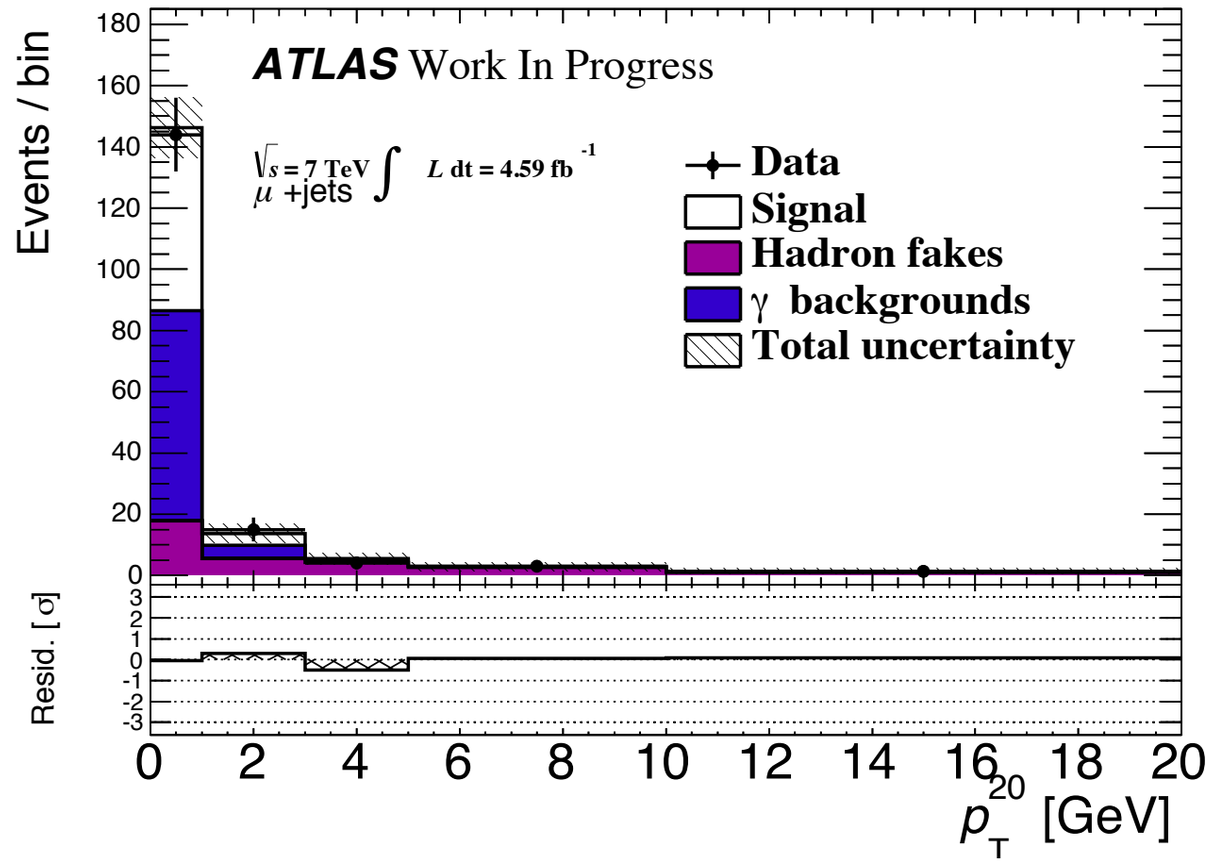
- Only a brief overview
  - Numerous checks/validations not presented here
    - ✦ Profile Likelihood Method, closure tests, etc …
  - Details of background calculations omitted
- Significance
  - Expected to be at observation level for the $t\bar{t}\gamma$ final state
- Numbers not final!
  - Work in Progress, Publication expected soon
- Measured cross section:
  - Good agreement with NLO calculation with in statistical uncertainties
  - Good agreement with two different generators

Additional Material

Fiducial Fit

- *N*(events)



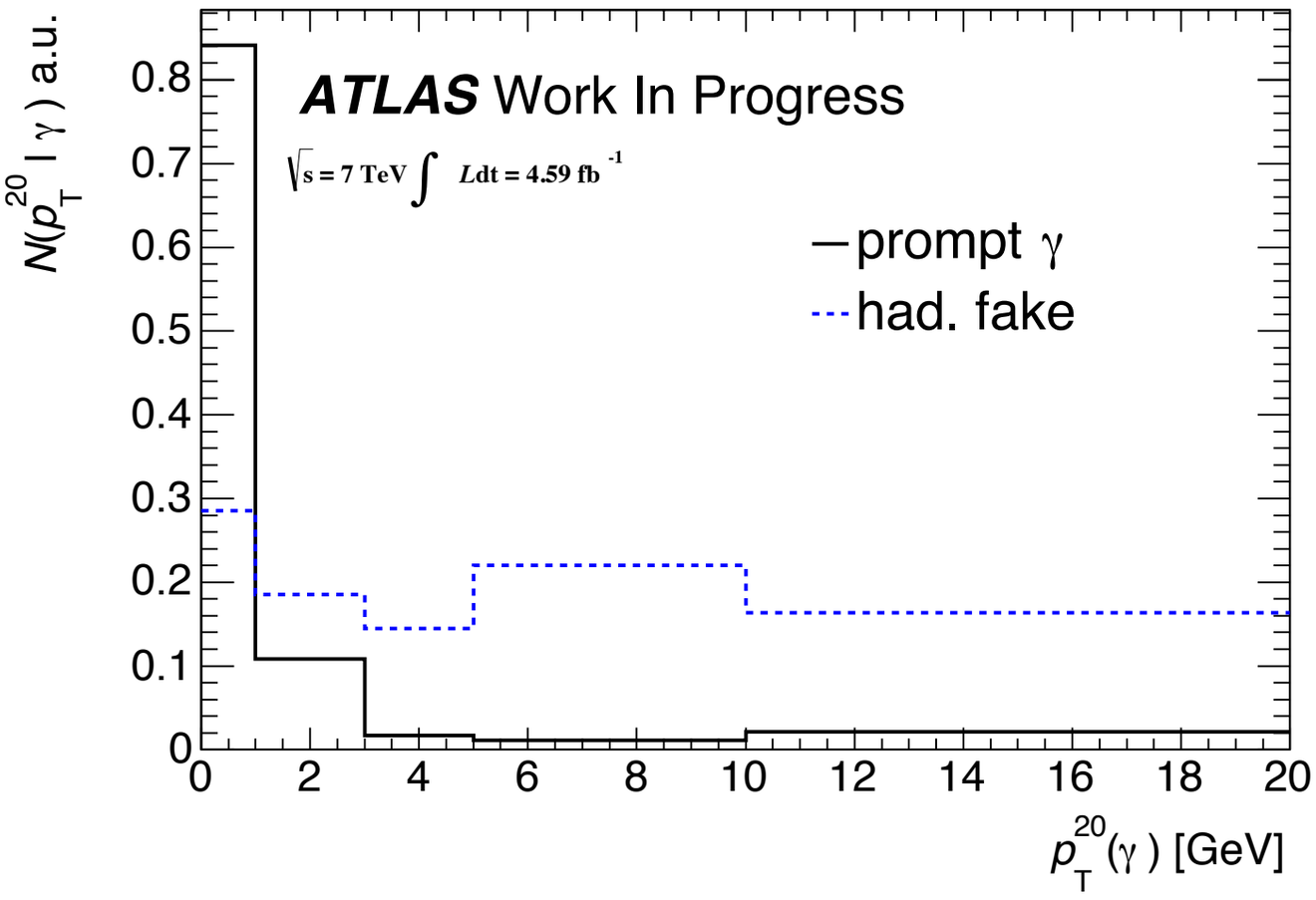


- Fit quality p-value: 0.92 (el) 0.99 (μ)
- Non Fiducial events
  - ✦ scale with observed cross section
  - ✦ iterative procedure
- Background:
  - ✦ non t $\bar{t}$ γ backgrounds
  - ✦ non fiducial t $\bar{t}$ γ

contribution	el + jets	μ + jets	total
signal	38 ± 11	70 ± 22	109 ± 33
background	95 ± 12	142 ± 15	238 ± 21
expectation Whizard × k-fact	36.1 ± 1.0	66.9 ± 1.3	137.1 ± 2.3
expectation Madgraph × k-fact	36 ± 0.9	66.4 ± 1.1	137.65 ± 2.0
total	-	-	347 ± 39
candidates	140	222	362

Strategy

- Single lepton plus jets
  - $N_l(p_T(e(\mu)) > 25\ (20)) = 1, N_j(p_T(j) > 25) \geq 4,$ $N_j(b\text{-tag}) \geq 1, N_\gamma(E_T(\gamma) > 20\ \text{GeV}) \geq 1$
  - Photon candidates from rectangular cuts on shower shapes
    - ✦ rejection of $\pi^0, \eta^0 \rightarrow \gamma\gamma$ (main background)
- Photon track isolation as discriminant: $p_T^{20}(\gamma)$
  - π^0, η^0 wider showers than prompt γ
  - Data driven templates
    - ✦ photon $Z \rightarrow ee$, 4jets
    - ✦ hadron control region (C.R.)



- Signal Extraction with profile likelihood on $p_T^{20}(\gamma)$

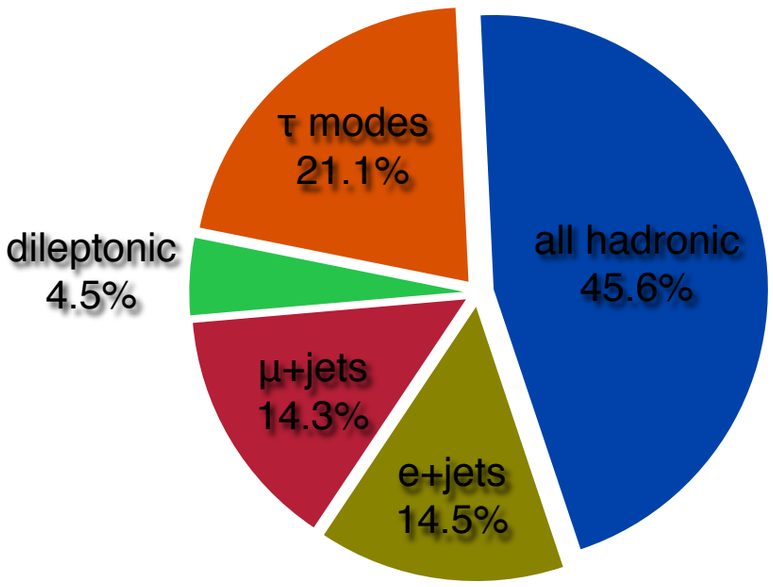
$$L\left(p_T^{\text{cone20}} \,|\, \sigma_{t\bar{t}\gamma},\, \mu(\varepsilon(\vec{\theta}), \mathcal{L}),\, N_b(\vec{\alpha})\right) =$$

$$\underbrace{\prod_{j=1}^{N_{\text{bins}}} \frac{\nu_j^{N_j}}{N_j!} \cdot \exp(\nu_j)}_{\text{poisson expectation}} \times \underbrace{\prod_{i=1}^{\text{bck-systs}} \mathcal{N}(\alpha_i|\hat{\alpha}_i, \sigma_{\alpha_i})}_{\text{background uncertainties}} \times \underbrace{\prod_{i=1}^{\text{systs}} \mathcal{N}(\theta_i|\hat{\theta}_i, \sigma_{\theta_i})}_{\text{efficiency/acceptance uncertainties}} \times \underbrace{\mathcal{N}(\mathcal{L}, \hat{\mathcal{L}}|\sigma_{\mathcal{L}})}_{\text{luminosity uncertainty}}$$

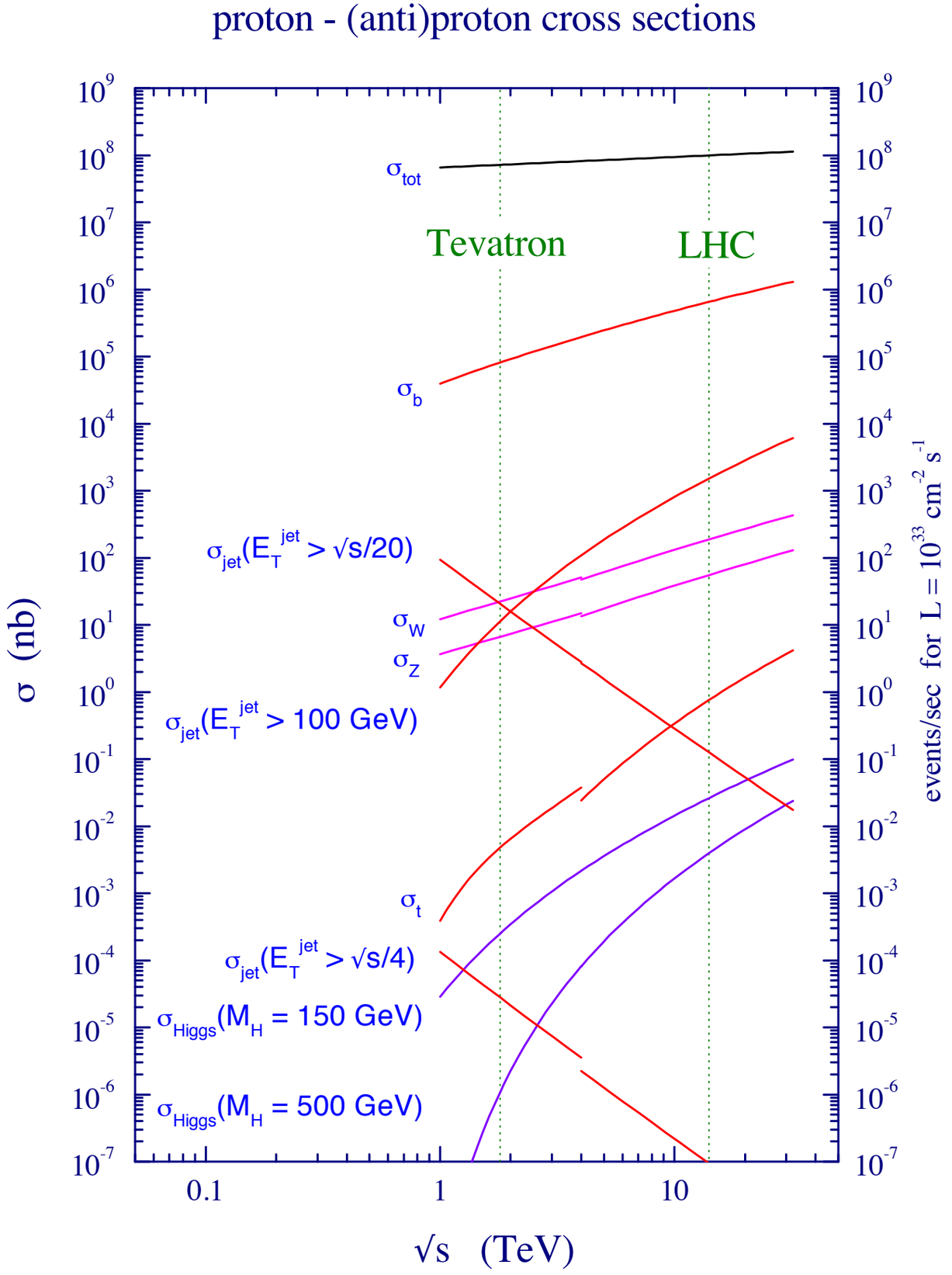
$$\nu_j = \nu_j(\sigma_{t\bar{t}\gamma}, \mu(\varepsilon(\vec{\theta})), N_b(\vec{\alpha})) = \mu\sigma_{t\bar{t}\gamma} \int dp_T^{\text{cone20}} F_S^j(p_T^{\text{cone20}}|\mu\sigma_{t\bar{t}\gamma}) + \sum_{i=1}^{n} N_b^i(\vec{\alpha}_i) \int dp_T^{\text{cone20}} F_{b^i}^j(p_T^{\text{cone20}}|N_b^i(\vec{\alpha}_i))$$

LHC: top factory machine

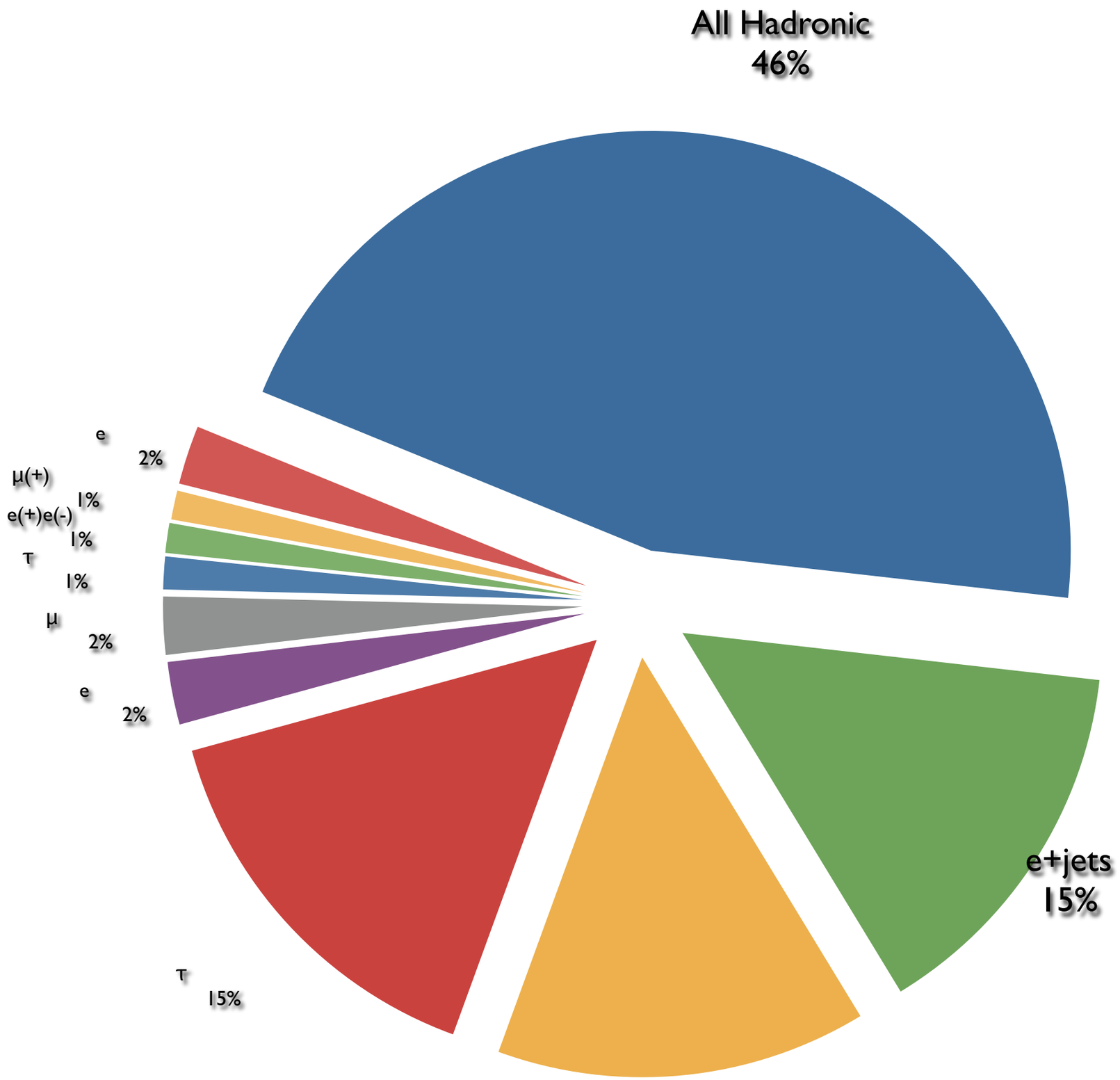
- Top Production at LHC:
  - $t\,\bar{t}$ pairs
  - Single top
- Leading Order diagrams
  - $q\,\bar{q} \rightarrow t\,\bar{t}$ *(15% at* $\sqrt{s}$ = 7 TeV)
  - $gg \rightarrow t\,\bar{t}$ *(*85% *at* $\sqrt{s}$ = 7 TeV)



- Top production per experiment
  - 5 fb^{-1} $\sqrt{s}$ = 7 TeV and 20 fb^{-1} $\sqrt{s}$ =8 TeV
  - 5.6× 10^6 $t\,\bar{t}$ events for
  - 2.7 × 10^6 Single top events

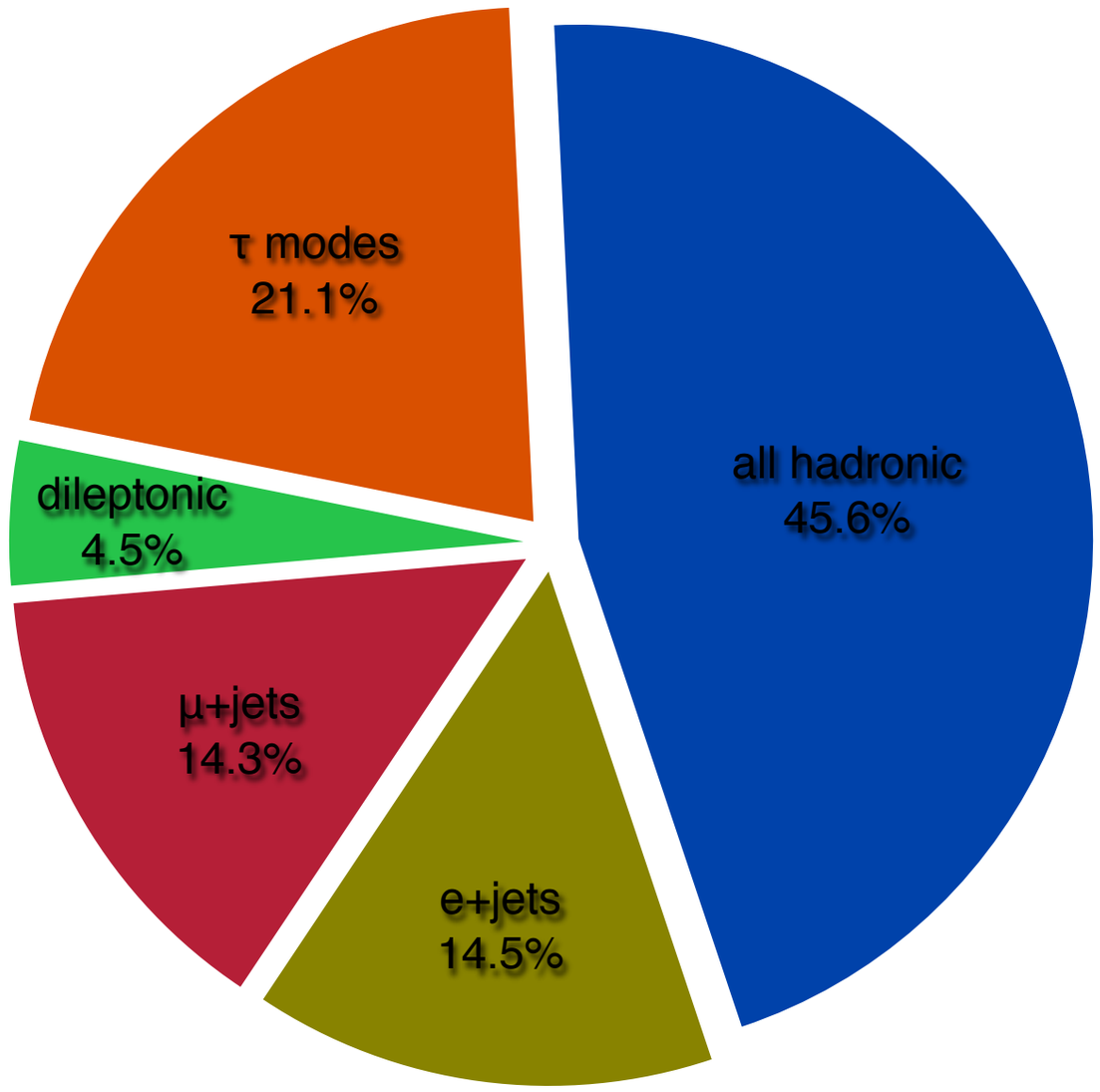


Top Decay Modes

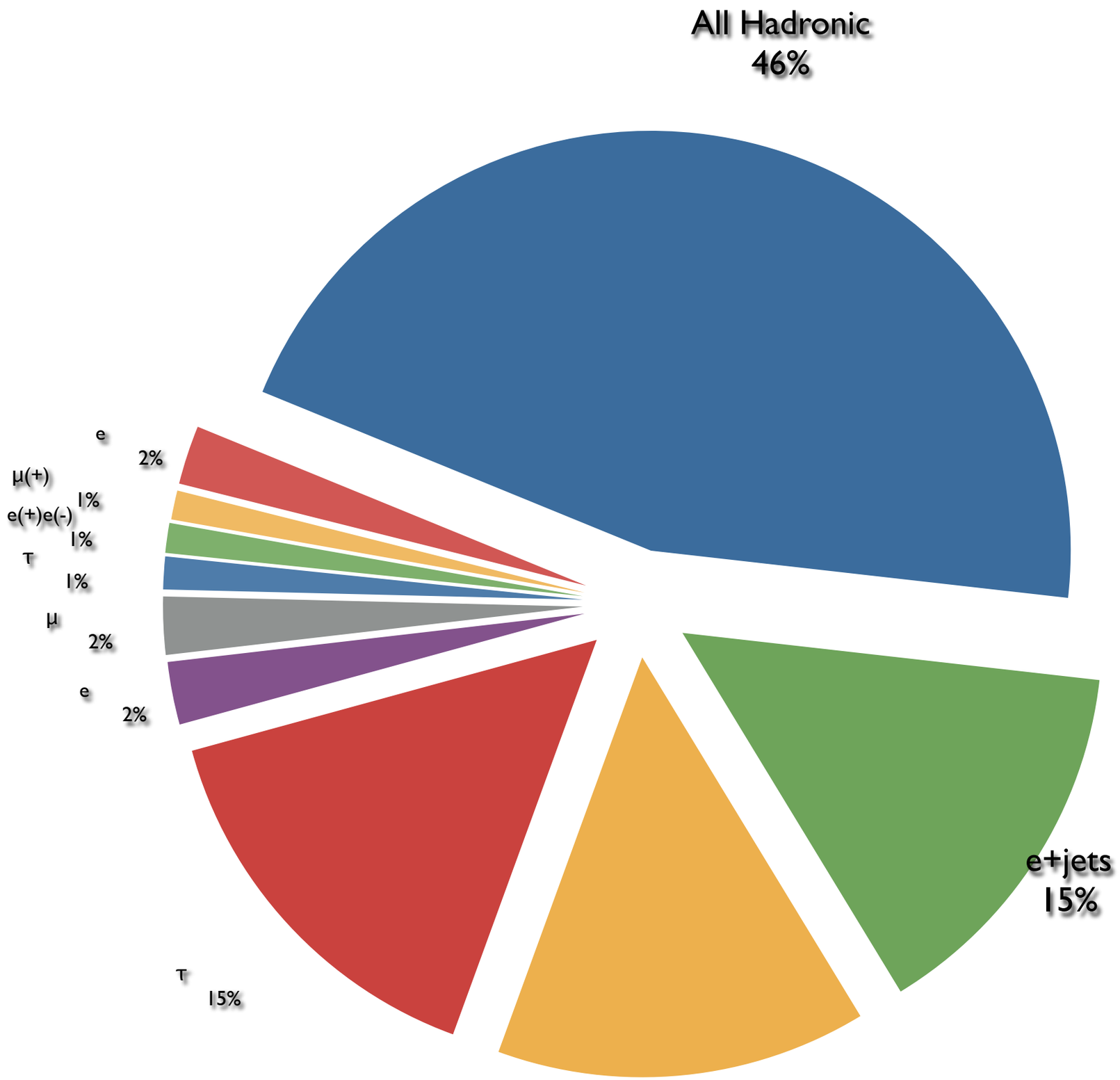


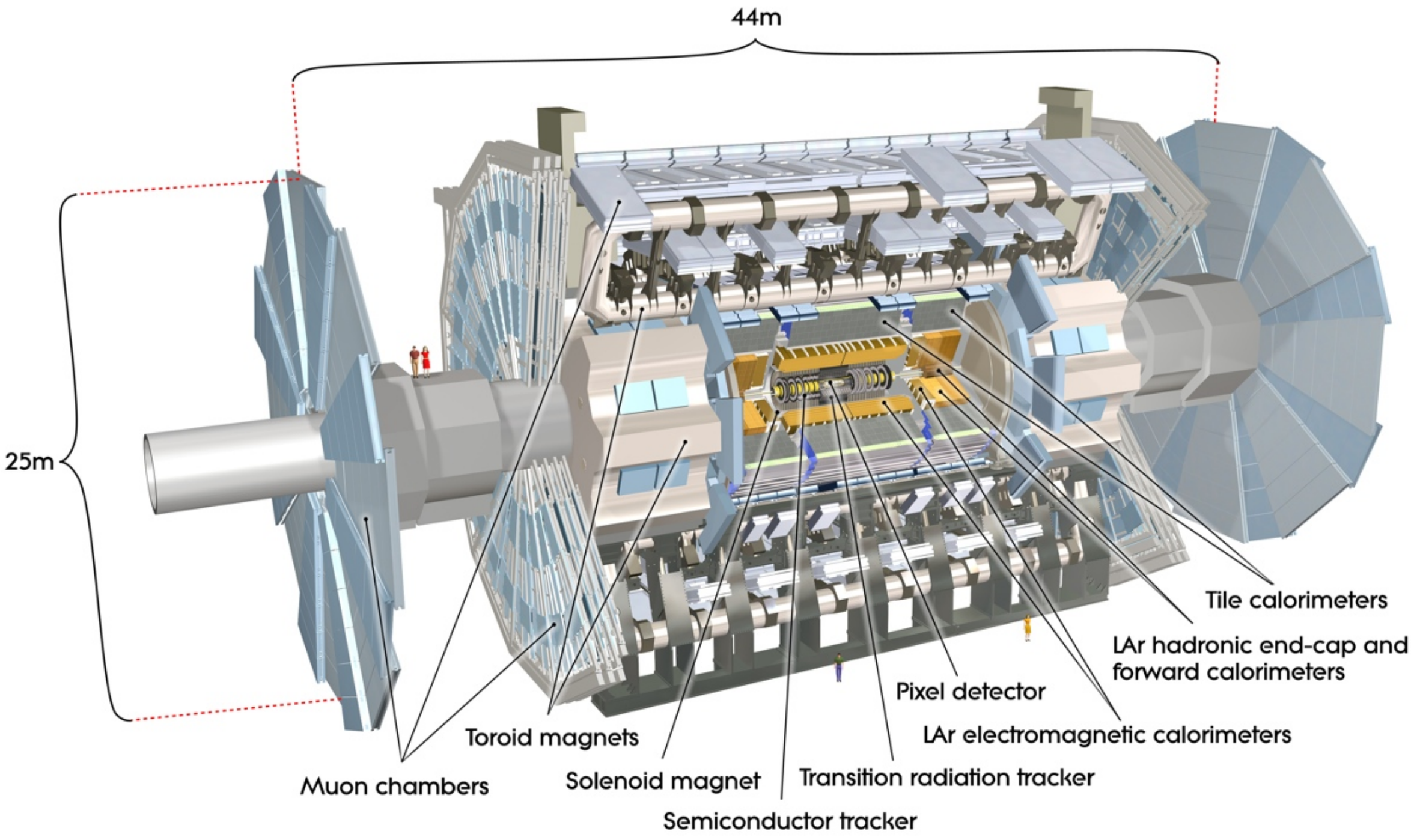
Motivations for Top Physics

- Probe Standard Model
  - top mass measurement
  - top EM couplings: $t\,\bar{t}\gamma$, $t\,\bar{t}Z$
  - Single Top production
- Precise tests of perturbative QCD
- Important background for many searches
  - New physics: SUSY, ..
  - Higgs searches in: $t\,\bar{t}H$, ...
- Searches for new physics:
  - vector like heavy new quarks



Top Decay Modes




44m
25m
Muon chambers
Toroid magnets
Solenoid magnet
Semiconductor tracker
Transition radiation tracker
Pixel detector
LAr electromagnetic calorimeters
LAr hadronic end-cap and forward calorimeters
Tile calorimeters