Probing e/μ asymmetry in flavor violating decays to leptons

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e/μ asymmetry in flavor violating decays to leptons

Look at $\Gamma(X\to\tau e)$ and $\Gamma(X\to\tau\mu)$

- X - any *non leptonic neutral* particle; Obvious candidate: the Higgs.
- e μ τ - the three charged lepton

$X\to\tau e(\mu)$: lepton flavor violating decay

$\Gamma(X\to\tau e) \neq \Gamma(X\to\tau\mu) \Rightarrow$ e/μ asymmetry

- Implies that either $\mathbf{\Gamma(X\to\tau e) \neq 0}$ or $\mathbf{\Gamma(X\to\tau\mu) \neq 0} \Rightarrow$ huge discovery

$\Gamma(X\to\tau e) = \Gamma(X\to\tau\mu) \neq 0$?

- Different approach is needed

Outline

Motivation:
- Lepton flavor conservation in the standard model
- Higgs properties
- Z & other non SM particles

Analysis strategy
- Channel selection
- Cut flow optimization

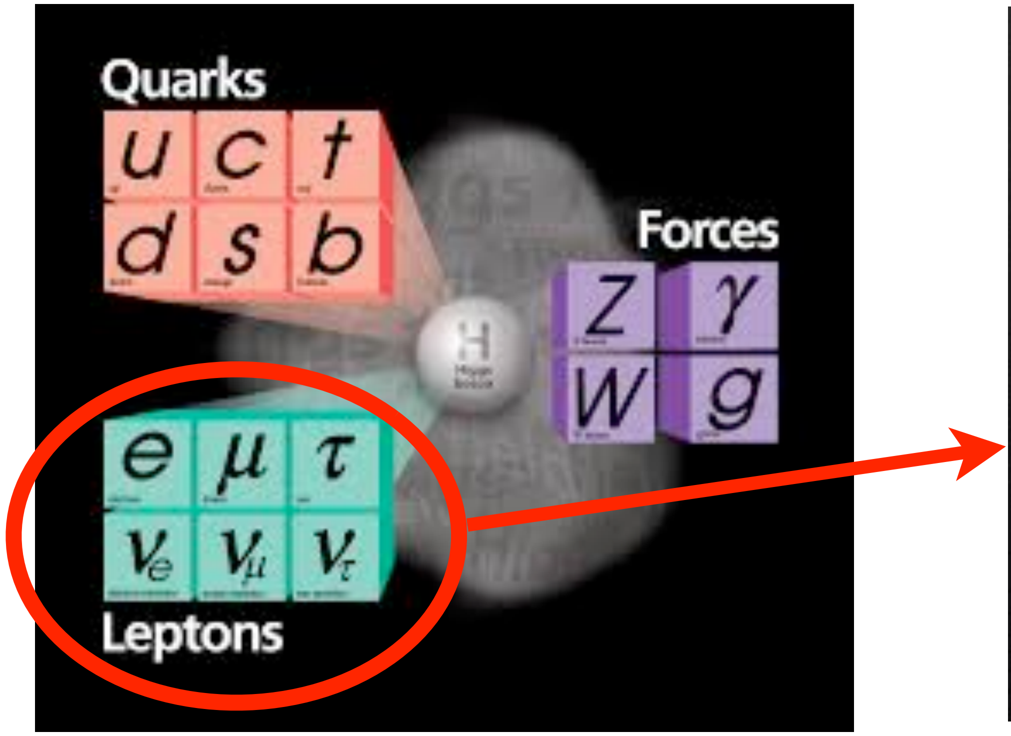
Background estimation
- The experimental challenge
- e / μ (a)symmetry: Quick introduction
- Data driven method

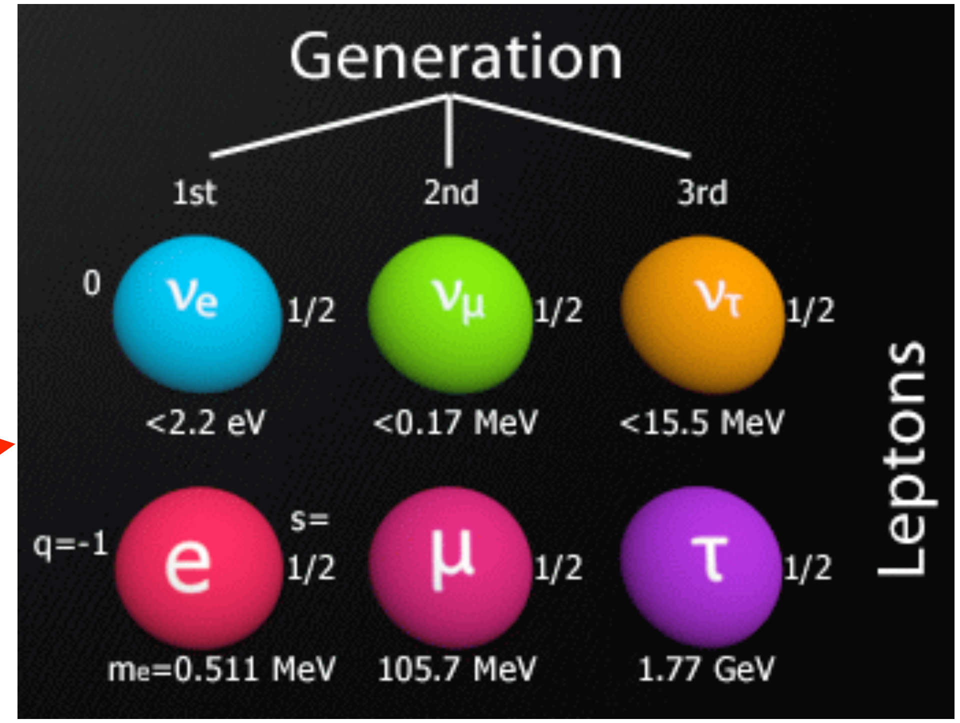
Analysis strategy - continued
- Statistical treatment
- Systematic uncertainties

Sensitivity to other models

Status & Plans

Lepton flavor ***conservation*** in the SM





ν oscillations ⇒ LFV in the neutral lepton sector ⇒ New physics

LFV in charged lepton interactions ⇒ physics beyond the standard model

e μ τ 3×ν : lepton number = 1

e μ τ : electrically charged

3×ν : electrically neutral

The lepton number is conserved in all the interactions ⇒
ν's are emitted in β decays
$p \to n\, e^+ \nu$

3 flavors : e μ τ

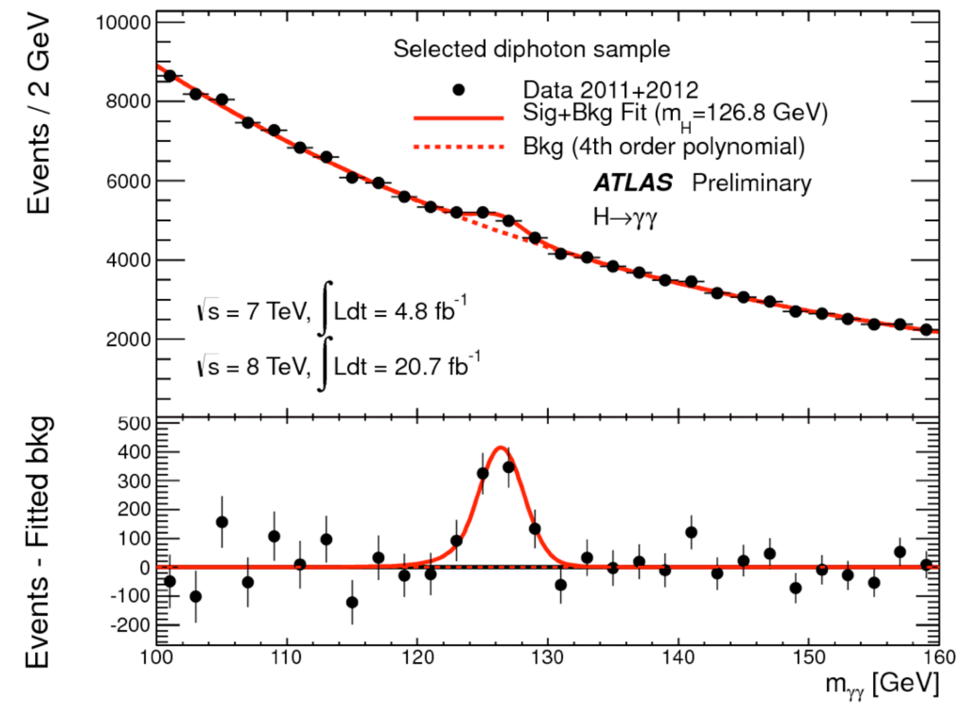
The lepton flavor is conserved in the gauge interactions ⇒
Weak decay: $\tau \to \mu\, \bar{\nu}_\mu\, \nu_\tau$

These are accidental symmetries of the SM Lagrangian

Higgs properties

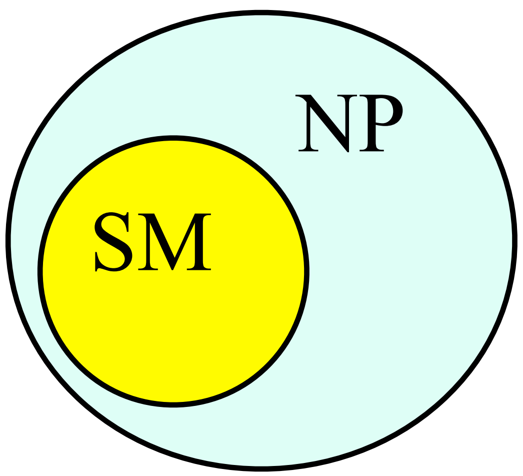
Is it the Higgs of the Standard Model ?

- Many measurements are in agreement with the standard model predictions
- Nevertheless, constraints on properties which are not predicted by the standard model are not always stringent

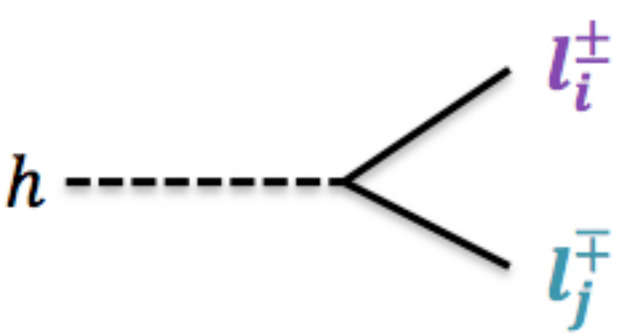


New physics coupled to the lepton sector could induce LFV Higgs decay

- Effective Lagrangian:



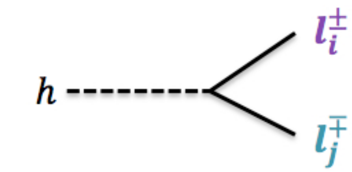
$$\sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \text{H.c.}$$



Bounds on LFV Higgs decays

The strongest bounds are all indirect

$$\sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \text{H.c.}$$



- $|C_{e\mu}|$: very small
- $|C_{\tau\mu}|$ or $|C_{\tau e}|$: could be as large as the standard model coupling of the Higgs to the τ lepton

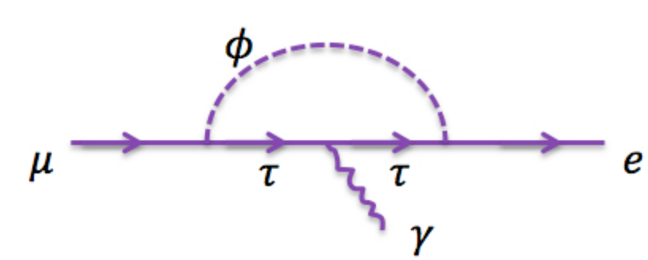
Eff. couplings	Bound	Constraint
$\lvert c_{e\mu}\rvert^2,\ \lvert c_{\mu e}\rvert^2$	1×10^{-12}	$\mathcal{B}(\mu\to e\gamma) < 5.7\times10^{-13}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$	5×10^{-4} [*]	$\mathcal{B}(\tau\to\mu\gamma) < 4.4\times10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c_{\tau e}\rvert^2$	3×10^{-4} [*]	$\mathcal{B}(\tau\to e\gamma) < 3.3\times10^{-8}$

MEG Collaboration, arXiv:1303.0754 [1]

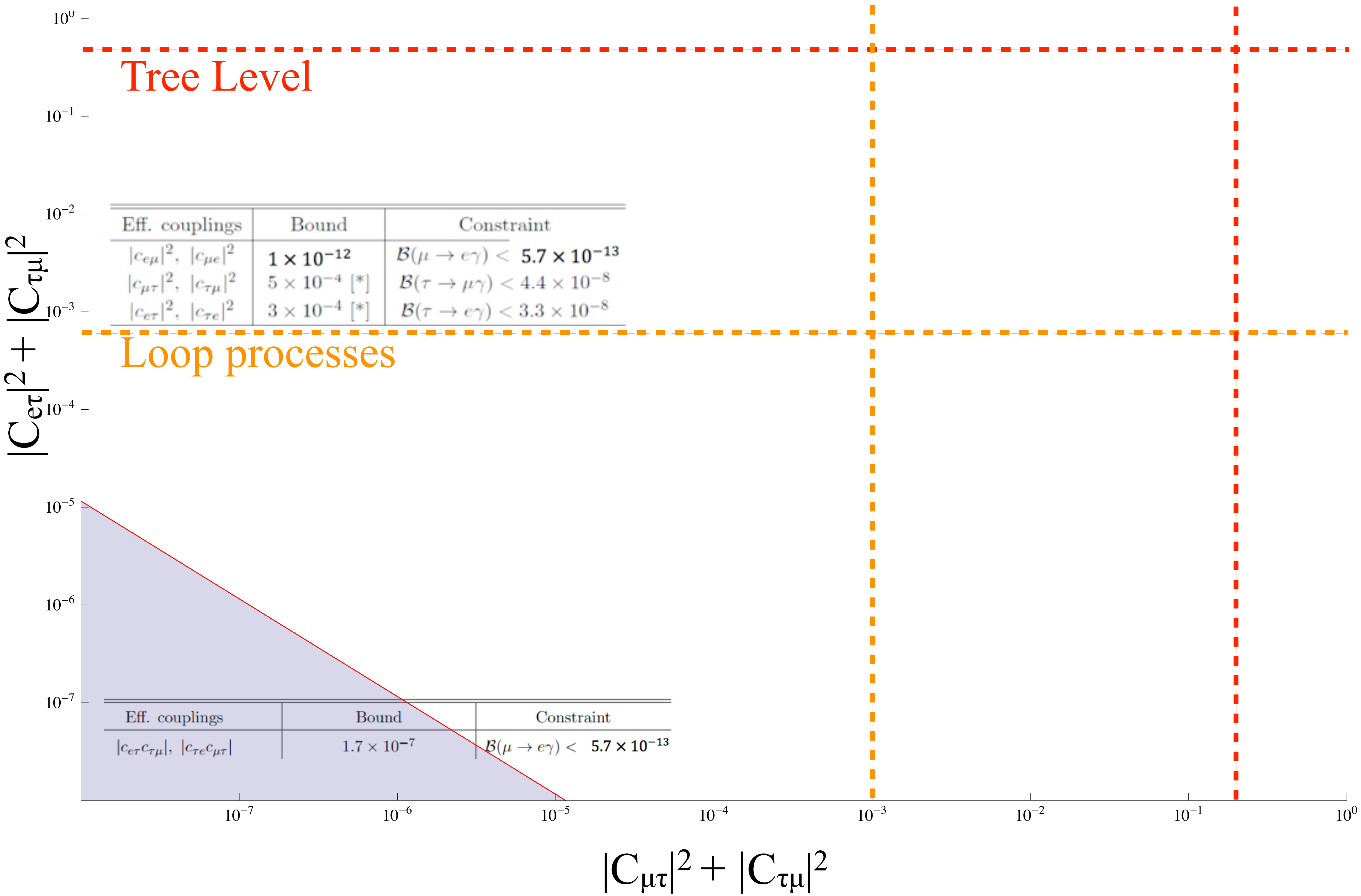
Blankenburg et al. arXiv: 1202.5704 [2]

- $|C_{e\tau}C_{\tau\mu}|$ & $|C_{\tau e}C_{\mu\tau}|$: very small

Eff. couplings	Bound	Constraint
$\lvert c_{e\tau}c_{\tau\mu}\rvert,\ \lvert c_{\tau e}c_{\mu\tau}\rvert$	1.7×10^{-7}	$\mathcal{B}(\mu\to e\gamma) < 5.7\times10^{-13}$



Bounds on LFV Higgs decays



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Bounds on LFV Higgs decays

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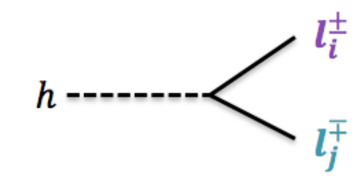

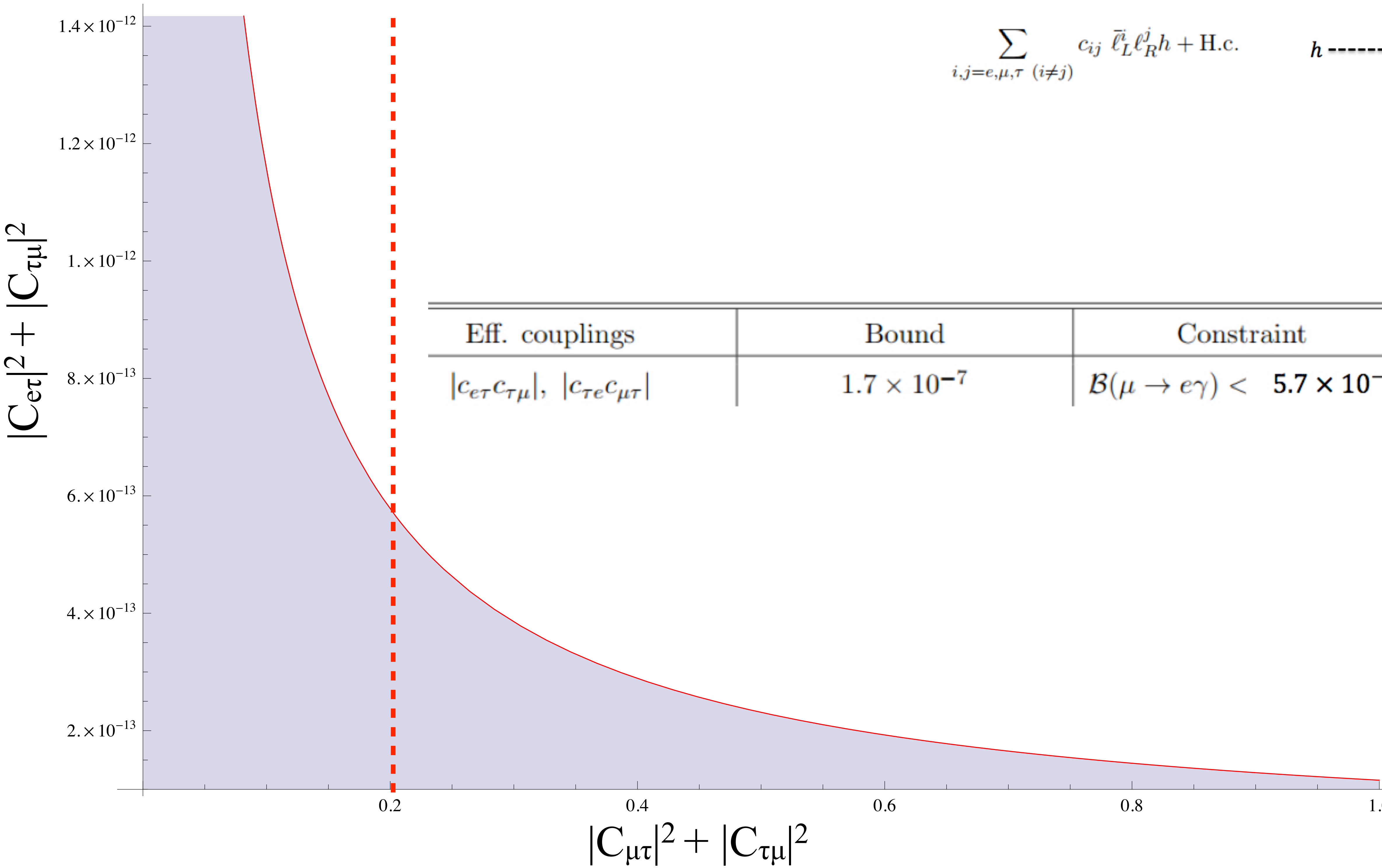

Eff. couplings	Bound	Constraint
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Bounds on LFV Higgs decays

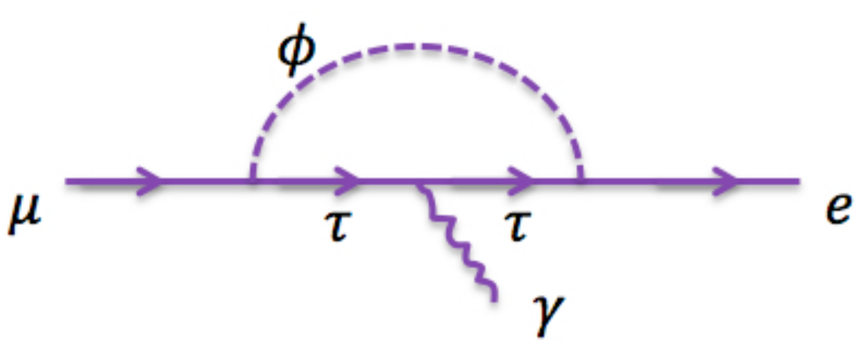
Expected numbers of events in 20 fb^{-1} of the ATLAS data

Assuming $BR(h \to \tau\mu) < 10^{-2}$ (10^{-1})

- $h \to e\mu$: $\ll 1$ events
- $h \to \tau\mu$: $\lesssim 4000$ (40000) events (tree level processes)
- $h \to \tau e$: $\lesssim 4000$ (40000) events (tree level processes)

➥ Can be seen on top of as high as 0.5 M (50 M) background events

- The bound on $|C_{e\tau}C_{\tau\mu}|$ & $|C_{\tau e}C_{\mu\tau}|$ are less robust
  - Additional diagrams may cancel the large contribution to the process $\mu \to e\gamma$

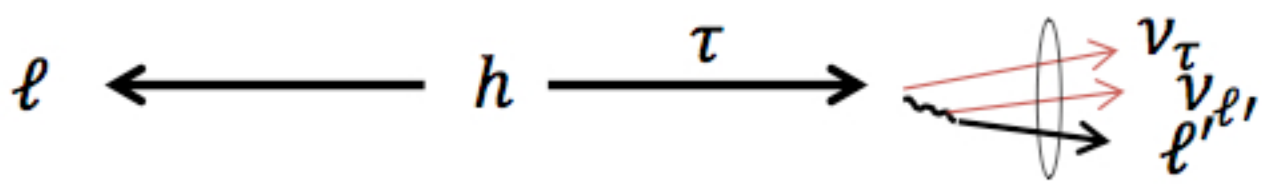


Analysis strategy: $h \rightarrow \tau\mu$

2 search channels depending on the τ decay mode

- Hadronic channel (τ decay to hadrons ~ 66%)
- Leptonic channel (~17 % to e and ~17% to μ)
- Experimentally different
- Similar sensitivity
  - Hadronic channel: Harnik, Kopp and Zupan arXiv:1209.1397
  - Leptonic channel: Davidson and Verdier arXiv:1211.1248

⇒ Start with the leptonic channel and later combine with the hadronic

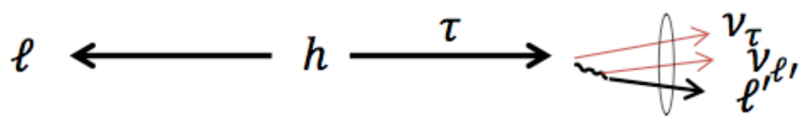


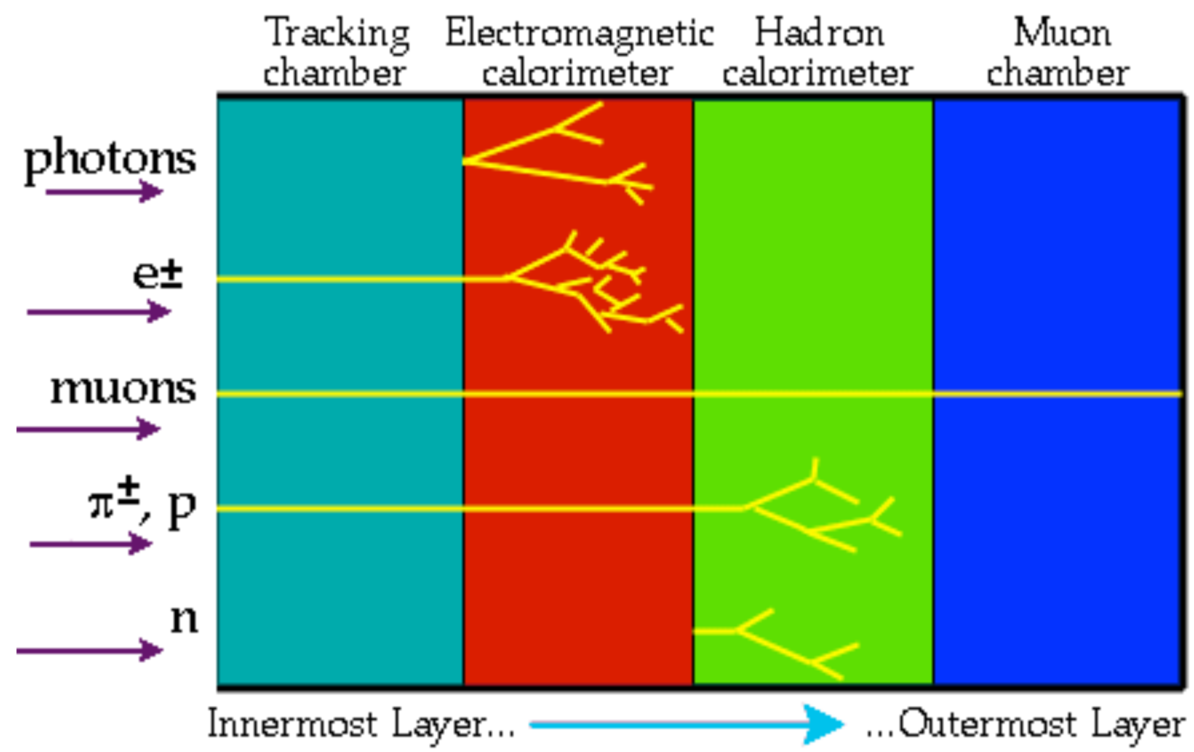
Signal events in 20 fb^{-1} of the ATLAS data

- $h \rightarrow \tau\mu \rightarrow l\mu 2\nu$: < 1400 (14000) events
- $h \rightarrow \tau e \rightarrow l\mu 2\nu$: < 1400 (14000) events

➥ Can be seen on top of 0.8M (8M) background events

Event signature





$h \to \tau\mu \to l\mu 2\nu$: two options

- $\mu^+ \mu^-$ and some missing E_T
- $\mu^\pm e^\mp$ and some missing E_T

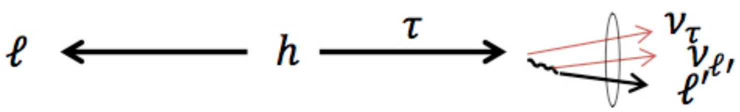
Count 2-lepton events ($\mu^+ \mu^-$ or $\mu^\pm e^\mp$) compare to the SM prediction

Signal events in 20 fb^{-1} of the ATLAS data

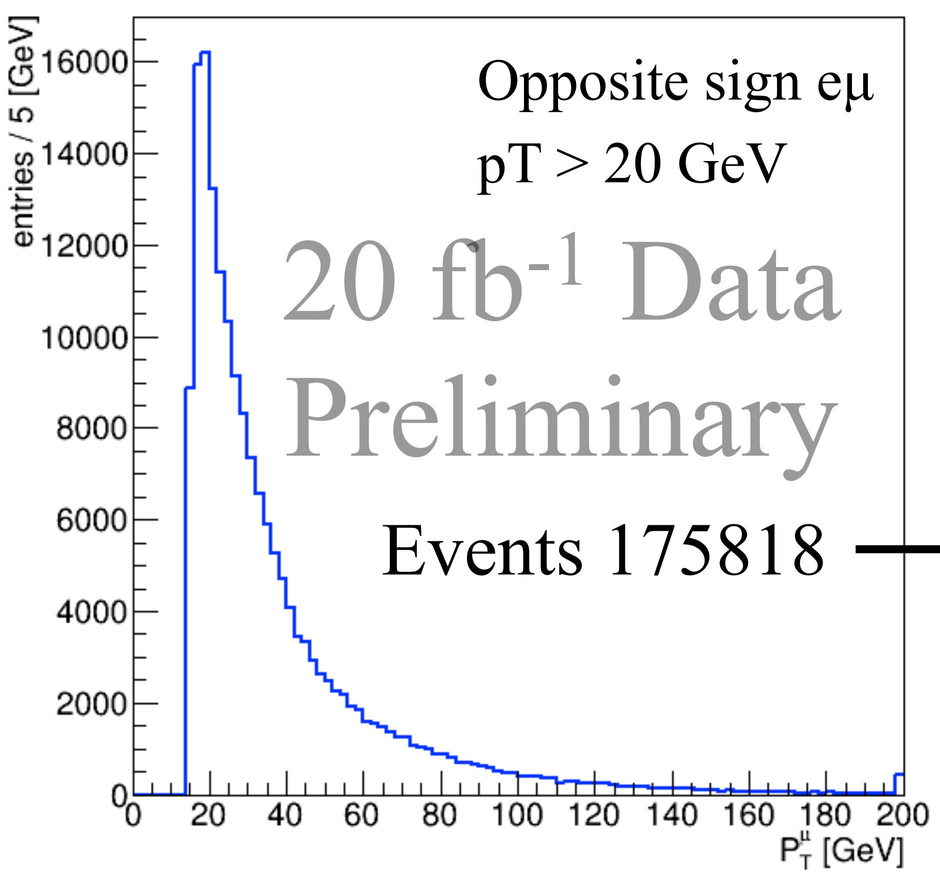
- $h \to \tau\mu \to l\mu 2\nu$: < 1400 (14000) events
- $h \to \tau e \to l\mu 2\nu$: < 1400 (14000) events

Channel selection: $H\to\tau\mu\to e\mu 2\nu$

Leptonic channel: two possible final states



- $\tau\to\mu 2\nu$: opposite sign μ + E_T^{miss}
  $\Rightarrow$ huge background from $Z\to\mu\mu$ (~ 20M in 20 fb^{-1} of data)
- $\tau\to e 2\nu$: <u>*opposite sign e&μ +* E_T</u>^{miss}
  $\Rightarrow$ $h\to\tau\mu\to e\mu 2\nu$: < 700 (7000) events
  no background from $Z\to\mu\mu$/ee, only background from $Z\to\tau\tau\to e\mu 4\nu$

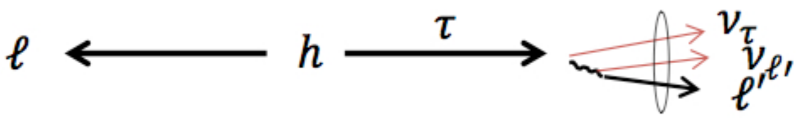


Very naively
$s/\sqrt{B}$ ~ 1.7 (17)

More discriminators are needed

Event topology

h→τμ→eμ2ν



- The τ and μ are produced back-to-back in the transverse plan
- The τ is boosted ⇒ l' and the 2ν from the τ decay are collinear with the τ
- Jets are only from ISR

The collinear approximation

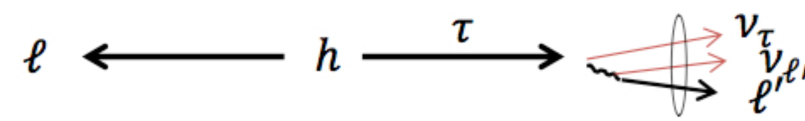
- Assumes that the τ decay products are in the direction of the τ
- Reconstruct the τ 4-momentum from the lepton and E_T^{miss}

The collinear mass: an estimation of the h mass:

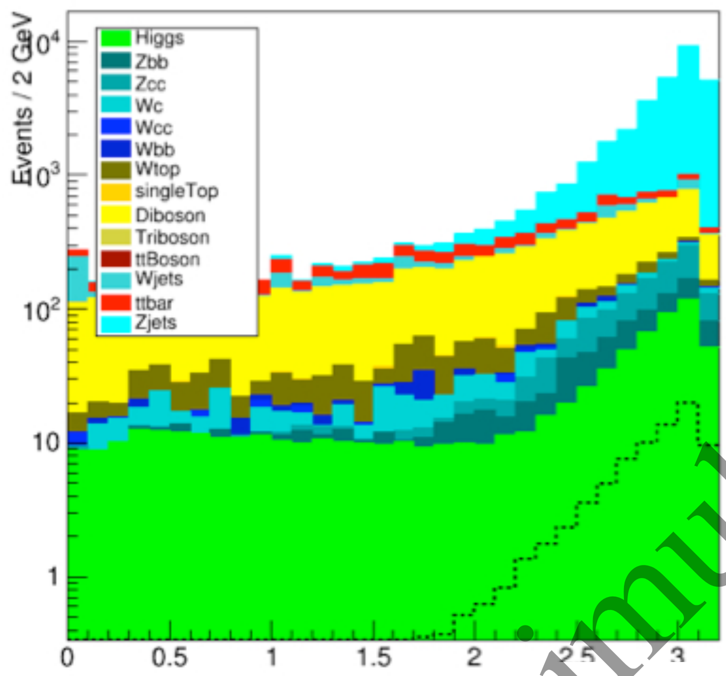
$$M_{coll}^2 = 2p_T^{\ell}(p_T^{\ell'} + MET)(\cosh\Delta\eta_{\ell\ell'} - \cos\Delta\phi_{\ell\ell'})$$

$$M_{inv}^2 = 2p_T^{\ell}p_T^{\tau}(\cosh\Delta\eta_{\ell\tau} - \cos\Delta\phi_{\ell\tau})$$

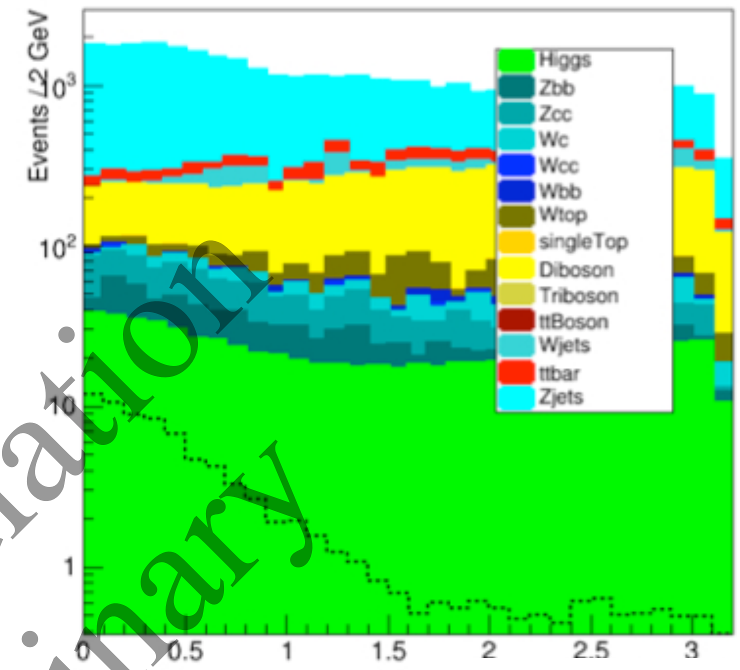
Event topology ⇒ S/B separation



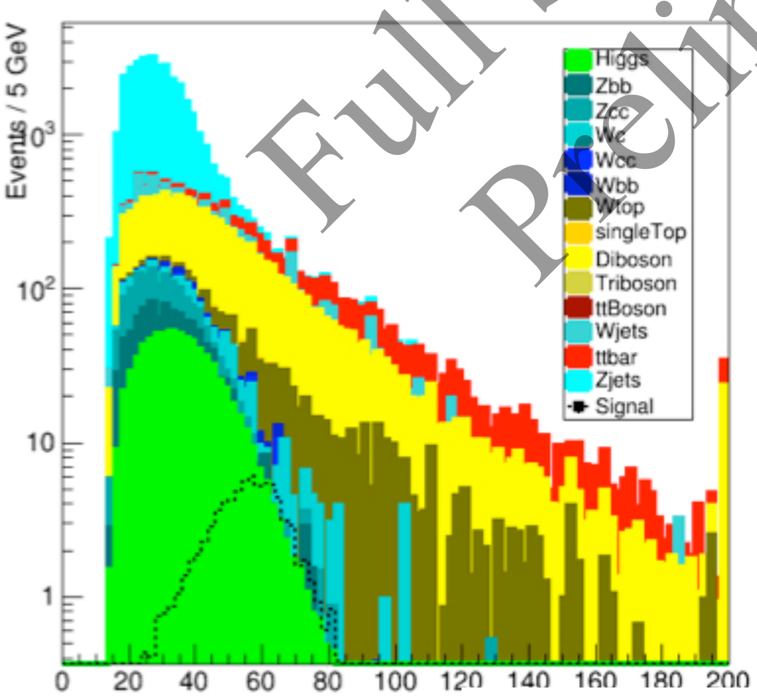
Trigger	Detail
Single Isolated *e*	EF_e24vhi_medium1
Single Isolated *μ*	EF_mu24i_tight
Combined *eμ*	EF_e12Tvh_medium1_mu8 EF_mu18_tight_e7_medium1



$\Delta\varphi(l,l')$



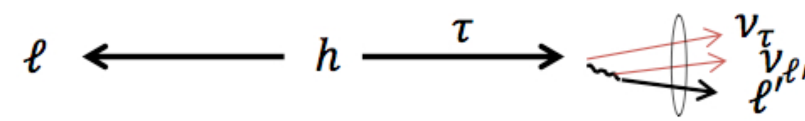
$\Delta\varphi(E_T^{miss},l')$



p_T^{l0} [GeV]

Selection criteria (w/ pre-selection)	Signal Eff.	Signal	Background
Exactly 1 e & 1 μ - opposite sign			
e: $p_T > 20$ GeV & $\|\eta\| < 2.5$			
μ: $p_T > 40$ GeV & $\|\eta\| < 2.1$			
Jet veto: $p_T > 30$ GeV & $\|\eta\| < 2.5$			
$\Delta\varphi(e, \mu) > 2.5$			
$\Delta\varphi(l', E_T^{miss}) < 0.5$	4%	29-290	1246

Event topology ⇒ S/B separation



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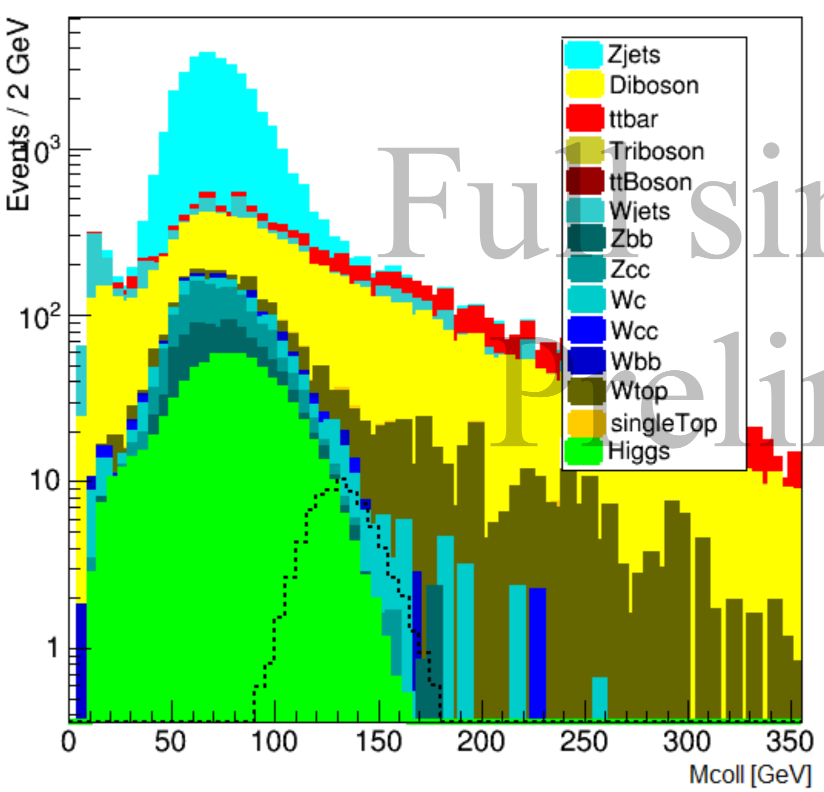
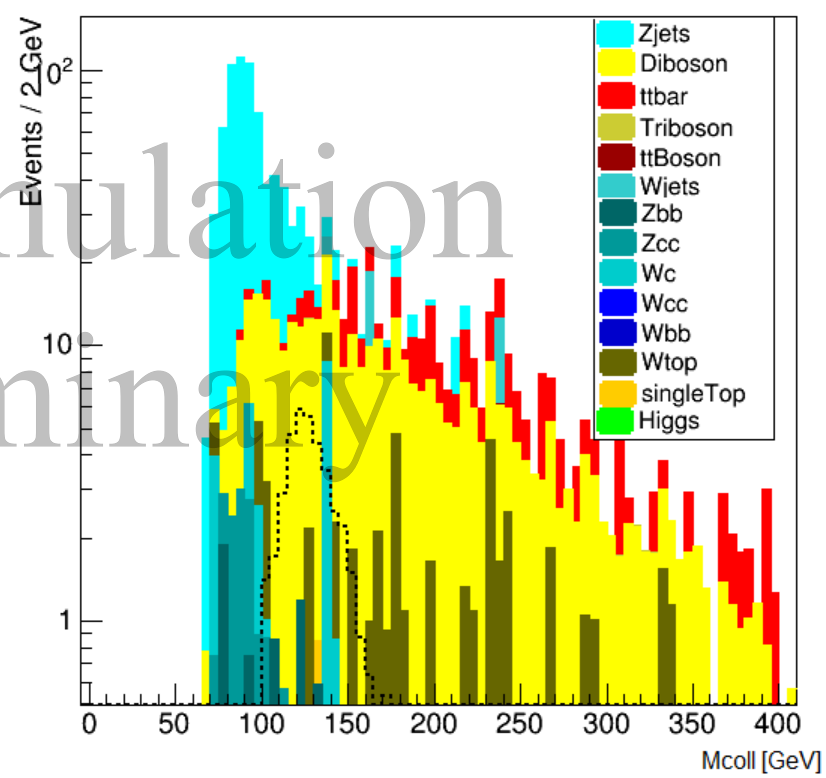




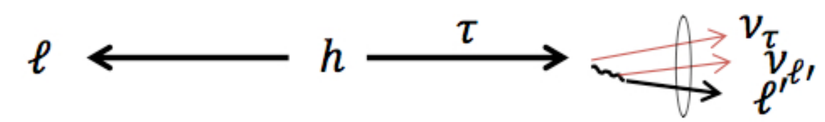
Main background sources:

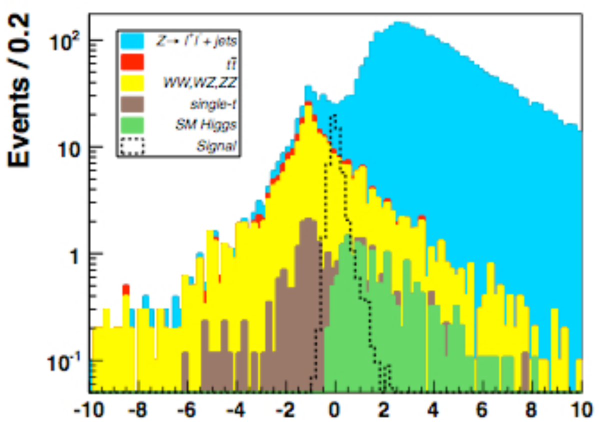
- $Z \rightarrow \tau\tau \rightarrow e\mu + E_T^{miss}$
- $WW \rightarrow e\mu + E_T^{miss}$
- ttbar

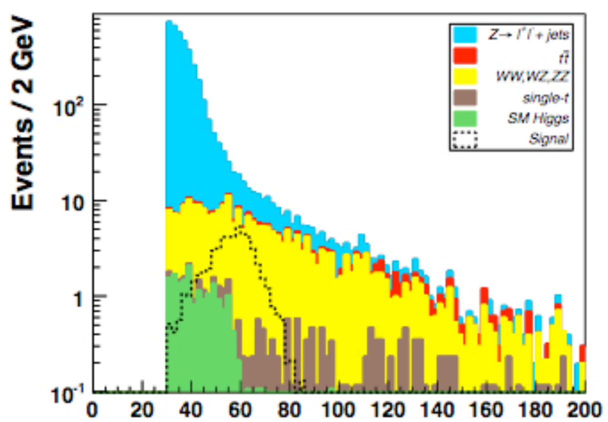
Event topology ⇒ S/B separation

Slightly different use of the collinear approximation

Davidson and Verdier arXiv:1211.1248

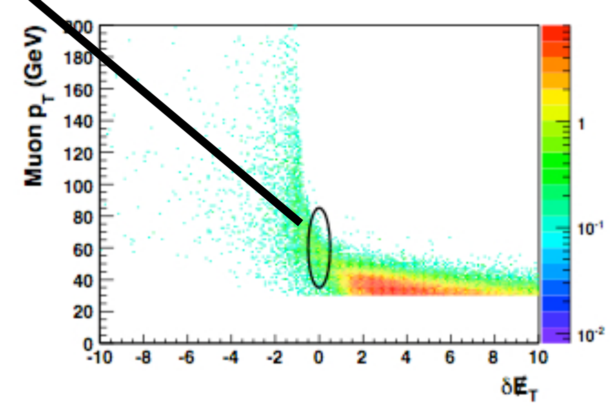


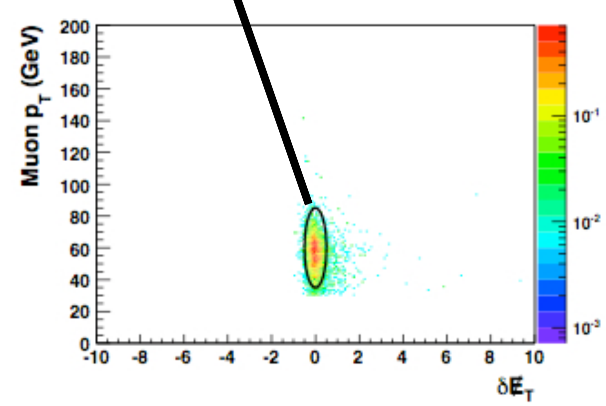




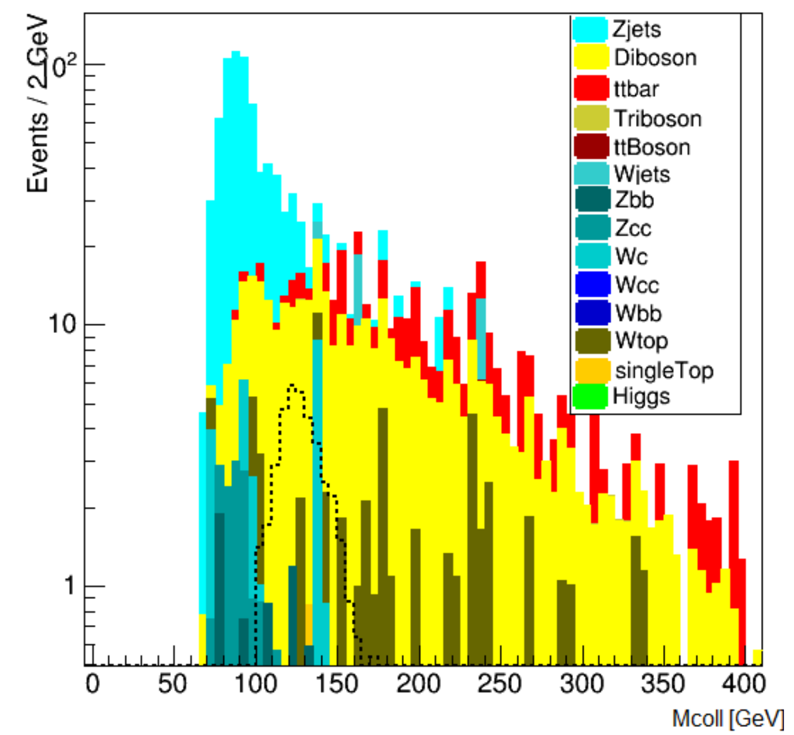
Selection criteria	$N_{backgrd.}$	$N_{h\to\tau\tau}$	$N_{h\to WW}$	$N_{h\to ZZ}$	Signal efficiency (%)	$N_{sig.}$
≥ 1 muon with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.1$ and ≥ 1 electron with $p_T > 15$ GeV and $\lvert\eta\rvert < 2.5$	59271 ± 76	$89. \pm 3.$	$235. \pm 5.$	4.2 ± 0.7	21.2 ± 0.1	145.4 ± 0.9
exactly 2 OS leptons	58447 ± 75	$89. \pm 3.$	$235. \pm 5.$	2.2 ± 0.5	21.2 ± 0.1	145.4 ± 0.9
jet veto: no jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.5$	19477 ± 44	$51. \pm 2.$	$123. \pm 3.$	1.0 ± 0.3	13.1 ± 0.1	89.7 ± 0.7
$\Delta\phi(e,\mu) > 2.7$	13261 ± 36	$40. \pm 2.$	8.7 ± 0.9	0.1 ± 0.1	10.7 ± 0.1	72.9 ± 0.7
$\Delta\phi(e,\not{E}_T) < 0.3$	3885 ± 20	$15. \pm 1.$	2.4 ± 0.5	0.1 ± 0.1	7.85 ± 0.09	53.7 ± 0.6
2D cut in $(\delta\not{E}_T, p_T^\mu)$ plane	53 ± 2	0.6 ± 0.3	0.5 ± 0.2	0	5.34 ± 0.07	36.5 ± 0.5

TABLE II: Selection criteria for the $h \to \tau^\pm\mu^\mp$ search at the $\sqrt{s} = 8$ TeV LHC with $\mathcal{L} = 20\ fb^{-1}$ with the total number of events expected from SM backgrounds, the contribution of SM Higgs decay to the total background, and the signal efficiency (%) and the number of signal events expected for $BR(h \to \tau^\pm\mu^\mp) = 10^{-2}$; uncertainties are statistical only.





Background estimation



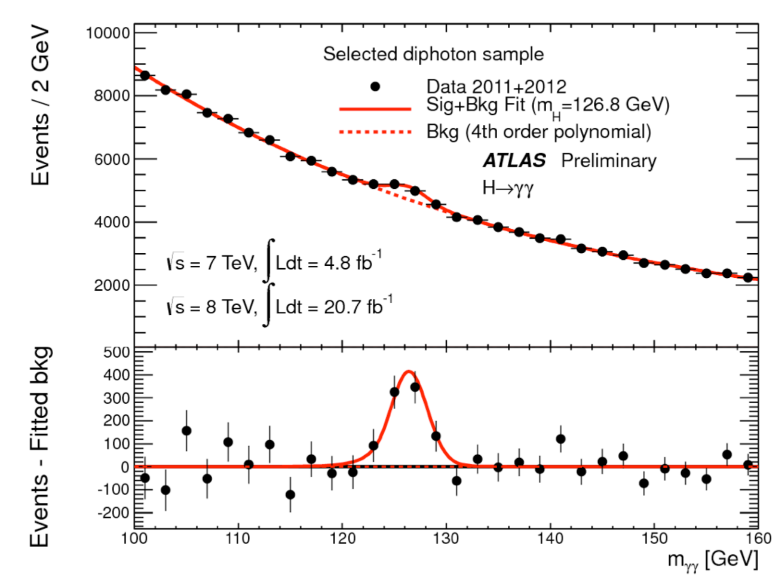
The experimental challenge:

1. How many standard model events passed the selection
2. How wrong we might be ⇒ systematic uncertainties

Difficulties

- The higgs peak is in an intermediate region between the sharp $Z \rightarrow \tau\tau$ peak and the flat WW and ttbar components
- "Traditional" background estimation techniques are likely to result in large systematic uncertainties

Traditional estimation methods



- Side band fit
  Difficult (impossible) to find a function describing both the Z peak and the other background sources
- Monte Carlo base
- Extrapolation from control regions
  No obvious $Z \rightarrow \tau\tau$ CR

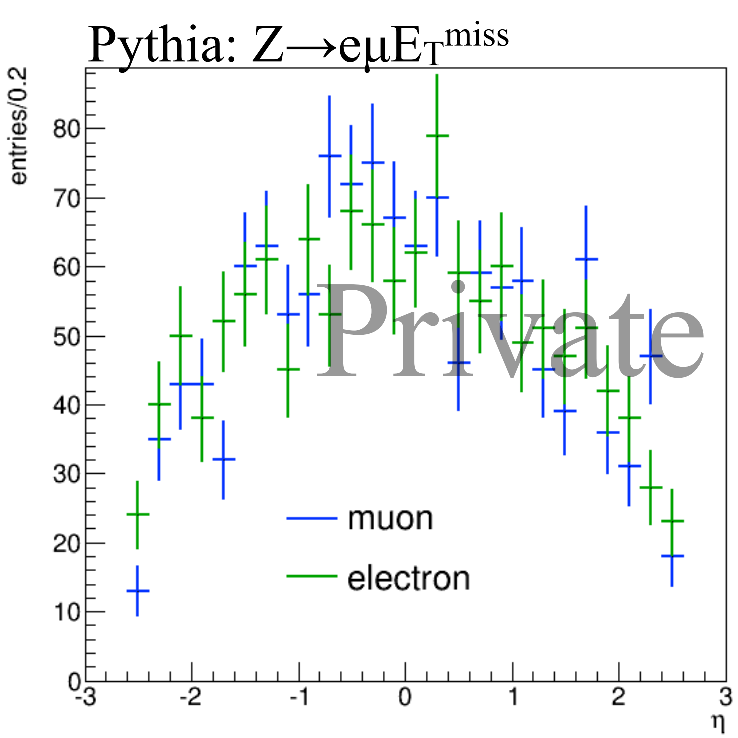
e / μ (a)symmetry

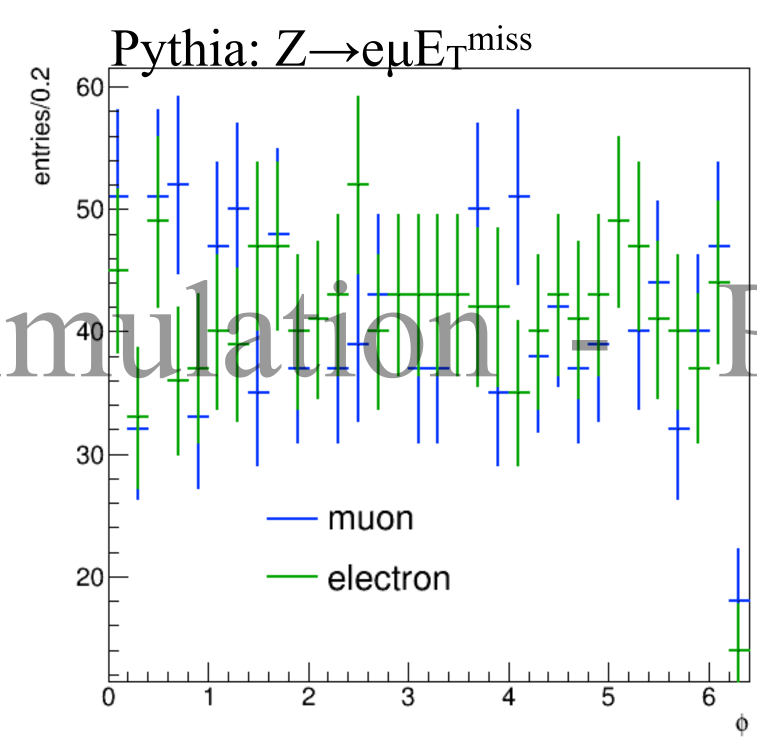
Charged lepton interactions in the standard model:

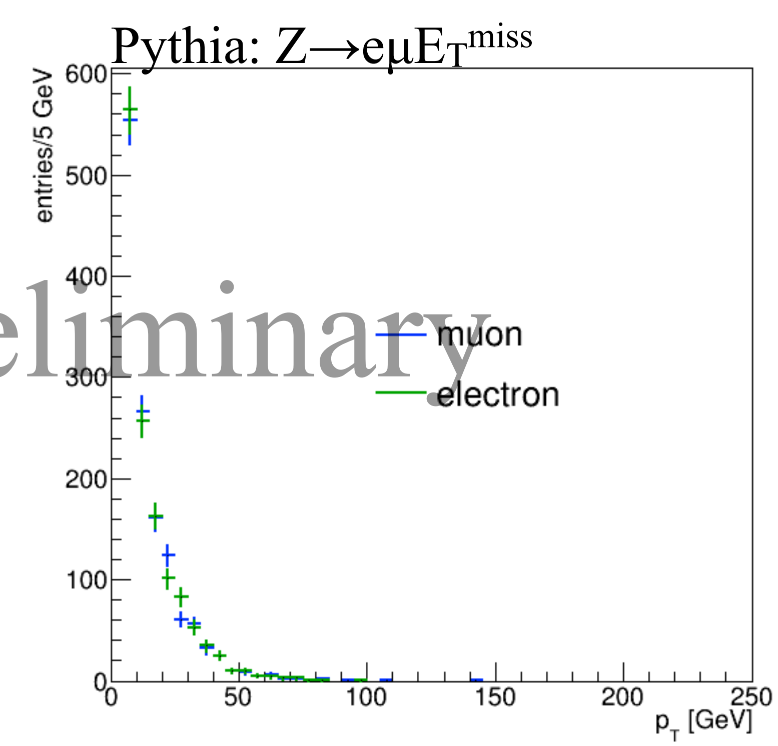
- Strong: not participating
- EM: proportional to the charge ⇒ e / μ symmetric
- Weak: universal gauge coupling ⇒ e / μ symmetric
- SM Yukawa: proportional to the mass ⇒ can be neglected

➥ Theoretically*: **Complete e/μ symmetry in the SM**

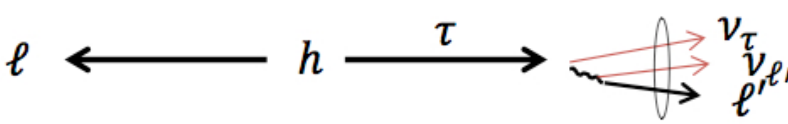
* up to small phase space corrections that can be neglected at the LHC energies







e / μ (a)symmetry

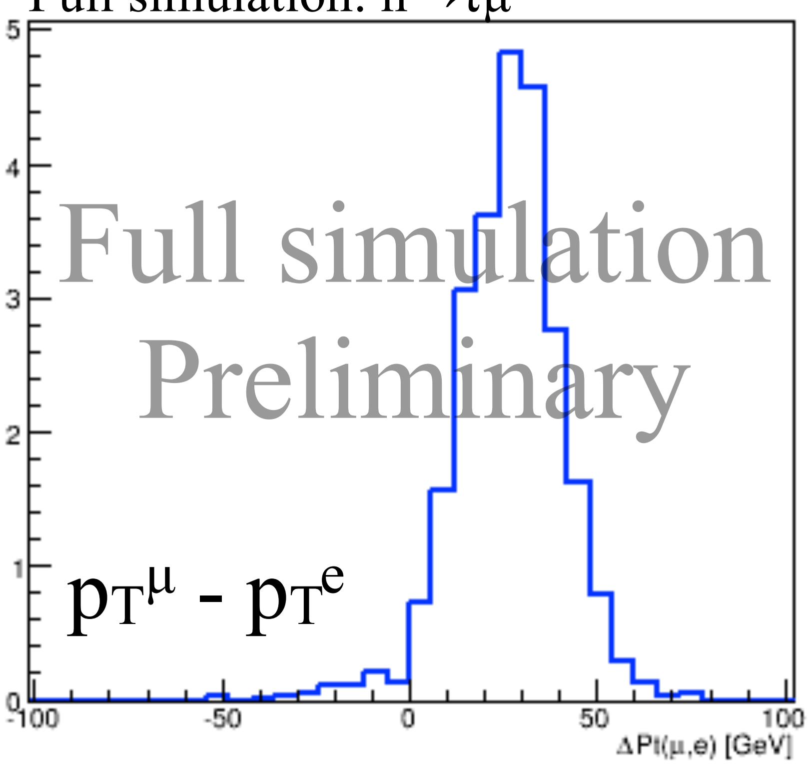


h→τμ→eμ2ν

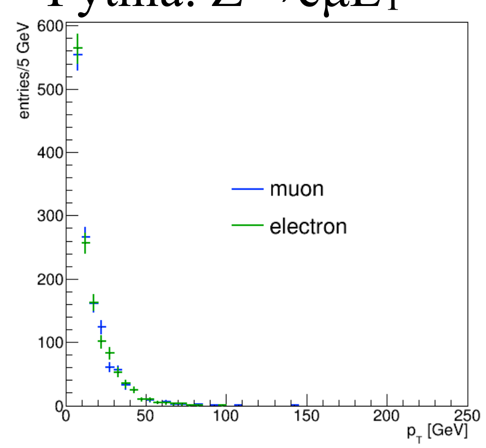
- h→τμ: the τ and μ take half the h energy (on the average)
- τ→e2ν: the e takes 1/3 of the τ energy (on the average)

➡ The μ is 3 time more energetic than the e
the e/μ symmetry breaks

Full simulation: h→τμ



Pythia: $Z \to e\mu E_T^{miss}$



Divide the data

Sample I: events with $p_T^\mu > p_T^e$ (μe)

Sample II: events with $p_T^e > p_T^\mu$ (eμ)

➡ SM processes are split to half

h→τμ→eμ2ν is in sample I

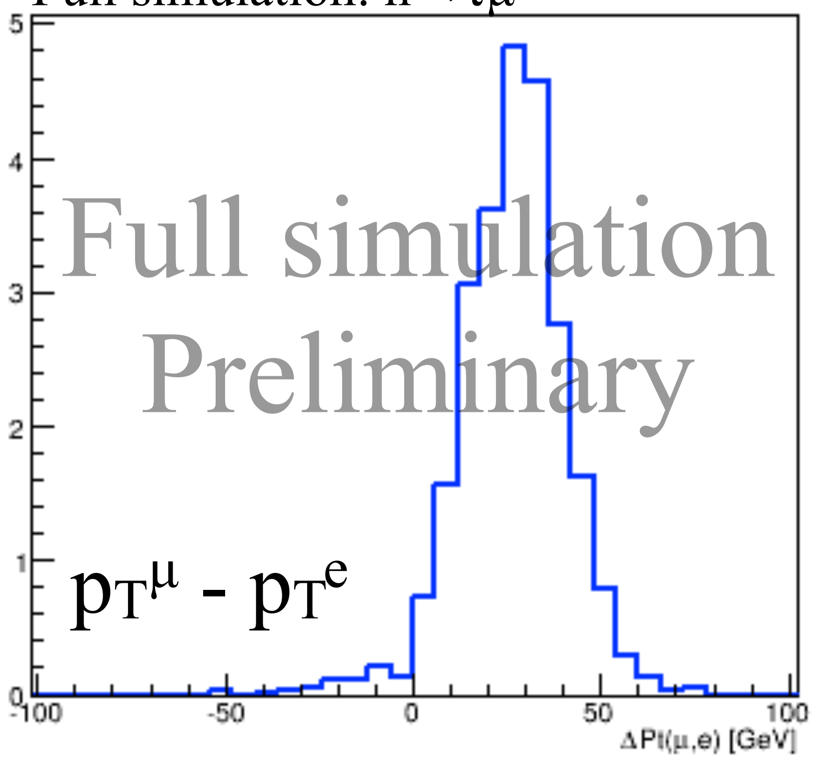
e / μ (a)symmetry

$h \to \tau\mu \to e\mu 2\nu$

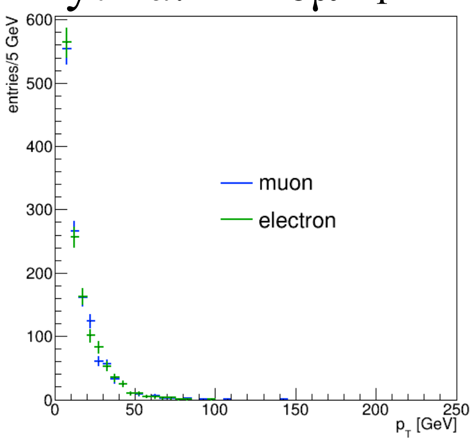
- $h \to \tau\mu$: the τ and μ take half the h energy (on the average)
- $\tau \to e2\nu$: the e takes 1/3 of the τ energy (on the average)

➥ The μ is 3 time more energetic than the e
the e/μ symmetry breaks

Full simulation: $h \to \tau\mu$



Pythia: $Z \to e\mu E_T^{miss}$



Divide the data

Sample I: events with $p_T^{\mu} > p_T^{e}$ (μe)

Sample II: events with $p_T^{e} > p_T^{\mu}$ (eμ)

➥ SM processes are split to half

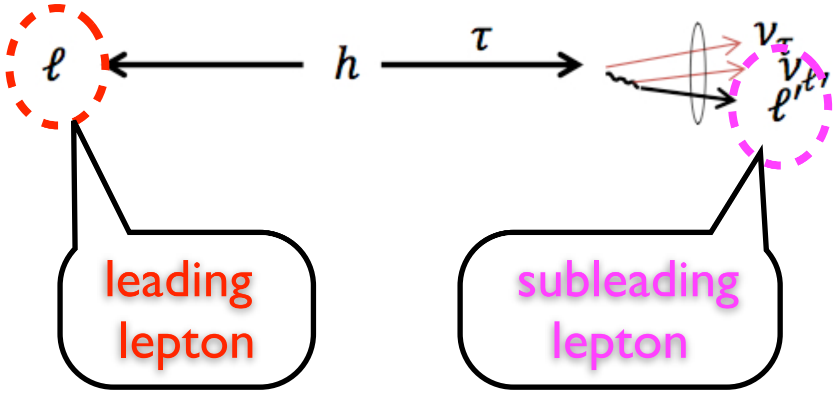
$h \to \tau\mu \to e\mu 2\nu$ is in sample I (μe)

Data driven method: H→τμ→eμ2ν

Divide the data

Sample I (μe): events with $p_T^{\mu} > p_T^{e}$ ⇒ the signal is here

Sample II (eμ): events with $p_T^{e} > p_T^{\mu}$



Calculate the collinear mass for each sample separately

$$M_{coll}^2 = 2p_T^{\ell}(p_T^{\ell'} + MET)(\cosh\Delta\eta_{\ell\ell'} - \cos\Delta\phi_{\ell\ell'})$$

- Use the leading and subleading leptons correctly

Note

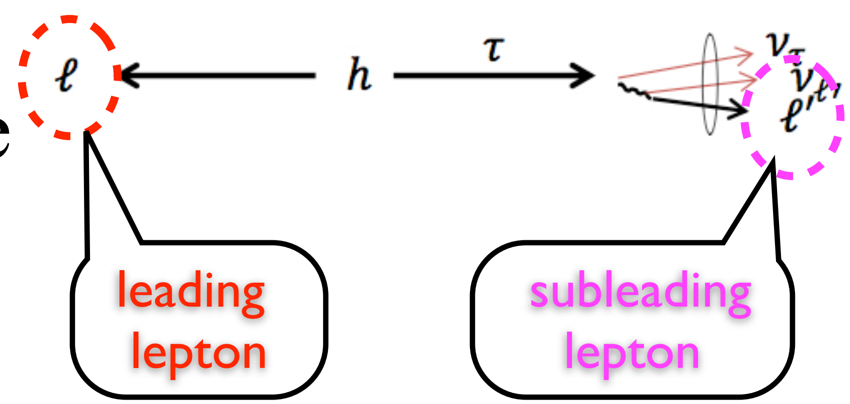
- e/μ symmetry in the SM ⇒
  the distributions of the background processes look the same in the two samples
  - As long as the leading and subleading leptons are defined correctly
- h→τμ ⇒ peaks at sample I (μe)

Data driven method: $H\rightarrow\tau\mu\rightarrow e\mu 2\nu$

Divide the data

Sample I (μe): events with $p_T^{\mu} > p_T^{e}$ $\Rightarrow$ the signal is here

Sample II ($e\mu$): events with $p_T^{e} > p_T^{\mu}$



Conclusion

The distributions obtained with sample II ($e\mu$) model the standard model background in sample I (μe)

Caveat

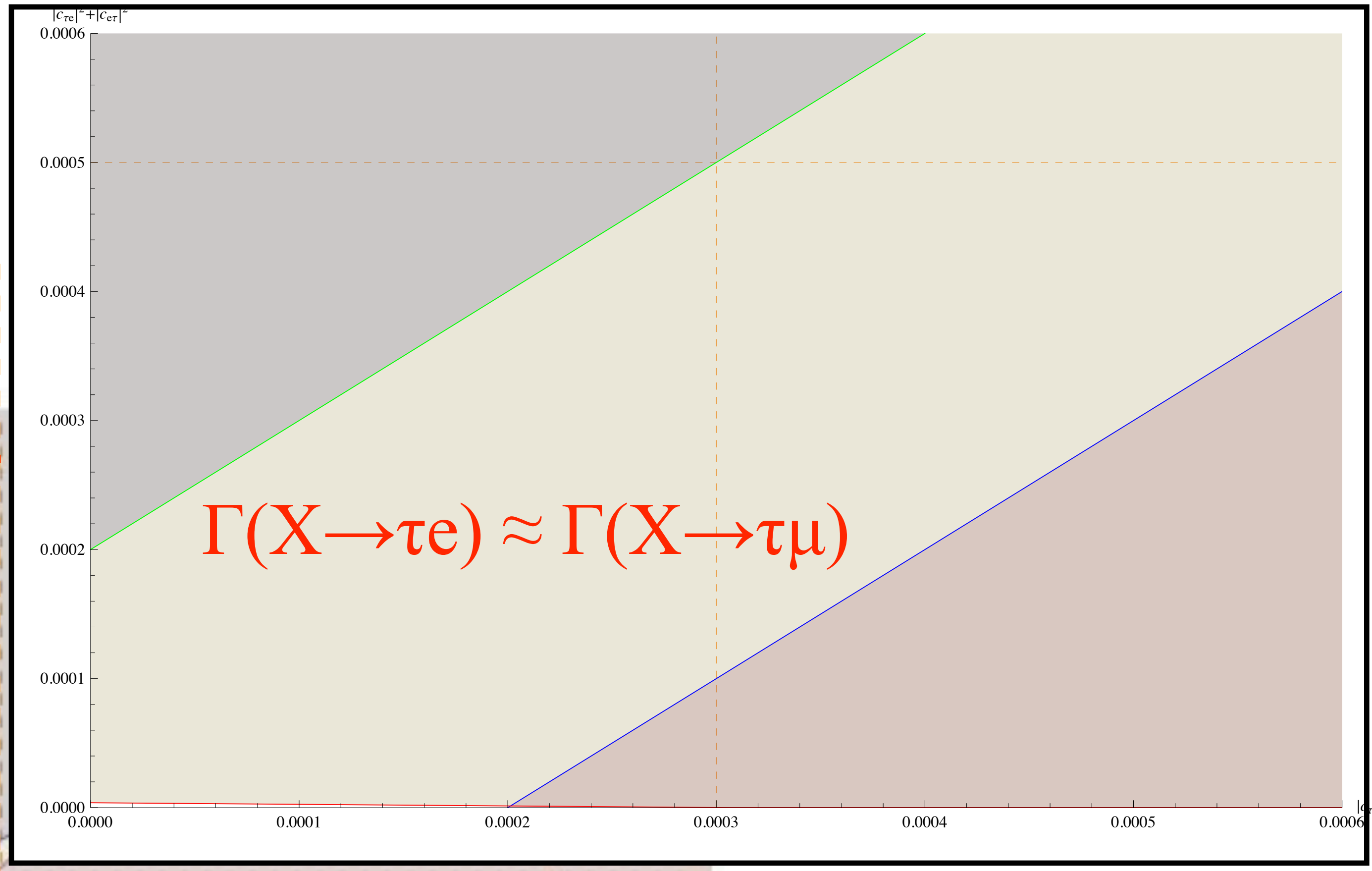
The method can probe differences between $\Gamma(X\rightarrow\tau e)$ and $\Gamma(X\rightarrow\tau\mu)$

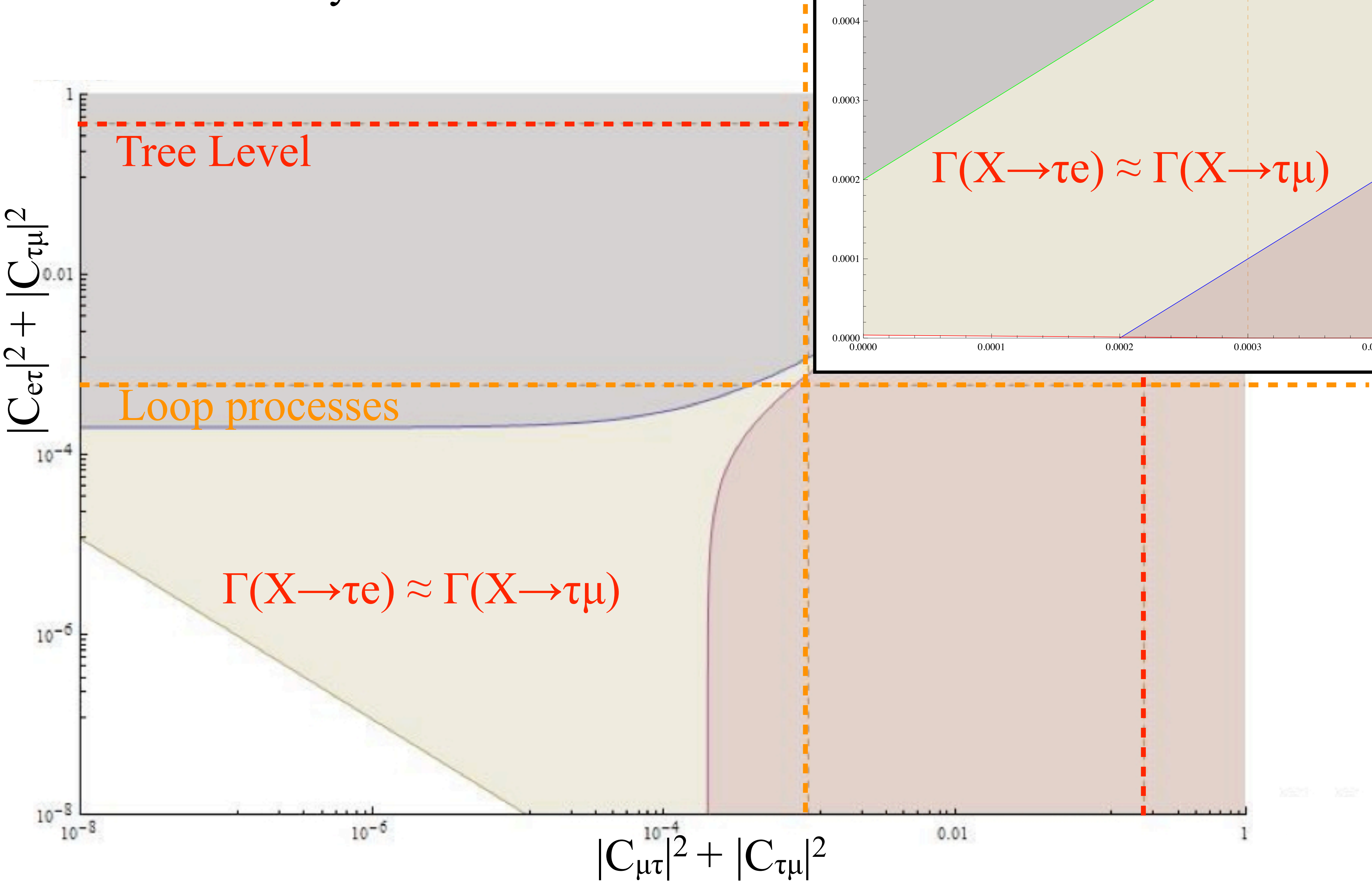
Any observation would imply physics beyond the standard model

Eff. couplings	Bound	Constraint
$\lvert c_{e\tau}c_{\tau\mu}\rvert$, $\lvert c_{\tau e}c_{\mu\tau}\rvert$	1.7×10^{-7}	$\mathcal{B}(\mu\to e\gamma) <$ 5.7×10^{-13}

Sensitivity: H→τμ→eμ2ν

Assuming 225 background events
⇒ Uncertainty of 15 events

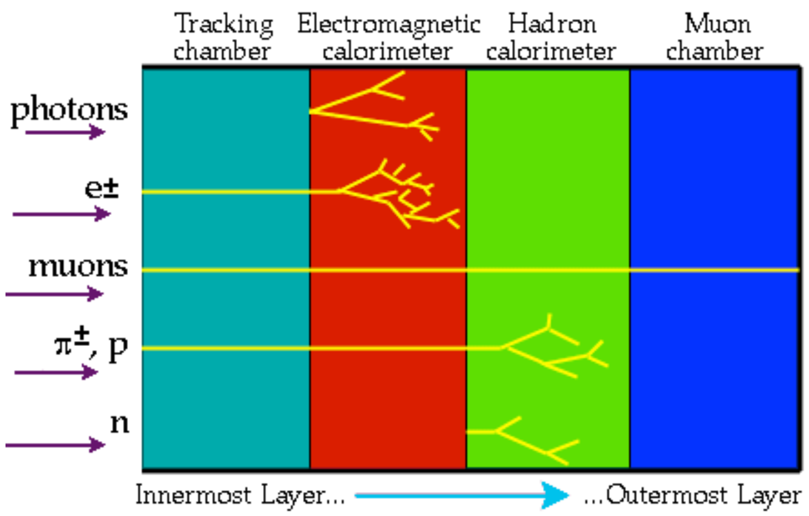




Things that may go wrong

Experimentally, e & μ are different objects

- Electrons emit Bremsstrahlung radiation (small dependence on the electron energy)
  - p_T^e may have lower spectrum
  - The electron direction may be mis-measured
- Different momentum resolution
- Different reconstruction efficiency
- Different trigger efficiency
- Different fake rate



➥ "Theoretically: Complete e/μ symmetry in the SM"

Experimentally things are more difficult

But

The final state has both e & μ

⇒ cancels most of the potential systematic uncertainties

p_T dependent effects are the main problem

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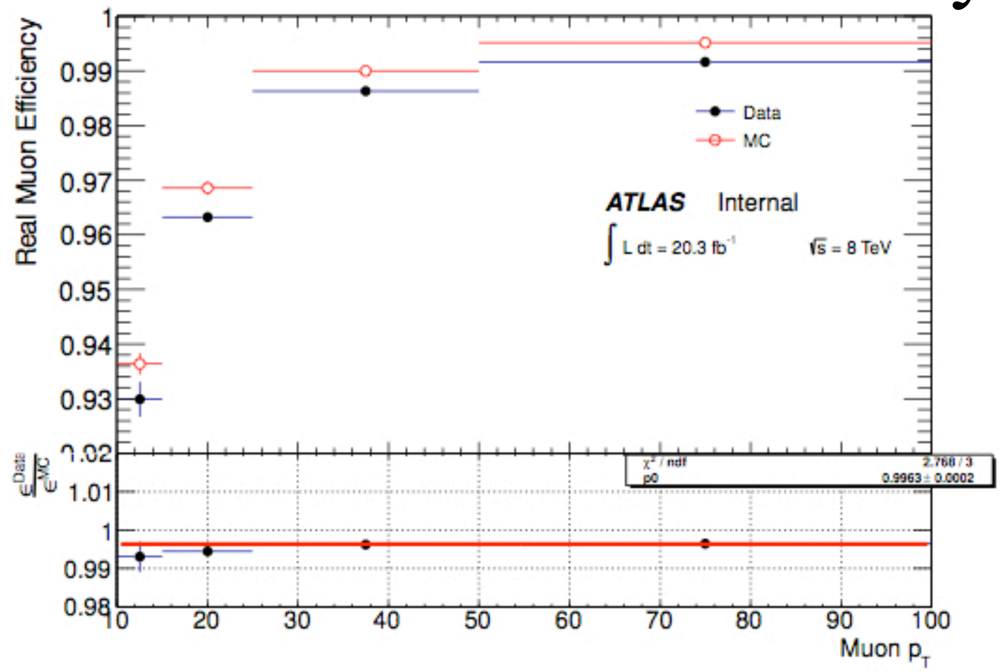
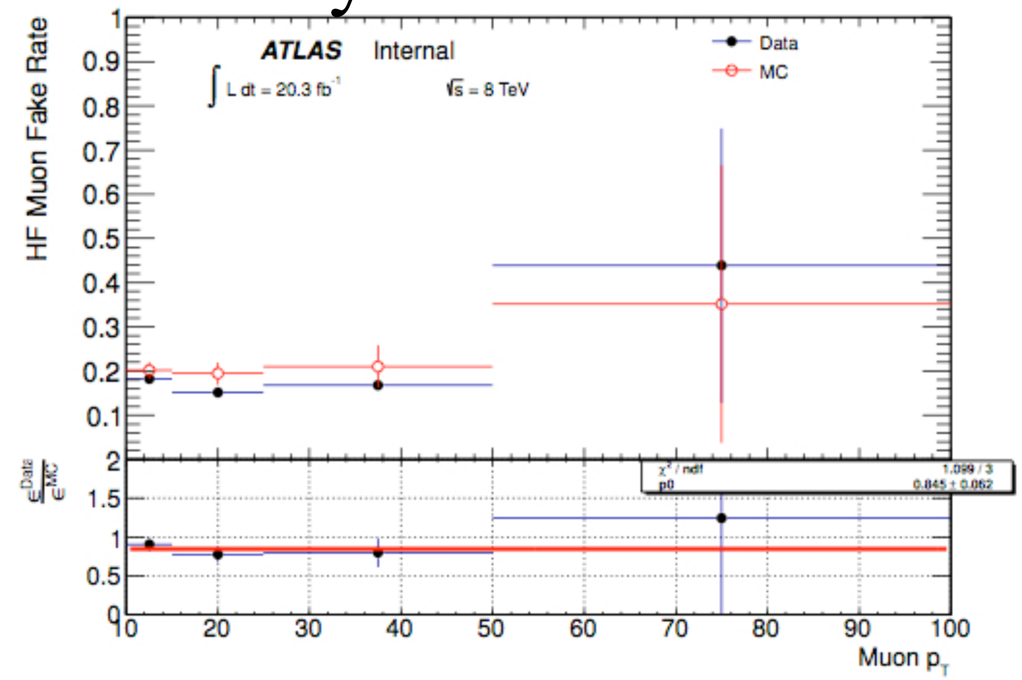
Things that may go wrong: examples

Reconstruction efficiency

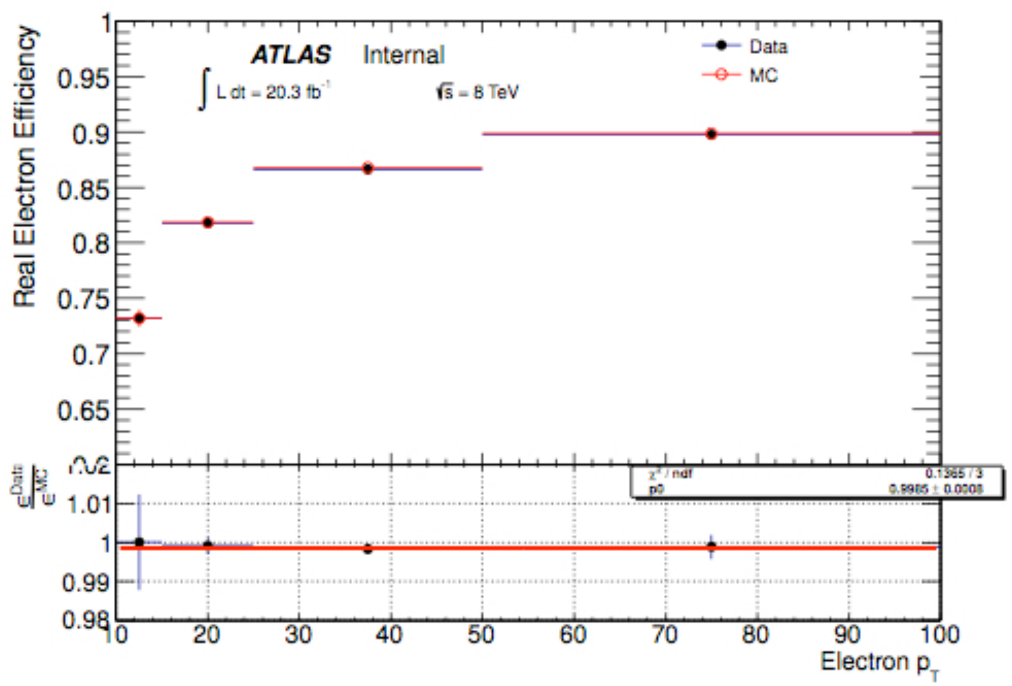
Heavy flavor fake rate

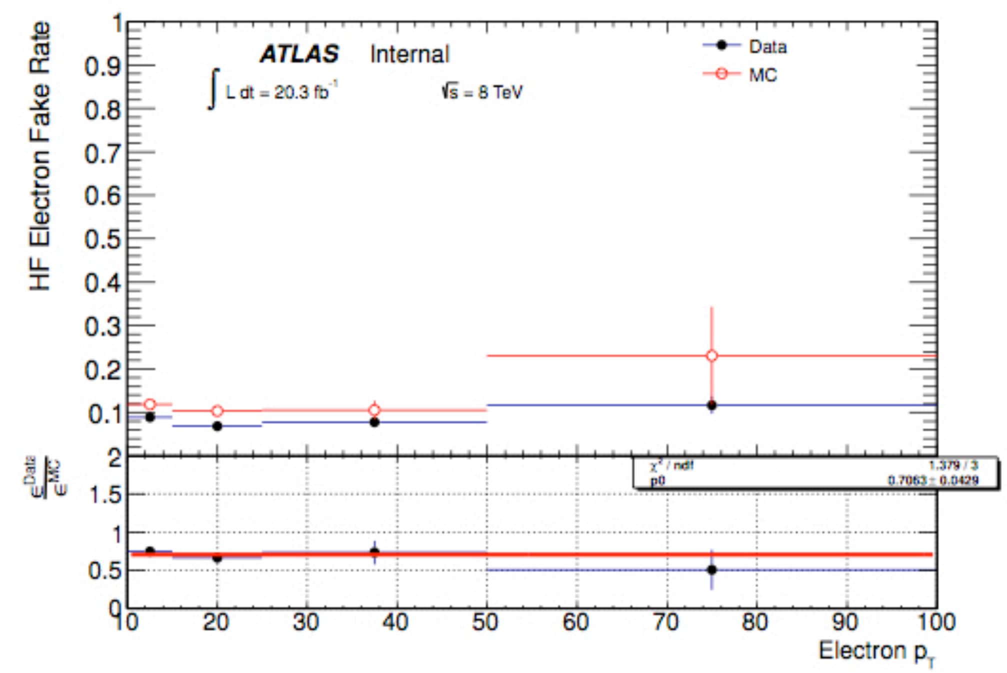
μ





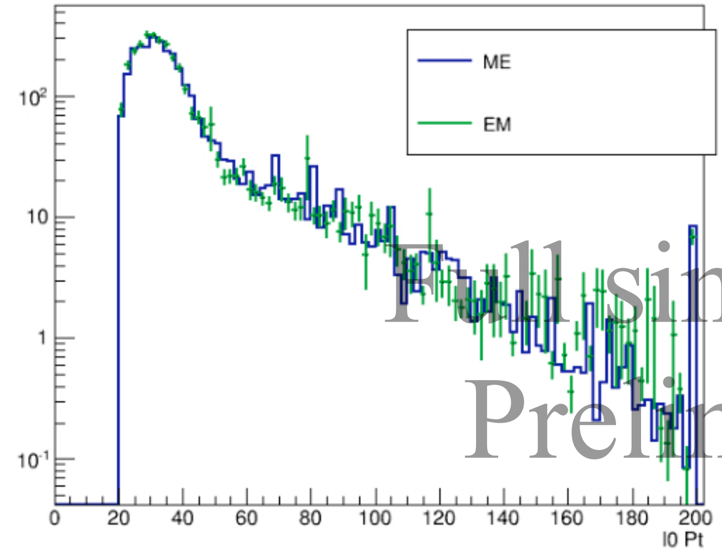
e

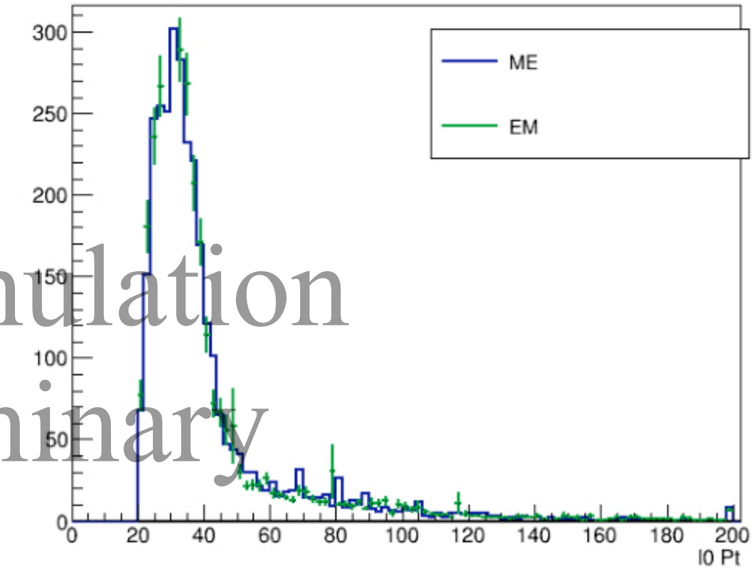


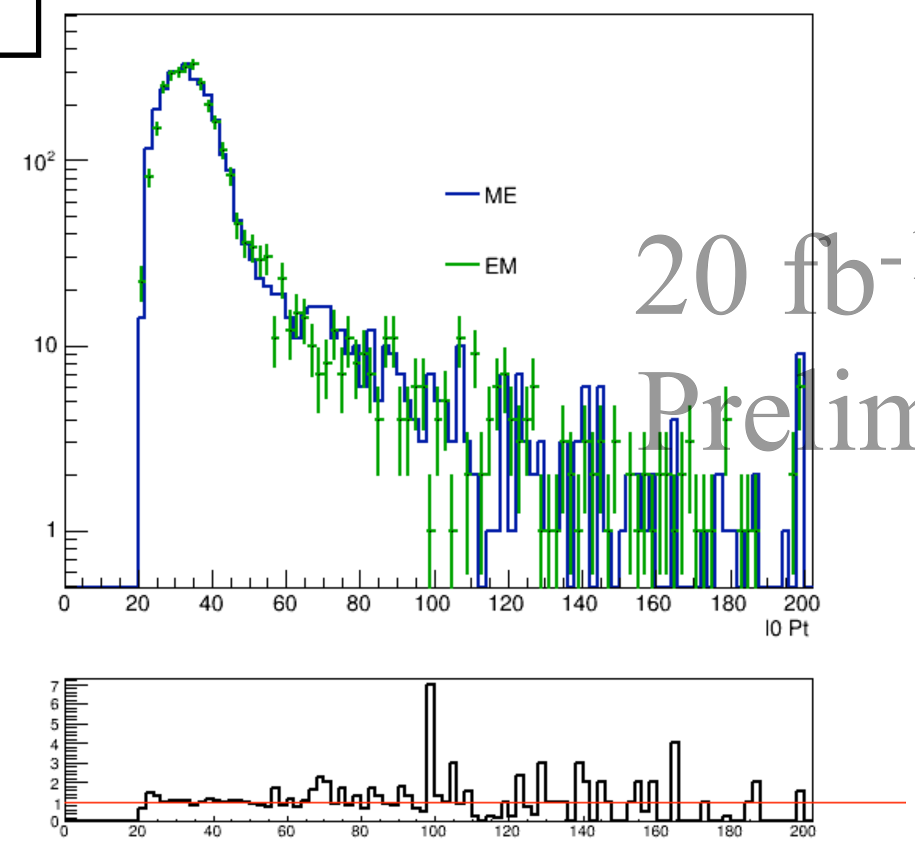


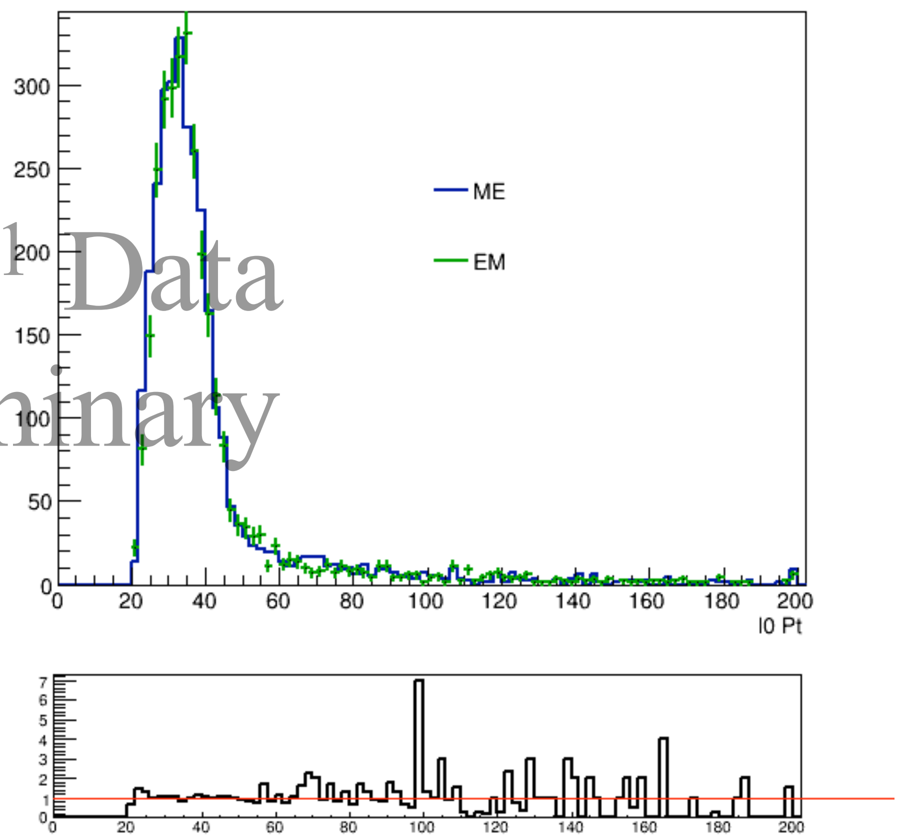
Testing the symmetry: leading lepton p_T

Selection criteria (w/ pre-selection)
Exactly 1 e & 1 μ - opposite sign
e: p_T > 20 GeV & $\|\eta\|$ < 2.5
μ: p_T > 20 GeV & $\|\eta\|$ < 2.1
Jet veto: p_T > 30 GeV & $\|\eta\|$ < 2.5
$\Delta\varphi(e, \mu) > 2.5$
$\Delta\varphi(l', E_T^{miss}) < 0.5$





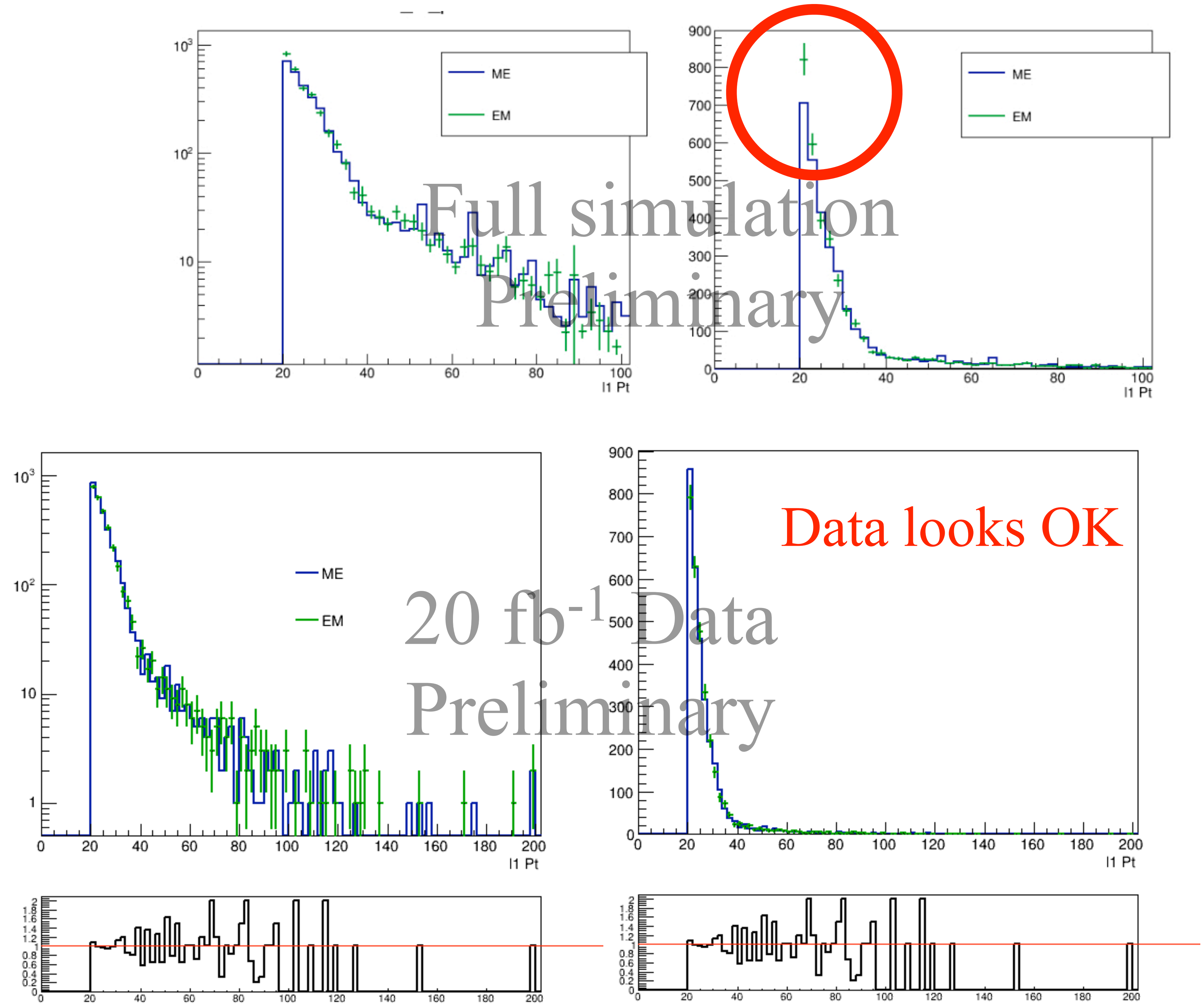




Sample I: μe
Sample I: eμ

Testing the symmetry: subleading lepton p_T

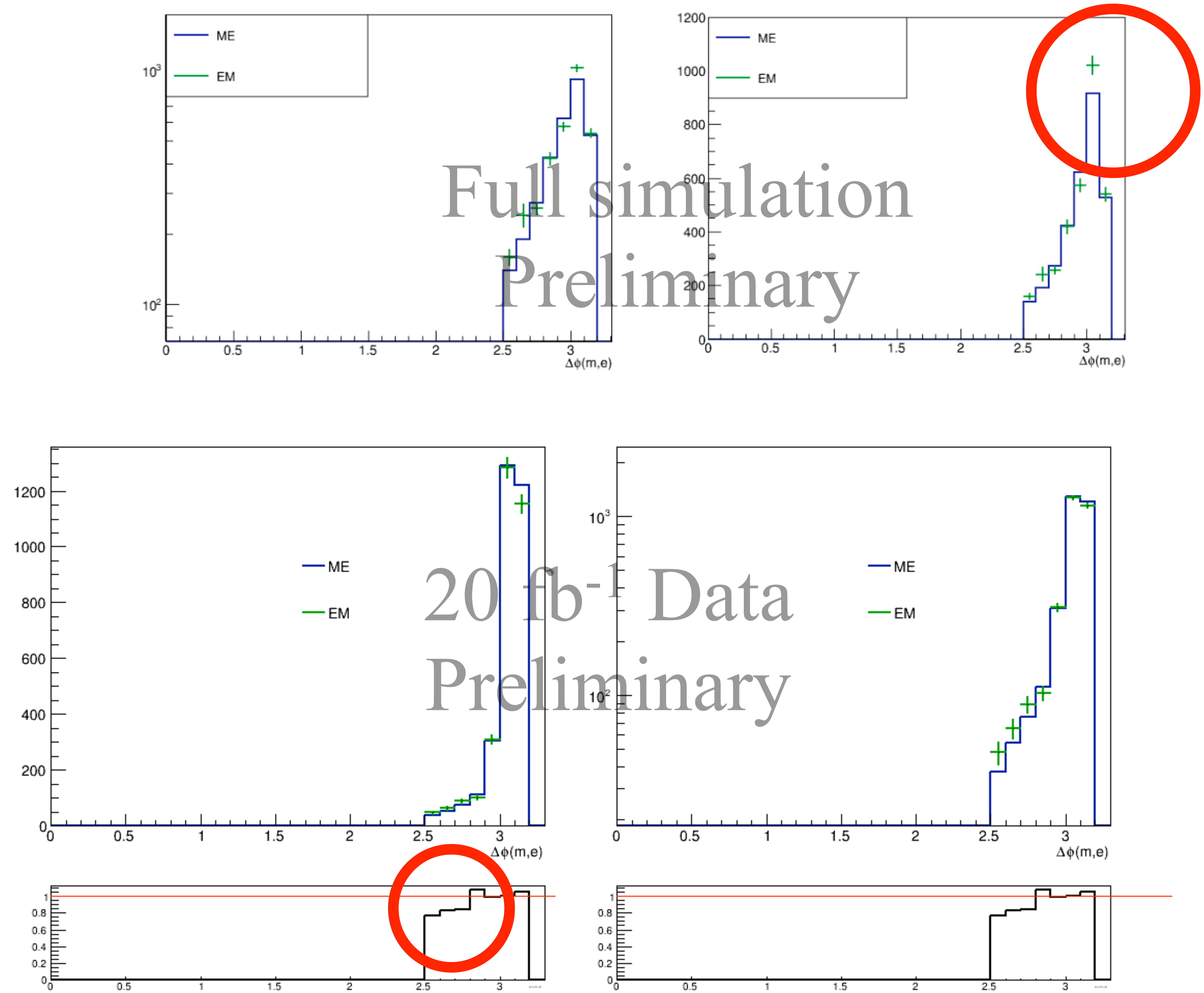
Selection criteria (w/ pre-selection)
Exactly 1 e & 1 μ - opposite sign
e: $p_T > 20$ GeV & $\|\eta\| < 2.5$
μ: $p_T > 20$ GeV & $\|\eta\| < 2.1$
Jet veto: $p_T > 30$ GeV & $\|\eta\| < 2.5$
$\Delta\varphi(e, \mu) > 2.5$
$\Delta\varphi(l', E_T^{miss}) < 0.5$



Sample I: μe
Sample I: eμ

Testing the symmetry: $\Delta\varphi(e,\mu)$

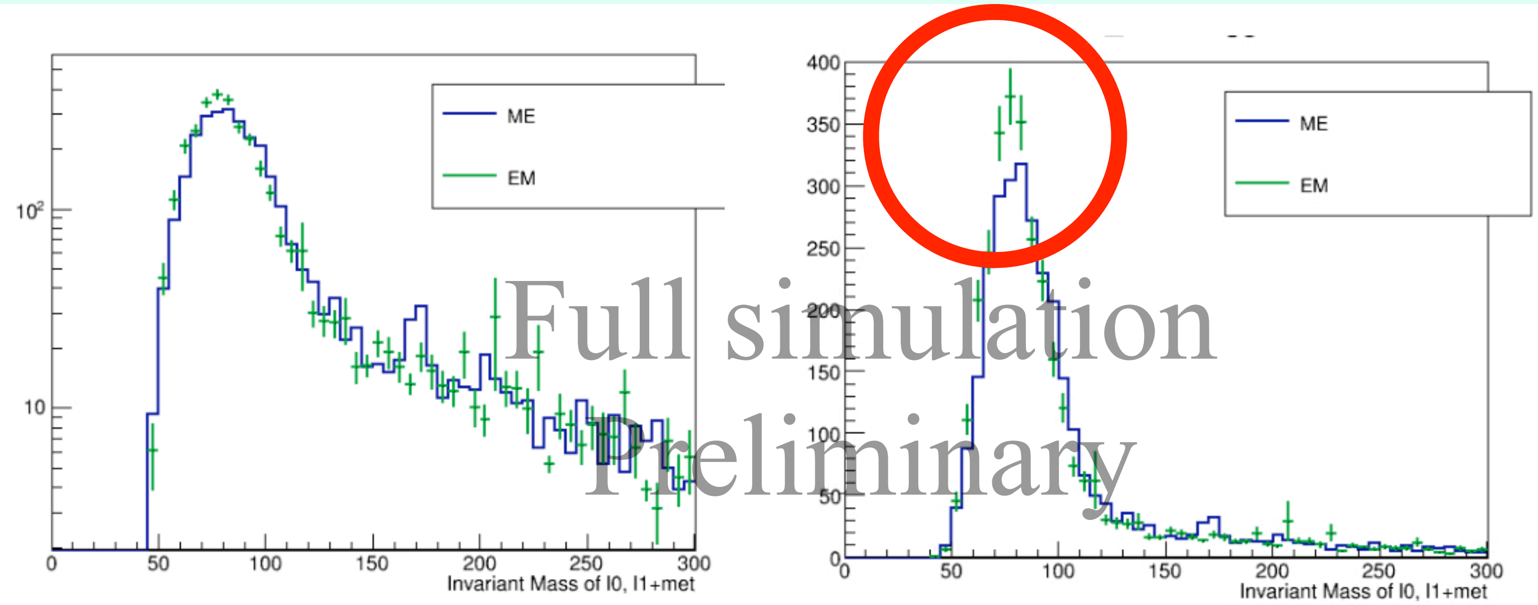
Selection criteria (w/ pre-selection)
Exactly 1 e & 1 μ - opposite sign
e: $p_T > 20$ GeV & $\lvert\eta\rvert < 2.5$
μ: $p_T > 20$ GeV & $\lvert\eta\rvert < 2.1$
Jet veto: $p_T > 30$ GeV & $\lvert\eta\rvert < 2.5$
$\Delta\varphi(e, \mu) > 2.5$
$\Delta\varphi(l', E_T^{miss}) < 0.5$

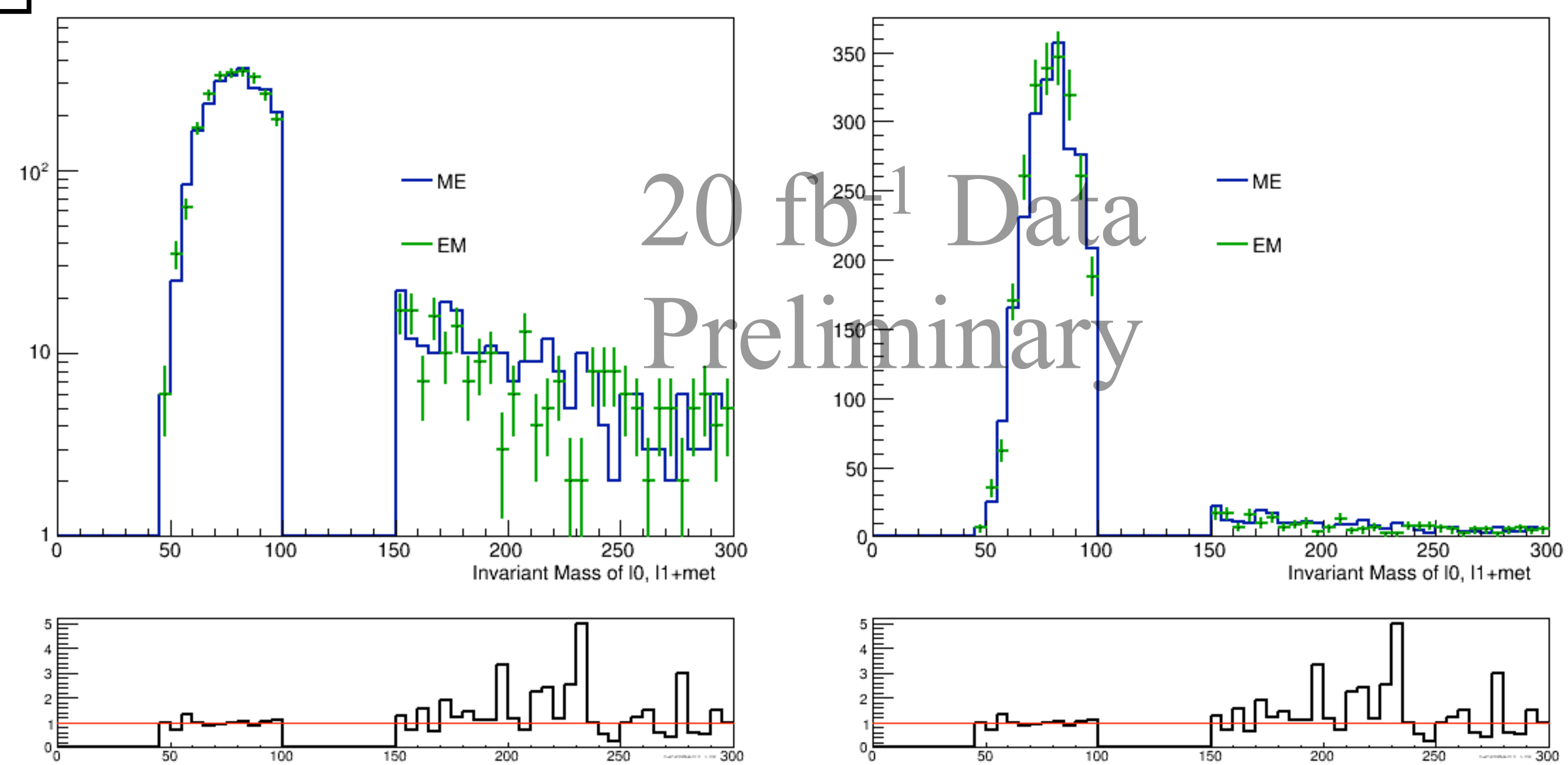


Sample I: μe
Sample I: eμ

Testing the symmetry: collinear mass

Selection criteria (w/ pre-selection)
Exactly 1 e & 1 μ - opposite sign
e: p_T > 20 GeV & $\|\eta\|$ < 2.5
μ: p_T > 20 GeV & $\|\eta\|$ < 2.1
Jet veto: p_T > 30 GeV & $\|\eta\|$ < 2.5
$\Delta\varphi(e, \mu) > 2.5$
$\Delta\varphi(l', E_T^{miss}) < 0.5$





Sample I: μe
Sample I: eμ

Data looks OK

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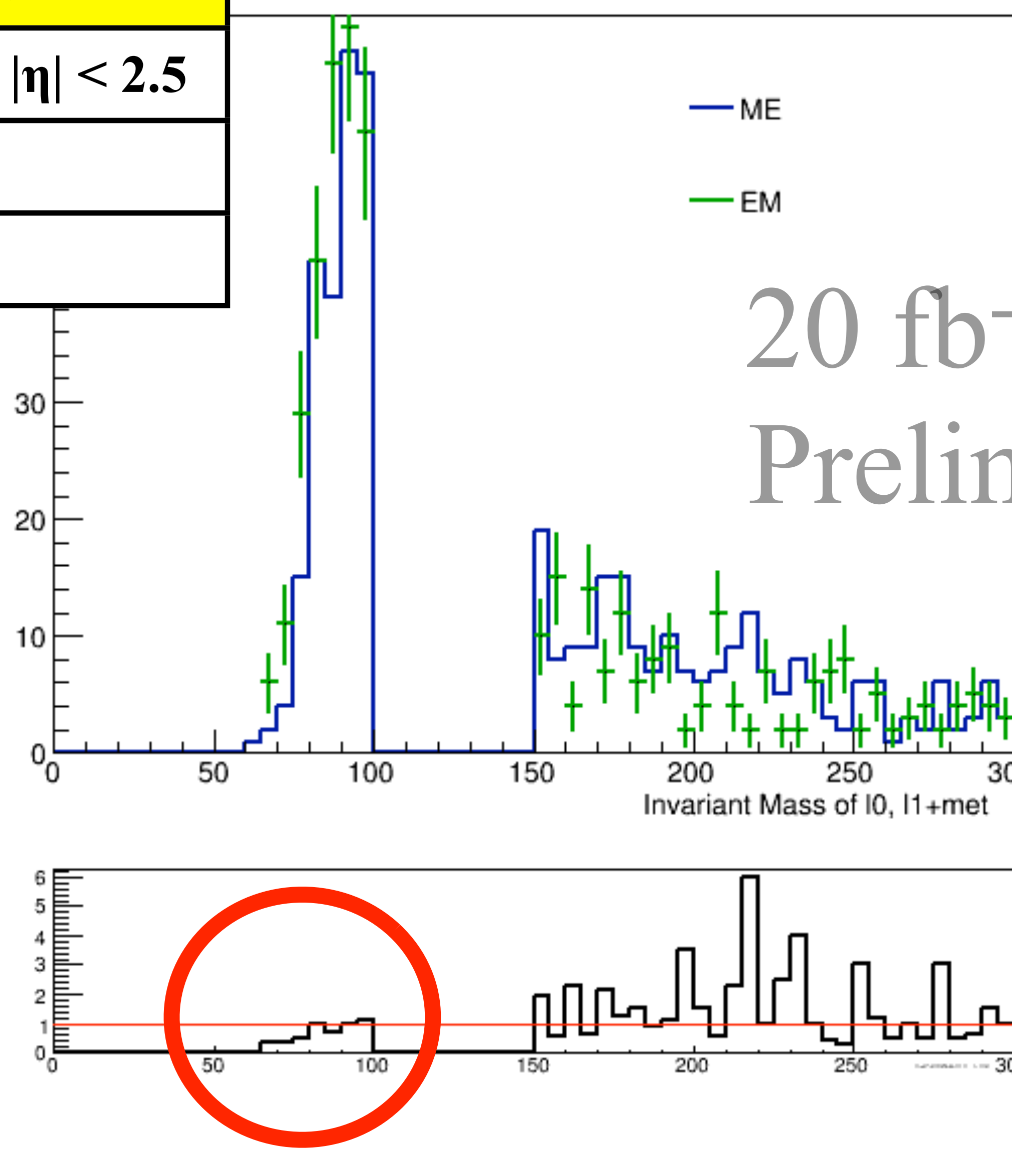
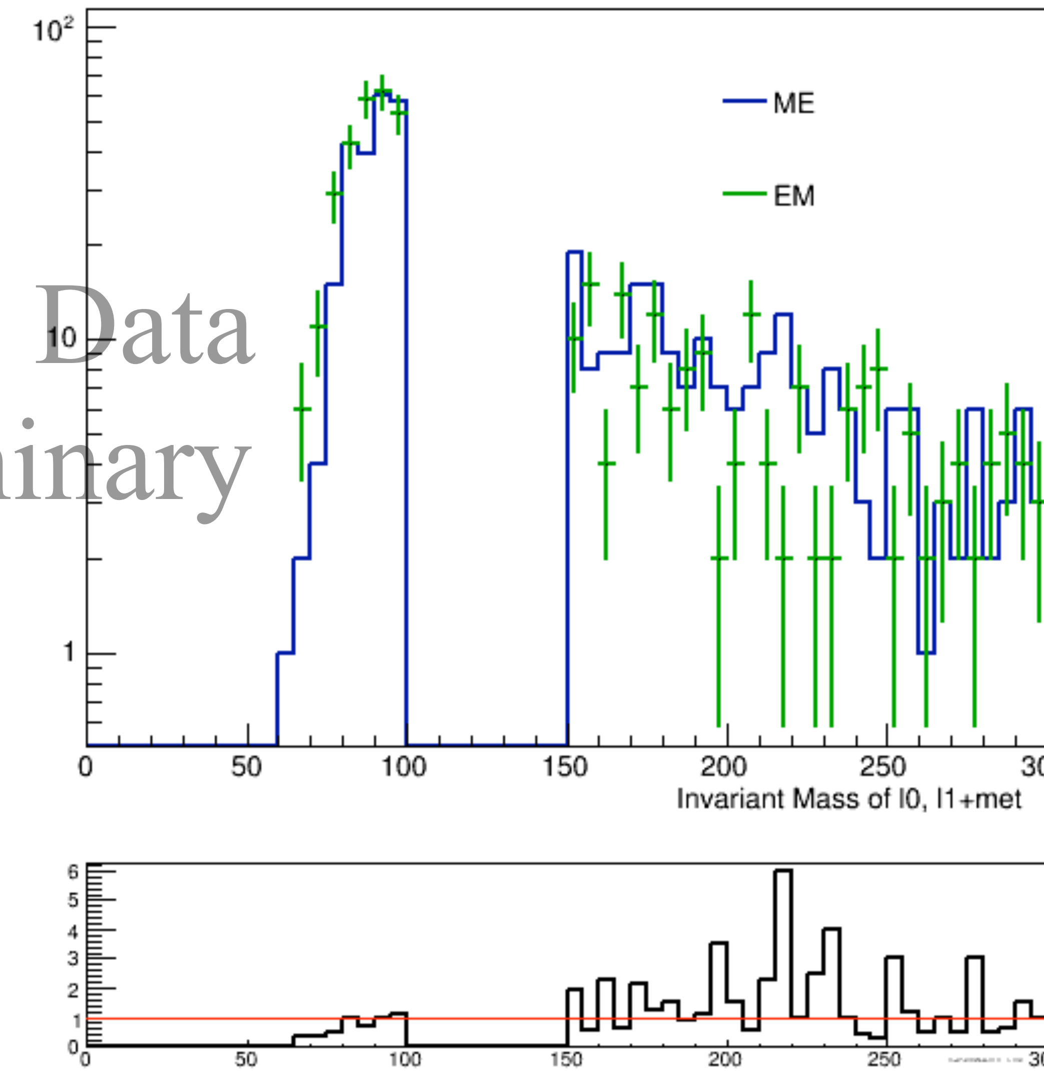
Testing the symmetry: asymmetric p_T cuts

Selection criteria (w/ pre-selection)
Exactly 1 e & 1 μ - opposite sign
l_0: $p_T > 40$ GeV & $\lvert\eta\rvert < 2.5$
l_1: $p_T > 20$ GeV & $\lvert\eta\rvert < 2.1$
Jet veto: $p_T > 30$ GeV & $\lvert\eta\rvert < 2.5$
$\Delta\varphi(e, \mu) > 2.5$
$\Delta\varphi(l', E_T^{miss}) < 0.5$

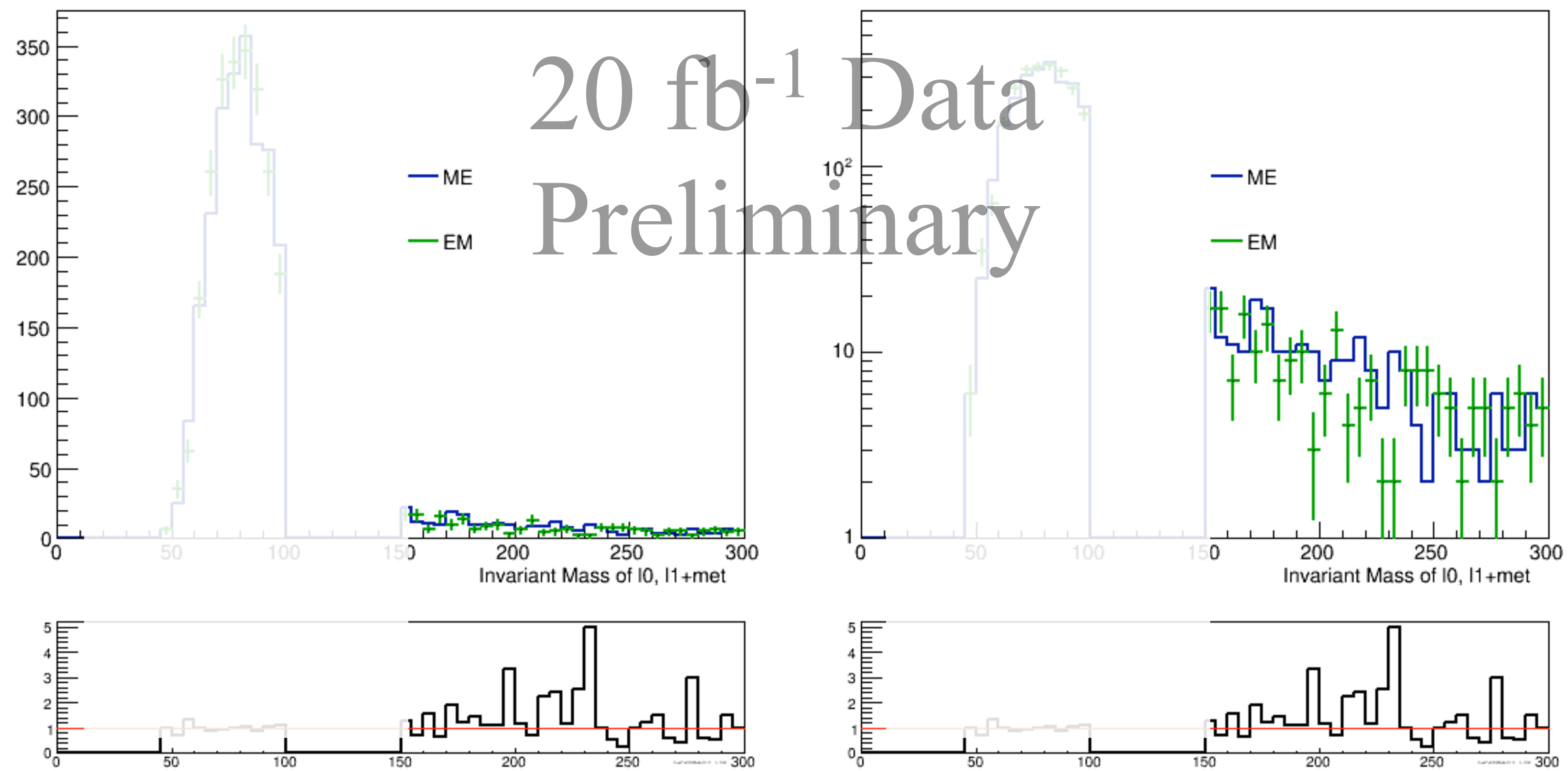




Sample I: μe
Sample I: eμ

Statistical treatment

Sample I: μe
Sample I: eμ



Can we say something about higher mass resonances?

How can we quantify the level of μe eμ symmetry?

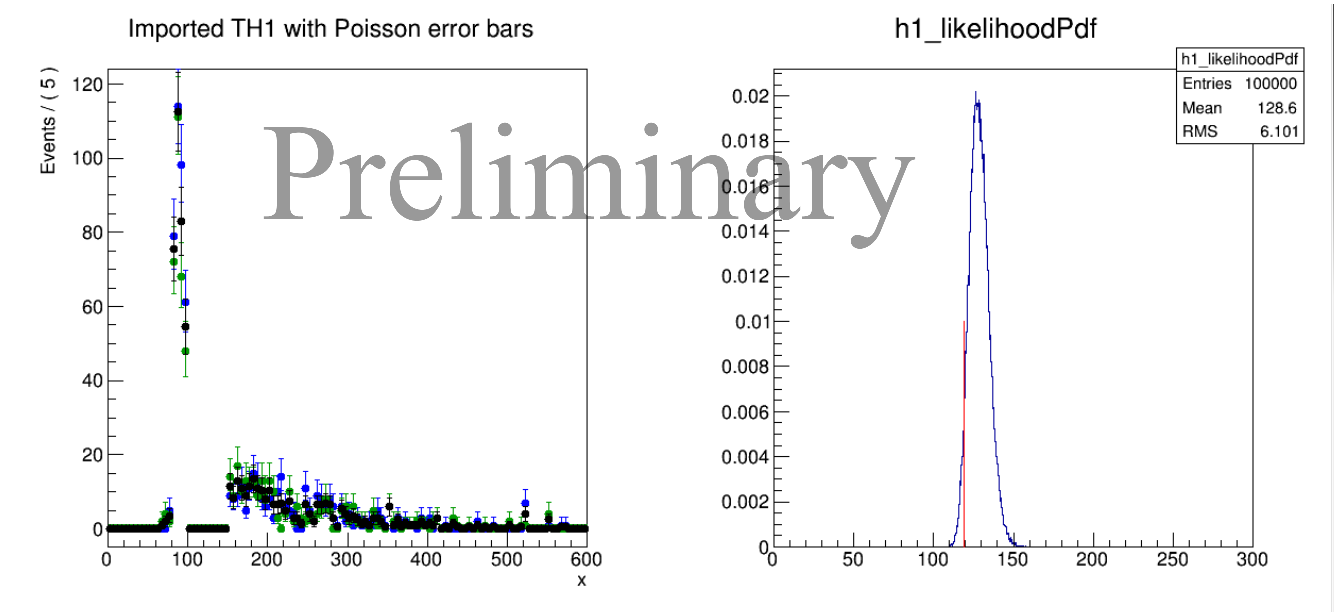
How can we quantify the level of μe eμ asymmetry if observed?

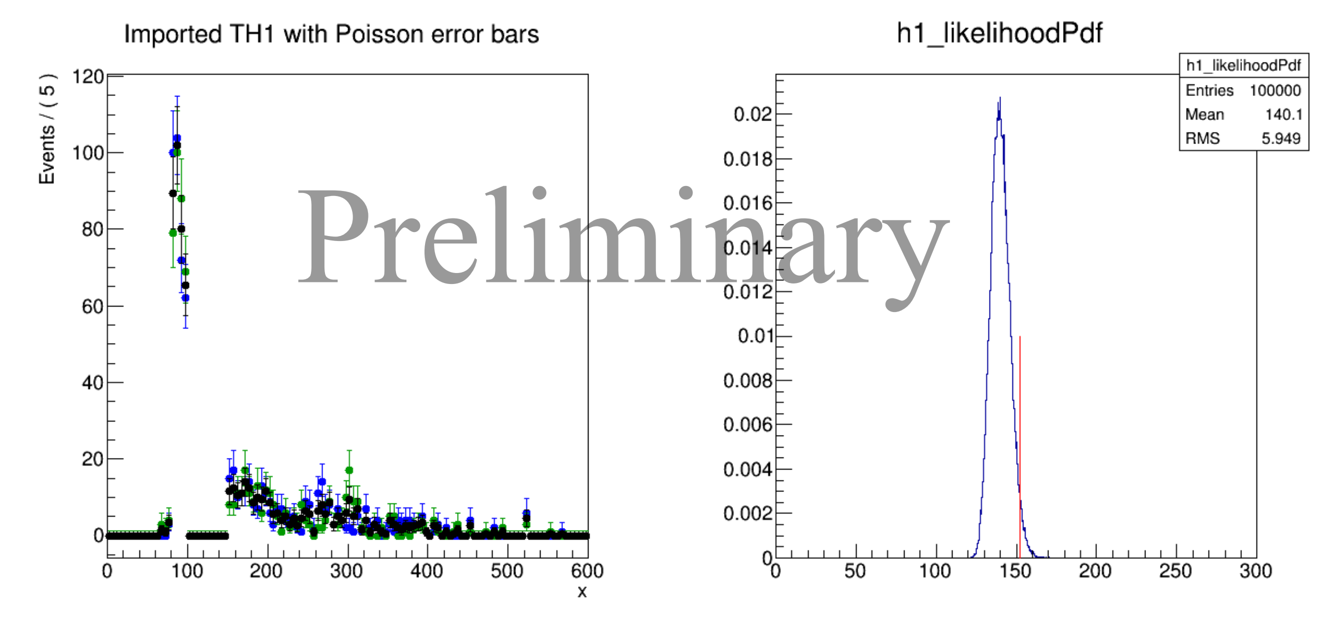
Statistical treatment

ATLAS has many existing tools but for now we are studying the problem using private (simple) code

Step 0:

- No systematic uncertainties
- Using likelihood as test statistics
- Take the mean of μe & eμ distributions as background pdf
  - p-value ~ 0.95
- Add 30 events around 300 GeV
  - p-value ~ 0.03 ⇒
    a hint for a mismatch
    not enough to reject the 0 hypothesis
  - This is only step 0





Step 1:

- No systematic uncertainties
- Using profile likelihood ratio as test statistics

Systematic uncertainties

Signal related: Standard recommendations

- Smearing
- Scale factors ...

➥ The tools are in place

Background related:

- Main source: low statistics
  - Will improve with more data
  - Can employ smoothing techniques
- Imperfect eμ μe symmetry

➥ Using the statistical tools presented in the previous slides

Systematic uncertainties

Addressing uncertainties in the assumption of eμ / μe symmetry

Compare the symmetry assumption to alternate assumptions

- Smearing
- Shifts

Use control regions to determine the best model

- Side bands
- Reverse selection criteria that do not affect the e/μ symmetry
  - jets
  - Δφ
- Same sign*

Incorporate into the statistical model

Sensitivity to other models

LFV Z decays are strongly constraint by LEP

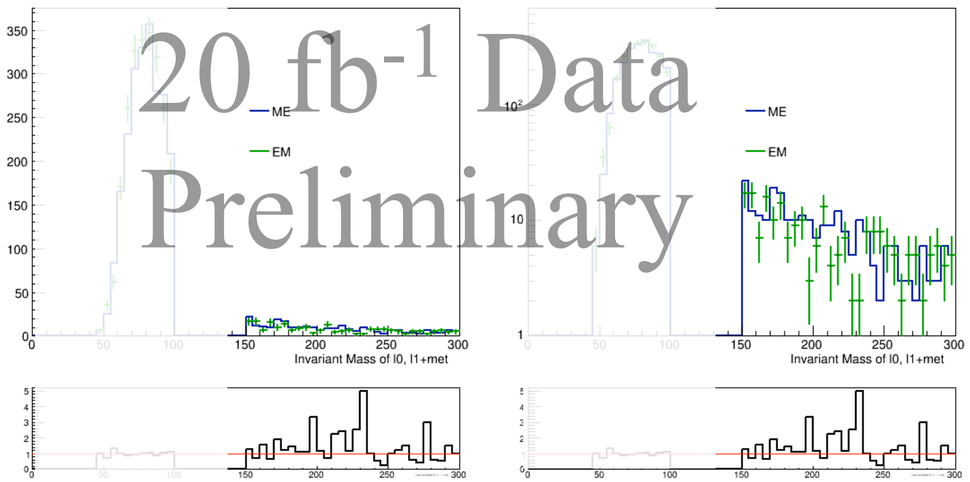
- $\Gamma(Z \to e\mu) : < 1.7 \times 10^{-6} \Rightarrow$
  $\lesssim$ 700 events in 20 fb^{-1} of data
- $\Gamma(Z \to \tau\mu) : < 9.8 \times 10^{-6} \Rightarrow \Gamma(Z \to \tau\mu \to e\mu 2\nu) : < 1.7 \times 10^{-6}$
  $\lesssim$ 1200 events in 20 fb^{-1} of data
- $\Gamma(Z \to \tau e) : < 1.2 \times 10^{-5} \Rightarrow \Gamma(Z \to \tau e \to e\mu 2\nu) : < 2.0 \times 10^{-6}$
  $\lesssim$ 1200 events in 20 fb^{-1} of data

➥ Can be seen on top of as high as 60K background events

➥ At 200 fb^{-1} can challenge LEP's bounds

Sensitivity to other models

LFV decays of non-SM particles



- Heavy Higgs, Z’
- Searches mostly focus on X→μe
  - experimentally easiest
  - Indirect weak bound also on X→μτ ⇒ weaker than the bound from a dedicated search ?
  - Low sensitivity to wide resonances

General searches

- Resonances in compound final states
- e/μ asymmetry (not necessarily a resonance) in compound final states
  - Using the statistical tools we are developing to test the symmetry assumption

Status

Cut flow optimization is on going

- Monte Carlo based

Statistical model is being built

- Will be used to determine symmetry uncertainties

Work in parallel on private Monte-Carlo production

- Emulate simple detector response
  - Using Yevgeny Kats's et. al "Pythia 8 + FastJet + private detector simulation"

http://arxiv.org/abs/arXiv:1106.0030
http://arxiv.org/abs/arXiv:1110.6444
http://arxiv.org/abs/arXiv:1209.0764
http://arxiv.org/abs/arXiv:1310.5758

& Plans

Find LFV higgs/Z/resonance decay

or improve existing bounds

Present in ATLAS WG

HSG? Exotics?

Establish the method before completing the search in ATLAS

Summary

The rate of higgs LFV decays to τμ & τe may be as high as 10%

- All the bounds are indirect
- These decays are not allowed by the SM
  ⇒ any observation would imply a discovery of new physics

We are searching for LFV in the charged sector

- The focus is on LFV higgs decays:
  $h\rightarrow\tau\mu$ & $h\rightarrow\tau e$ when the τ decays to leptons
- The search is sensitive to resonances at a wide mass range

Fully data driven background estimation method

- Probing differences between $\Gamma(X\rightarrow\tau e)$ and $\Gamma(X\rightarrow\tau\mu)$
- Promising preliminary results
- Main uncertainty due to the low statistics ⇒ improves with more data

Plenty of work ahead