The measurement of ttbar cross section with b-tagging at the ATLAS Experiment

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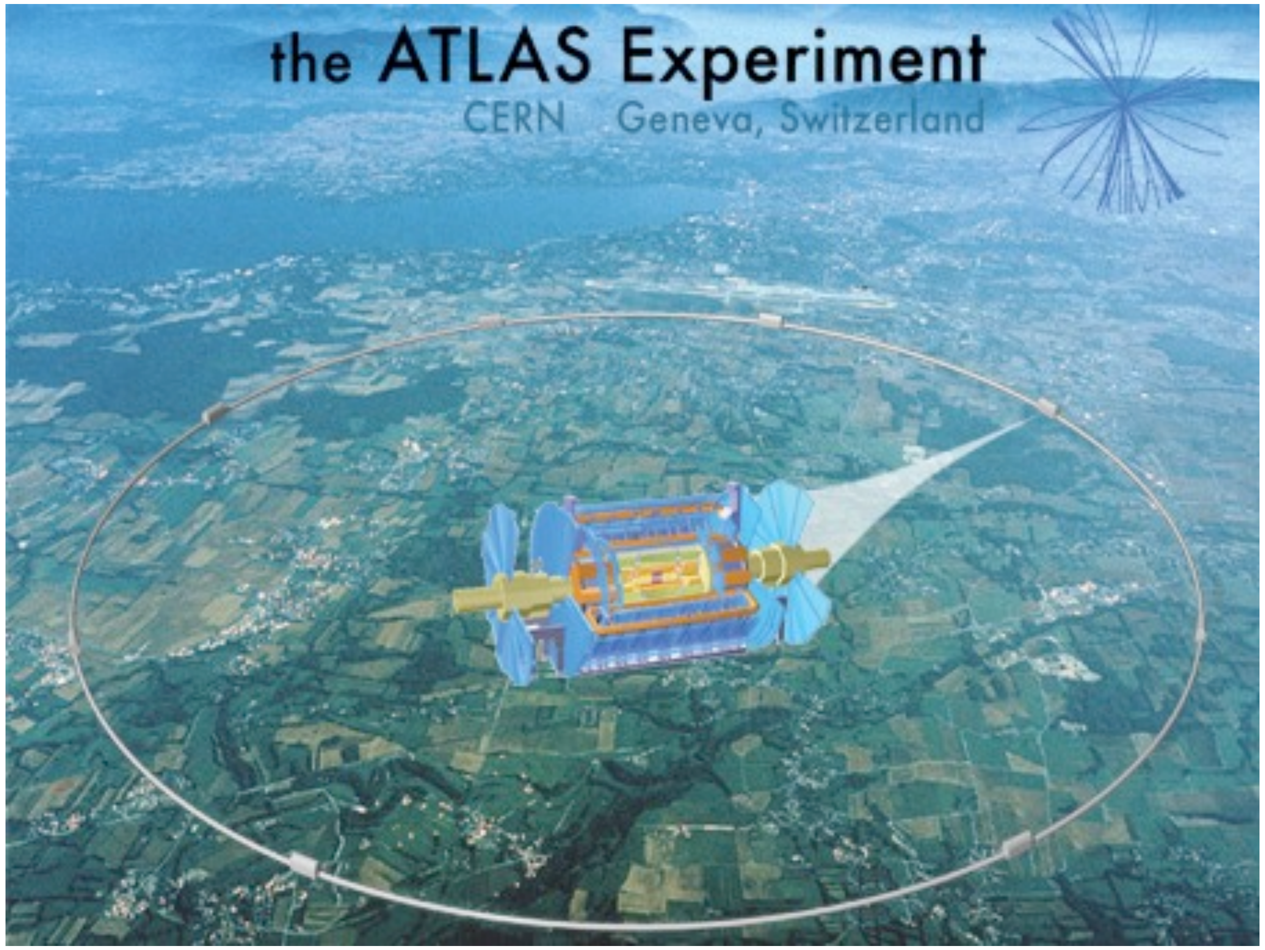
Introduction

- **Large Hadron Collider(LHC)**
  - The world's largest and most powerful collider.
  - Proton-Proton collisions.
  - running with $\sqrt{s}$ = 7TeV !!

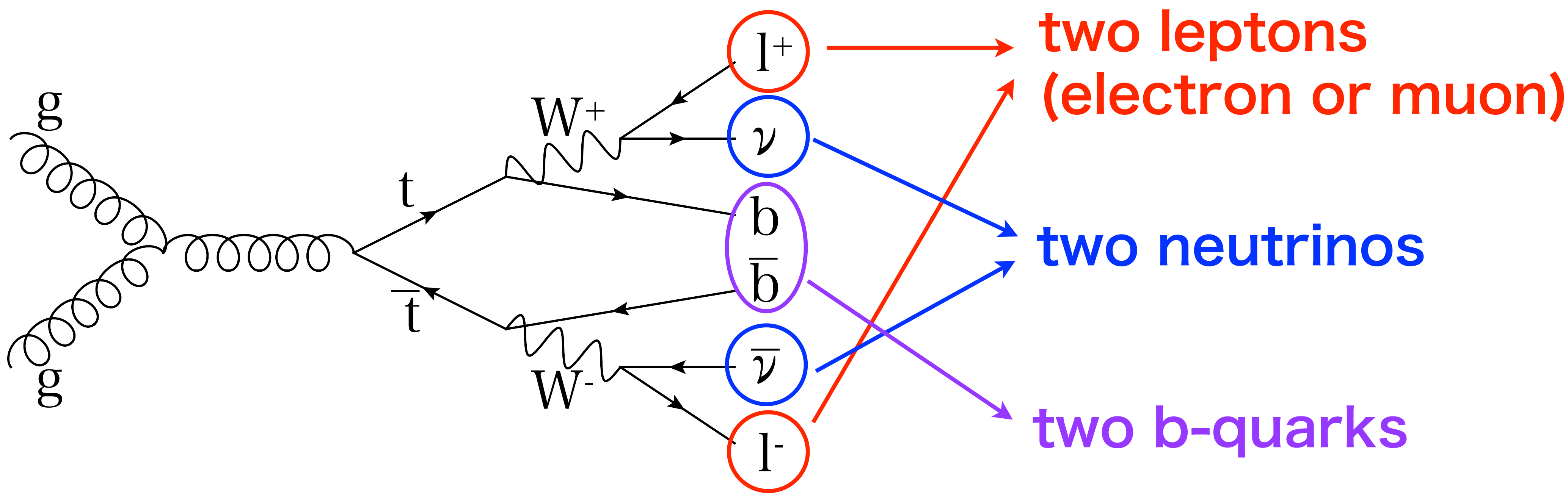


- **The ATLAS experiment**
  - General purpose detector.
    - ➡Higgs hunting.
    - ➡New physics search.
  - ~35pb^{-1} recorded in 2010.

Physics data taking for 2011 started!!

top quark cross-section measurement

- di-lepton final state of the top quark pair production



- Easy to distinguish from background !!

1) measure the cross section precisely

➡Validate QCD at higher energy

2) can be a good b-quark source

➡b-tagging plays important role to search for Higgs/SUSY

Cross-section extraction

- Cross-section will be extracted by this formula.

➡ $\sigma_{t\bar{t}} = \frac{N_{obs} - N_{BG}}{\mathcal{A} \times \mathcal{L}}$ ($\mathcal{A}$: acceptance, $\mathcal{L}$: Integrated Luminosity)

- N_{obs} : the number of remaining events after all selection
- $\mathcal{A}$: determined from ttbar MC sample(MC@NLO)
- $\mathcal{L}$: ATLAS recoded with Good Detector Condition(35.3pb^{-1})
- N_{BG} : Assumed background sources
  - ➡ Drell-Yann + jets
  - ➡ Fake leptons (mainly W+jets)

  → Estimated by Data-Driven method

  - ➡ Z($\rightarrow \tau\ \tau$) + jets
  - ➡ di-boson
  - ➡ single top

  → Estimated by Monte-Carlo

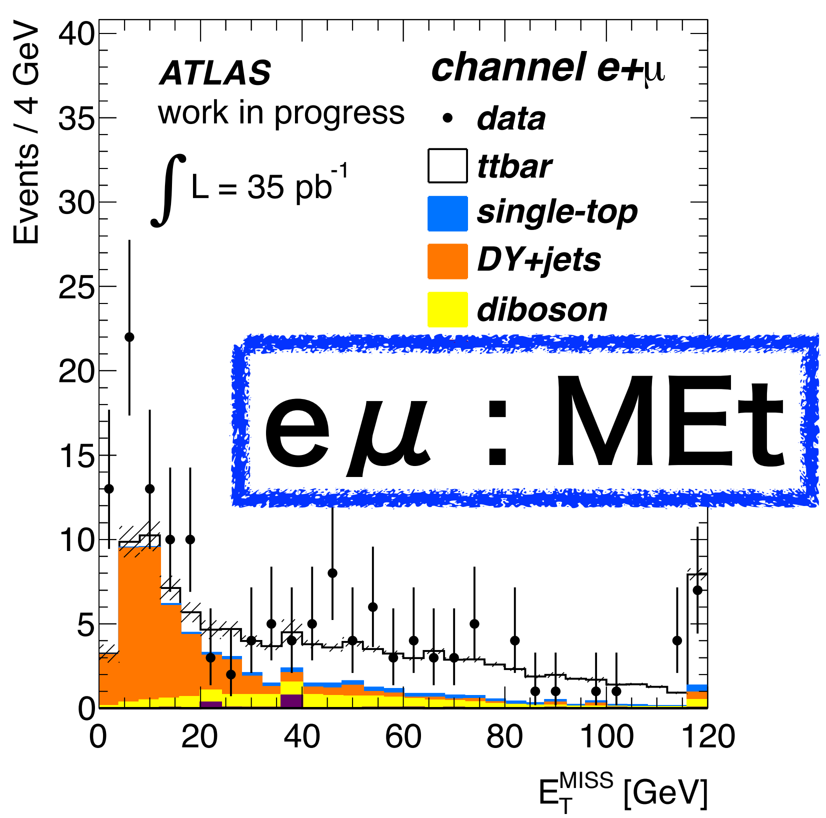
Event selection

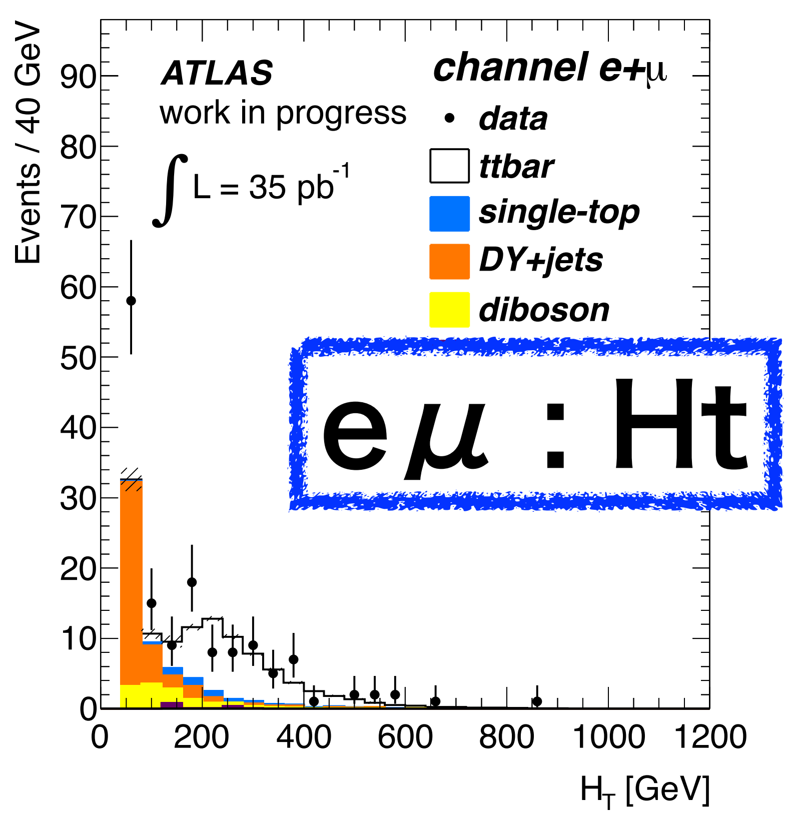
- **Common selection for all(ee, $\mu\mu$, eμ) channels**
  - #leptons == 2 && leptons are oppositely charged.
  - At least two jets
- **Channel dependent selection**
  - Missing Transverse Energy(MEt) > 30GeV
  - |Mll(dilepton mass)- Mz| > 5GeV (referred as Z-window cut)

  → ee, $\mu\mu$ channel

  - large Σ|Et|(so called Ht)>110GeV

  → eμ channel





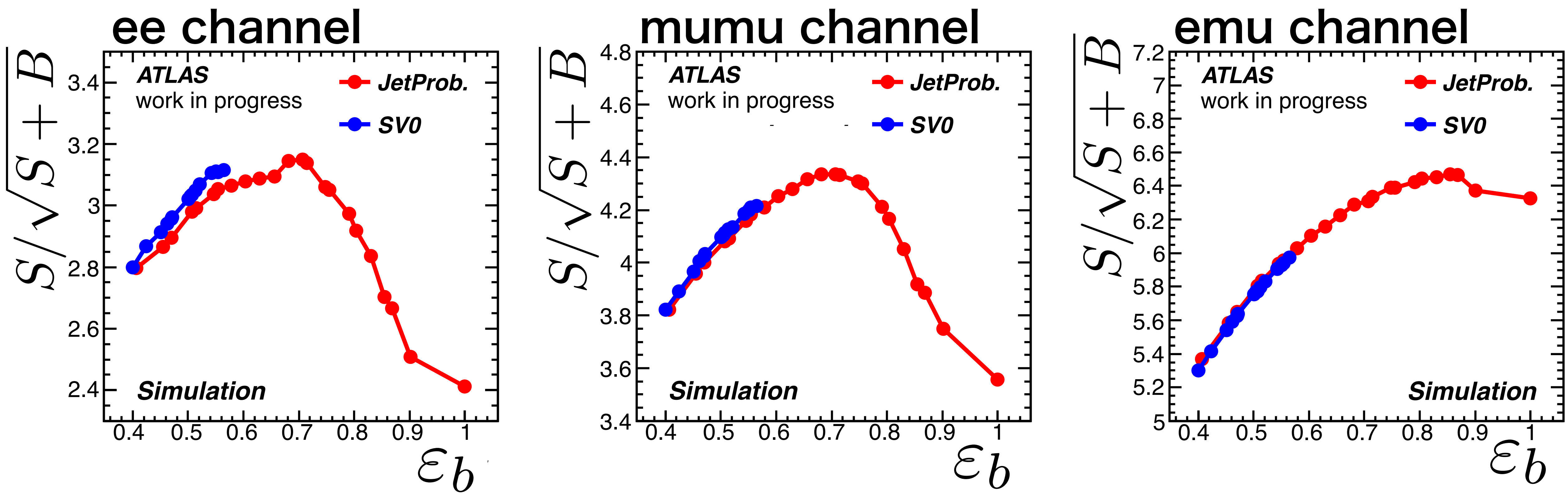
b-tagging requirement

- two b-quarks in final state
  - Requiring at least one b-tagged jet
    - ➡not to lose so many signals
    - ➡reduce systematic uncertainty from b-tagging efficiency
      - $\delta_{\sigma_{t\bar{t}}} \propto 2(1-\varepsilon_b)\delta_{\varepsilon_b}$ (Typical δ_{ε_b} ~ 14%)
      - Larger Efficiency $\rightarrow$ Smaller Uncertainty for $\sigma_{t\bar{t}}$

- Optimization
  - Which b-tagging algorithm is the best?
  - Which operation point is the best?
  - Next page...

b-tagging optimization for di-lepton analysis

- Available b-tagging algorithm in the early experiment
  - SV0 (secondary vertex base)
  - JetProb. (charged-track base)
- Calculate statistical significance($S/\sqrt{S+B}$) assuming $35pb^{-1}$

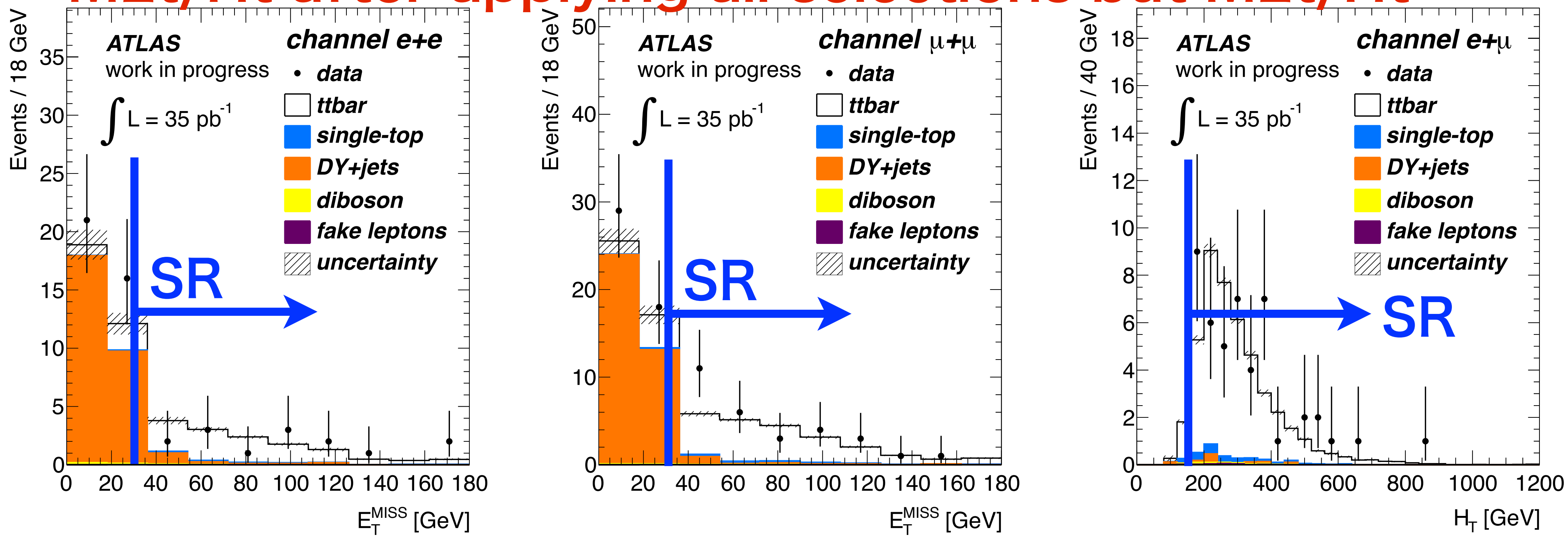


JetProb. is a preferred b-tagging algorithm!

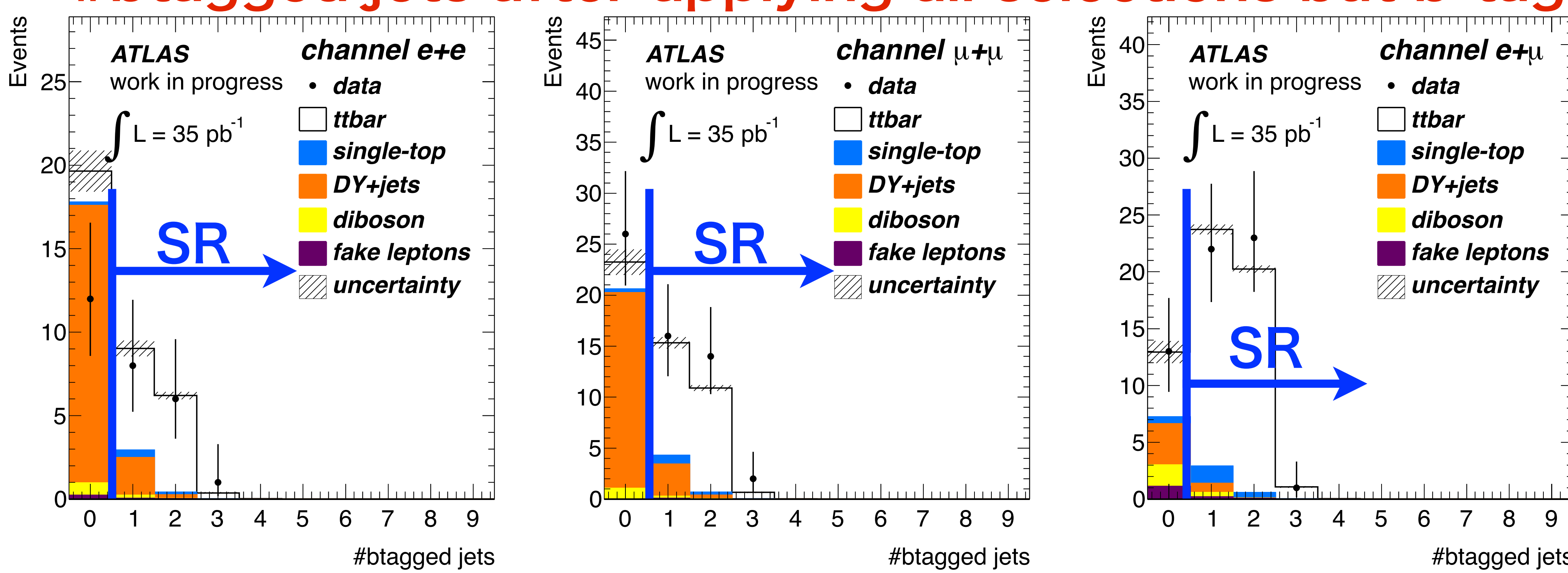
70% efficiency point works well!

Distributions in the Signal Region(SR)

MEt/Ht after applying all selections but MEt/Ht

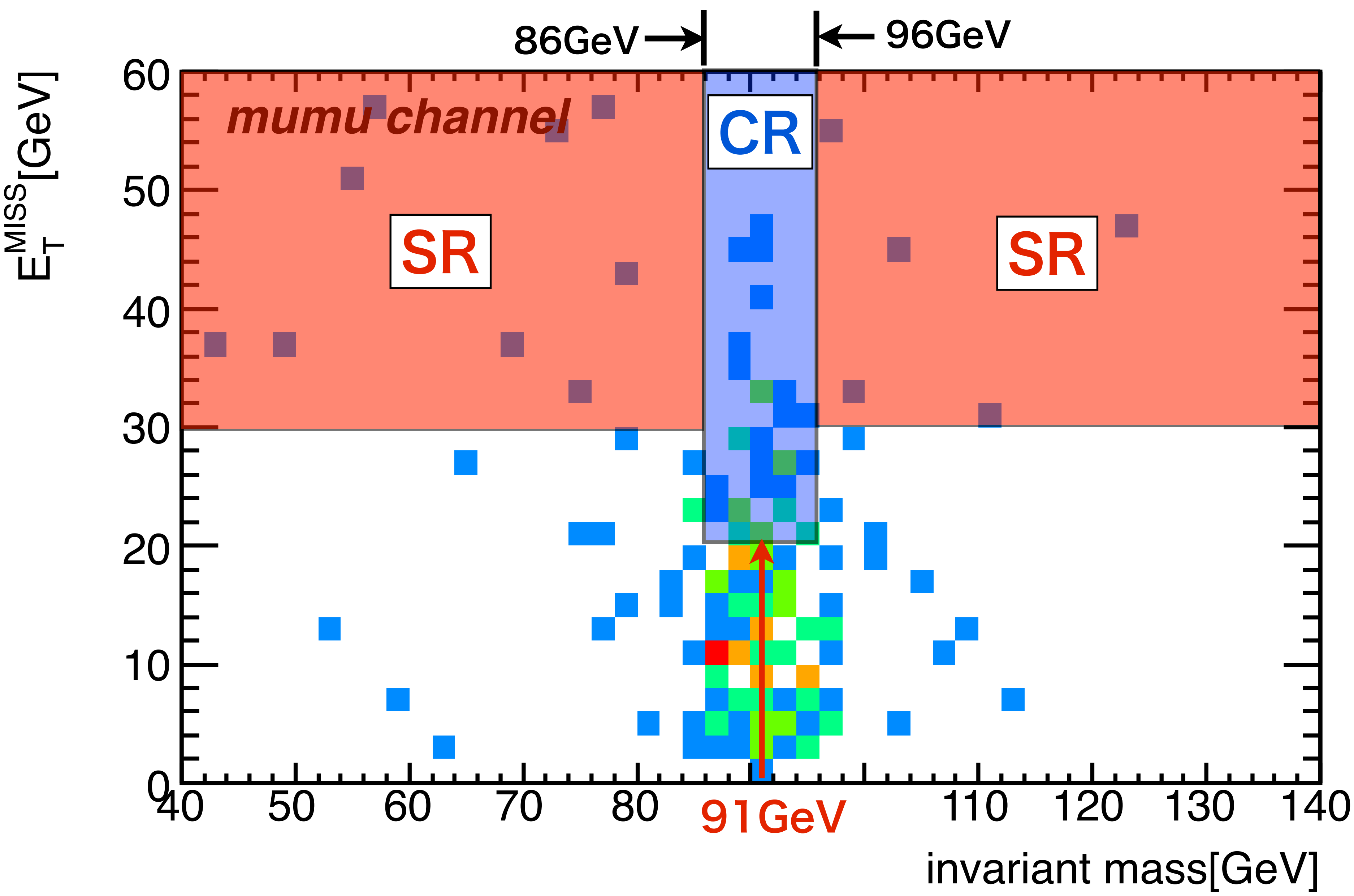


#btagged jets after applying all selections but b-tagging



BG estimation for Drell-Yann + jets

- Define Control Region(CR) and Signal Region(SR)
  - $N_{\mathrm{DY}}^{\mathrm{background}} = (Data(\mathrm{CR}) - MC_{nonDY}(\mathrm{CR})) \times \frac{MC_{\mathrm{DY}}(SR)}{MC_{\mathrm{DY}}(CR)}$



BG estimation for Drell-Yann + jets

channel	ee		$\mu\mu$	
	MC	Data Driven	MC	Data Driven
Expected Yields	2.24	1.50	3.35	5.21
Uncertainty Source	$\delta N_{DY}/N_{DY}[\%]$	$\delta N_{DY}/N_{DY}[\%]$	$\delta N_{DY}/N_{DY}[\%]$	$\delta N_{DY}/N_{DY}[\%]$
Data statistics	-	$\pm$ 34.2	-	$\pm$ 16.8
MC statistics	$\pm$ 19.2	$\pm$ 47.7	$\pm$ 15.5	$\pm$ 41.4
Method	-	$\pm$ 17.7	-	$\pm$ 9.3
Jet Energy Scale	+120.6/-34.0	+63.3/- 2.3	+35.0/-18.6	+ 0.0/-13.5
Jet Energy Resolution	$\pm$ 20.3	$\pm$ 25.2	$\pm$ 11.2	$\pm$ 8.0
Jet ID efficiency	$\pm$ 8.9	$\pm$ 4.8	$\pm$ 5.8	$\pm$ 4.1
Lepton Energy Scale	+ 4.4/- 2.1	+16.9/- 0.0	+ 0.0/- 3.7	+ 0.0/- 5.0
Lepton Energy Resolution	+ 7.7/-11.8	+12.6/-15.4	+ 5.2/- 3.3	+ 8.9/- 6.9
Lepton ID Efficiency	$\pm$ 9.4	+ 1.4/- 1.2	$\pm$ 0.7	$\pm$ 0.0
Lepton Trigger Efficiency	$\pm$ 1.0	$\pm$ 0.0	$\pm$ 0.2	$\pm$ 0.1
MC Theory cross-section	$\pm$ 37.5	-	$\pm$ 35.0	-
b-tag efficiency	$\pm$ 4.3	$\pm$ 2.2	$\pm$ 4.8	+ 1.7/- 1.5
l-tag efficiency	+ 8.4/- 9.5	+ 0.0/- 0.4	$\pm$ 10.0	+ 0.9/- 1.3
Luminosity	$\pm$ 3.4	-	$\pm$ 3.4	-
Total Uncertainty	+130.6/-61.5	+94.2/-68.3	+54.8/-46.2	+47.4/-49.2

Data Driven method has an advantage in terms of systematic uncertainty.

Predicted/Observed Event Yields

Process	Event Yields		
	ee	$\mu\mu$	$e\mu$
Drell-Yann + jets	$1.5^{+1.4}_{-1.0}$	5.2 ± 2.5	N/A
$Z(\rightarrow \tau\tau)$ + jets	0.2 ± 0.2	0.3 ± 0.2	0.7 ± 0.5
Fake leptons	0.5 ± 0.5	0.5 ± 0.5	1.9 ± 1.1
Single top	0.6 ± 0.1	1.2 ± 0.2	1.9 ± 0.4
Dibosons	0.2 ± 0.1	0.2 ± 0.1	0.4 ± 0.1
Total Predicted Backgrounds	$2.9^{+1.5}_{-1.1}$	7.4 ± 2.6	5.0 ± 1.3
Predicted $t\bar{t}$ Signal	12.1 ± 1.4	$21.9^{+1.9}_{-2.2}$	$41.4^{+3.5}_{-3.9}$
Total Predicted	15.0 ± 1.9	29.3 ± 3.3	$46.4\ ^{+3.7}_{-4.1}$
Data	15	32	46

Estimated BGs

Observed and Predicted Yields are consistent !!

cross-section extraction

- ee : $\sigma_{t\bar{t}} = 163^{+57}_{-48}(\mathrm{Stat.})^{+31}_{-27}(\mathrm{Syst.})^{+8}_{-5}(\mathrm{Lumi.})[\mathrm{pb}]$
- $\mu\mu$: $\sigma_{t\bar{t}} = 185^{+51}_{-45}(\mathrm{Stat.})^{+34}_{-21}(\mathrm{Syst.})^{+8}_{-7}(\mathrm{Lumi.})[\mathrm{pb}]$
- eμ : $\sigma_{t\bar{t}} = 162^{+28}_{-25}(\mathrm{Stat.})^{+19}_{-14}(\mathrm{Syst.})^{+7}_{-5}(\mathrm{Lumi.})[\mathrm{pb}]$
- **combined** : $\sigma_{t\bar{t}} = 171 \pm 22(\mathrm{Stat.})^{+21}_{-16}(\mathrm{Syst.})^{+7}_{-6}(\mathrm{Lumi.})[\mathrm{pb}]$
- **NLO Prediction** : $164.57^{+8.34}_{-11.33}[\mathrm{pb}]$ @ $\mathrm{M_t} = 172.5\mathrm{GeV}$

Consistent with theoretical prediction

Systematic Uncertainties

	ee	$\mu\mu$	$e\mu$	combined
Uncertainty Source	$\Delta\sigma/\sigma[\%]$	$\Delta\sigma/\sigma[\%]$	$\Delta\sigma/\sigma[\%]$	$\Delta\sigma/\sigma[\%]$
Data Statistics	+34.8/-29.3	+27.5/-24.2	+17.2/-15.6	+13.2/-12.3
Luminosity	+ 4.7/- 2.9	+ 4.4/- 3.9	+ 4.1/- 3.2	+ 4.2/- 3.4
MC Statistics	+ 2.5/- 2.9	+ 3.2/- 5.3	+ 0.8/- 1.0	+ 2.2/- 0.5
Lepton energy scale	+ 1.4/- 3.1	+ 1.5/ 0.0	+ 0.0/- 0.6	+ 0.0/- 0.5
Lepton energy resolution	+ 2.0/- 1.9	+ 0.0/- 3.5	+ 0.0/- 0.6	+ 0.7/- 0.9
Lepton ID/Trigger Efficiency	+ 8.3/- 5.2	+ 0.0/- 2.7	+ 4.5/- 3.5	+ 3.9/- 3.2
Jet energy scale	+ 8.1/-12.4	+10.7/- 4.5	+ 4.1/- 3.4	+ 5.1/- 4.8
Jet energy resolution	+ 4.2/- 4.0	+ 0.0/- 3.6	+ 0.0/- 0.6	+ 1.5/- 1.5
Drell-Yann estimation	+ 2.0/- 2.4	+ 0.0/- 3.4	+ 0.0/ 0.0	+ 1.8/ 0.0
fake lepton estimation	+ 3.8/- 4.2	+ 0.0/- 3.6	+ 2.6/- 2.8	+ 2.4/- 1.0
b-tag efficiency	+ 9.3/- 4.9	+10.1/- 5.8	+ 8.2/- 5.1	+ 8.3/- 5.6
l-tag efficiency	+ 0.8/- 0.8	+ 0.0/- 3.0	+ 0.6/- 0.6	+ 0.5/- 0.5
Generator	+ 1.4/- 0.8	+ 0.0/- 2.9	+ 1.0/- 1.0	+ 1.3/- 1.1
Parton shower modeling	+ 3.1/- 1.9	+ 0.0/ 0.0	+ 3.6/- 2.7	+ 2.6/- 2.1
Initial state radiation	+ 1.7/- 1.1	+ 0.0/- 2.9	+ 0.6/- 0.6	+ 0.9/- 0.9
Final state radiation	+ 4.8/- 2.8	+ 3.9/- 3.8	+ 1.2/- 1.0	+ 2.2/- 1.7
Parton Distribution Function	+ 3.5/- 2.0	+ 2.8/- 3.4	+ 2.5/- 1.9	+ 2.8/- 2.1
Under lying event modeling	+ 3.3/- 3.1	+ 2.0/- 4.7	+ 1.2/- 0.8	+ 2.1/- 1.7
Theorical X-sec	+ 0.8/- 1.3	+ 0.0/- 2.8	+ 0.8/- 1.0	+ 0.7/- 0.9
All systematics	+19.3/-16.9	+19.2/-11.7	+12.6/- 9.0	+13.0/-10.0
Stat. + Syst.	+39.8/-33.8	+33.5/-26.9	+21.3/-18.0	+18.6/-15.9

- **measurement with 18% precision is achieved!!**

Systematic Uncertainties

$$\delta_{\sigma_{t\bar{t}}} \propto 2(1-\varepsilon_b)\delta_{\varepsilon_b}$$ (δ_{ε_b}~ 14%)

$$\text{when } \varepsilon_b = 50\% \rightarrow \delta_{\sigma_{t\bar{t}}} \propto 1.0 \times \delta_{\varepsilon_b}$$

$$\text{when } \varepsilon_b = 70\% \rightarrow \delta_{\sigma_{t\bar{t}}} \propto 0.6 \times \delta_{\varepsilon_b}$$ (this analysis)

Drell-Yann estimation	+ 2.0/- 2.4	+ 0.0/- 3.4	+ 0.0/ 0.0	+ 1.8/ 0.0
fake lepton estimation	+ 3.8/- 4.2	+ 0.0/- 3.6	+ 2.6/- 2.8	+ 2.4/- 1.0
b-tag efficiency	+ 9.3/- 4.9	+10.1/- 5.8	+ 8.2/- 5.1	+ 8.3/- 5.6
l-tag efficiency	+ 0.8/- 0.8	+ 0.0/- 3.0	+ 0.6/- 0.6	+ 0.5/- 0.5
Generator	+ 1.4/- 0.8	+ 0.0/- 2.9	+ 1.0/- 1.0	+ 1.3/- 1.1
Parton shower modeling	+ 3.1/- 1.9	+ 0.0/ 0.0	+ 3.6/- 2.7	+ 2.6/- 2.1
Initial state radiation	+ 1.7/- 1.1	+ 0.0/- 2.9	+ 0.6/- 0.6	+ 0.9/- 0.9
Final state radiation	+ 4.8/- 2.8	+ 3.9/- 3.8	+ 1.2/- 1.0	+ 2.2/- 1.7
Parton Distribution Function	+ 3.5/- 2.0	+ 2.8/- 3.4	+ 2.5/- 1.9	+ 2.8/- 2.1
Under lying event modeling	+ 3.3/- 3.1	+ 2.0/- 4.7	+ 1.2/- 0.8	+ 2.1/- 1.7
Theorical X-sec	+ 0.8/- 1.3	+ 0.0/- 2.8	+ 0.8/- 1.0	+ 0.7/- 0.9
All systematics	+19.3/-16.9	+19.2/-11.7	+12.6/- 9.0	+13.0/-10.0
Stat. + Syst.	+39.8/-33.8	+33.5/-26.9	+21.3/-18.0	+18.6/-15.9

- **measurement with 18% precision is achieved!!**

→ Thanks to small uncertainty from b-tag efficiency

Conclusions

- **measurement of ttbar cross-section with b-tagging@35pb^{-1}**
  - b-tagging : 70% efficiency point

- **measured Cross-Section is consistent with NLO prediction**
  - combined result : $\sigma_{t\bar{t}} = 171 \pm 22(\mathrm{Stat.})^{+21}_{-16}(\mathrm{Syst.})^{+7}_{-6}(\mathrm{Lumi.})[\mathrm{pb}]$
    (ATLAS Preliminary)
  - NLO predicted : $\sigma_{t\bar{t}} = 164.57^{+8.34}_{-11.33}[\mathrm{pb}]$ @ $\mathrm{M_t} = 172.5\mathrm{GeV}$

measurement with 18% precision is achieved !!

backup

Object Definition(detail)

- Electrons
  - “Tight” electron with track matching
  - Pt > 20GeV, 0<|eta|<1.37 or 1.52<|eta|<2.47
- Muons
  - Reconstructed with MuID algorithm, pass “Tight” requirement
  - Requirement on number of hits in ID, cosmic rejection
  - Pt>20GeV, |eta| < 2.5
  - Remove muons overlapping with selected jet(Pt>20GeV) within dR<0.4
- Jets
  - AntiKt 0.4 TopoCluster jets with EM+JES calibration
  - Pt>20GeV, |eta| < 2.5
  - Remove a jet overlapping with selected electron within dR<0.2

b-tagging algorithm

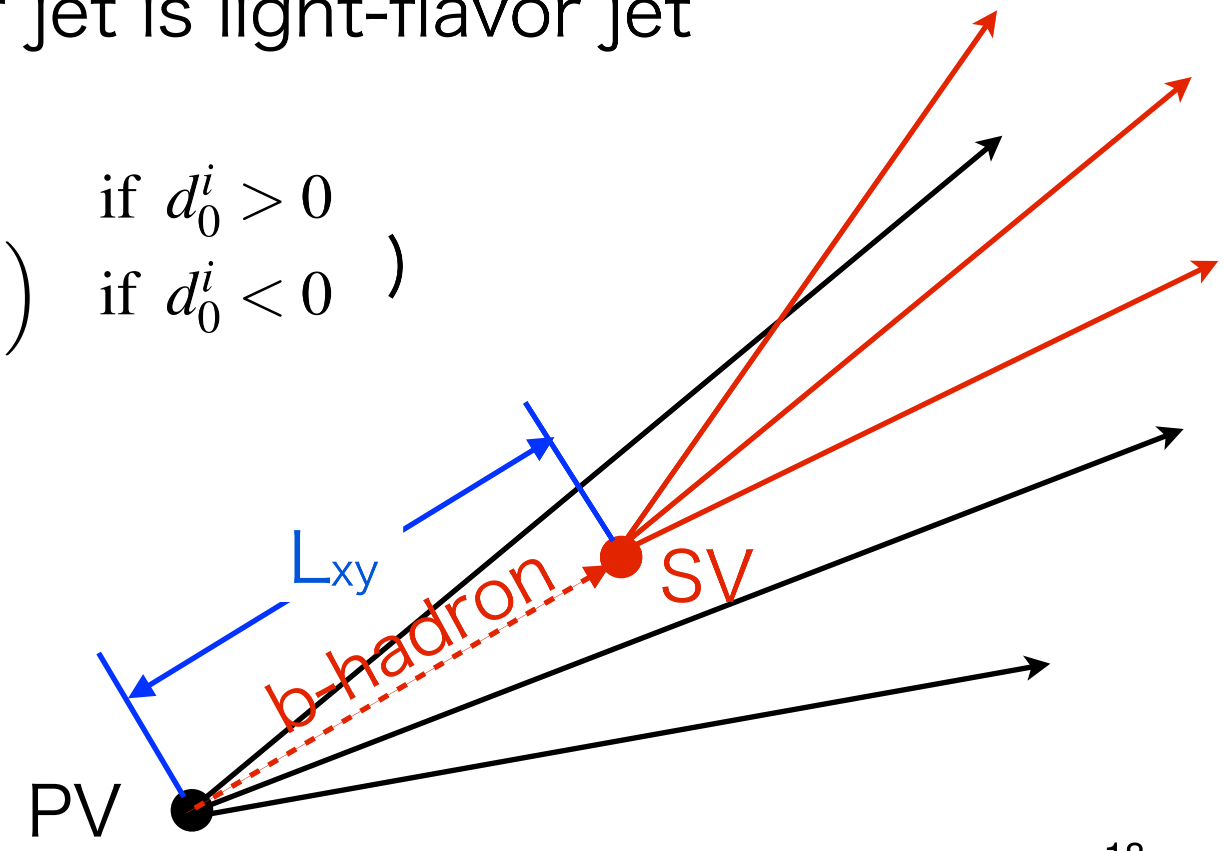
- **SV0** : Secondary Vertex(SV) base
  - Distance between Primary Vertex and Secondary Vertex ~ L_{xy}
  - discriminant : $L_{xy}/\sigma_{L_{xy}}$

- **JetProb** : charged track base

$$\mathscr{P}_i = \int_{-\infty}^{-|d_0^i/\sigma_{d_0}^i|} \mathscr{R}(x)dx$$: Likelihood of tracks comes from PV

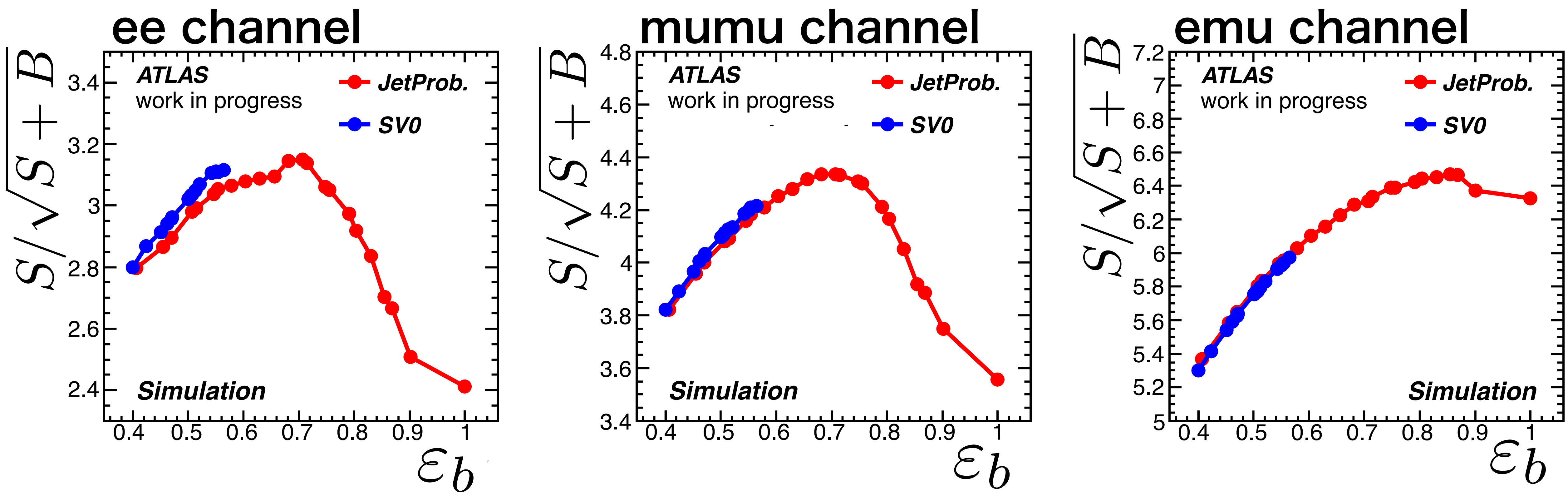
$$\mathscr{P}_{jet} = \mathscr{P}_0 \sum_{j=0}^{N-1} \frac{(-ln\mathscr{P}_0)^j}{j!}$$: Likelihood of jet is light-flavor jet

(where $\mathscr{P}_0 = \prod_{i=1}^{N} \mathscr{P}_i'$ and $\begin{cases} \mathscr{P}_i' = \frac{\mathscr{P}_i}{2} & \text{if } d_0^i > 0 \\ \mathscr{P}_i' = \left(1 - \frac{\mathscr{P}_i}{2}\right) & \text{if } d_0^i < 0 \end{cases}$)



b-tagging optimization(detail)

- Calculate statistical significance(S/√S+B) assuming 35pb^{-1}



analysis with SV0 shows higher significance

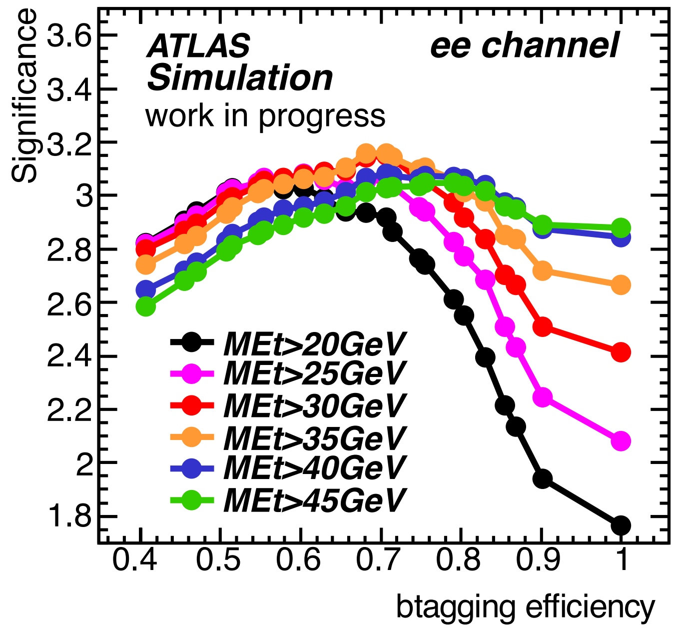
→ SV0 has good performance in terms of a light-flavor jet rejection

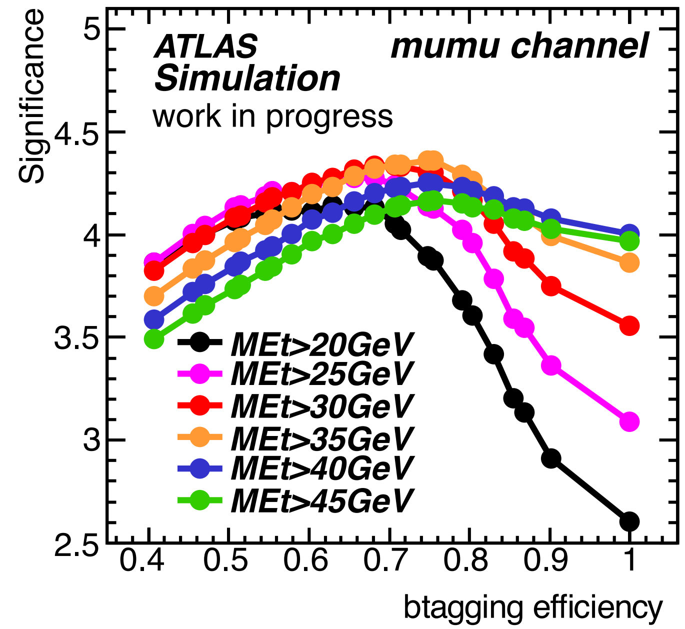
(JetProb@50% efficiency : Light jet rejection factor(1/Eff.) ~ 130

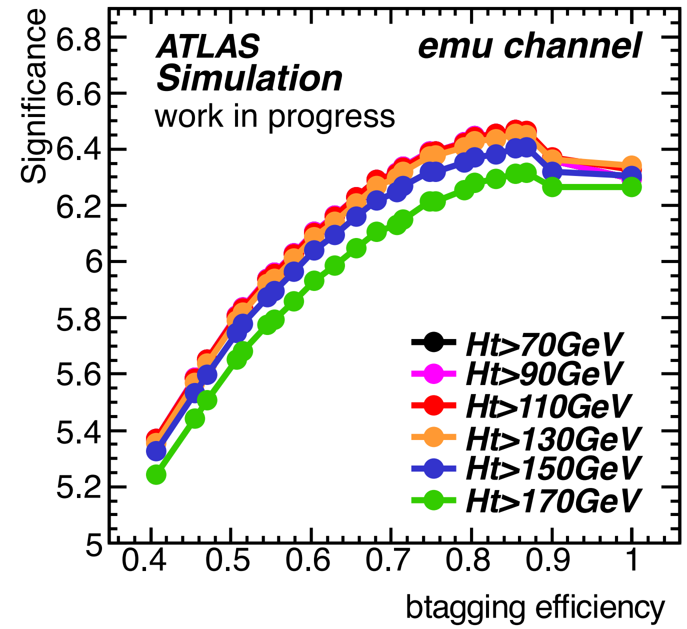
SV0@50% efficiency : Light jet rejection factor(1/Eff.) ~ 270)

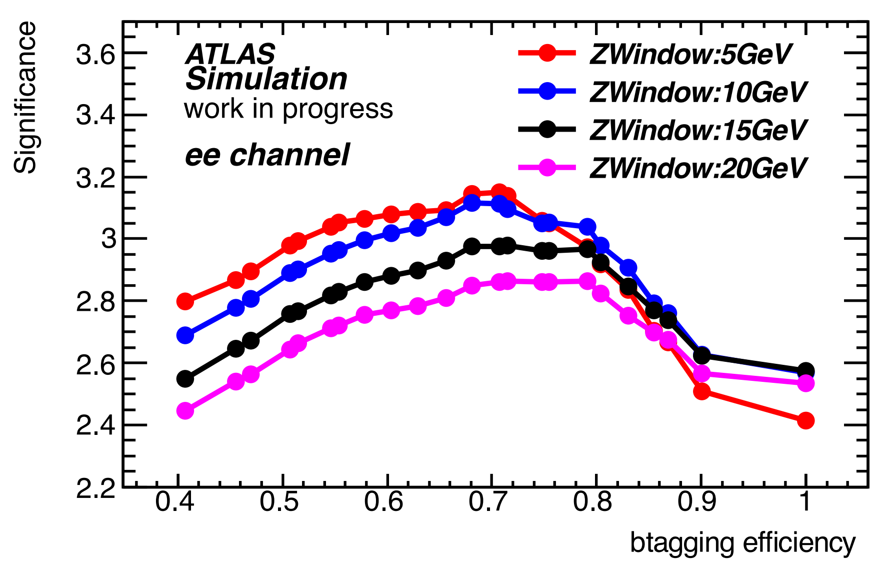
MEt/Ht/Z-window optimization

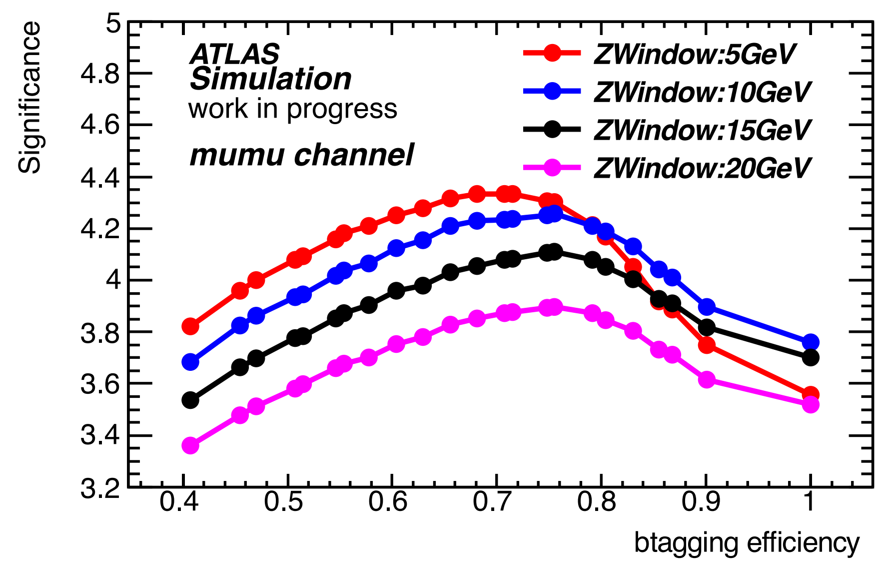
- To maximize statistical significance with JetProb. 70% Efficiency point.











Preferred Cut Values

- MEt>30GeV(ee, $\mu\mu$), Ht>110GeV(eμ)
- Z-window = 5GeV(ee, $\mu\mu$)

BG Estimation for Fake Leptons

- **Matrix Method**
  - Define "Tight/Loose" lepton
    ➡count the remaining #events(N_{TT}, N_{LL} etc.)
  - Measure a probability "r" and "f"
    ➡"r(f)" : the probability of a real(fake) lepton which pass the "loose" criteria will pass the "tight" criteria.
    - "r" : measured in Z→ll process
    - "f" : measured in QCD process
  - Solve this matrix...

contribution from fake leptons

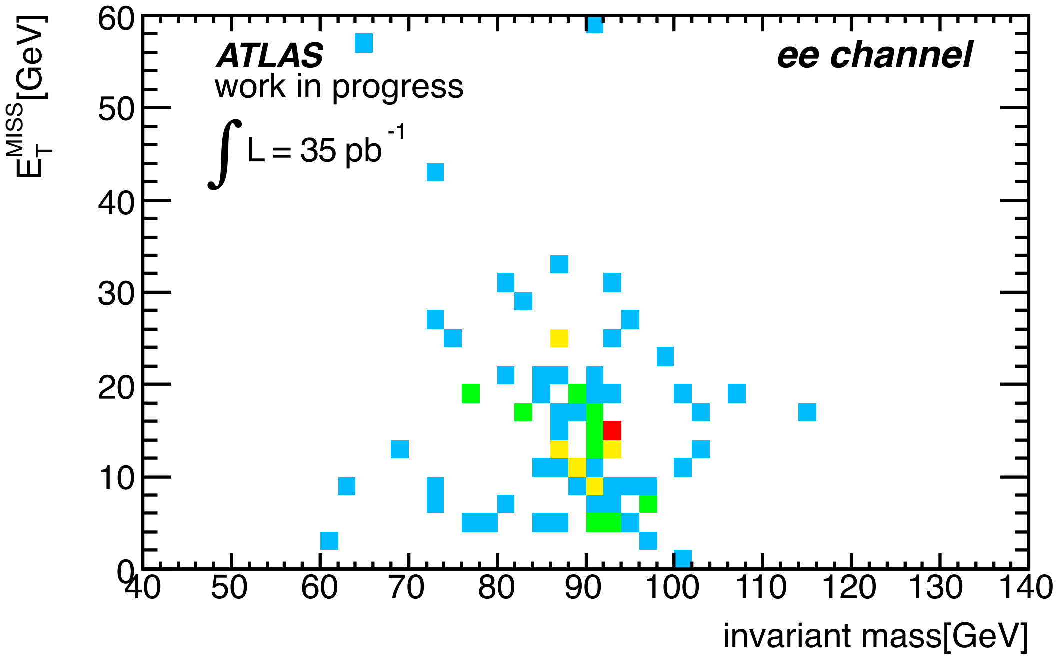
$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

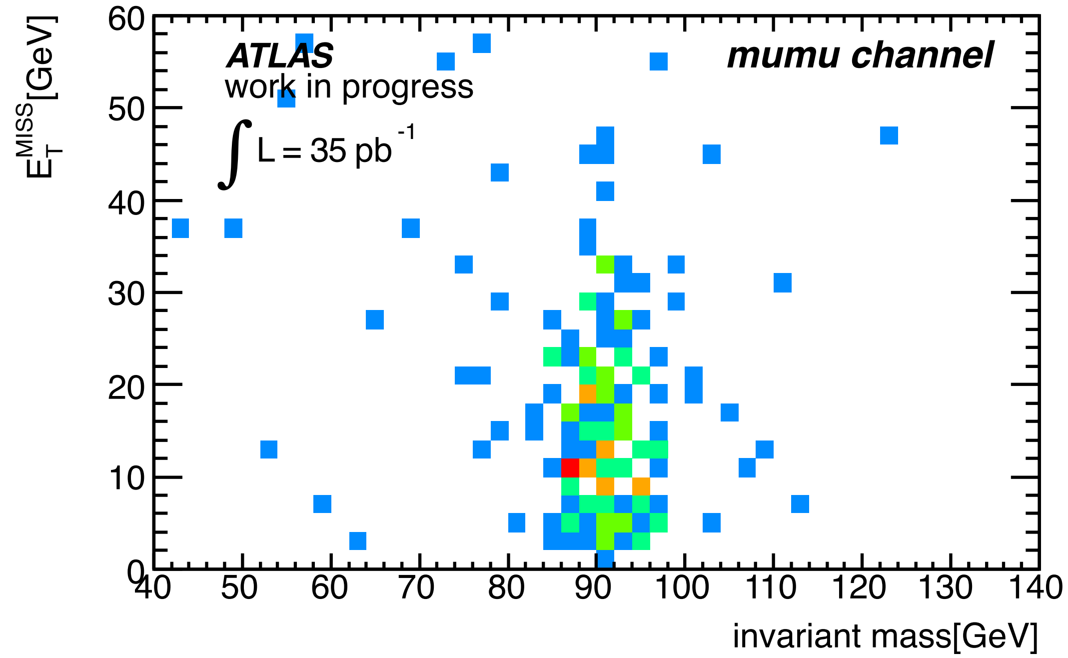
- **Results** : ee : 0.5 ± 0.5 (Stat.+Syst.)
  $\mu\mu$: 0.5 ± 0.5 (Stat.+Syst.)
  eμ : 1.9 ± 1.1 (Stat.+Syst.)

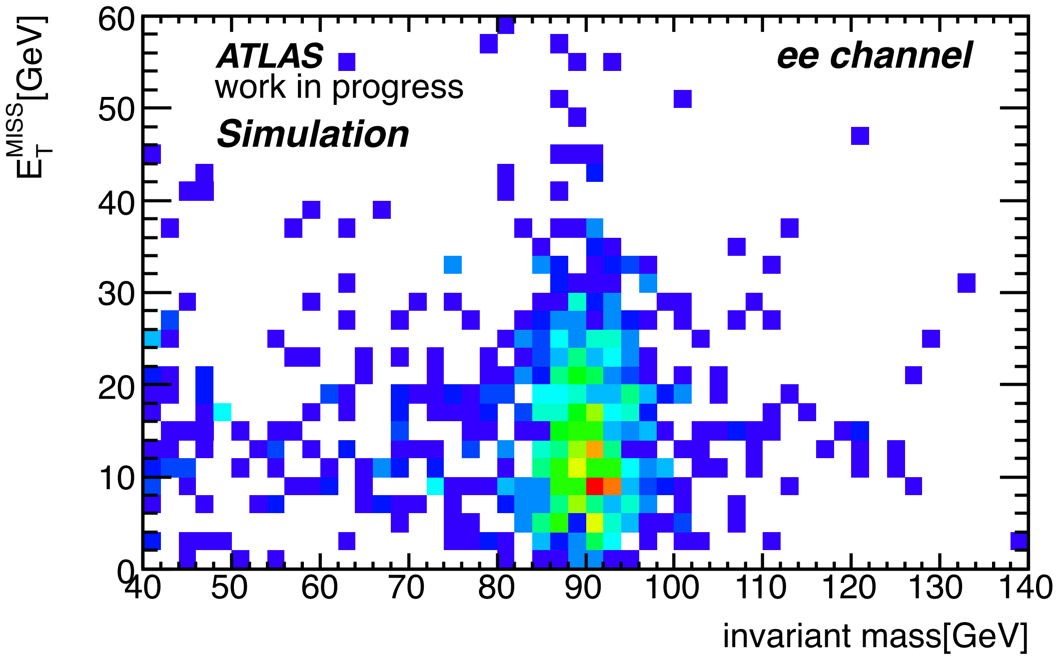
Event Selection Criteria

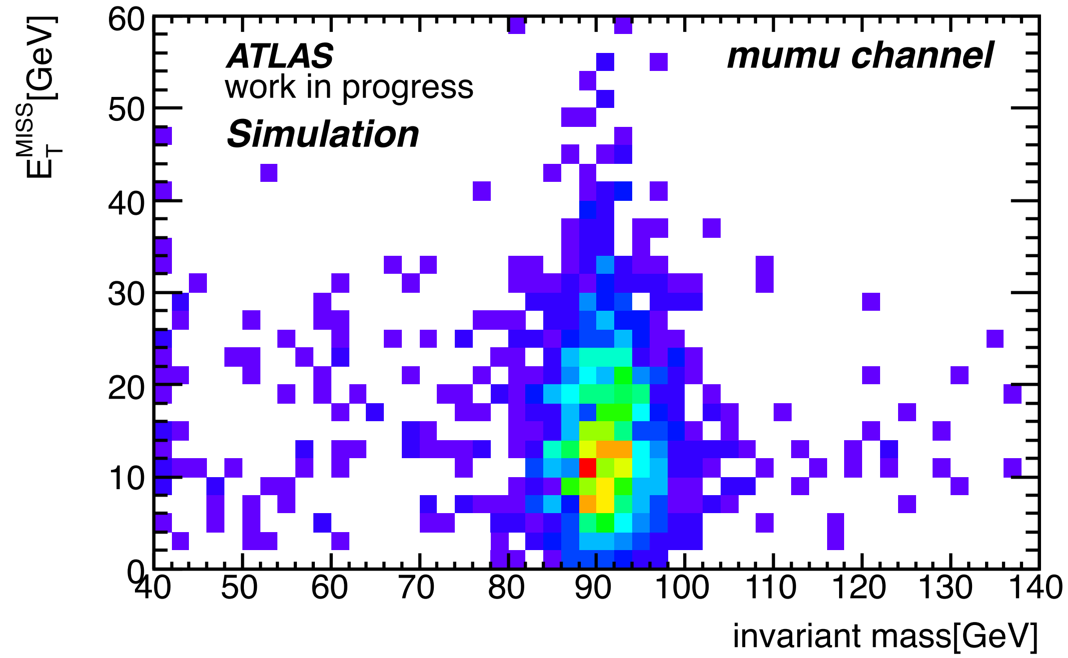
cut	ee	$\mu\mu$	$e\mu$
no cut			
trigger	EF_e15_medium	EF_mu13_tight	EF_e15_medium or EF_mu13_tight
Jet Cleaning	not include bad jets		
Non collision BG rejection	include vertex with #tracks>4		
electron/muon overlap	reject event if electron and muon share a track		
lepton req.	$N_e \geq 2$	$N_\mu \geq 2$	$N_\mu + N_e \geq 2$
E_T^{miss}/H_T	E_T^{miss}> 30 GeV		H_T >110 GeV
jet req.	at least 2jets		
lepton req.	exactly 2 selected leptons		
sign req.	opposite sign		
Z-mass veto	5 GeV		-
Trigger Match	match lepton trigger $\Delta R < 0.15$		
Truth Match	match from MCTruthClassifier to lepton from Wboson		
b-tagging	at least one b-tagged jet (-log(JetProb.)>2.05)		

MEt vs Invariant Mass





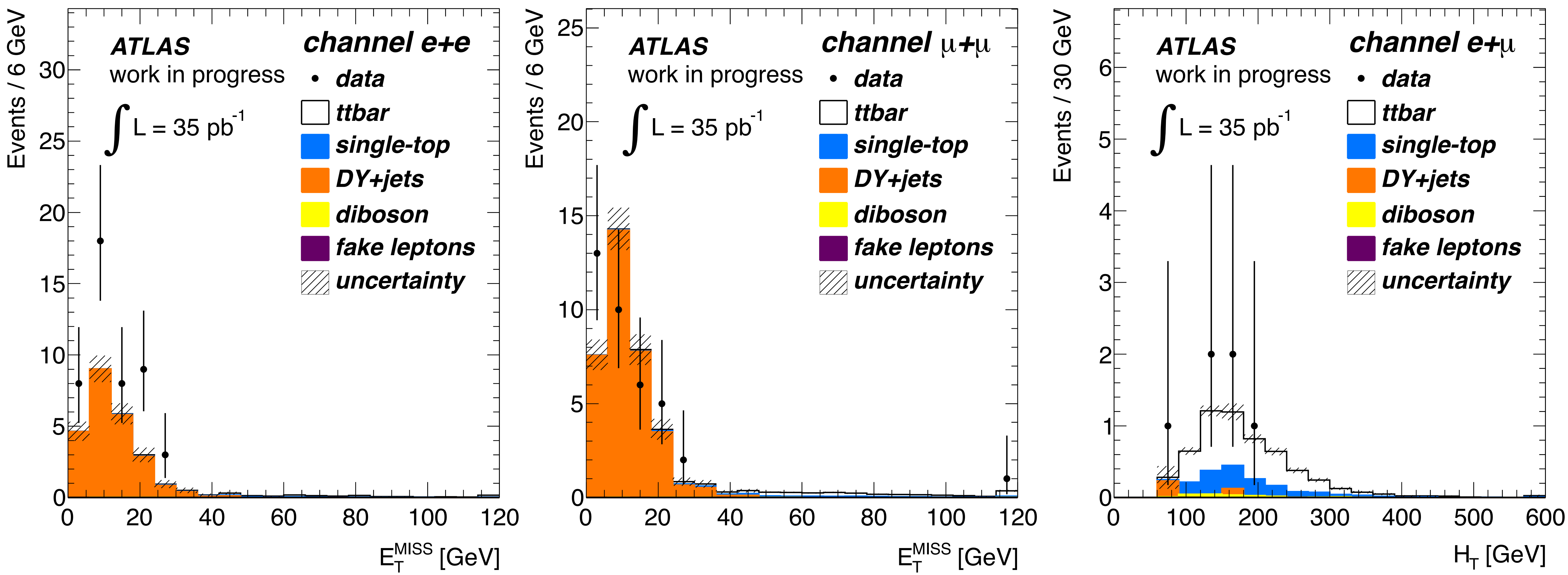




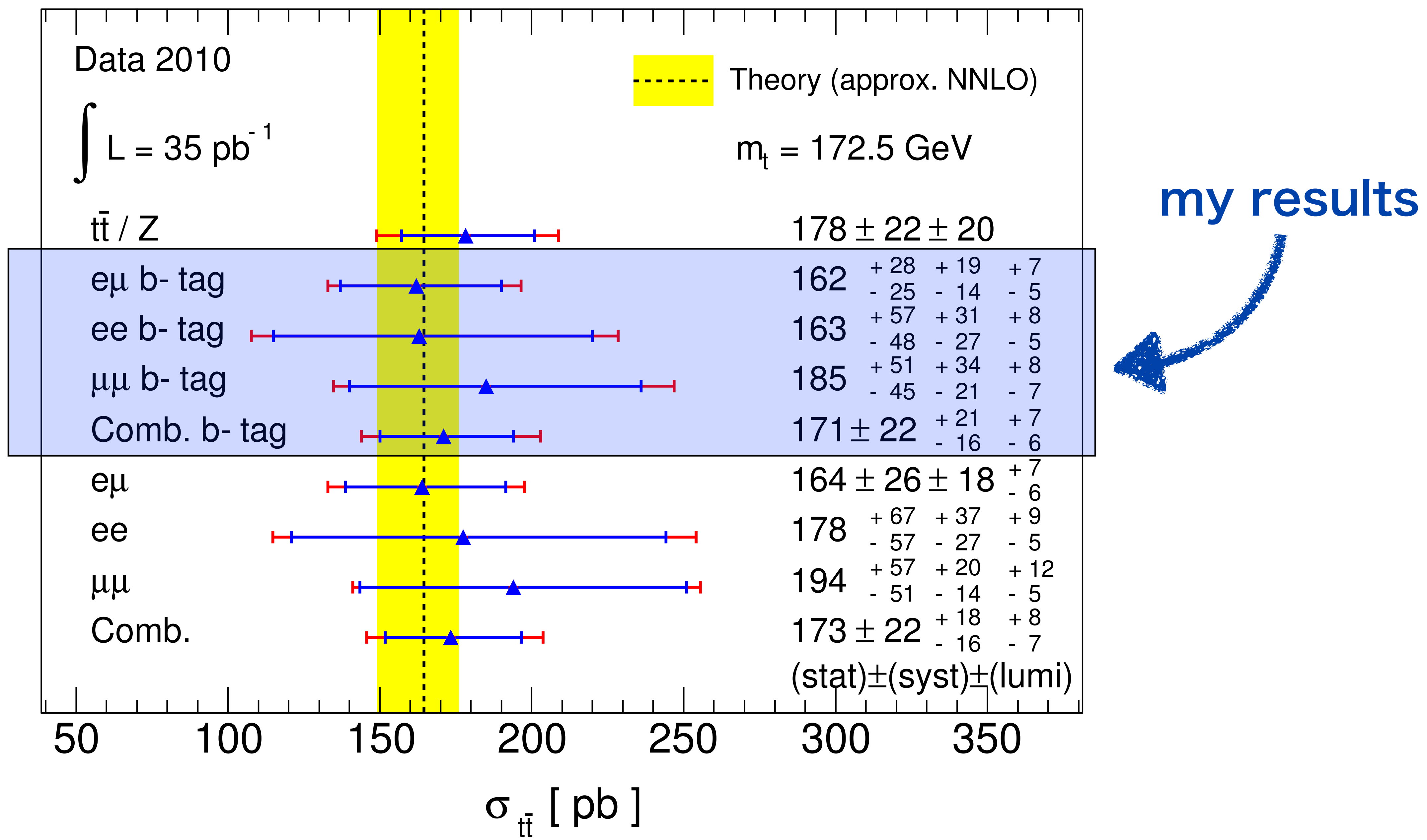
Distributions in Control Region

CR : event with 1 or 2 jet

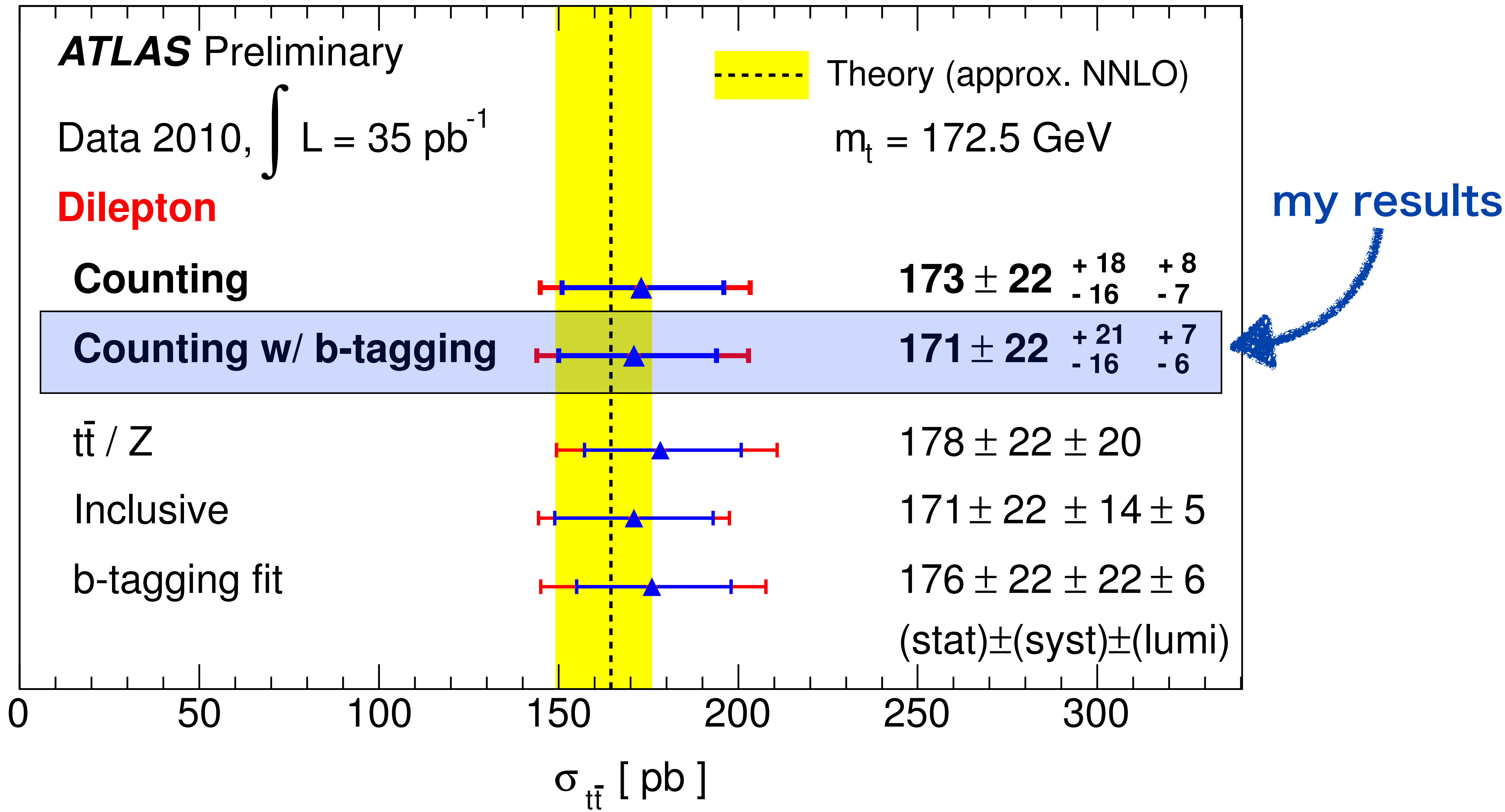
after applying all selection but #jet requirement



Measured cross-section



Measured cross-section(more)



Systematic uncertainty on the Acceptance

Process	ee	$\mu\mu$	$e\mu$
Acceptance	0.124	0.224	0.213
Uncertainty Source	$\Delta A/A[\%]$	$\Delta A/A[\%]$	$\Delta A/A[\%]$
Jet ES	+4.4/-5.6	+4.3/-5.1	± 3.1
Jet ER	± 0.8	± 0.6	± 0.1
Jet ID SF	± 3.7	± 3.8	± 3.4
El. ES	+0.9/-1.2	± 0.0	+0.2/-0.1
El. ER	+0.0/-0.1	± 0.0	± 0.0
El. ID SF	± 5.9	± 0.0	± 3.7
El. Trig. SF	± 1.0	± 0.0	± 0.5
Mu. ES	± 0.0	+0.1/-0.2	± 0.0
Mu. ER (ID)	± 0.0	± 0.1	± 0.0
Mu. ER (MS)	± 0.0	± 0.1	± 0.0
Mu. ID SF	± 0.0	± 0.1	± 0.4
Mu. Trig SF	± 0.0	± 0.3	± 0.0
b-tag efficiency	+5.3/-6.6	+5.3/-6.6	+5.3/-6.6
l-tag efficiency	± 0.2	± 0.2	± 0.3
Generator	± 1.1	± 1.6	± 0.9
Parton shower	± 2.4	± 0.0	± 3.2
ISR/FSR	± 3.7	± 3.3	± 1.0
PDF	± 2.7	± 2.0	± 2.2
Pile-up	± 0.6	± 1.7	± 1.5
Total	± 11.9	+9.0/-10.2	± 9.5

Systematic uncertainty on the BG estimation

Process	ee	$\mu\mu$	$e\mu$
Total Background	2.93	7.37	4.98
Uncertainty Source	$\Delta N/N[\%]$	$\Delta N/N[\%]$	$\Delta N/N[\%]$
MC Statistics	± 9.9	± 13.0	± 7.2
Jet ES	+36.6/- 3.6	+ 0.0/- 7.7	+7.3/-4.0
Jet ER	± 12.4	± 5.9	± 1.8
Jet ID SF	± 3.8	± 5.0	± 2.1
El. ES	+ 8.9/- 0.0	± 0.0	+0.1/-0.0
El. ER	+ 7.3/- 8.8	± 0.0	+0.1/-0.0
El. ID SF	+ 1.4/- 1.3	± 0.0	± 2.3
El. Trig. SF	± 0.3	± 0.0	± 0.3
Mu. ES	± 0.0	+ 0.0/- 3.6	± 0.0
Mu. ER (ID)	± 0.0	+ 0.0/- 4.0	± 0.0
Mu. ER (MS)	± 0.0	+ 6.5/- 3.0	+1.8/-0.0
Mu. ID SF	± 0.0	± 0.2	± 0.2
Mu. Trig SF	± 0.0	± 0.0	± 0.0
b-tag efficiency	+ 0.7/- 0.9	+ 0.6/- 0.5	± 4.5
l-tag efficiency	+ 0.1/- 0.2	+ 1.2/- 1.6	± 2.4
DY estimation	± 9.1	± 6.6	-
fake lepton estimation	± 16.4	± 7.2	± 22.3
diboson normalization	+ 2.0/-1.3	± 0.5	± 1.6
single top normalization	+ 4.4/-3.8	± 2.8	+ ± 6.9
Pile-up	± 10.8	± 4.4	± 4.3
Total	+47.3/-29.0	± 20.6	± 26.3