Accessing the fourth family at the LHC with multileptons

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Multi-lepton final states in search for New Physics at the LHC workshop in Lisbon

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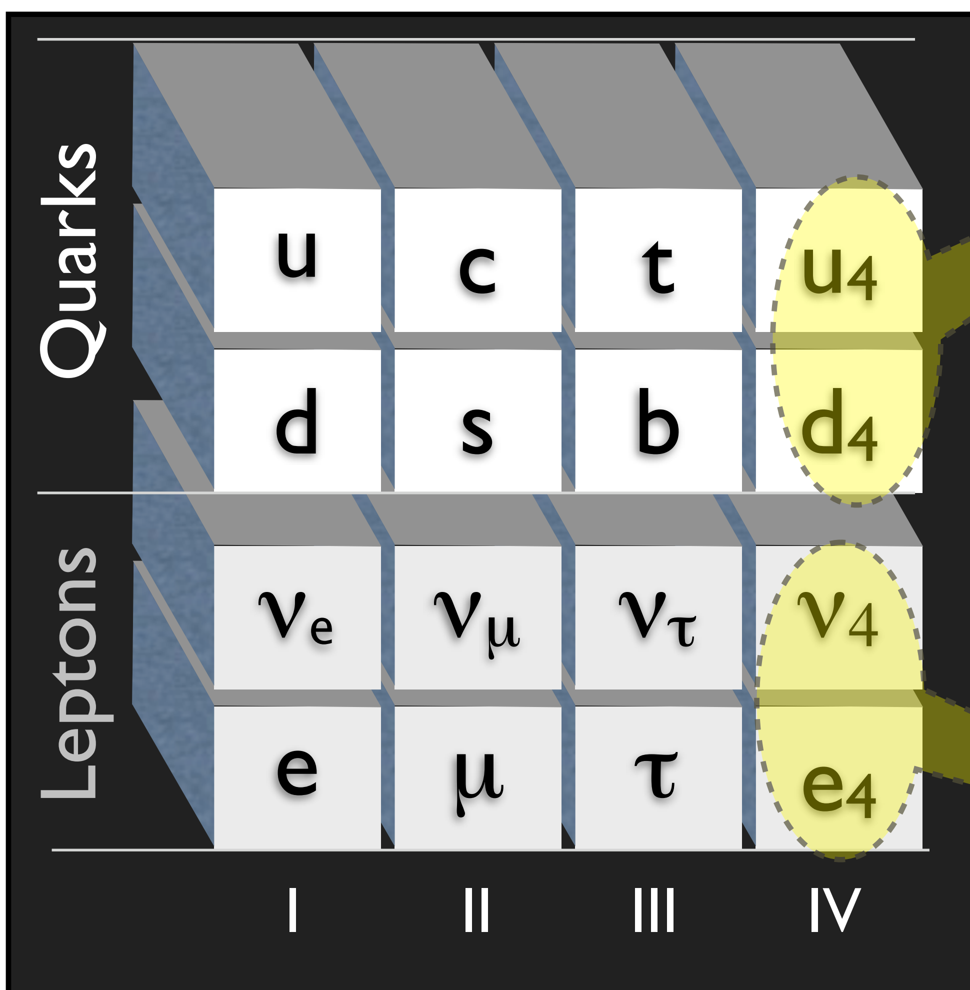
The fourth family

- 4^{th} generation is the simplest "modification" to SM
  - ➡SM does not give #families => not a true modification
  - ➡upper bound from QCD (asymptotic freedom): #families < 9
  - ➡predicted by DMM conjecture (details here)
  - ➡introduces 4 new heavy fermions with 1TeV > m >100GeV



Quark Sector: no FCNC in FF model
multi-leptons could be from
pp-->QQ-->Wj Wj--> ℓνj ℓνj
some work in ATLAS for this mode
very small background
assume colinearity for ℓ & ν
Please see the presentation from JAAS
for details of the quark sector

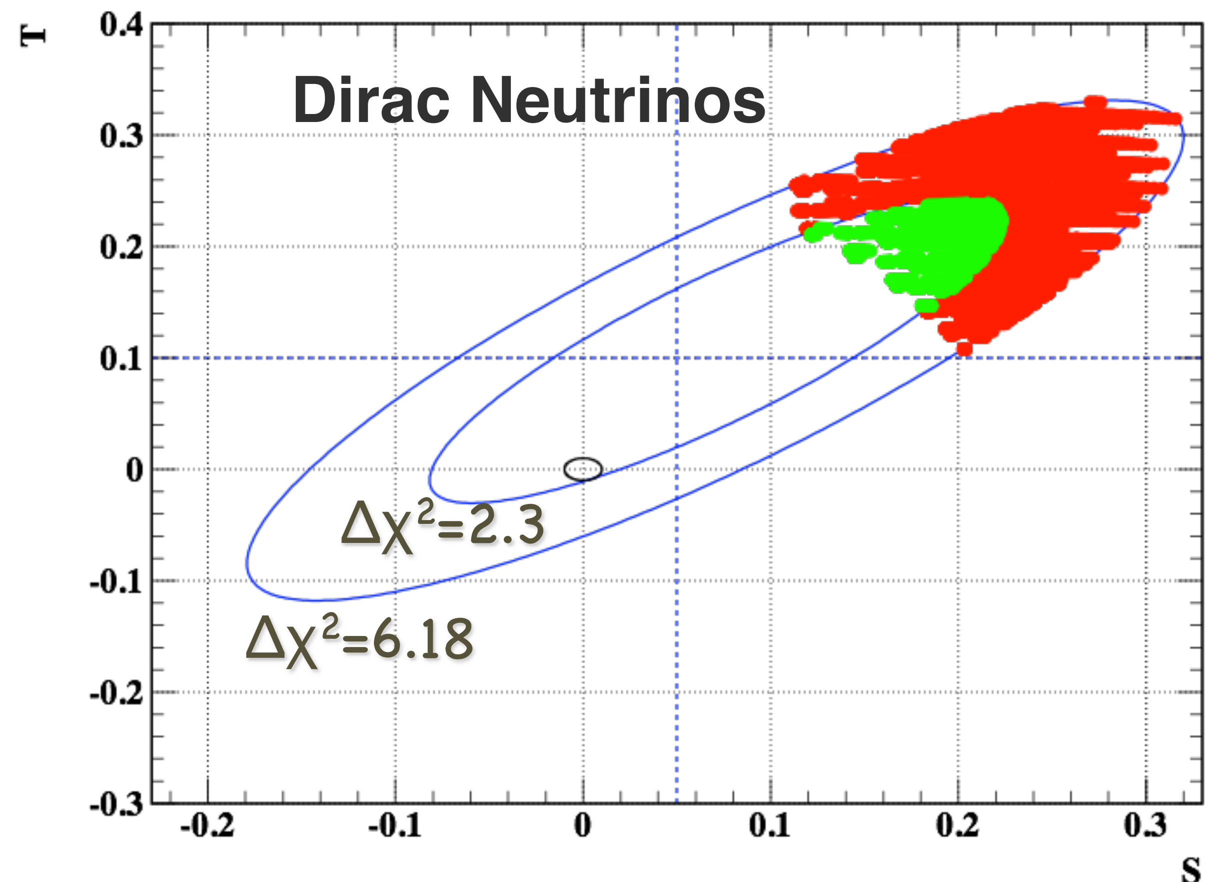
Lepton Sector: we will discuss now...

but is this possible?

- These are really heavy objects, current limits are:

$$m_{t'} > 256\,\text{GeV}; \qquad m_{b'} > 128\,\text{GeV (CC decay; 199 GeV for 100\% NC decay)};$$
$$m_{\tau'} > 100.8\,\text{GeV}; \qquad m_{\nu'_\tau} > 90.3\,\text{GeV (Dirac coupling; 80.5 GeV for Majorana coupling)}$$

- Isn't the 4th generation killed by the EW precision data? (i.e. what about S, T parameters?)
  - ➡evaluate correctly: $$\delta S = \frac{2}{3\pi} - \frac{1}{3\pi}\left[\log\frac{m_{t'}}{m_{b'}} - \log\frac{m_{\nu'_\tau}}{m_{\tau'}}\right]$$
- Is this true for any mass?
  - ➡use OPUCEM (details here)



m_{u4}	m_{d4}	m_{V4}	m_{e4}	m_H	$\Delta\chi^2$
400	380	90	200	200	0.87
390	380	90	210	250	1.09
840	830	90	210	250	1.1
550	550	90	220	300	1.3

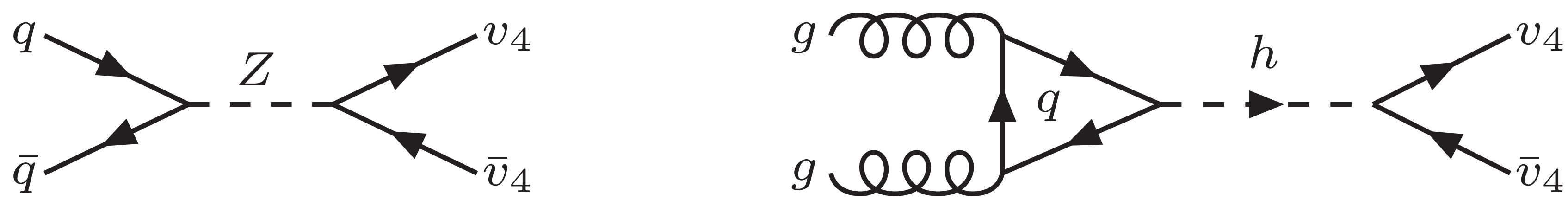
Some example points. $\Delta\chi 2(SM3) \approx 1.7$

the neutral lepton

- Can we produce the 4th family heavy neutrinos at the LHC?
  - ➡ what if there is a Higgs to help the production?
    - pp --> h --> v4 v4(bar)
  - ➡ what if there is no Higgs?
    - pp --> Z --> v4 v4(bar)
- Can we see the 4th family heavy neutrinos in ATLAS?
  - ➡ v4 -->l W, attention to Dirac or Majorana nature
    - particle =? anti-particle
- Any benefit to Higgs hunt from fourth family ?
  - ➡ we might have a signal with negligible background

v4 production

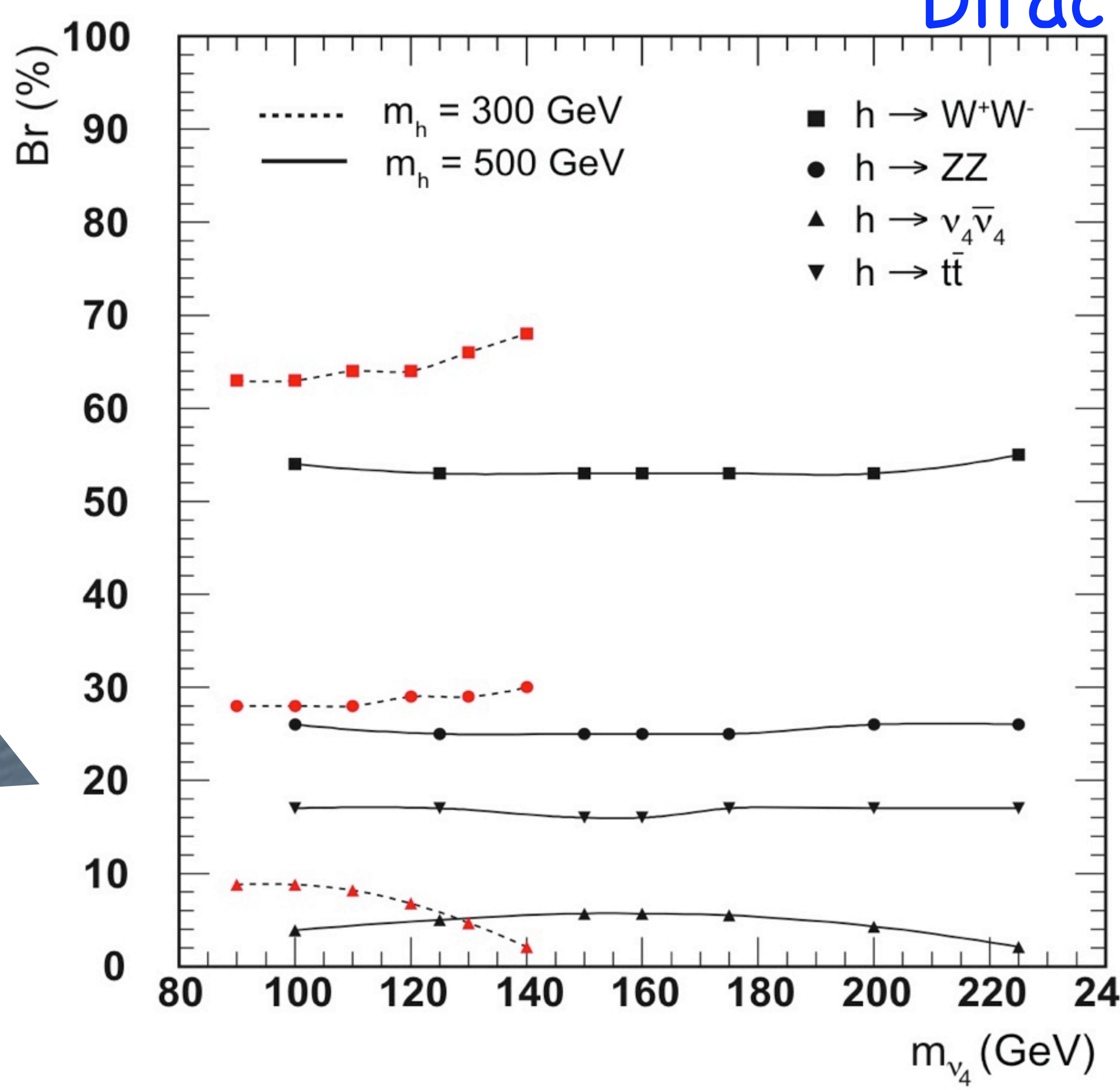
JHEP 0810:074,2008.



consider the pair production of v4 at LHC

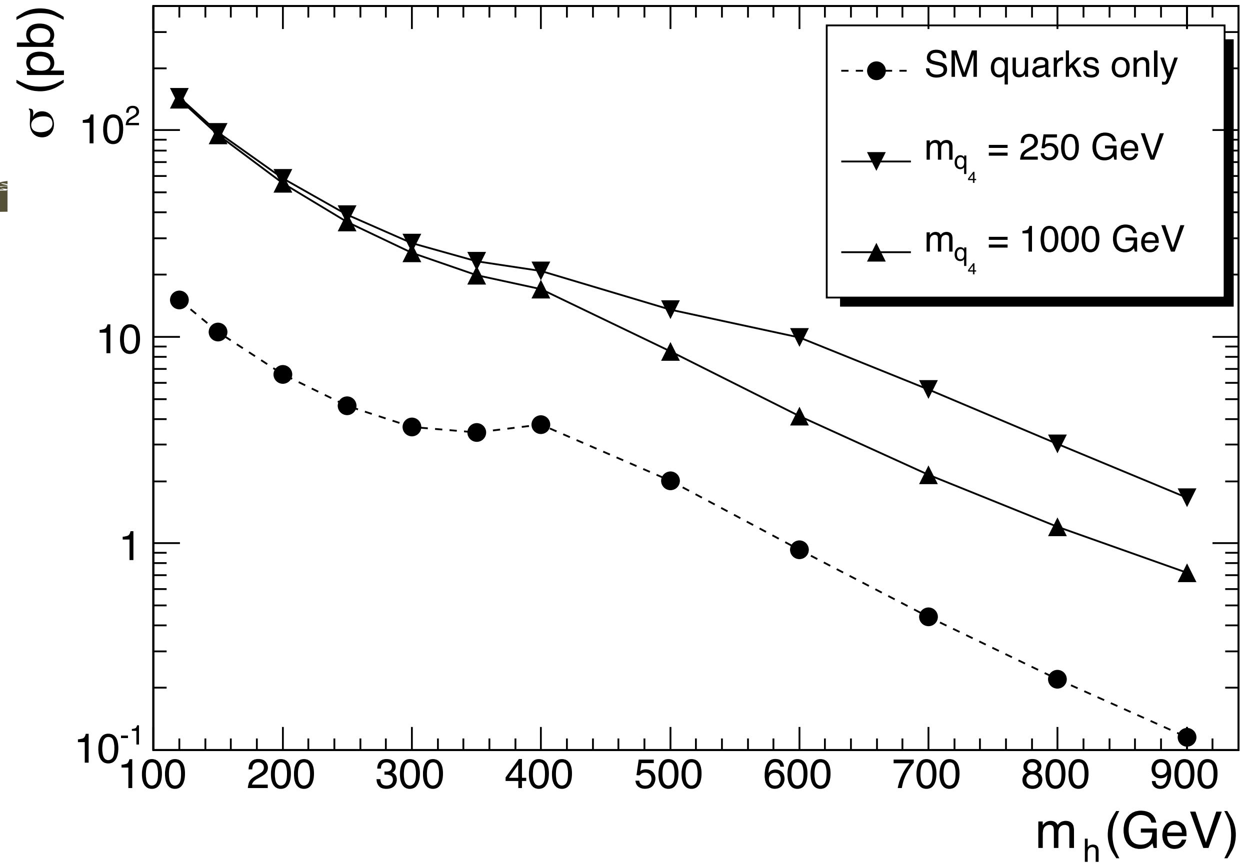
- Z mediated channel always present
- h mediated channel may be present
  - existence, mass and width of the Higgs boson
  - for the Higgs channel, we need to know:
    - u4, d4 contribution in the gluon loop like top & b
    - the updated decay Higgs BRs

Dirac

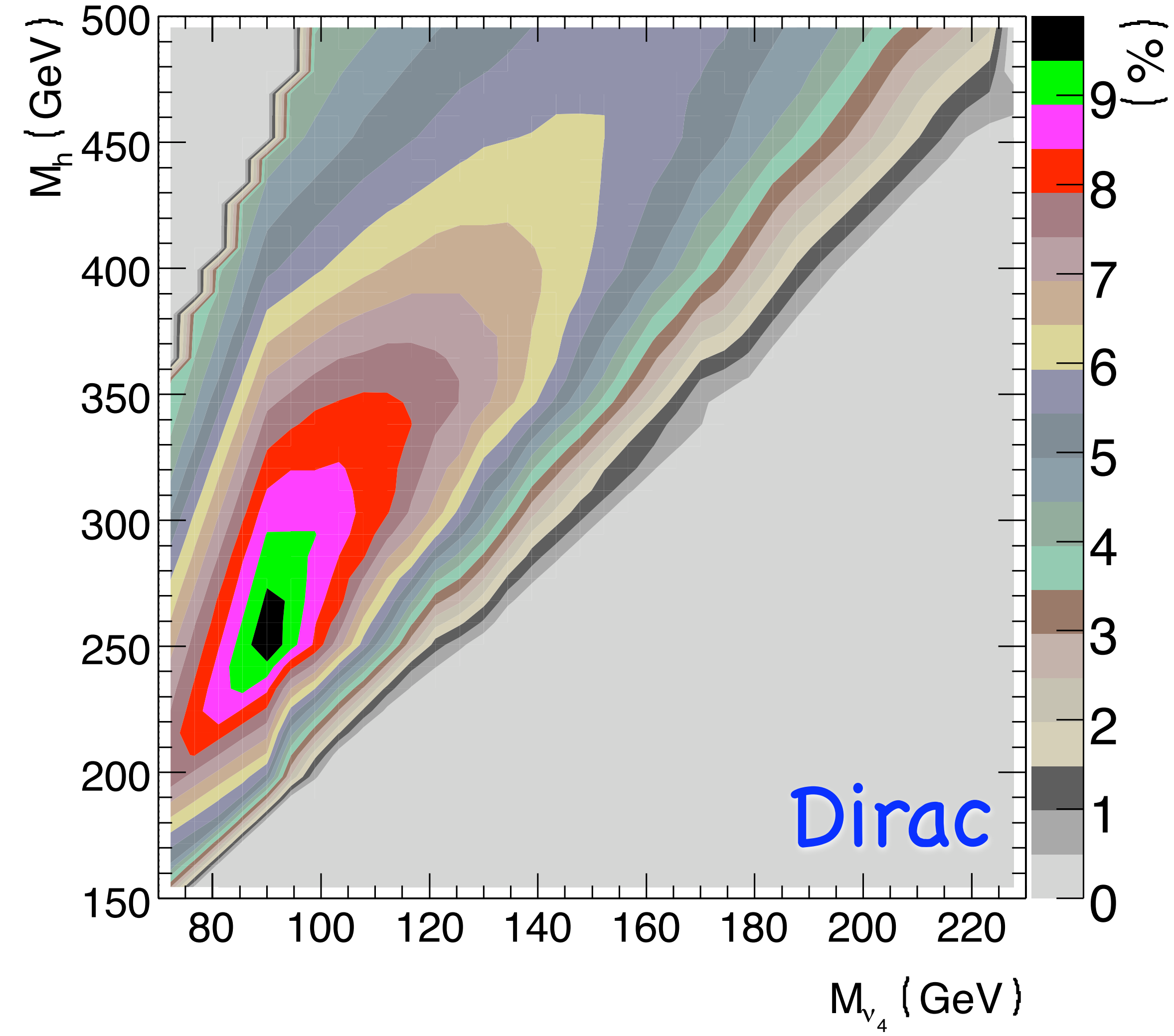


The Higgs job

- gluon fusion --> Higgs
  - ➡ depends on the M_{q4}
  - ➡ calculated with Higlu
    - 4th Fam quarks added @ LO
  - ➡ From now on:
    - $M_{u4}=M_{d4}=500GeV$

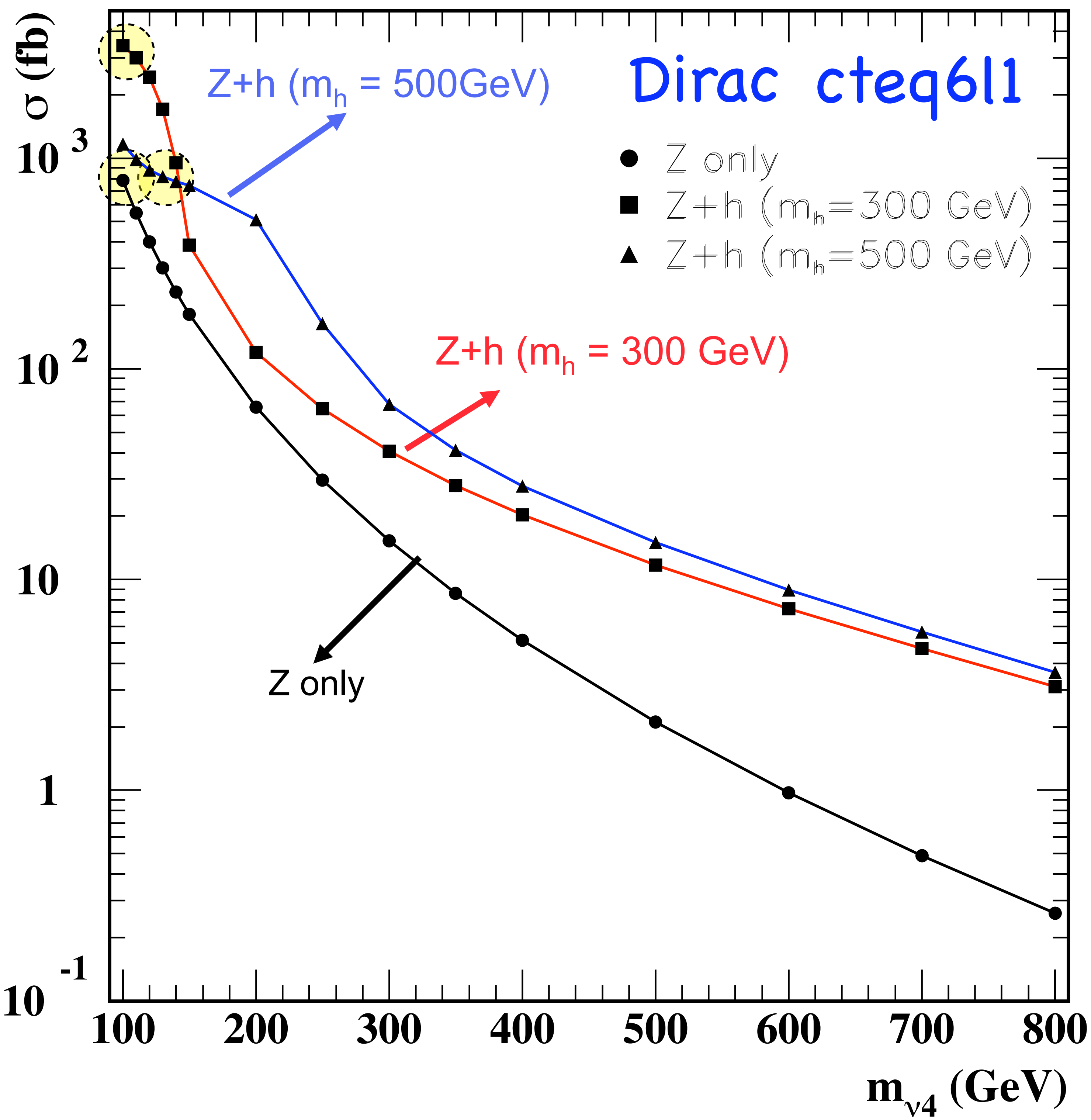


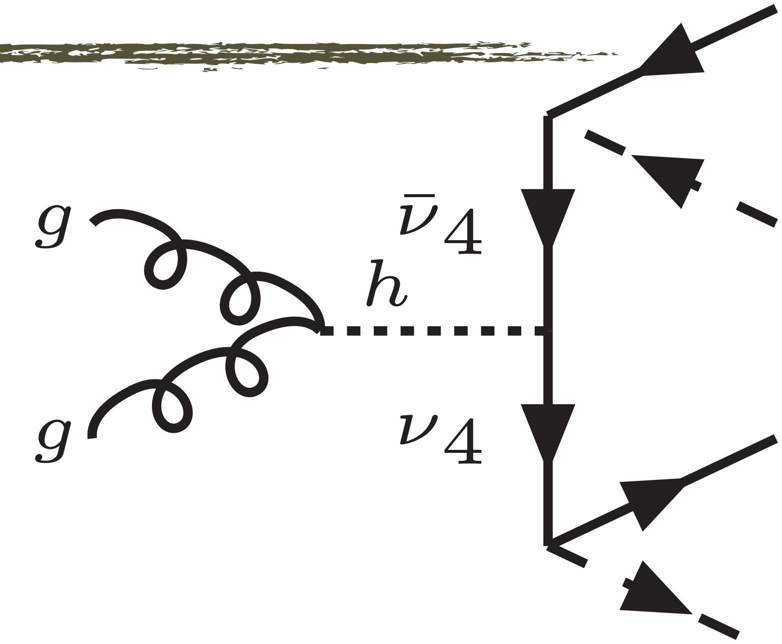
- Higgs decay BRs
  - ➡ implemented in CompHEP
  - ➡ BR[h->ν4ν4] ≤ 10%
  - ➡ test with 2 Higgs masses:
    - M_h = 300, 500 GeV (Γ=9, 67 GeV)



The method

pp-> v4v4 production x-section





- The v4 pair production (from CompHEP + Higlu)
  - ➡ ggh effective coupling implemented in CompHEP

Define 3 benchmark points

	s1	s2	s3
v4	100	100	160
h	-	300	500

The signal

pp --> v4 v4 --> ℓ W ℓ W

- signs not written: Dirac & Majorana cases separately studied
  - Dirac type v4 v4(bar) decay to
    - 100% opposite sign leptons + bosons
  - Majorana type v4 v4 decay to
    - 50% opposite sign leptons + bosons
    - 50% same sign leptons + bosons

➡ we choose ℓ =μ since BR[v4 -->μW]=68%

- from 4x4 MNS matrix parameterization in Phys. Rev. D 72 (2005) 053006.
- compatible w/ neutrino mixing measurements

➡ taking jet decays of Ws, final signal becomes: 2μ+4j

	$\sigma_{pp\to Z\to\nu_4\bar{\nu}_4}$ (fb)	m_h (GeV)	$\sigma_{gg\to h}$ (pb)	m_{ν_4} (GeV)	BR($h\to\nu_4\bar{\nu}_4$)	$\sigma_{pp\to\nu_4\bar{\nu}_4\to WW\mu\mu}$ (fb)
S1	782	N/A	N/A	100	N/A	362
S2	782	300	30	100	0.088	1583
S3	144	500	10	160	0.055	321

The backgrounds

- diboson associated dimuon production: $2V+2\mu$ $V=W,Z$
  - ➡ <5 fb : negligible (MadGraph)
    - $p_{T\,\mu}>15$, $|\eta_\mu|<2.5$, $m^{QCD}=m_Z$

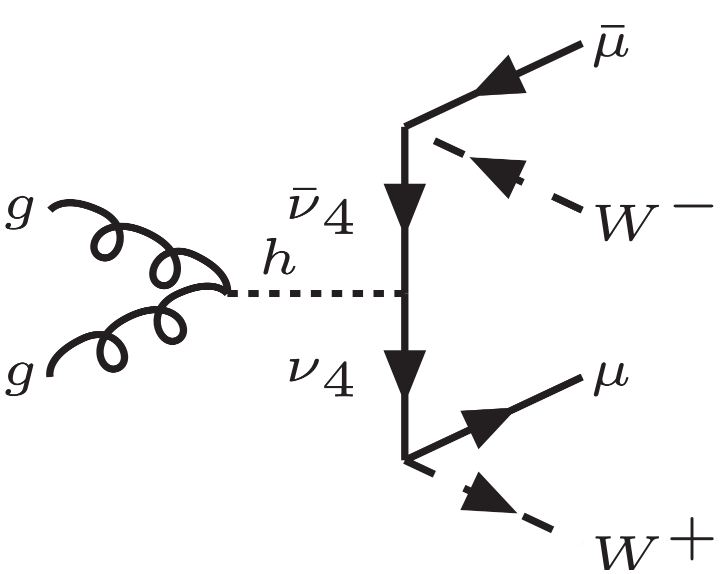
Process	cross section (fb)
$W^+W^-\mu^+\mu^-$	2.56 ± 0.02
$ZZ\mu^+\mu^-$	0.70 ± 0.06
$W^+Z\mu^+\mu^-$	0.97 ± 0.01
$W^-Z\mu^+\mu^-$	0.48 ± 0.06
Direct Total	4.71 ± 0.09

- dimuon + 4jet
  - ➡ <57 pb : NOT negligible (AlpGen)
  - ➡ this is Z/γ +4j (muons mostly from Z/γ decays)
    - $p_{T\,\mu,j}>15$, $|\eta_\mu|<2.5$, $|\eta_j|<5$, $\delta R_j>0.4$, $m^{QCD}=m_Z$

- ttbar as indirect background source:
  - ➡ <755 pb : NOT negligible (MadGraph)

The analysis -1

- Events produced in CompHEP (signal) and MadGraph (background)
  - ➡ also a small sample in AlpGen for compatibility checks(details)
- hadronization in pythia
- fast detector simulation from PGS4
  - ➡w/ ATLAS parameterization



PGS is a simulation of a generic high-energy physics collider detector with a tracking system, electromagnetic and hadronic calorimetry, and muon system. It is designed to take events generated with popular event generators like PYTHIA and HERWIG and produce semi-realistic reconstructed physics objects such as photons, electrons, muons, hadronically decaying taus, and hadronic jets (including b- and charm-tagging). Many basic detector parameters are configurable using a detector parameter file, which includes calorimeter segmentation and resolution, tracking coverage and resolution, and other configurable parameters.

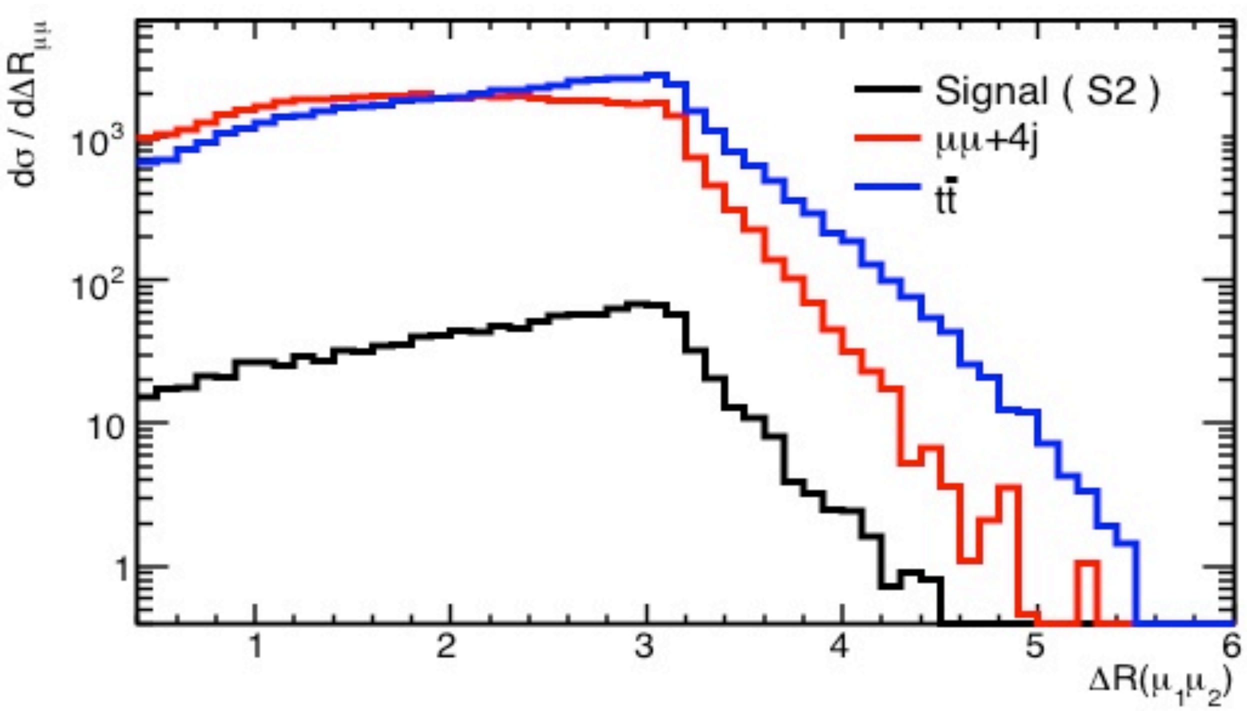
PGS is very simple: for every final state generated particle, a calorimeter energy deposit is simulated, and a track is simulated in the case of long-lived charged particles. From this information, the "high-level" physics objects (photons, electrons, ...) are reconstructed just as in most modern high energy physics experiments.

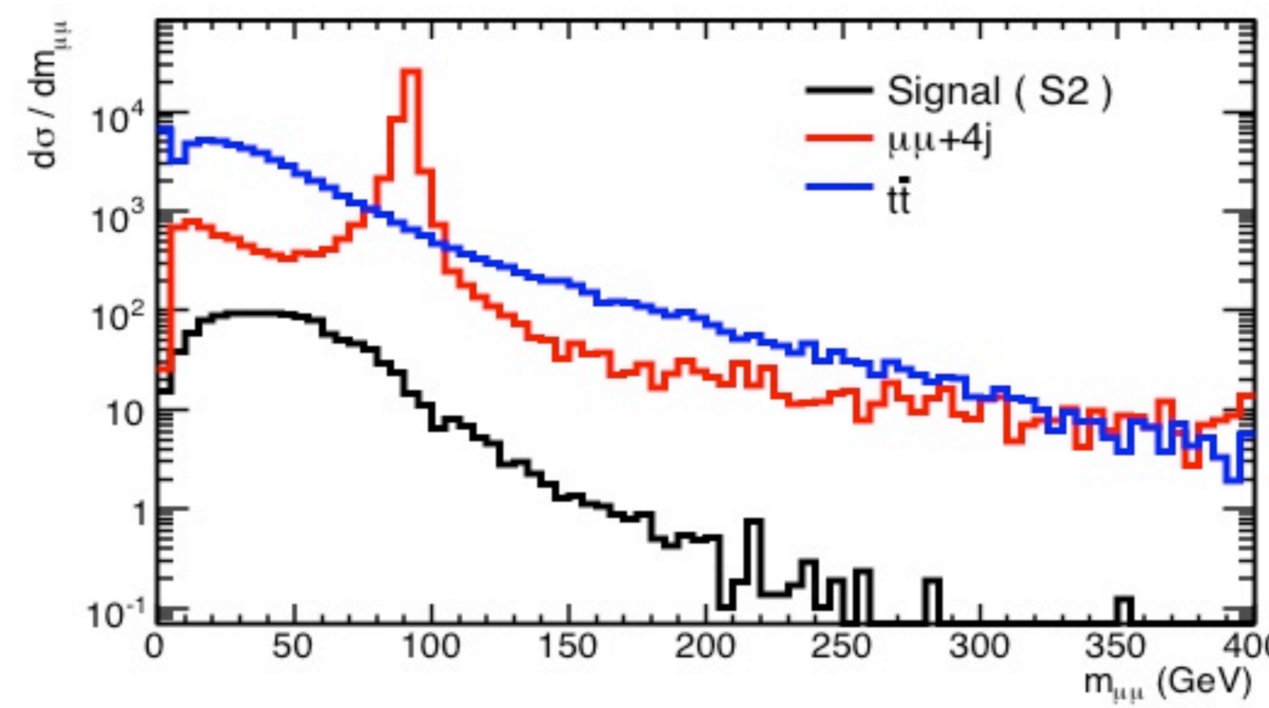
PGS is designed to be fast. And, that having been said, there are many things that are not simultaed in PGS, including secondary interactions, multiple interactions, z-vertex spread, bremsstrahlung, pair production, decays in flight, magnetic field effects, detector material, and probably other things as well. But it's fast.

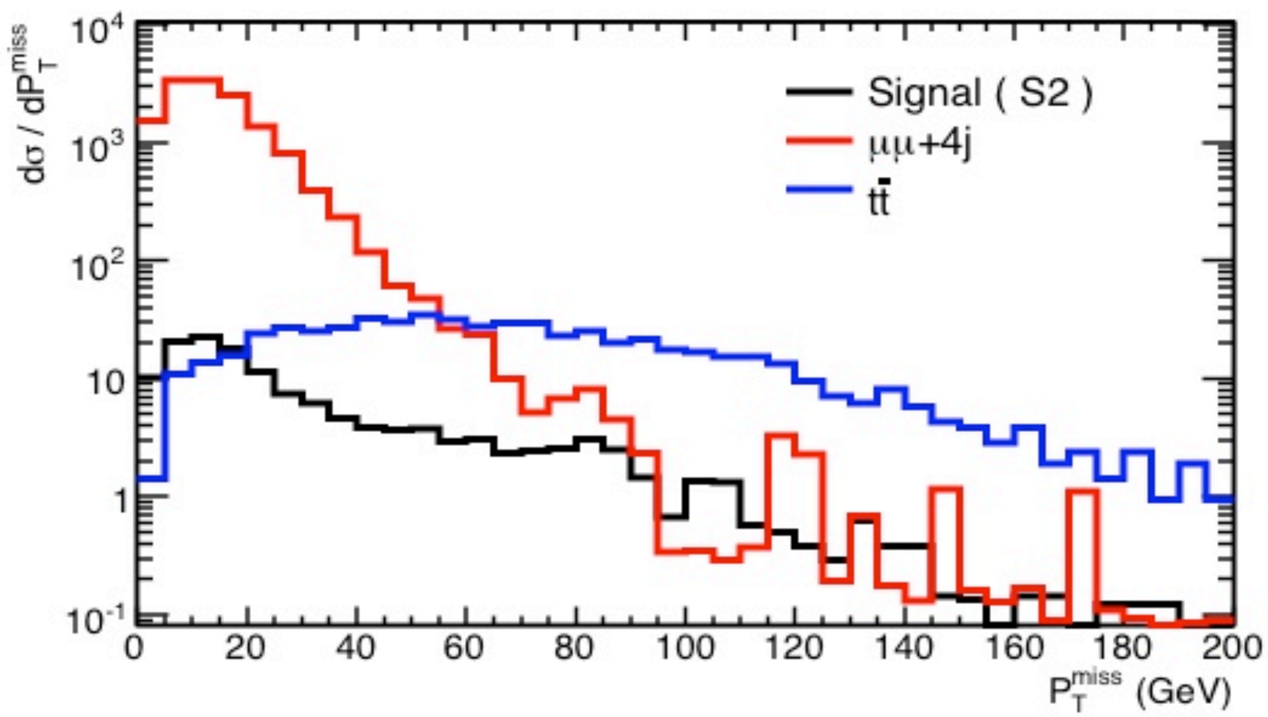
PGS is, well, pretty good. Most collider detector analyses suffer most from geometric acceptance and resolution issues and PGS gets those mostly right. For many analyses you will find (we hope!) that the answer from PGS agrees within a factor of two of the answer you might obtain with a full-fleged detector simulation. In many cases the agreement is much better, of the order of 20%. But, as with any detector simulation, you should always be aware of the limitations and avoid drawing physics conclusions which might depend too much on absolute accuracy. PGS is an excellent tool for prototyping analyses and techniques, but it only goes so far.

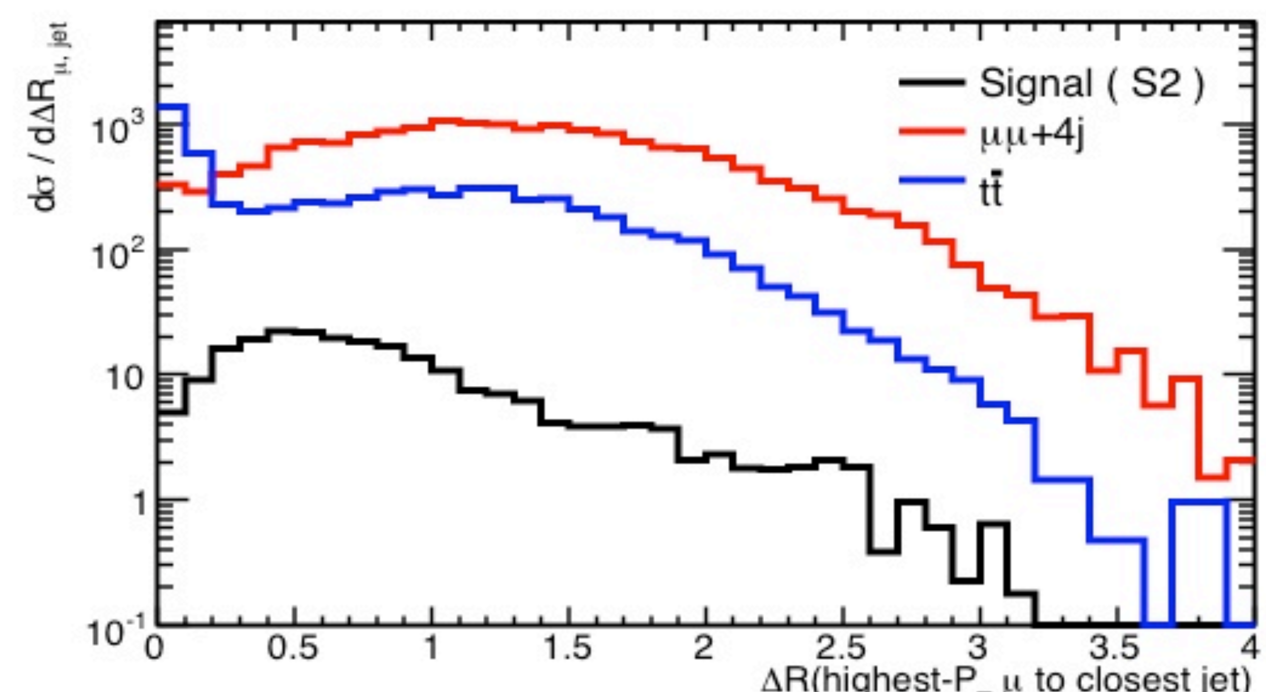
The analysis -2

Example kinematic plots for s2









$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

The analysis -3

The reconstruction cuts (common)

Selection criterion	S1	S2	S3	$2\mu4j$	tt
At least 2μ	63.6	77.9	84.1	93.3	8.1
$p_T(\mu) > 15$ GeV	50.7	55.1	95.1	88.8	29.5
At least 4j	73.6	82.3	82.6	86.0	88.7
$p_T(j) > 15$ GeV	53.3	65.6	72.2	70.4	76.0
$\|M_{jj} - M_W\| < 20$ GeV	63.1	60.5	60.3	45.9	52.8
$\Delta R_{\mu j} > 0.4$	64.5	65.9	77.4	83.0	17.4
No j_b	93.6	92.0	91.5	93.6	53.4
Missing $E_T < 30$ GeV	74.4	64.9	68.7	79.4	15.4
Common ε_{reco}	3.7	5.7	13.4	24.2	1.2×10^{-2}

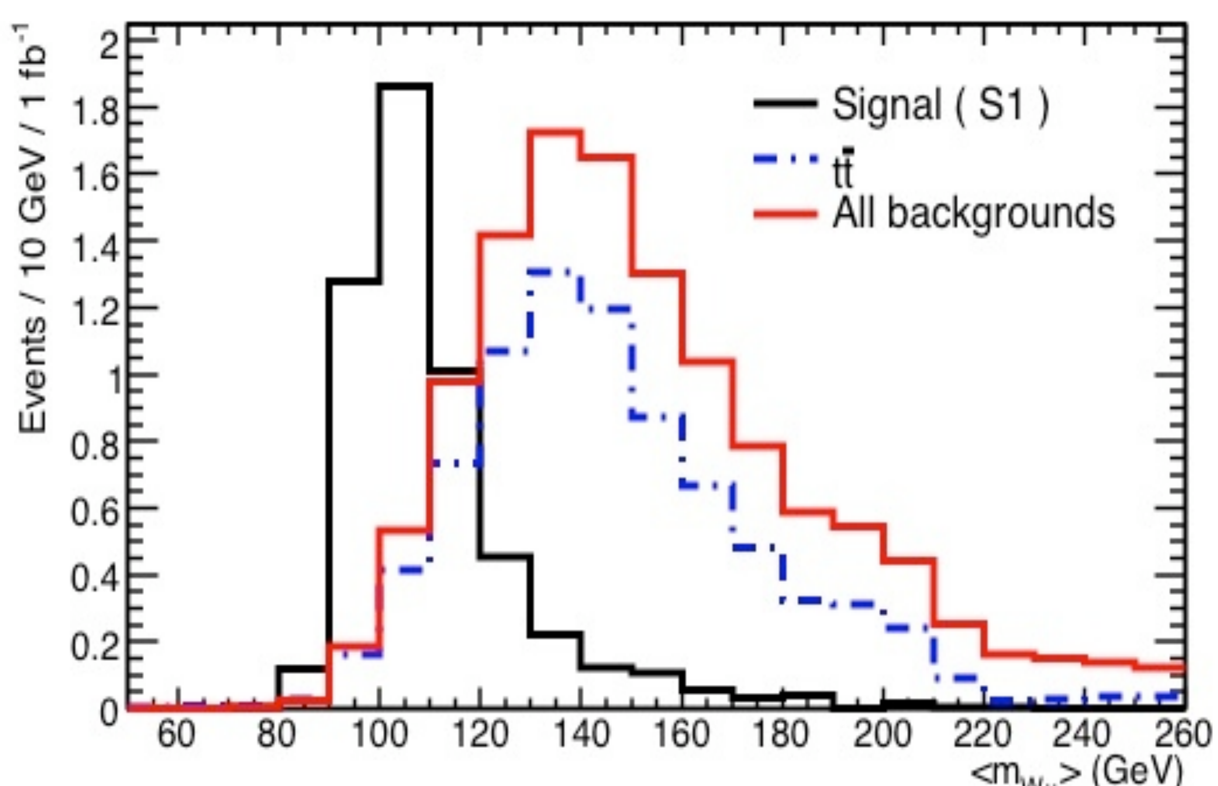
Algorithm

- ➡ select 2 muons of enough p_T, not coming from Z decays and having large angular separation
- ➡ select 4 non-btagged jets of enough p_T, make the 2 best W mass,
- ➡ mu-jet angular separation (b decay veto)
- ➡ E_T^{miss} (ttbar veto)

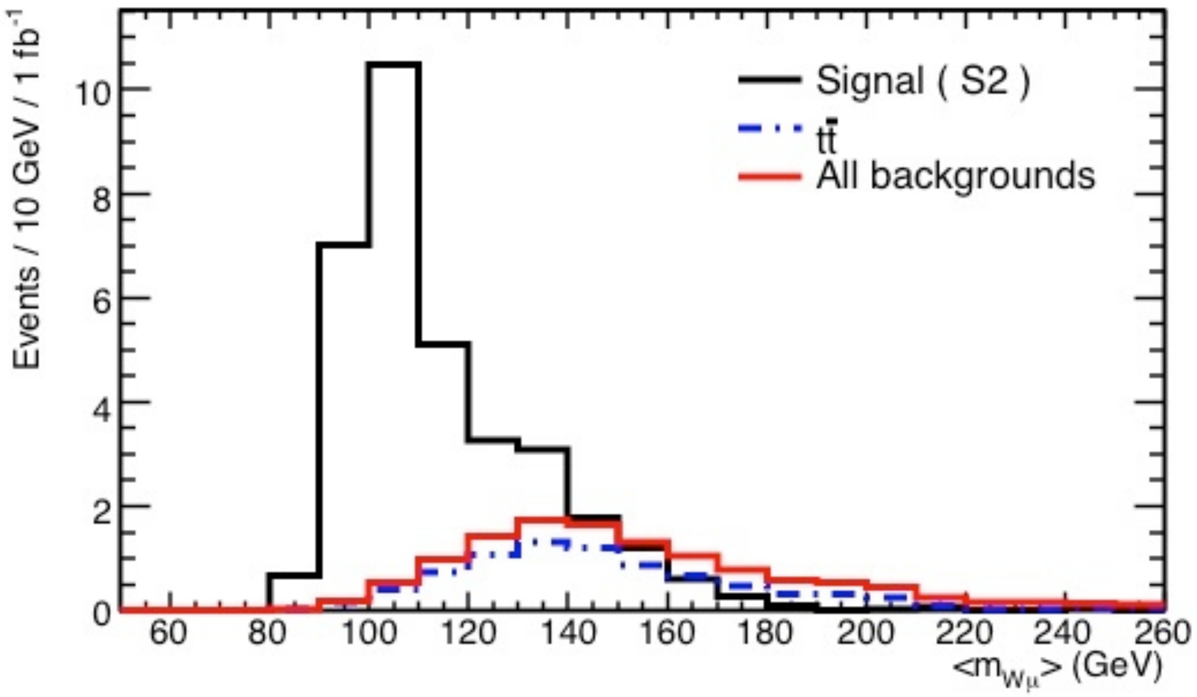
The analysis -4a: Majorana case

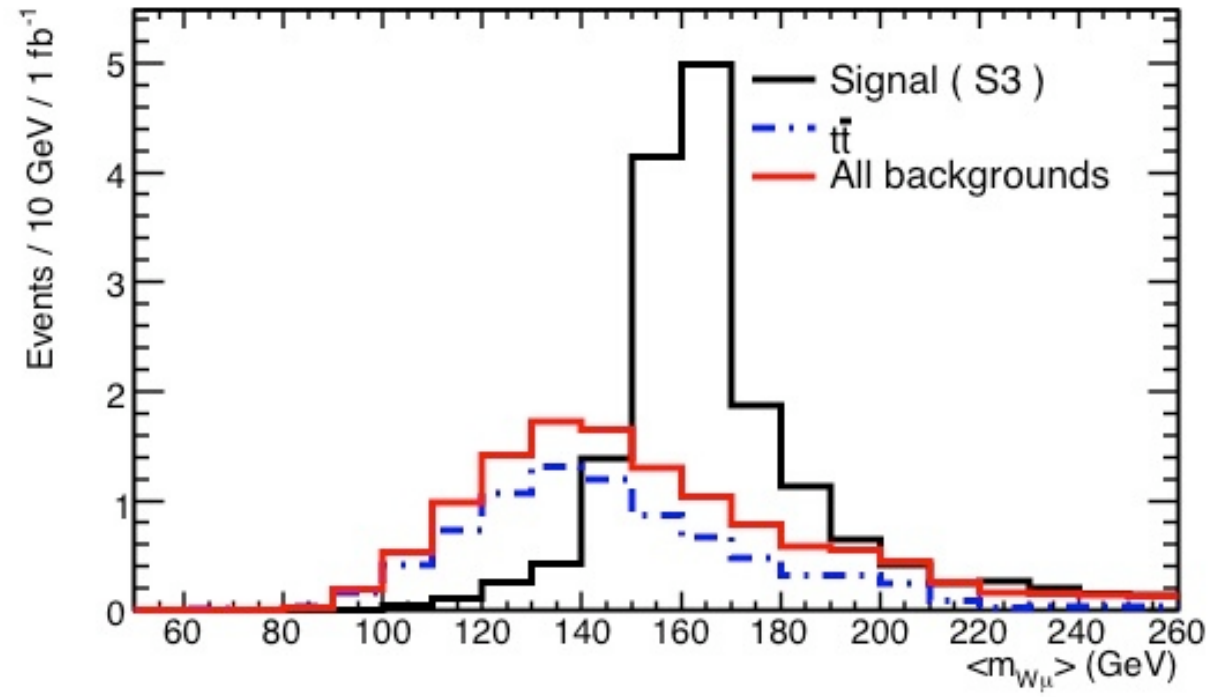
- Only same sign case studied
  - ➡ good signal in all benchmark points w/ $1fb^{-1}$ of data

Selection criterion	S1	S2	S3	$2\mu 4j$	tt
$Sign(\mu_1)xSign(\mu_2) = 1$	46.6	45.5	51.2	$6.8x10^{-2}$	15.5
$\Delta m_{\nu 4} / \Delta m_{\nu 4} < 0.25$	88.2	85.2	74.3	52.0	58.8
Majorana ε_{total}	1.5	2.1	5.3	$8.6x10^{-3}$	$1.1x10^{-3}$

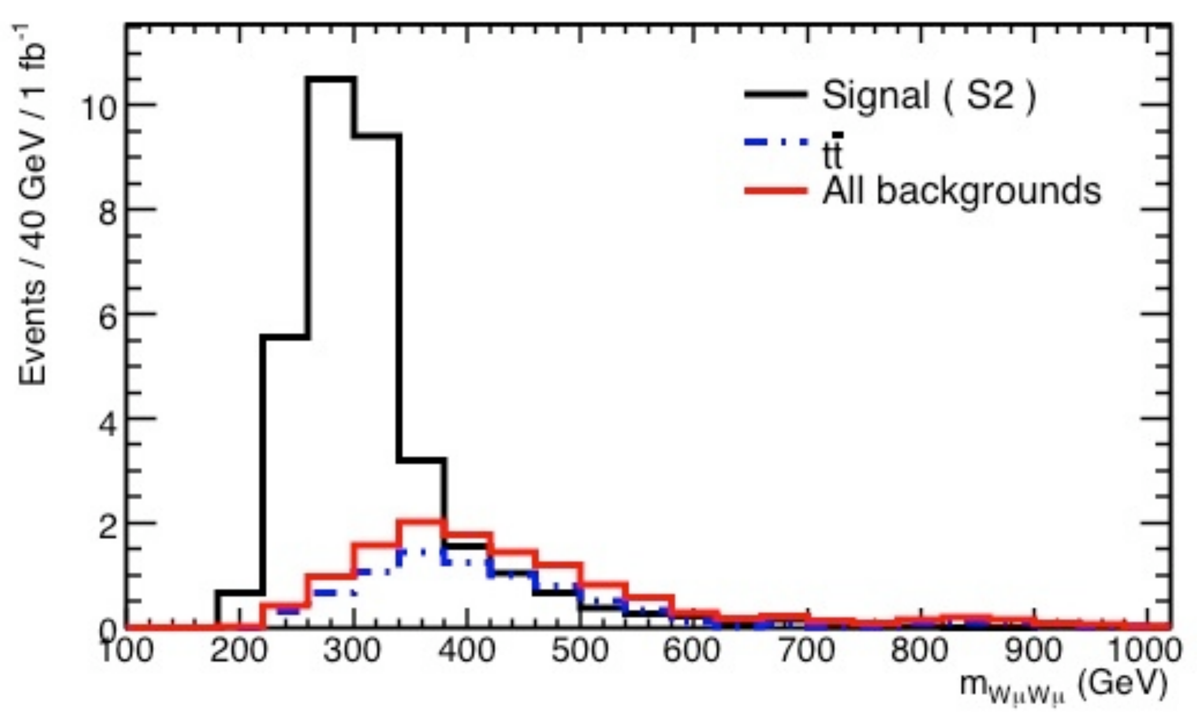


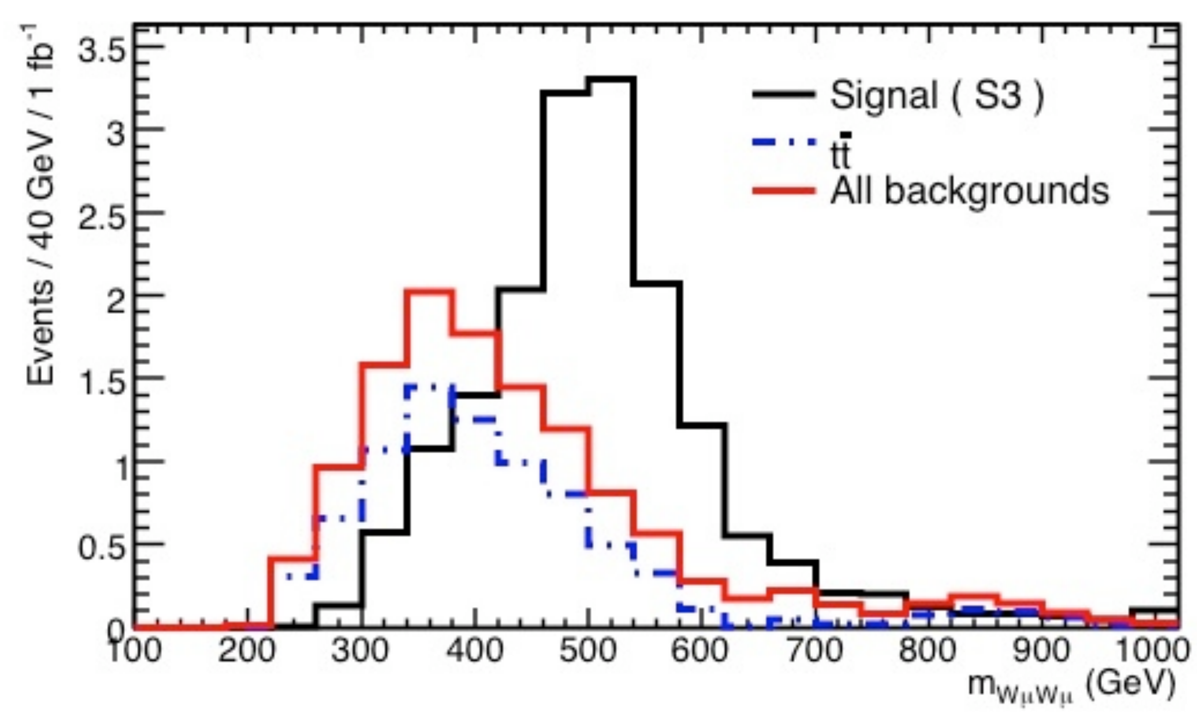
The analysis -4b: Majorana case





Reconstructing also the Higgs mass

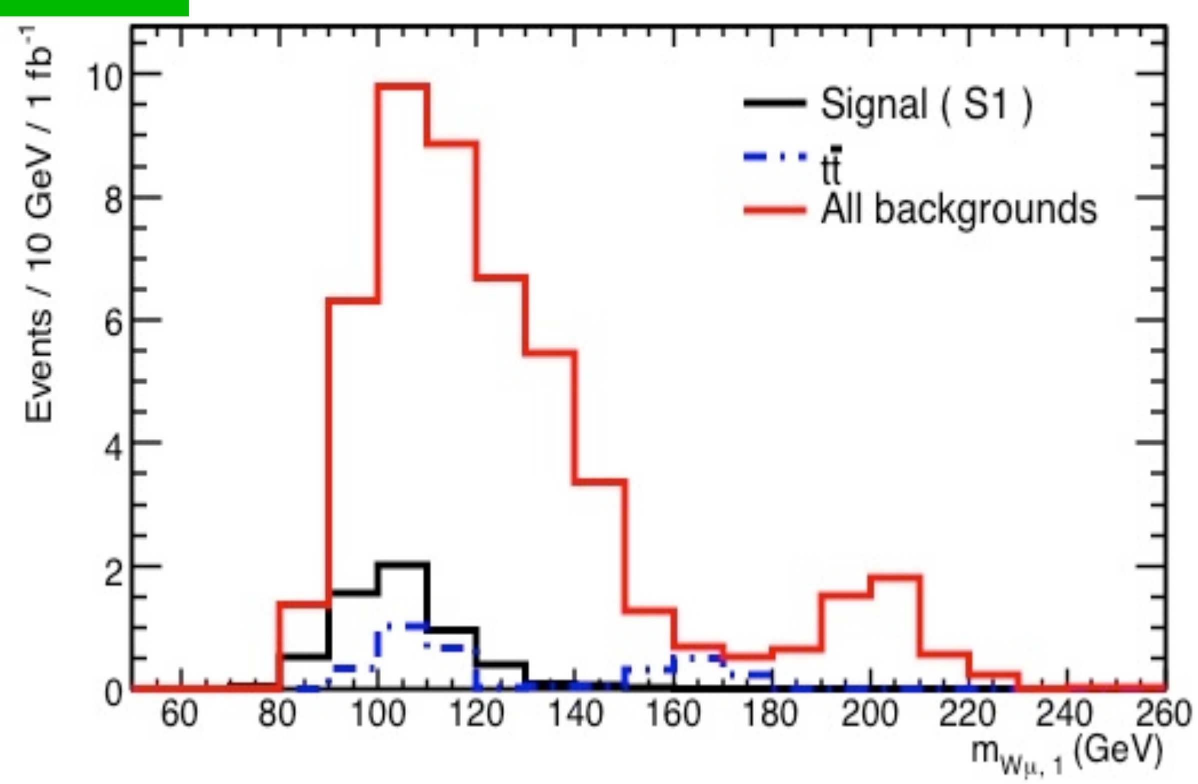




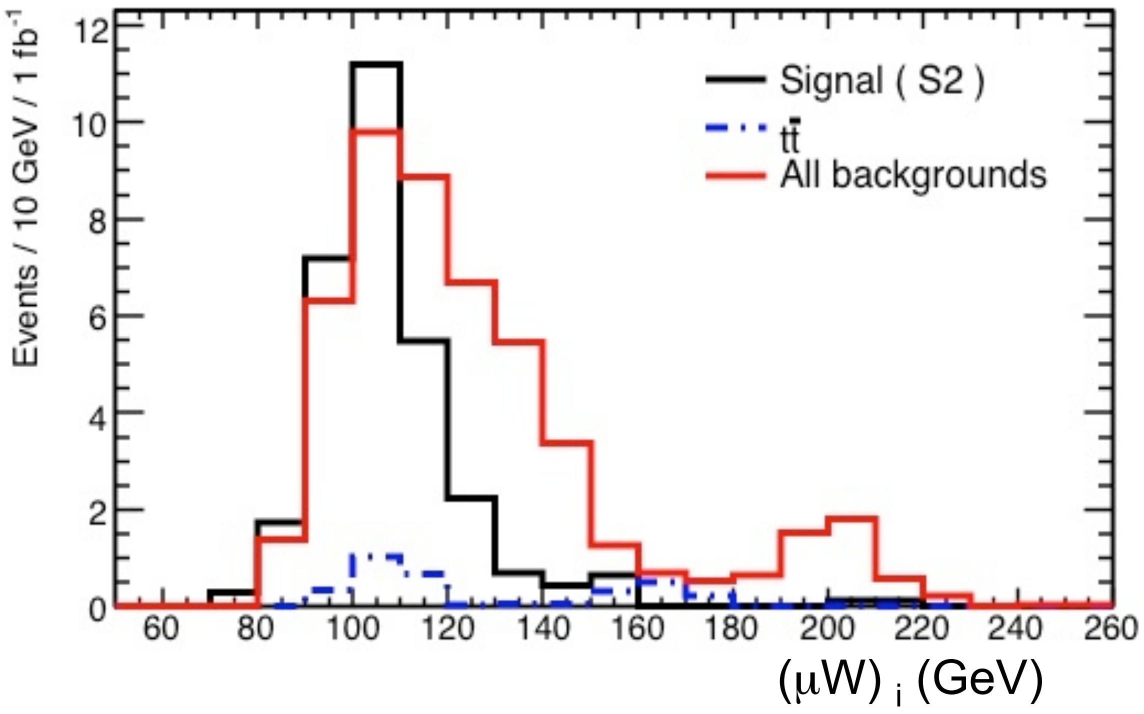
The analysis -5a: Dirac case

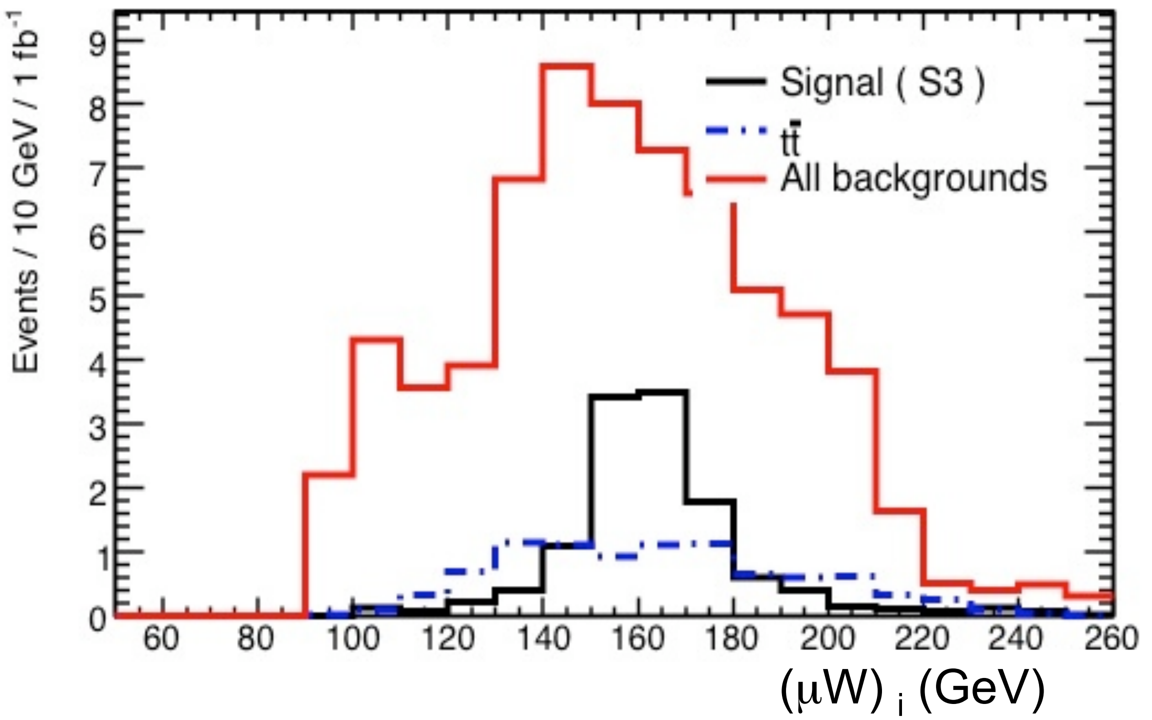
- More signal but much more background too
  - ➡2D sliding cut window applied.

Selection criterion	S1	S2	2μ4j	tt	S3	2μ4j	tt
$Sign(\mu_1)xSign(\mu_2) = -1$	97.3	96.5	99.9	84.5	99.2	99.9	84.5
$\|m_{\mu+\mu-} - m_Z\| > 25$ GeV	79.1	74.1	10.0	67.7	77.6	10.0	67.7
$\Delta R_{\mu\mu} > 2.0$	72.9	65.6	34.3	59.5	74.7	34.3	59.5
$\|\Delta m_{\nu 4}$ (reco) - $\Delta m_{\nu 4}$(true) $\| < 20$ GeV	67.9	60.4	5.5	6.1	39.6	6.06	13.6
Dirac ε_{total}	1.4	1.6	4.5x10^{-2}	2.5x10^{-4}	3.1	5.0x10^{-2}	5.7x10^{-4}

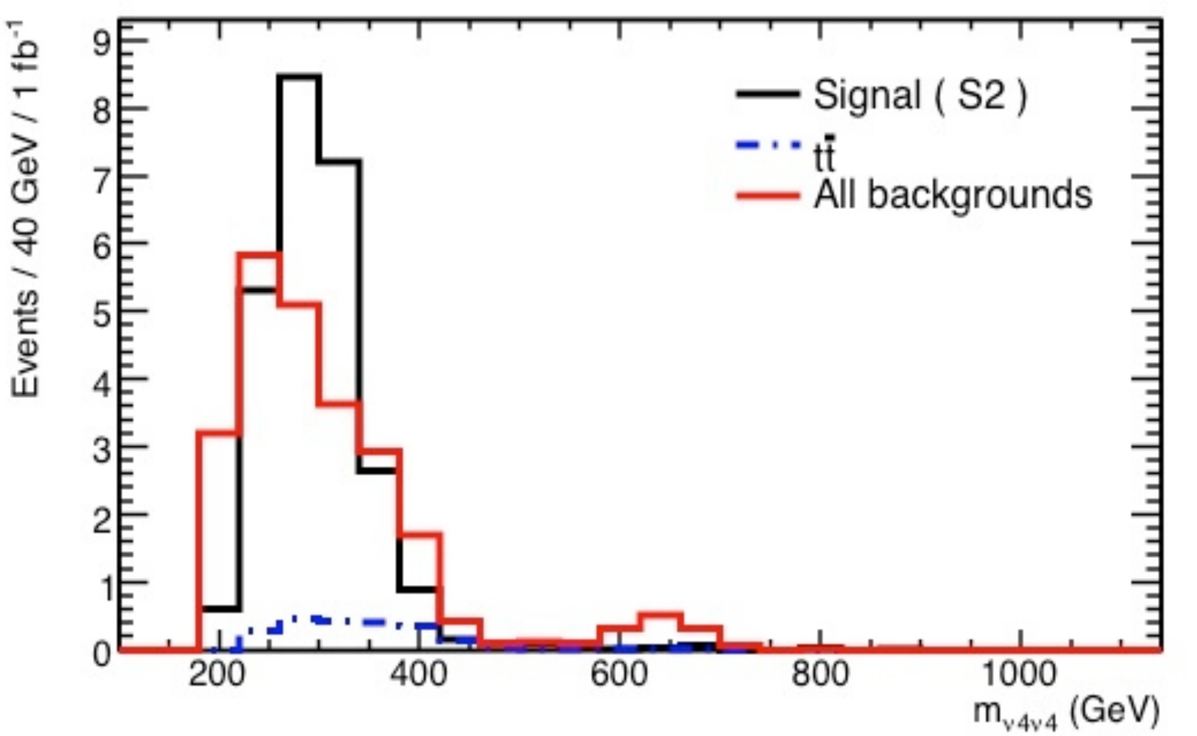


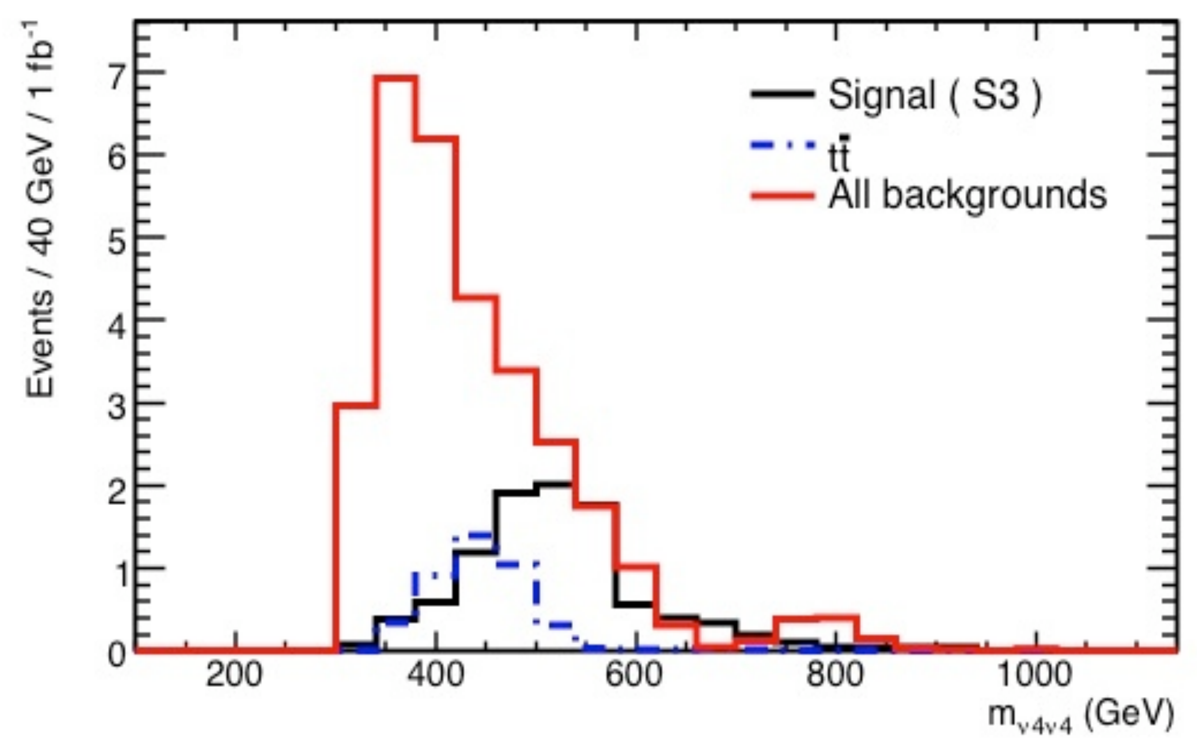
The analysis -5b: Dirac case





Reconstructing also the Higgs mass



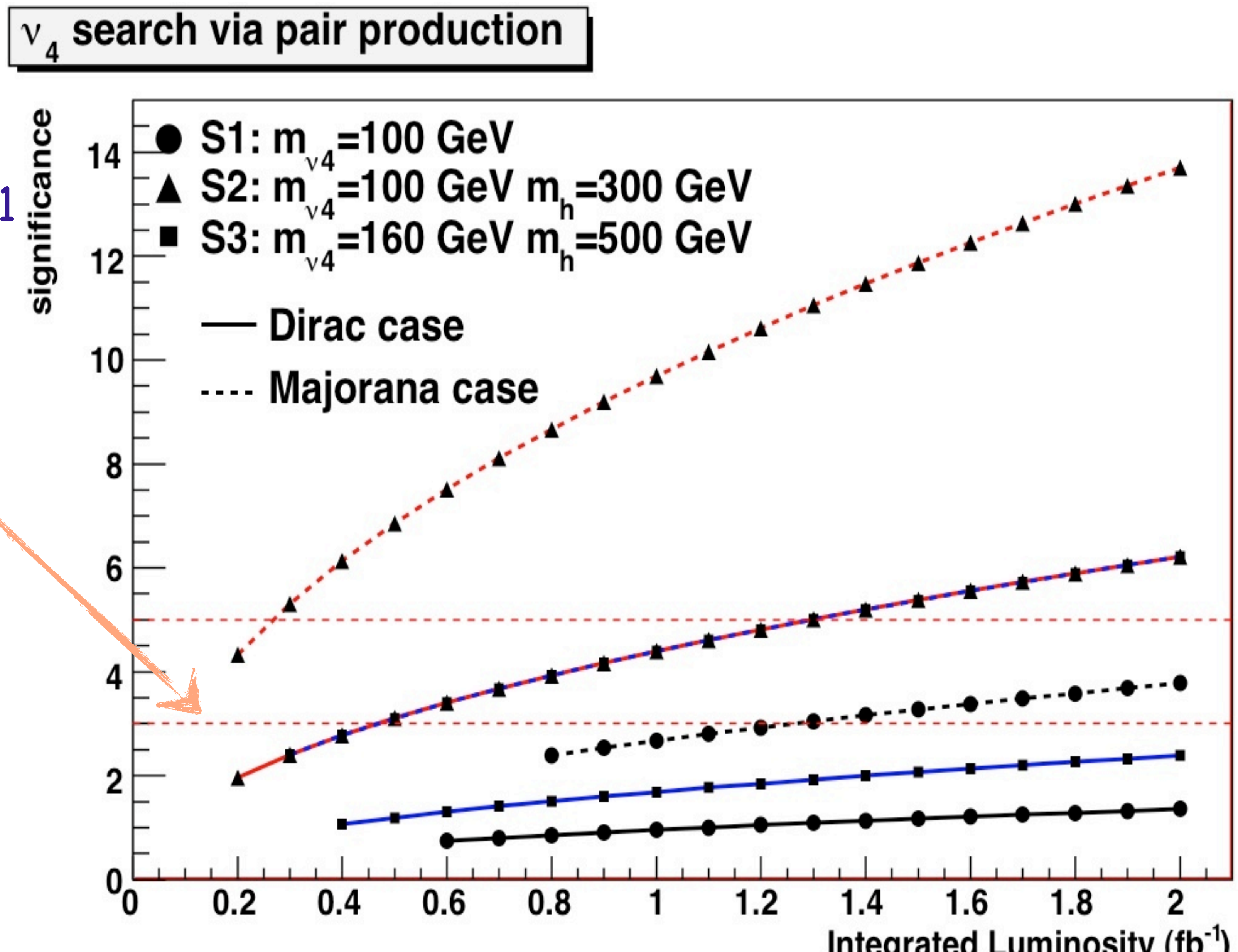


the results -1 : V4 discovery

- Significance definition(details):
  - ➡ events in 4 most populated bins are collected
  - ➡ at least 3 signal events required

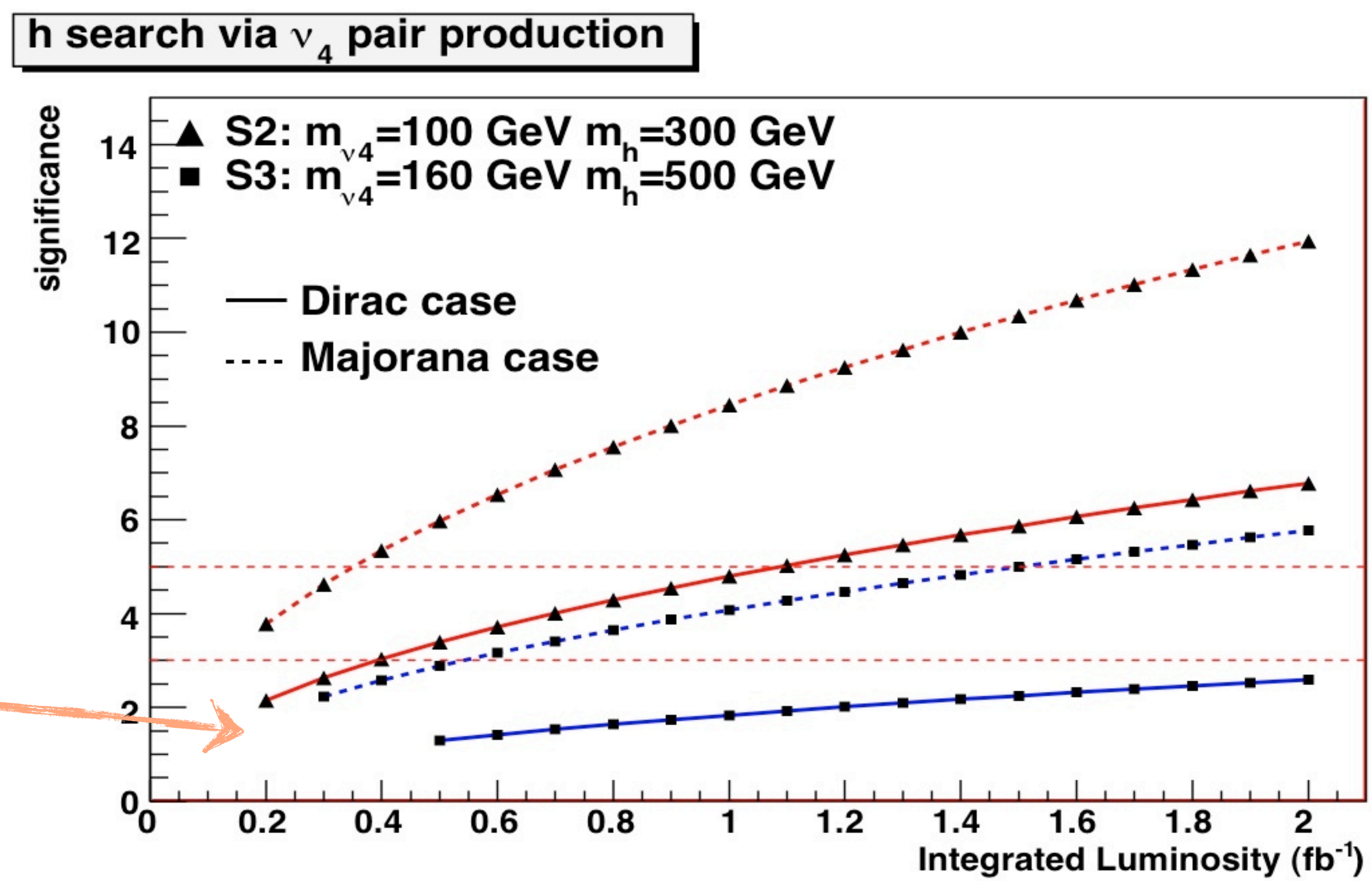
$$\mathcal{S} = \sqrt{2 \times [(s+b)\ln(1+\frac{s}{b}) - s]}$$

- using the first 1-2 fb^{-1}
  - ➡ Majorana v4 is accessible with or without Higgs
  - ➡ Dirac v4 needs Higgs
    - else it might escape undetected



the results -2 : Higgs discovery

- Majorana case:
  - ➡ mh = 300 GeV, 5σ with 0.3 fb^{-1} can be achieved
  - ➡ mh = 500 GeV, 3σ with 1.5 fb^{-1} can be achieved
- Dirac case: requires ~2x more luminosity to achieve the same significance



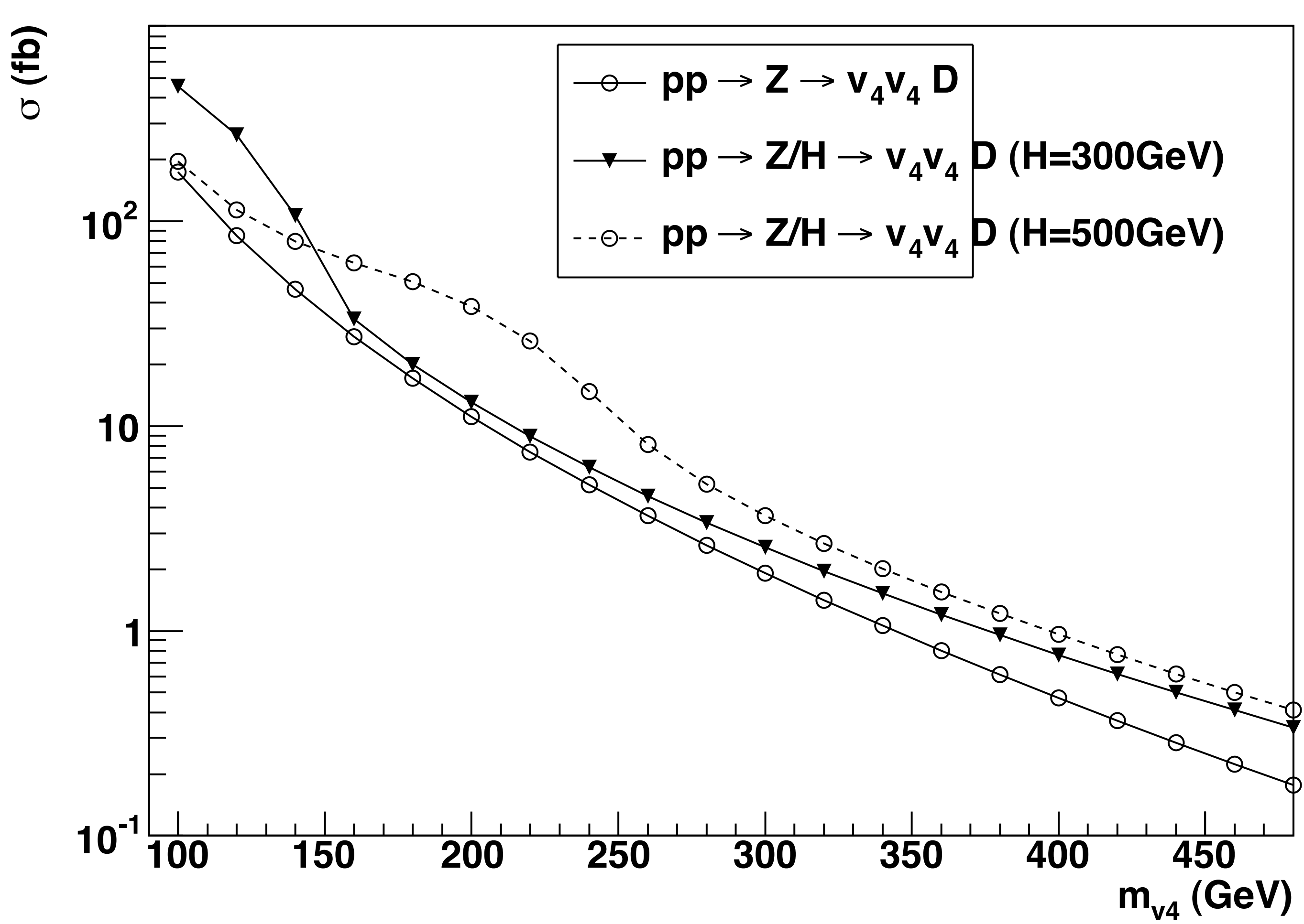
➡ at least 3 signal events required.

Conclusions & 7 TeV prospects

- Majorana case seems more promising than Dirac case
- 14 TeV with the first 1-2 fb-1 of data,
  - ➡ v4 discovery via Z only: seems difficult
  - ➡ v4 discovery via Z+H : seems possible
  - ➡ Higgs discovery via v4 : seems possible
- 7 TeV prospects, a simple estimation for S2-Majorana
  - ➡ Signal x-section: ~250fb vs 1583 : reduced 6.3 times (25-->4 evts/fb^{-1})
  - ➡ main bg is ttbar : x-section reduced 5.8 times (3.1-->0.5 evts/fb^{-1})
  - ➡ Significance > 3σ (CMS/poisson) BUT: tough job with very few events

v4-v4 production cross section

7 TeV



The charged leptons

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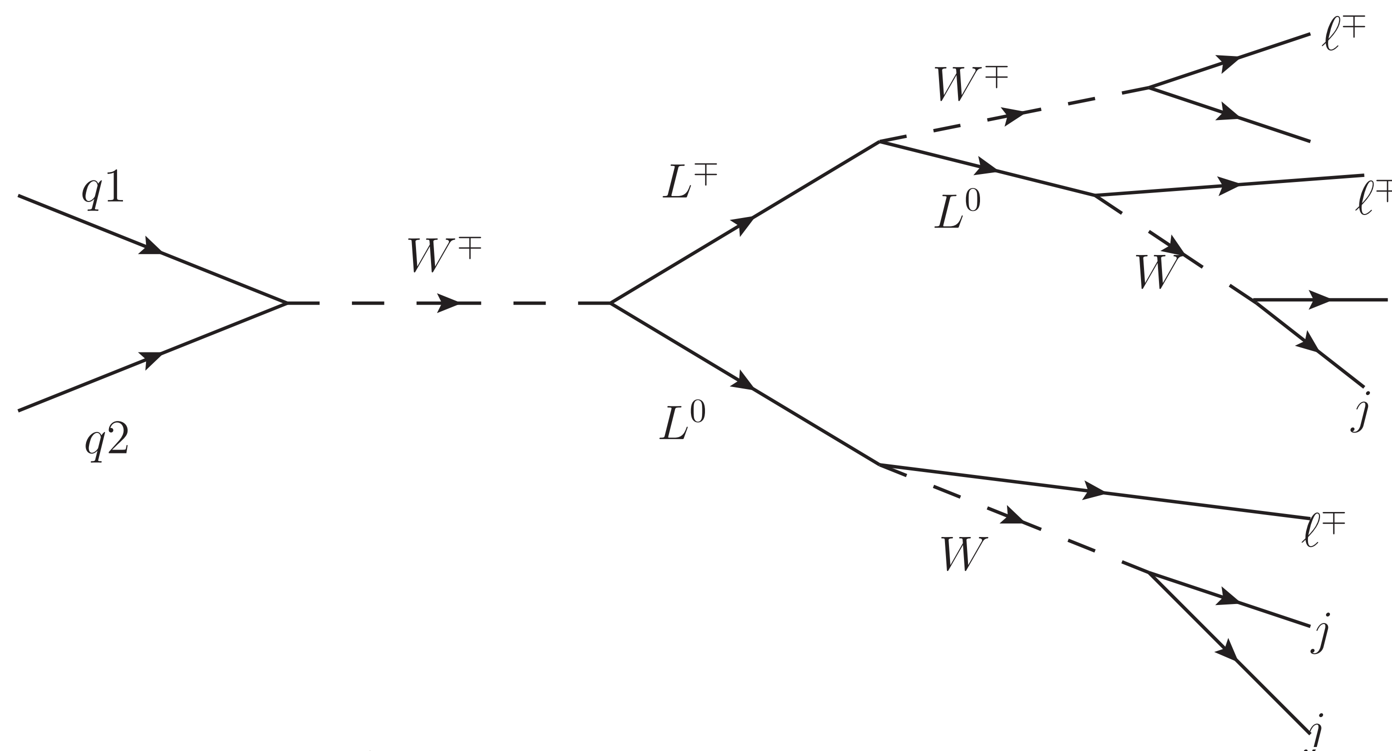
- Do we need a LC to find the charged Leptons?
- LHC has a chance, if
  - ➡the neutrino is of Majorana nature
  - ➡$m_{\text{charged lepton}} > m_{\text{neutral lepton}}$
- via 3 same sign lepton final states.
  - ➡assume BR($L^{\pm}\to L^0 W$)≈1 & BR($L^0\to\mu W$)≈0.68
  - ➡The effective BR≈0.012
    - (2μ+1e / 3μ) + 4jets + MET

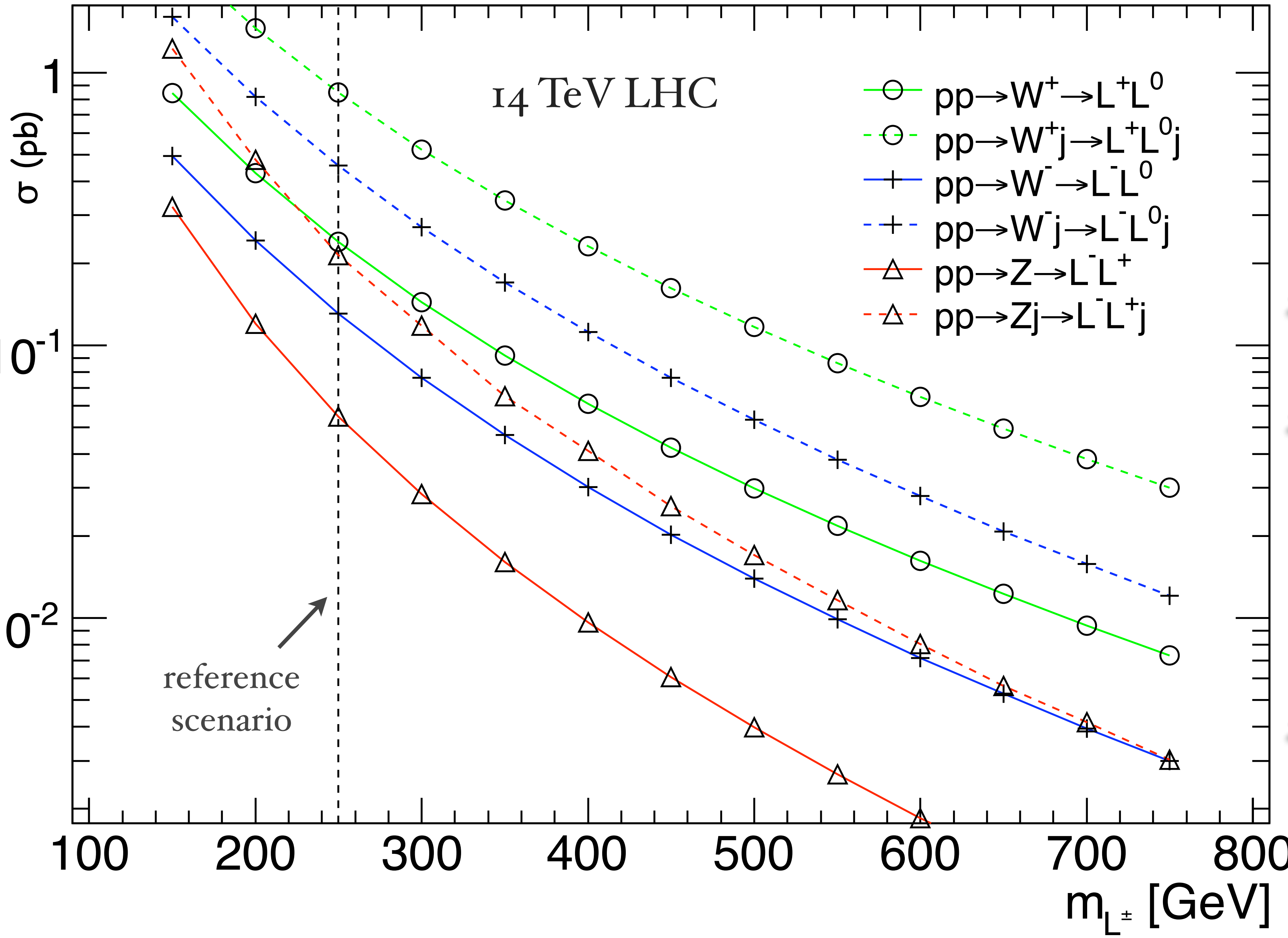
$$pp\to L^{\pm}L^0\to WL^0L^0\to W_{l\nu}W_{jj}\mu W_{jj}\mu$$



Notation:
L^0 instead of ν4
$L^{\pm}$ instead of e4

Model independent study: Results can be applied to E6GUT leptons too. (with appropriate σ & BR adjustments)

$e_4\nu_4$ Production & Decay



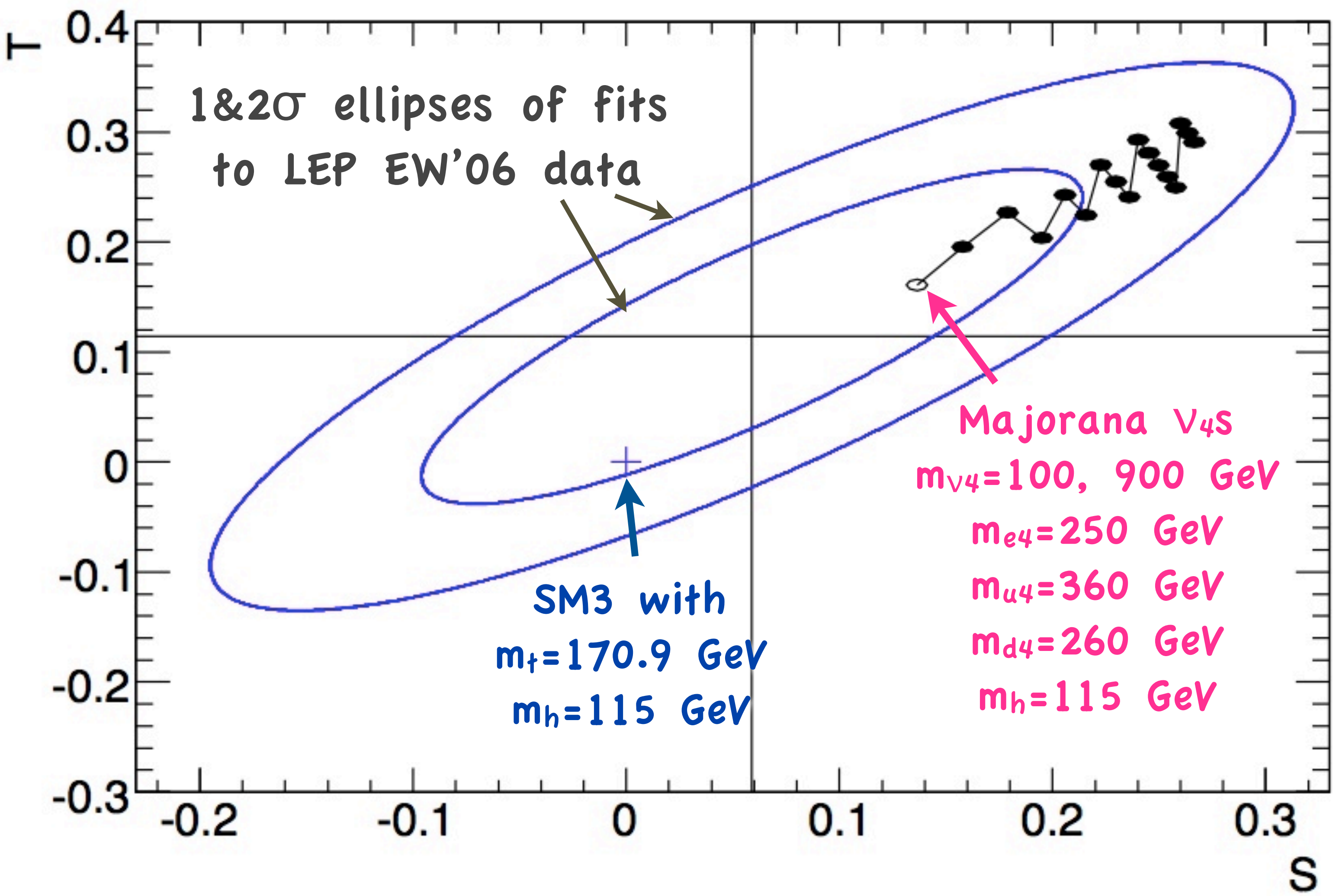
- Majorana neutrinos 100 & 900 GeV (Equivalent m_{Dirac}=300GeV)
- Ref. scenario me4=250GeV σ≈1.6pb
  - Consider both L^+L^0 & L^-L^0
  - Consider the leading order + 1 jet
- The final state has 2μ +3W:

  $pp \rightarrow e_4\nu_4 \rightarrow W\nu_4\nu_4 \rightarrow W_{l\nu}W_{jj}\mu W_{jj}\mu$

  yielding **18 events/fb^{-1}**

  (E6GUT leptons: 21 events/fb^{-1})
- The expected SM background=0
  - beware of the fakes!!!

how likely is this?



Black solid circles represent m_h going from 150 to 900 GeV in steps of 50 GeV, while the best value of m_{u4} goes slowly up to 390 GeV.

- Refer to EW precision data via OPUCEM
  - ➡Implemented exact one-loop calculations from:
    - B.A.Kniehl & H.G.Khors, PRD48(1993)225.
    - H.J.He, N.Polonsky & S.F.Su, PRD64(2001)053004.
- Reference scenario can accommodate light or heavy Higgs alike.
  - ➡maybe more likely than SM...

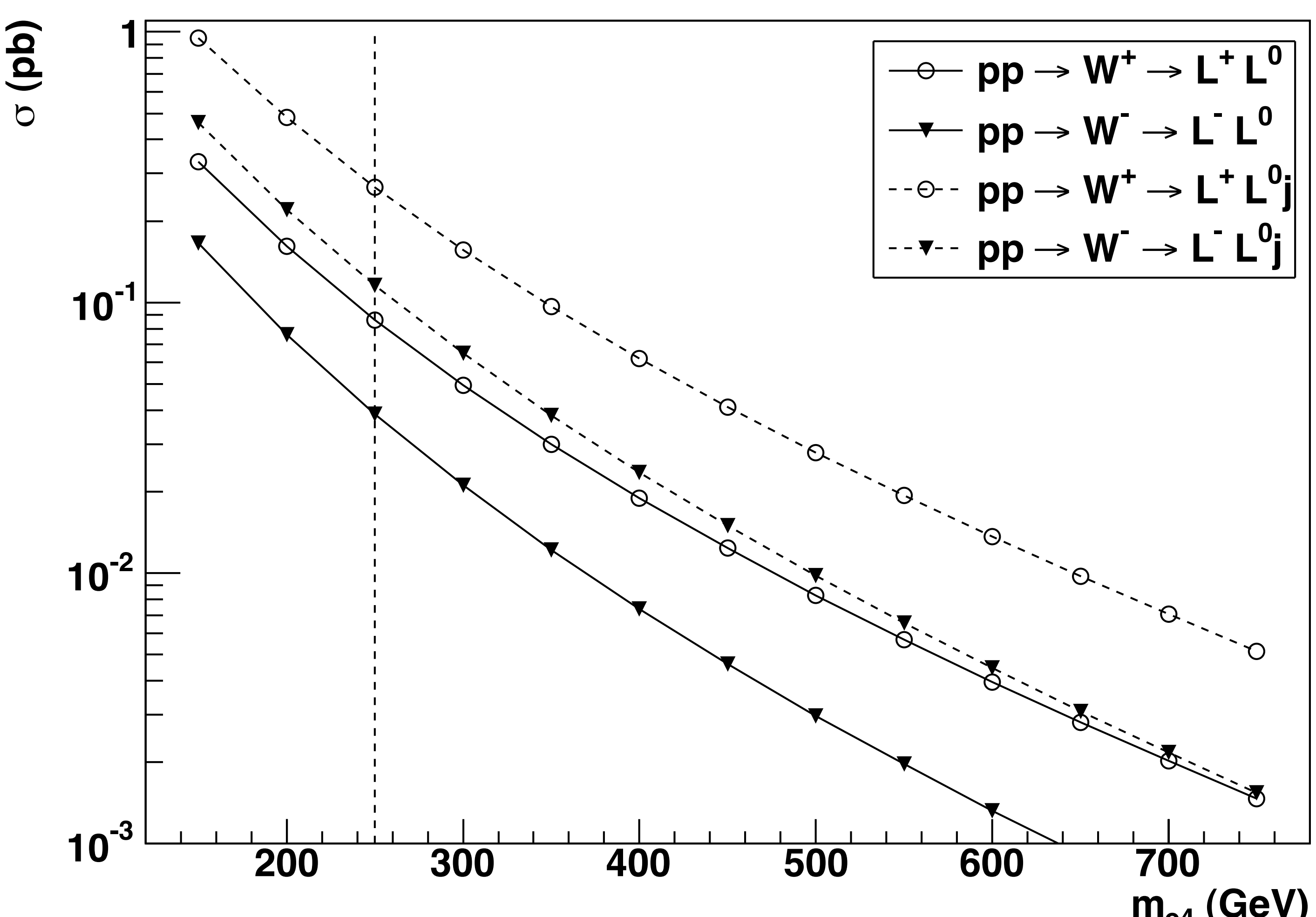
results & 7 TeV considerations

- Acceptance: $P_T^{e/\mu}$>10 GeV $|\eta^{e/\mu}|$<2.5
- For trigger: One lepton with $P_T^{e/\mu}$>20 GeV
- Estimate fakes using pythia & madgraph (ATLAS parameters)
  - $\nu \ell^\pm \ell^\pm \ell^\mp \not\Rightarrow \nu \ell^\pm \ell^\pm \ell^\pm$: 0.04/fb^{-1}
  - jets as leptons (using k_T-jets in W+jet events): 0.01/fb^{-1}
  - leptonic Ws + 2bs from ttbar faking the signal: 0.17/fb^{-1}
    - $R_{\ell j}$>0.05, $R_{\ell\ell}$>0.2, $MTD_{\ell\ell}$>0.4mm

ε_{signal}≈40%:
7 signal vs 0.22 bg events/fb^{-1}
(over 5σ)

see talk by E.Ozcan for BG & fake estimation details

e4-v4 production cross section



- @ 14 TeV vs 7 TeV for me4=250 mv4=100GeV
  - ➡ signal: 1.6 pb vs 0.51 pb
  - ➡ tt: 750pb vs 130pb
  - ➡ factor 3.1 in signal vs factor 5.8 in bg
- estimations for 7TeV 1fb^{-1}
  - ➡ 3 signal vs 0.04 bg evts
    - ‣ other BGs scale like signal
  - ➡ over 4 sigma

conclusions

- EW observables allow SM4 with Dirac or Majorana-type neutrinos.
- If the 4th generation exists, LHC experiments can also discover its leptons in addition to its quarks.
  - ➡ ν4 pair production for the neutral leptons
  - ➡ e4ν4 associated production for charged leptons
- In particular Majorana neutrinos are promising for early data:
  - ➡ Searches can start with as low as a few hundred pb^{-1}.
  - ➡ Double discovery with Higgs possible via the Higgs "silver" channel.
- If LHC reveals the signals, the detailed study can be made @ a LC.
- Bonus
  - ➡ Searches can be applied to other models as well (e.g. E6GUT).

- Thank you for listening...
- Q. & A.
- Backup slides

Democratic Mass Matrix

Same Yukawa Couplings for all fermions

- ➡ Higgs should be flavour blind
- ➡ mass matrix should have same coefficients (1)

$$a^d \approx a^u \approx a^\ell \approx a^\nu \quad \approx \quad a$$
$$e = g_W \sin\theta_W \quad < a/\sqrt(2) < \quad g_Z = g_W / \cos\theta_W$$

Diagonalize NxN matrix which has all entries as 1.

- ➡ (N-1) EigenValues = 0 ; Nth eigenvalue = N
- ➡ One is left with M4 >> M3,M2,M1
- ➡ current masses are perturbations to this scheme

$$a\eta \begin{bmatrix} 1 & 1+\gamma & 1+\beta & 1-\beta \\ 1+\gamma & 1+2\gamma & 1+\beta & 1-\beta \\ 1+\beta & 1+\beta & 1+\alpha & 1-\alpha \\ 1-\beta & 1-\beta & 1-\alpha & 1+\alpha+2\beta \end{bmatrix}.$$

- SM3 doesn't fit this scheme $m_{\nu\tau} \ll m_\tau < m_b \ll m_{top}$
- One expects: $m_{\nu 4} \lesssim m_{e4} \approx m_{d4} \approx m_{u4}$
- By the same token a 5th generation is not needed.

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Why should you want a 4th generation

CPV source (for BAU)

- ➡3x3 CKM is 10^{10} too short to match WMAP data
- ➡new quarks of (300) 600 GeV would give (10^{13}) 10^{15} more CPV

Alternative EW symmetry breaking

- ➡4th generation fermion condensate can play the Higgs role
- ➡5D AdS, K.K. excitations of gauge bosons interacting w/ 4th generation fermions => Yukawa couplings & mass hierarchy

Fermion mass hierarchy

- ➡observed masses of fermions in the first 3 families arise from perturbations to a flavour-blind 4x4 mass matrix.

Dark Matter candidates

- ➡hadrons from stable t′, ν′, additional fermions of spin-charge unification models

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OPUCEM Details-1

Oblique Parameters Using C with Error-checking Machinery

- A free and open-source C (C++) library for calculating STU parameters.
- The aim is to provide minimum-dependence code to facilitate the sharing of formulas, such that:
  - ➡ Article authors can provide typo-free versions of their formulas that match their published numerical results.
  - ➡ Cross-checks are done to compare formulas in different papers directly.
  - ➡ Reviews by any interested party is possible.
  - ➡ Further studies can refer to a certain version of the code and future errata can easily be done.
- The following models are implemented
  - new lepton doublets with Dirac-or-Majorana-type neutral leptons
  - new quark doublets
  - SM and 2HDM Higgs boson
  - recalculation of the SM origin in the S-T plane based on reference values of the masses of the top quark and the Higgs boson
  - mixing between 3rd and 4th gen. quarks available
- Hosted on CEDAR Hepforge: https://projects.hepforge.org/opucem/

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OPUCEM details-2

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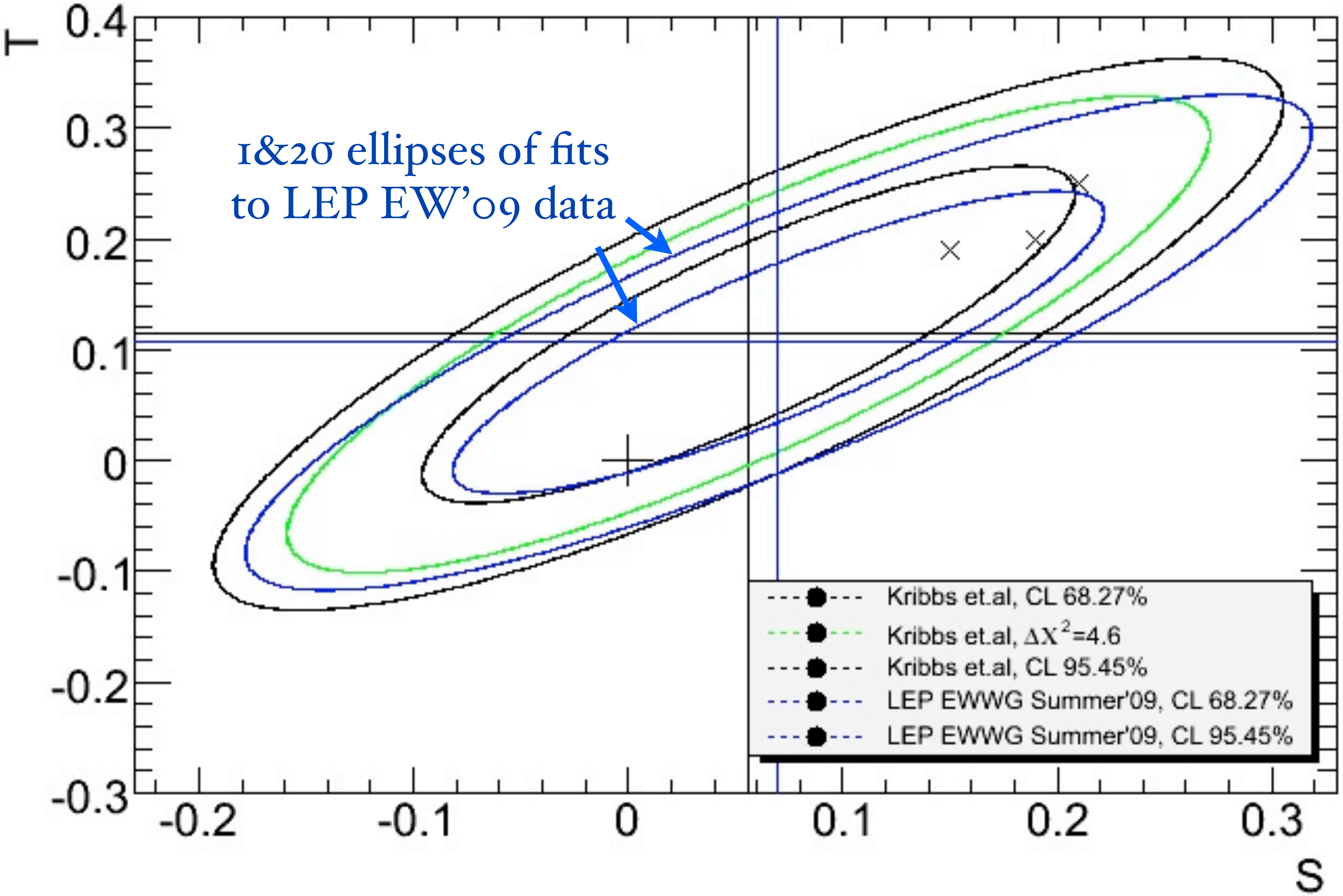
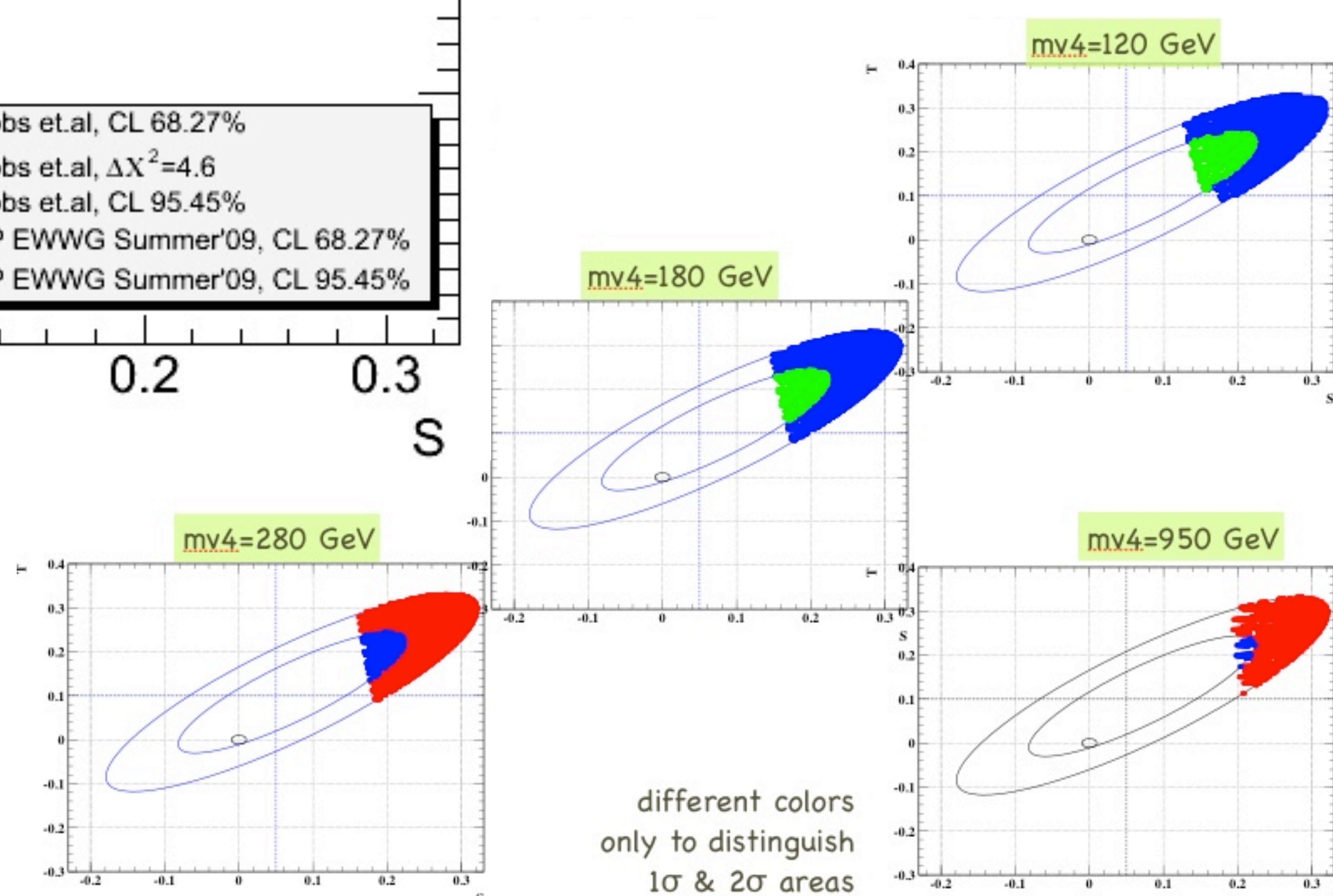


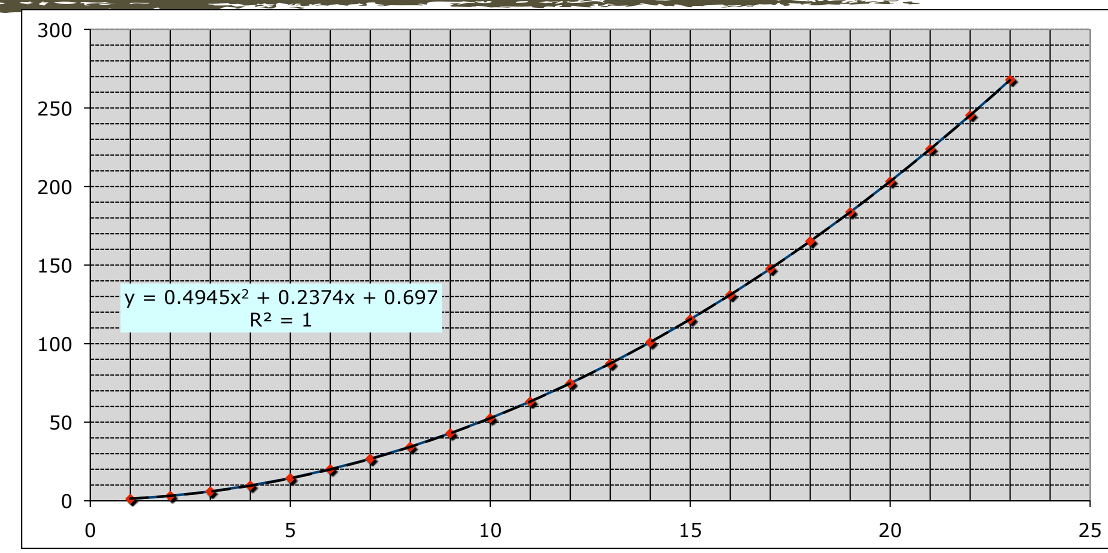


statistics $\sqrt{2[(s+b)\ln(1+\frac{s}{b})-s]}$

probabilities calculated using poisson distribution for small # signal & bg events:

total	15.38	18.7
signal	**7.43**	**10.1**
background	7.95	8.6
probability	0.018989157	0.00858712
- ln prob'	3.963887121	4.75749201

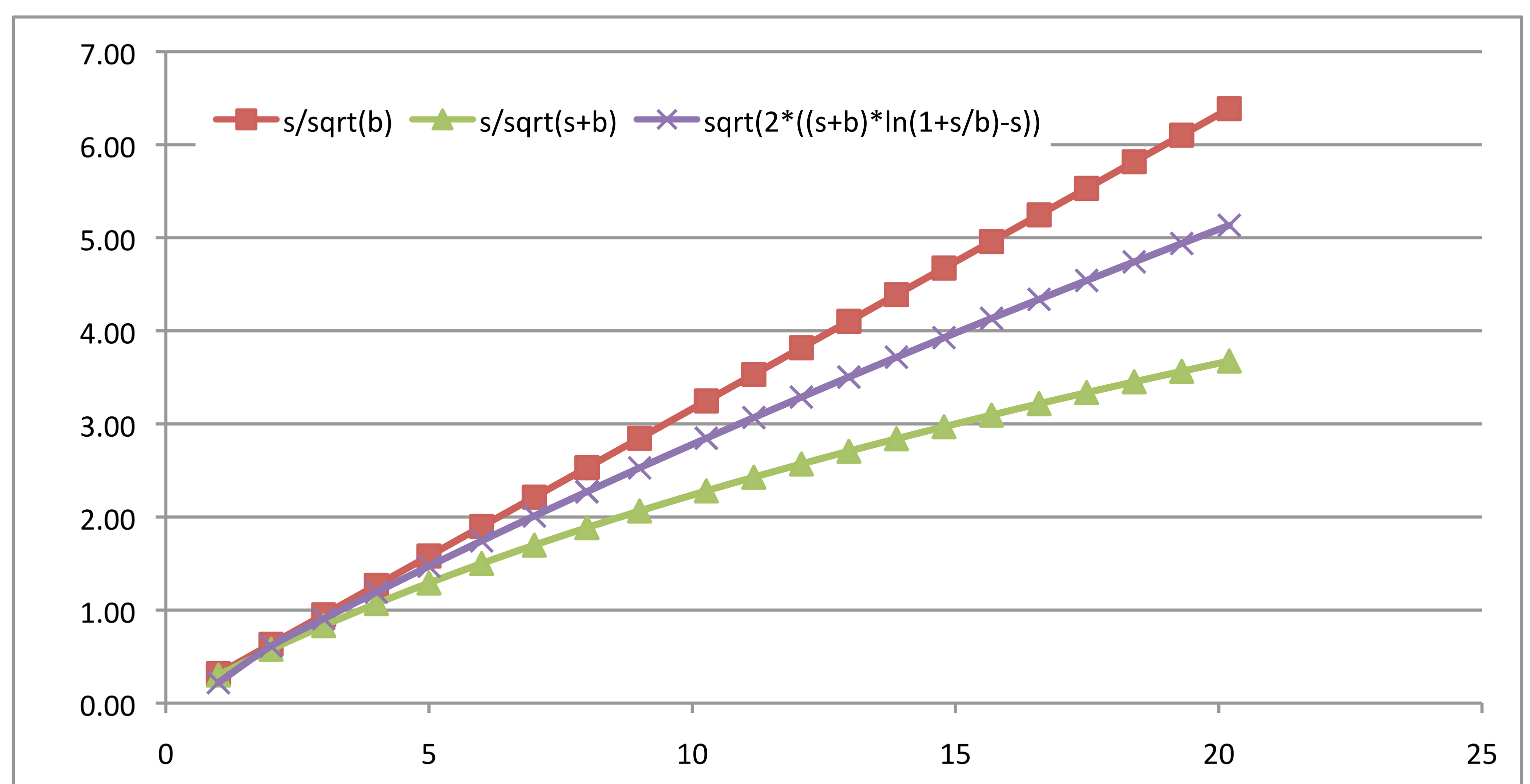
3.9602002	2.34
4.7702032	2.64
"-lnProb(fit)	sigma



Signal	Background	toplam	s/sqrt(b)	s/sqrt(s+b)	sqrt(2*((s+b)*ln(1+s/b)-s))
7.43	7.95	15.3800	2.6351	1.8946	2.3320
10.1	8.6	18.7000	3.4441	2.3356	2.9750

- probability calculated from normalized gaussian distribution and a 2nd order polynomial fitted
- comparing the -ln(p) calculated from poisson statistics to the gaussian curve, one can 'read' the associated σ value, σ_e
- compare σ_e to the results from estimators

significance vs signal (bg=10 events)



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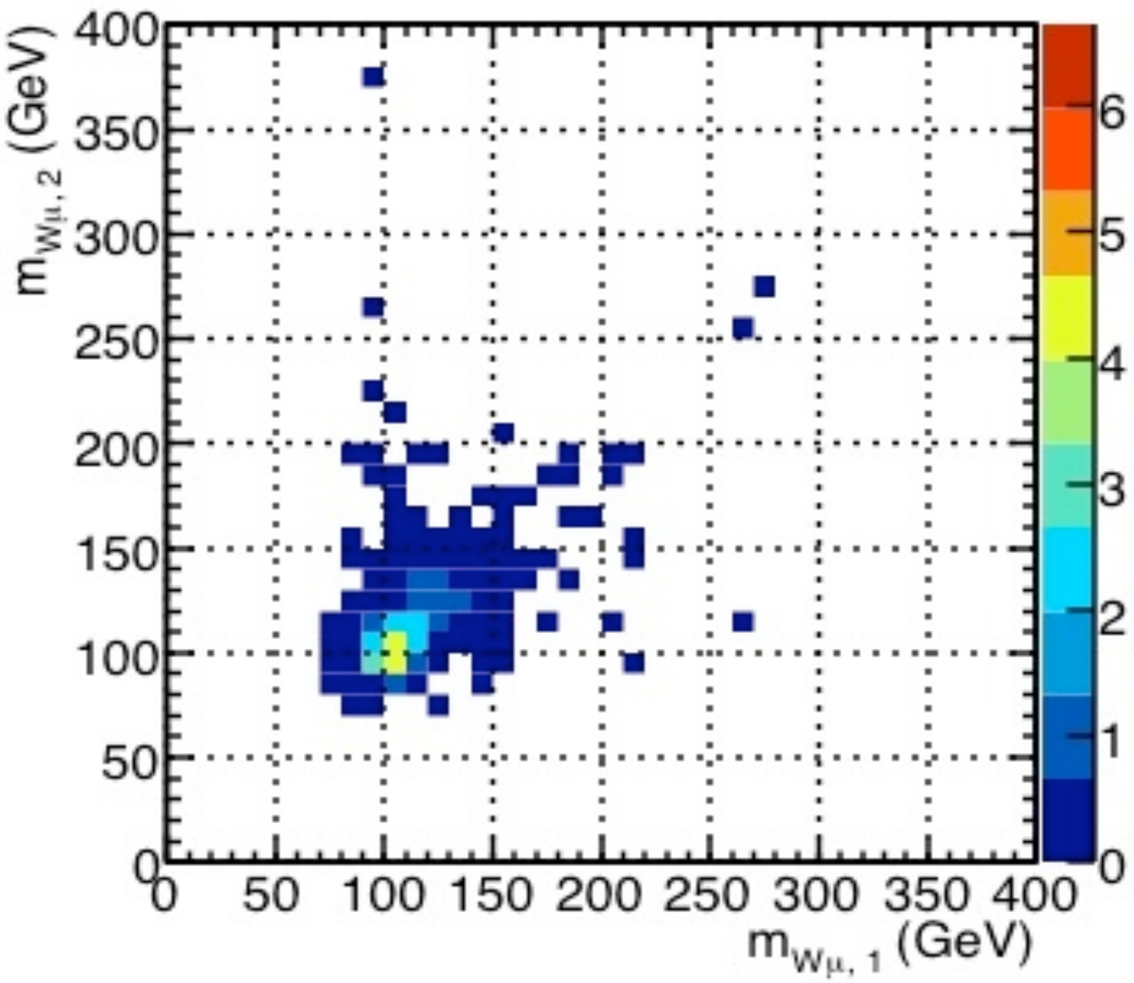
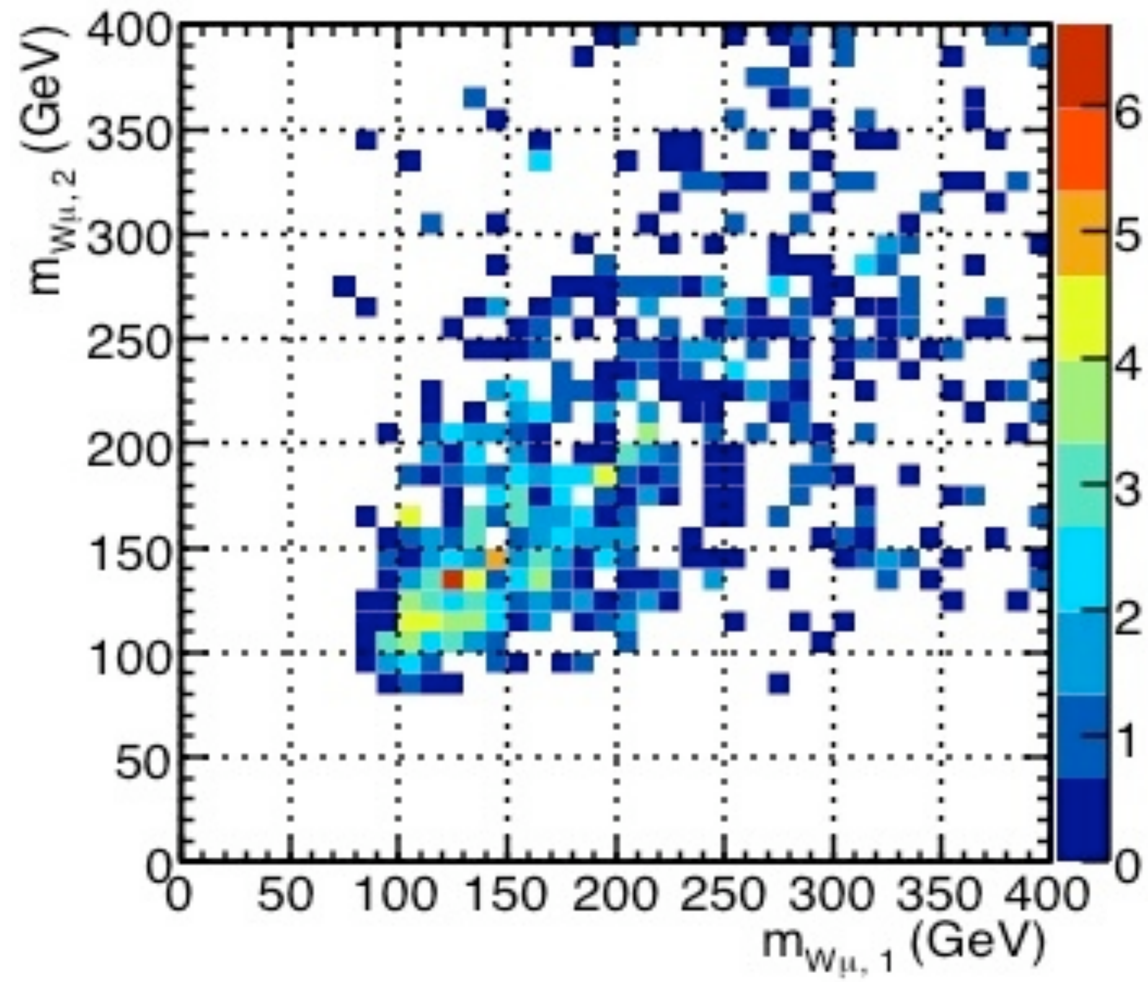
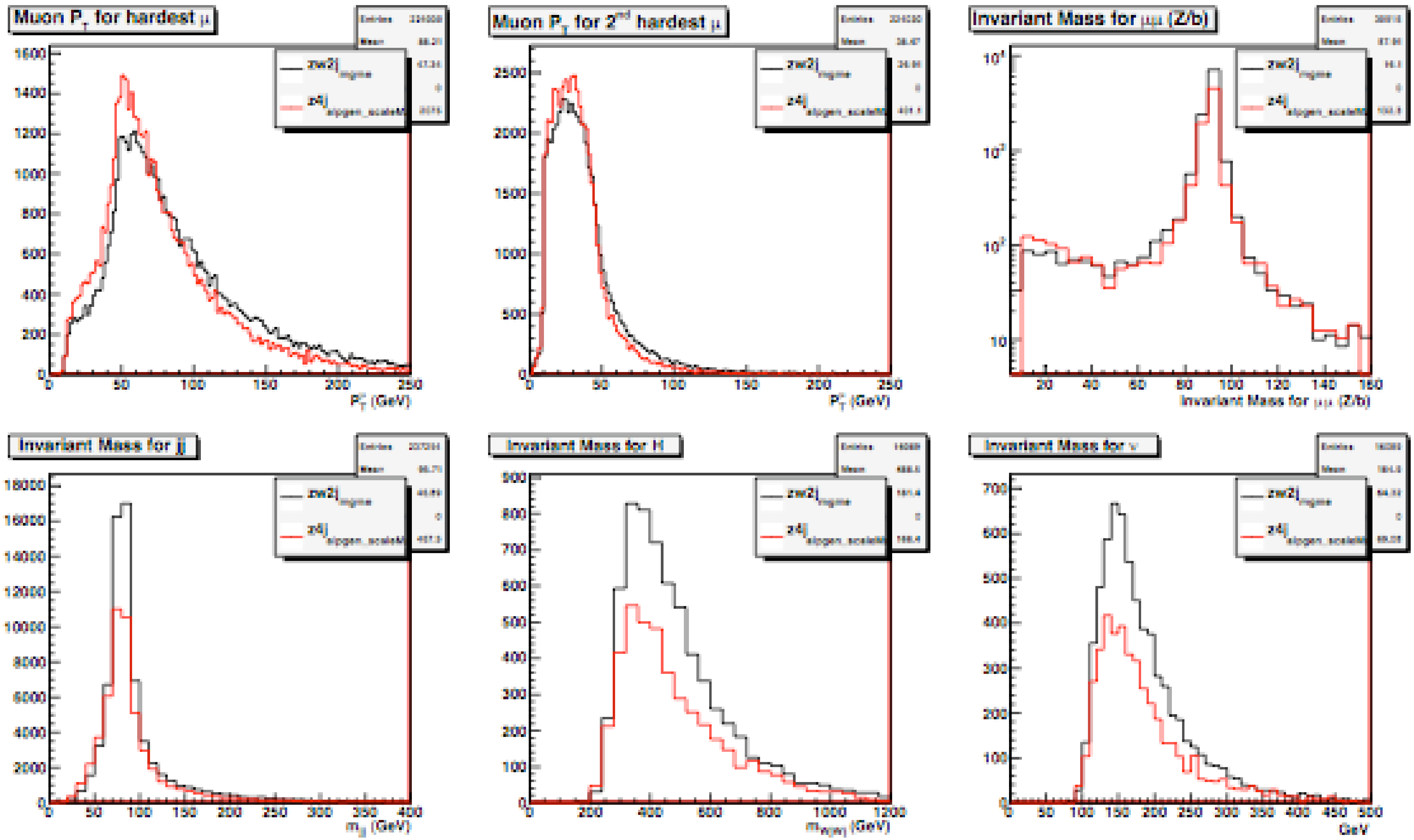
Dirac case details





- 2D sliding mass window for 2 objects of same mass

Compatibility of Generators



- (Red line) : AlpGen : Z/γ + 4j
- (Black line) : MadGraph: Z/γ + W+2j (W→jj) (scaled to AlpGen)

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