ATLAS

# Testing lepton flavour and lepton number violation at ATLAS

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on behalf of ATLAS Collaboration

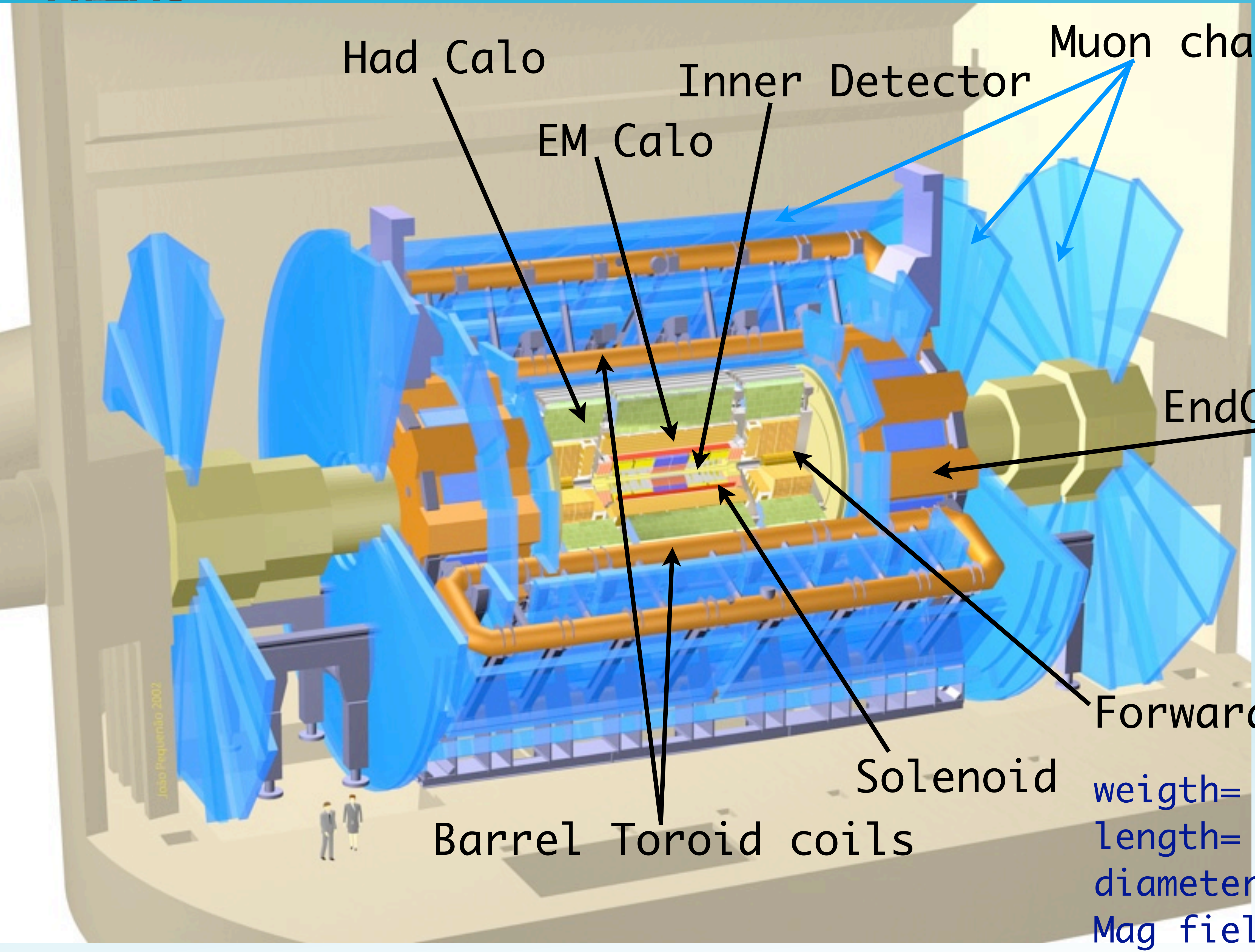
FLAVLHC-09, CERN
December 14th-16th, 2009

# Outline

- ATLAS - generalities
- LHC time table - what we expect
- Motivations for LFV / LNF
- Possible channels & previous studies
  - $\tau \to \mu \gamma$
  - SuSY & Sugra models
  - 2HDM model
  - Double Charged Higgs
  - LR symmetric models
- Outlook

ATLAS

# Detector Overview



Had Calo

Inner Detector

Muon chambers

EM Calo

EndCap Toroid

Forward Calo

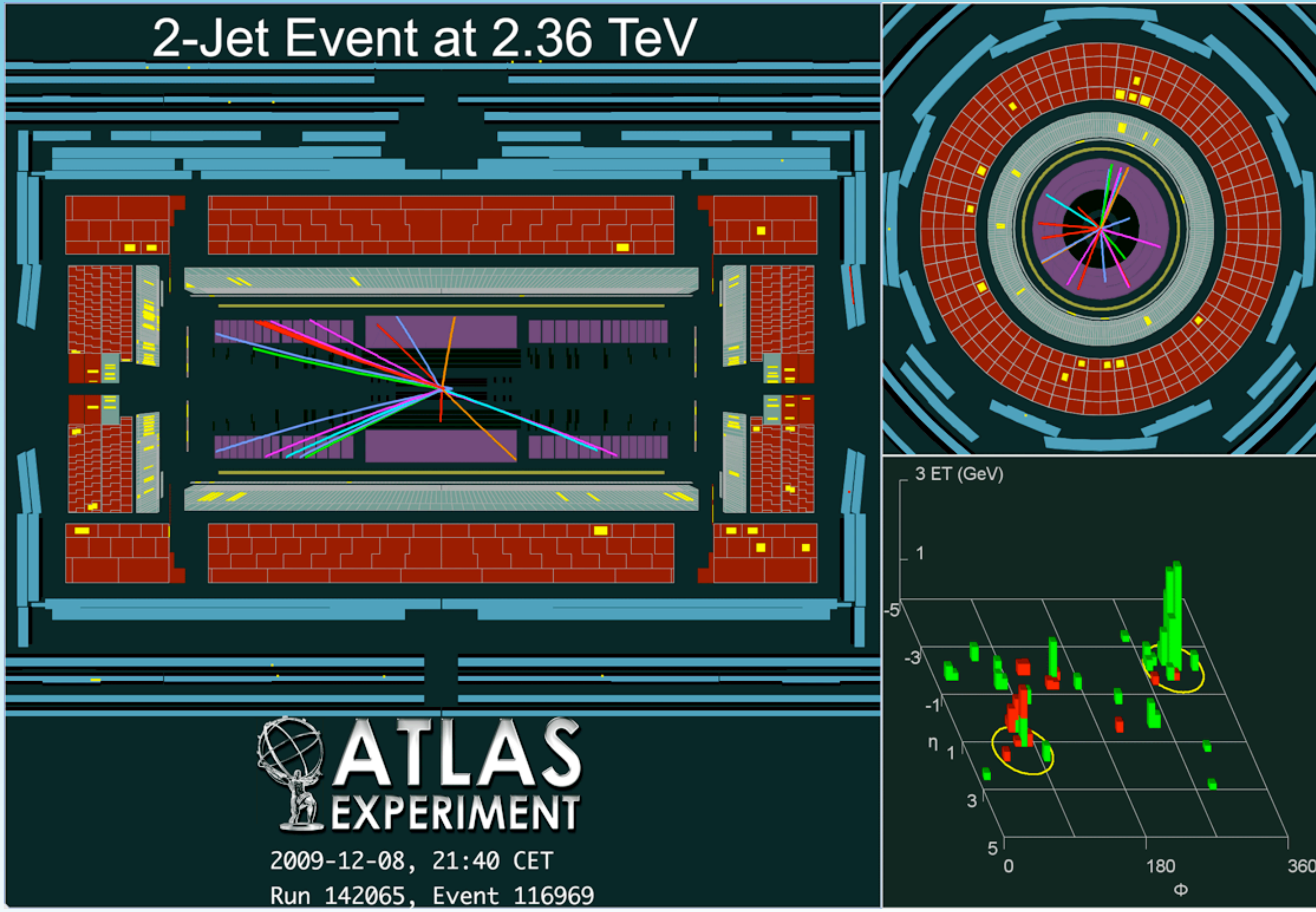
Solenoid

Barrel Toroid coils

weigth= 7 000 Tons
length= 44 m
diameter= 22 m
Mag field = 2 Tesla

# Experiment status

- In most of 2009, ATLAS recorded cosmic rays which were used for calibration & alignment.
- ATLAS has started taking beam data
    - all sub-detectors are active, providing data
    - collisions √s=2.36TeV are recorded.
        - Display of a 2-jet candidate with uncalibrated ET of 23GeV & 16GeV and η of -2.1 & 1.4, respectively.
    - collisions with stable √s=900GeV are being recorded.



# LHC Schedule

- initial period:
  - late 2009: first collisions @ $\sqrt{s} = 0.9$ TeV
  - 2010 collisions @ $\sqrt{s} = 7$ TeV, later $\sqrt{s} = 10$ TeV
  - 2011 collisions @ $\sqrt{s} = 14$ TeV
  - $\mathcal{L}=1.2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, expect 10 $\mathrm{fb}^{-1}$/year, =<u>low luminosity</u>

- nominal runs (after 2011):
  - $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ , expect 100 $\mathrm{fb}^{-1}$ /year, =<u>nominal luminosity</u>
  - Ultimately, $\mathcal{L} = 2.3\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (cryo limited)

- SLHC (after 2020?):
  - $L = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ , expect 1000 $\mathrm{fb}^{-1}$ /year

# LFV Motivations

- Atmospheric/Solar/Accelerator/Reactor experiments all favor Neutrino Oscillations

K2K, accelerator:

$$\nu_\mu \longrightarrow \nu_\tau$$

Kamland, Reactor:

$$\overline{\nu_e} \longrightarrow \nu_x$$

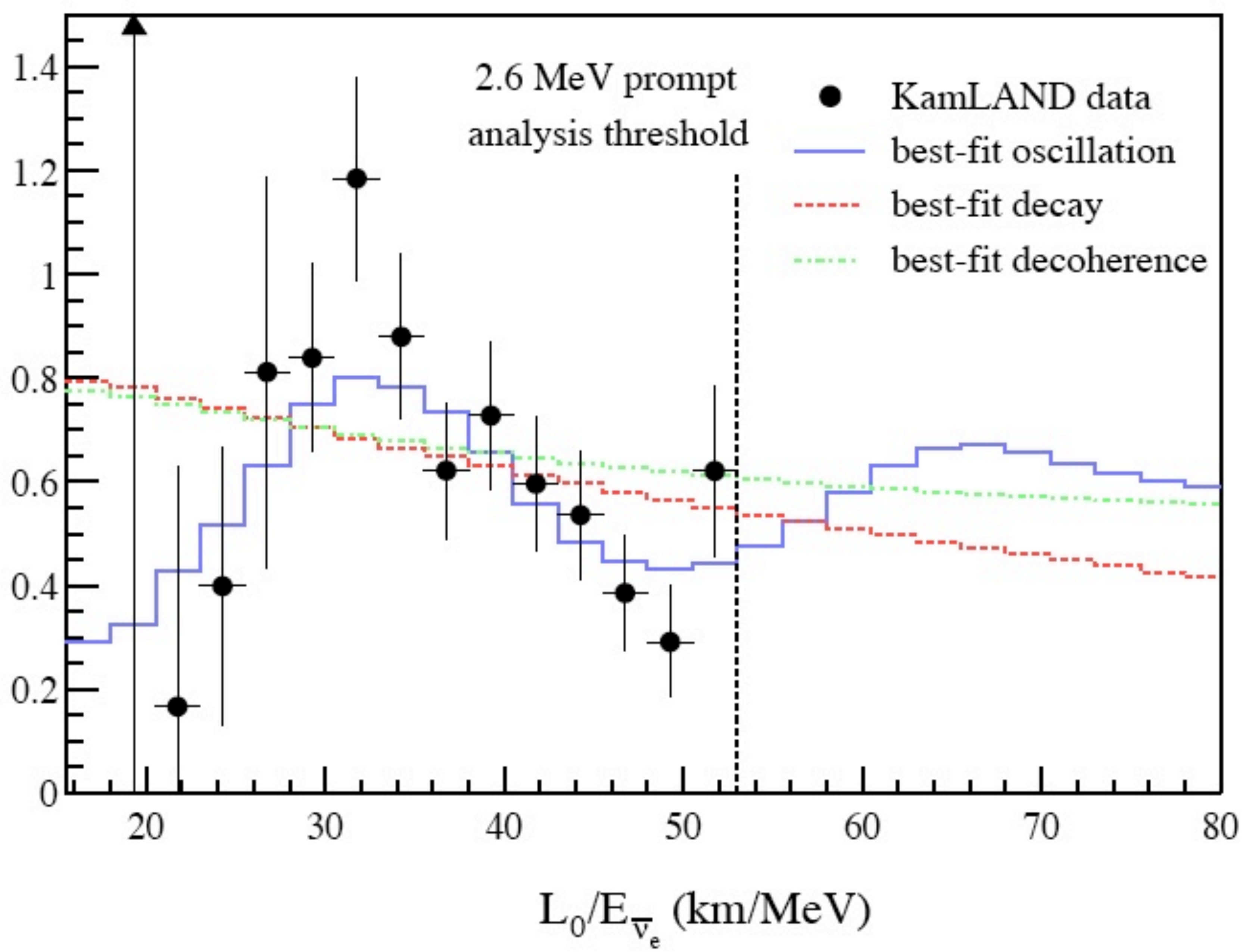
SK2, Atmospheric:

$$\nu_\mu \longrightarrow \nu_\tau$$

SNO, Solar:

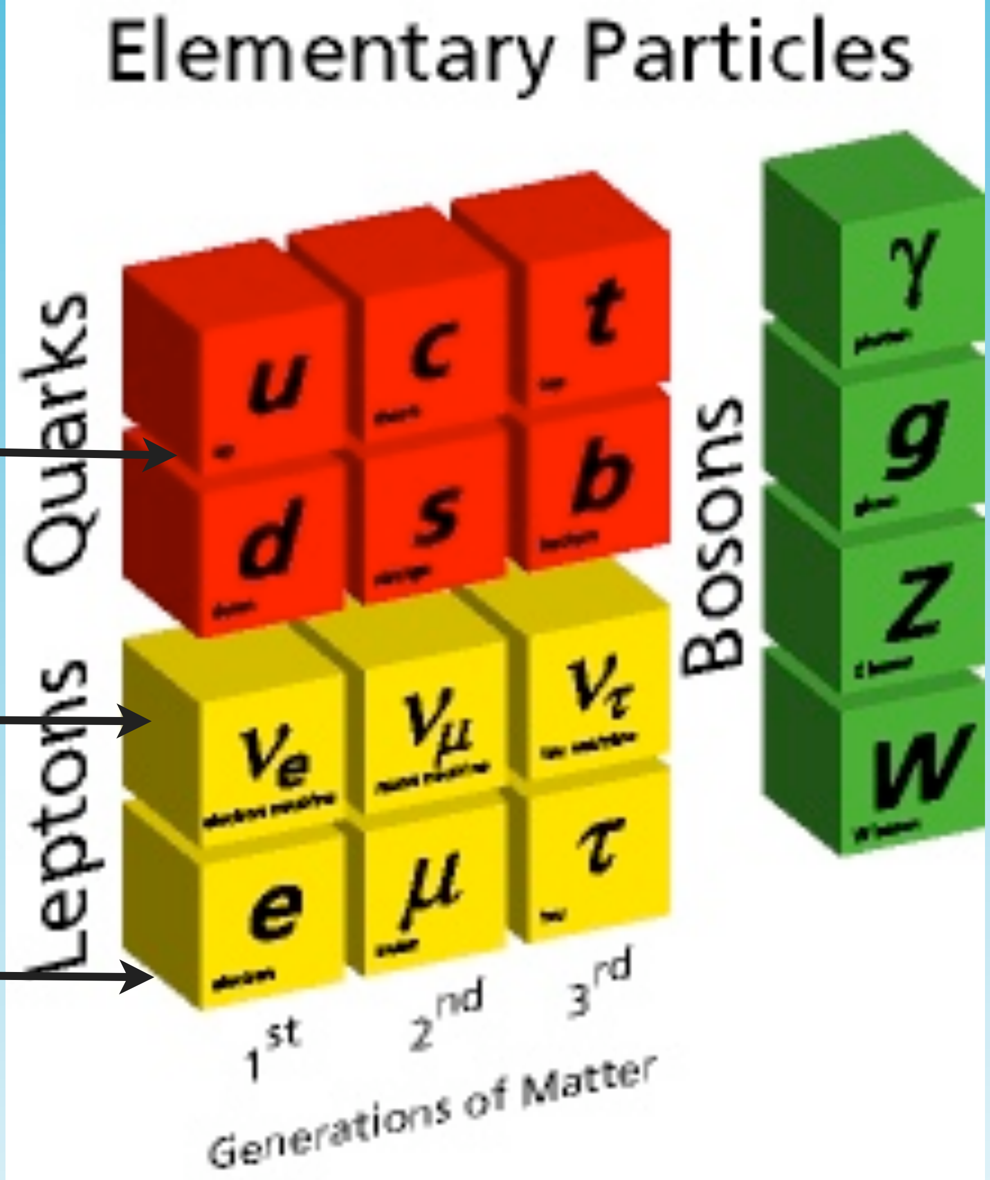
$$\nu_e \longrightarrow \nu_x$$

Phys.Rev.Lett.94:081801,2005



# more motivations

Lepton Flavor Conservation is not a true requirement of the SM !



mixing.

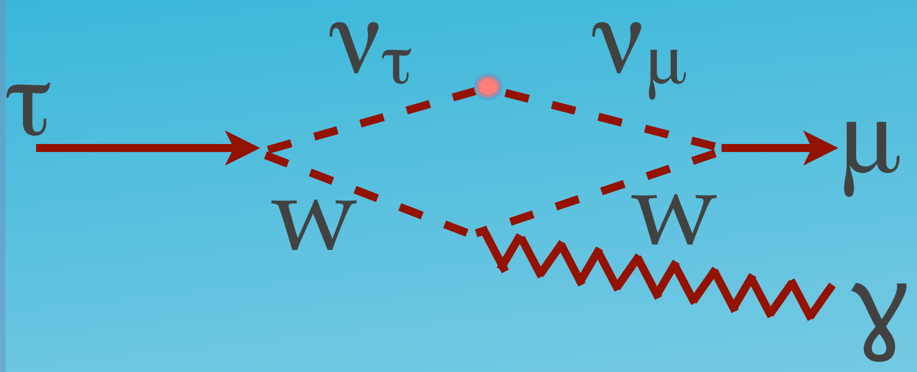
mixing!

mixing?

The same for Lepton Number Conservation if charge conservation can be satisfied or for Majorana fermions.

# LFV diagrams

EW theory from neutrino oscillations:



BABAR collaboration

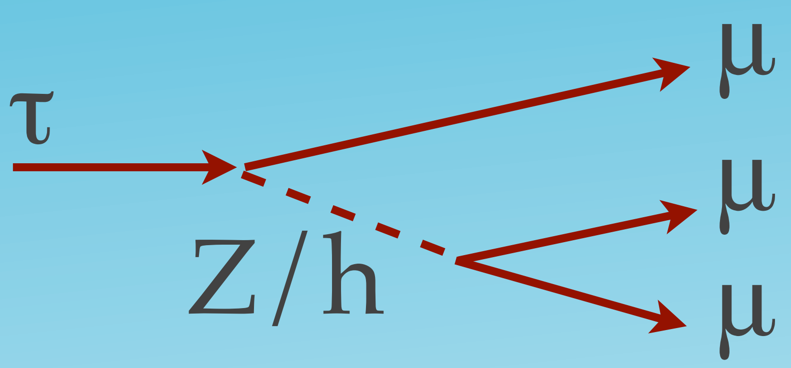
Phys. Rev. Lett. 95 (2005) 041802

BR ($\tau^\pm \to \mu^\pm\gamma$) < $6.8\times10^{-8}$ @ 90% CL

arXiv:0908.2381 (2009)

BR ($\tau^\pm \to \mu^\pm\gamma$) < $4.4\times10^{-8}$ @ 90% CL

if LFV exists, SM:

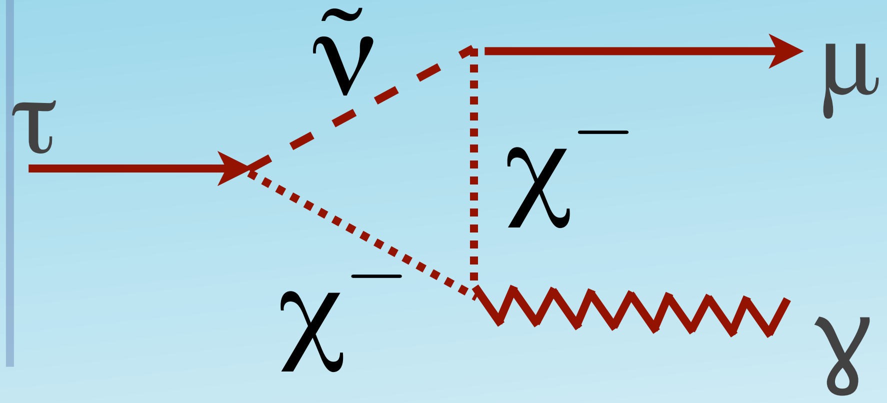


Belle Collaboration

arXiv:0708.3272, proceedings of lepton-photon 2007 & EPS 2007

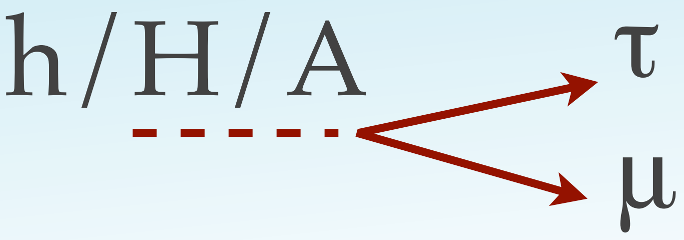
BR($\tau^\pm \to \mu^\mp \mu^\pm \mu^\pm$) < $3.2\times10^{-8}$ @ 90% CL

if LFV and beyond SM exist:



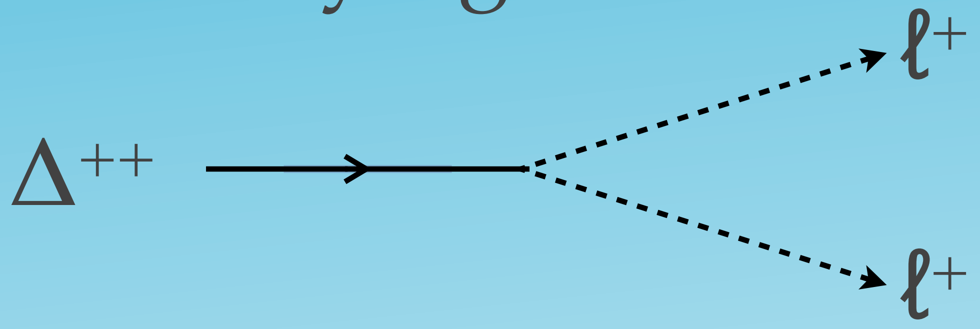
PDG-04

$$\tau \to \mu\gamma < 1.1\times10^{-6}$$
$$\tau \to e\gamma < 2.7\times10^{-6}$$
$$\tau \to \mu\mu\mu < 1.9\times10^{-6}$$
$$Z \to e\mu < 1.7\times10^{-6}$$
$$Z \to \mu\tau < 1.2\times10^{-5}$$
$$Z \to e\tau < 9.8\times10^{-6}$$

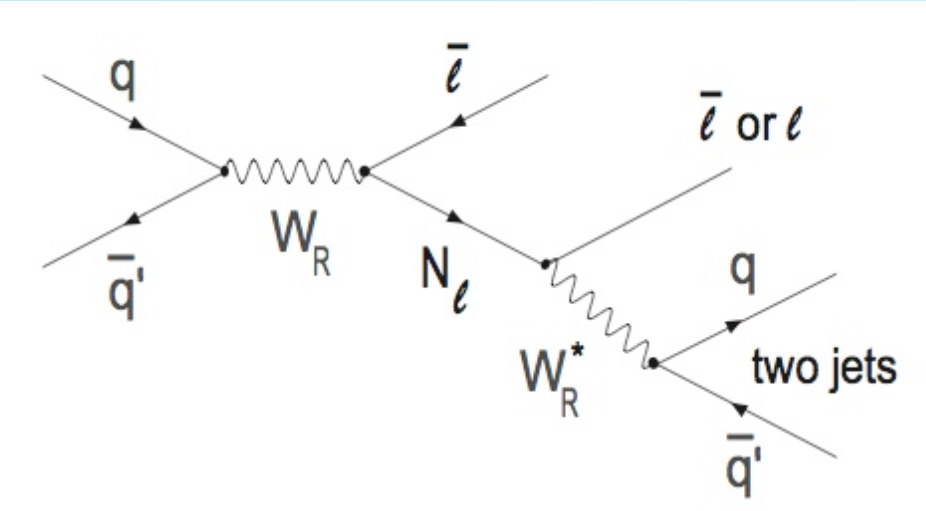


# LNV diagrams

- new particles could give rise to LNV
  - e.g. doubly charged Higgs, $\Delta^{++}$ decaying leptonically



- Majorana Neutrino (N) is its own anti-particle
  - N decay gives LNV 50% of the time



# some signal channels

$$W \rightarrow \tau\, \nu_\tau$$

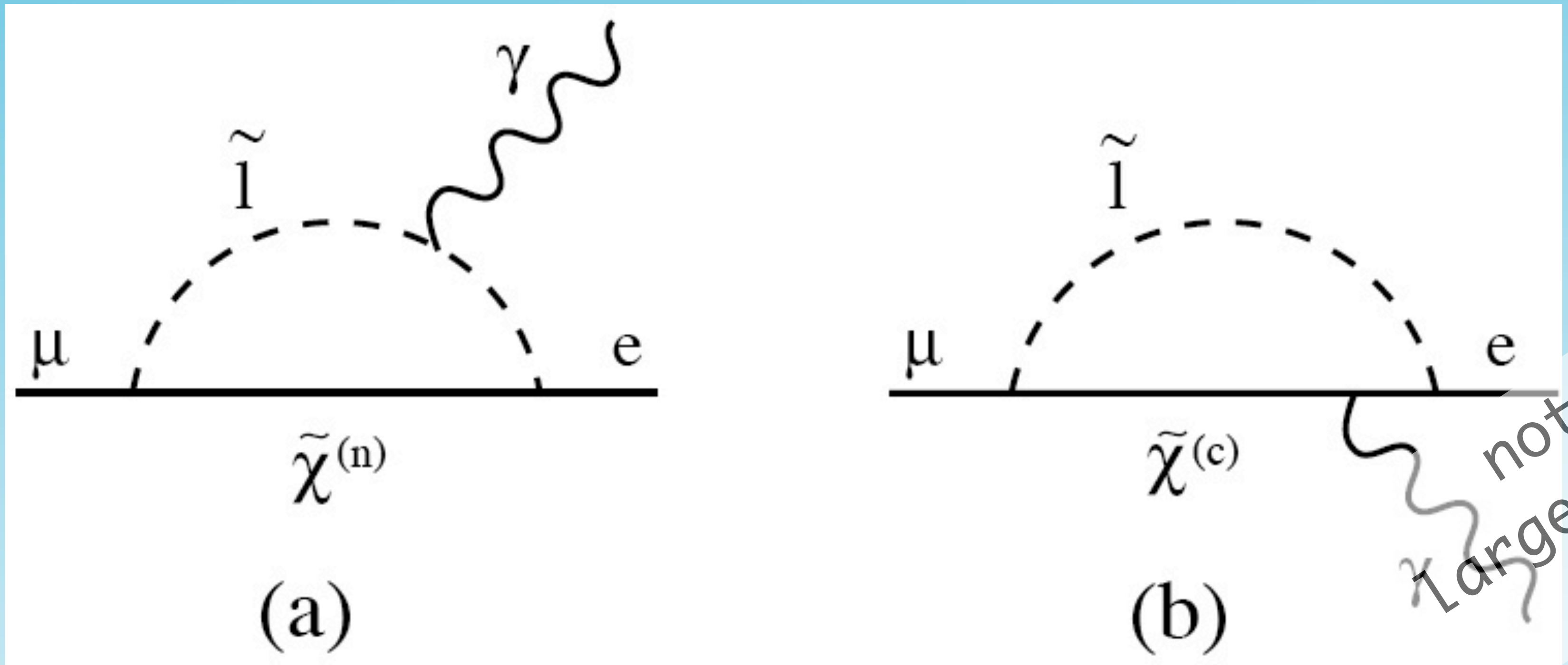
$$Z \rightarrow \tau\, \tau$$

$$B \rightarrow \tau\, \nu_\tau\, X$$

$\tau$ sources

- $\tau \rightarrow \mu\, \mu\, \mu$
- $\tau \rightarrow \mu\, \gamma$
- $\chi_2 \rightarrow \chi_1\, \tau\, \mu$
- $H/A \rightarrow \tau\, \mu$
- $\mu \rightarrow e\, \gamma$
- $\mu \rightarrow e\, e\, e$
- $\tau \rightarrow e\, e\, e$

not feasible
large e background/
small mixing



Eur.Phys.J. C14, 319, 2000

# $\tau \to \mu \gamma$

Source: $q\,\bar{q} \to W \to \tau\,\nu_\tau$

$BR(\tau \to \mu\gamma) < 10^{-6}$

*generator cuts:* $|\eta|_{(\gamma\&\mu)} < 2.5$

$6\ \mathrm{GeV/c} < p_T(\mu)$

$20\ \mathrm{GeV/c} < E_T(\gamma)$

*analysis cuts:* $0.08 < \Delta R$

$6\ \mathrm{GeV/c} < p_T(\mu) < 20\ \mathrm{GeV/c}$

Background from FSR & Radiative production:

$W \to \mu\,\nu_\mu + \gamma$

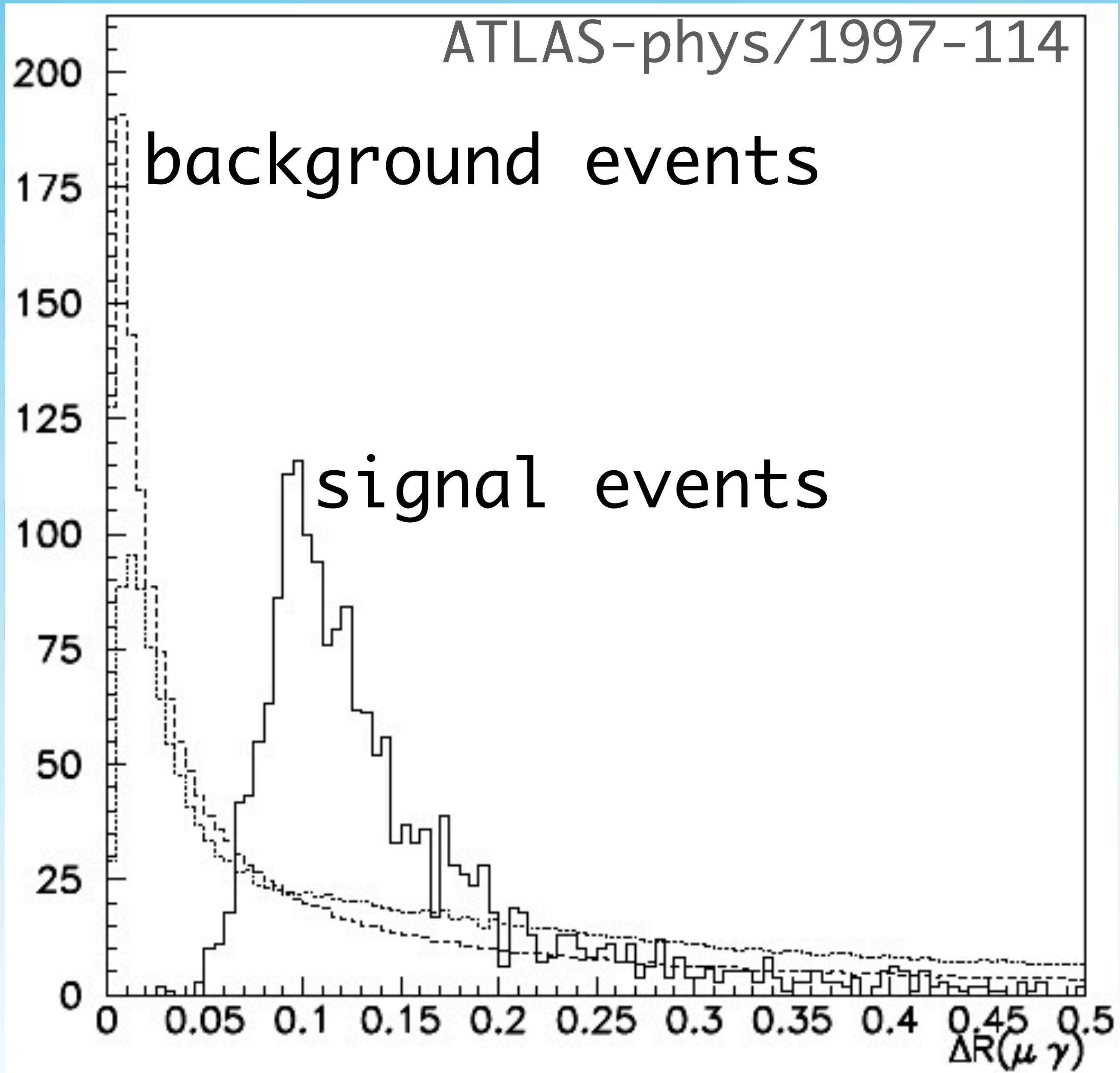
$W \to \tau\,\nu_\tau \to \mu\,\nu_\mu\,\nu_\tau + \gamma$

*Pythia + Photos + Fast smearing was used.*

*low luminosity*

17 bg events/year for $m_\tau$

<8 signal events/year



Phys. Rev. D 63, 115006 (2000)

# susy -1

*Assume 6x6 slepton mass matrix :* $\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$

$$\begin{bmatrix} M_L^2 + D_L & 0 & 0 & 0 & 0 & 0 \\ 0 & M_L^2 + D_L & M_{\mu\tau}^2 & 0 & 0 & 0 \\ 0 & M_{\mu\tau}^2 & M_{\tau_L}^2 + D_L & 0 & 0 & m_\tau \bar{A}_\tau \\ 0 & 0 & 0 & M_R^2 + D_R & 0 & 0 \\ 0 & 0 & 0 & 0 & M_R^2 + D_R & 0 \\ 0 & 0 & m_\tau \bar{A}_\tau & 0 & 0 & M_{\tau_R}^2 + D_R \end{bmatrix}$$

*LF breaking Term*

*Chirality breaking Term*

LFV strength: $\delta = \dfrac{M_{\tau\mu}^2}{M_L^2}$

Consider mSUGRA:

$m_0 = 100\text{GeV}$

$m_{1/2} = 300\text{GeV}$

$A_0 = 300\text{GeV}$

$\tan(\beta) = 10$

$\text{sgn}\ \mu = +$

if: $\delta = 0$

$m_{\tilde{\chi}_1^0} = 122\text{GeV}$

$m_{\tilde{\chi}_2^0} = 228\text{GeV}$

$m_{\tilde{l}_L} = 232\text{GeV}$

$m_{\tilde{l}_R} = 156\text{GeV}$

$m_{\tilde{\tau}_1} = 145\text{GeV}$

$m_{\tilde{\tau}_2} = 233\text{GeV}$

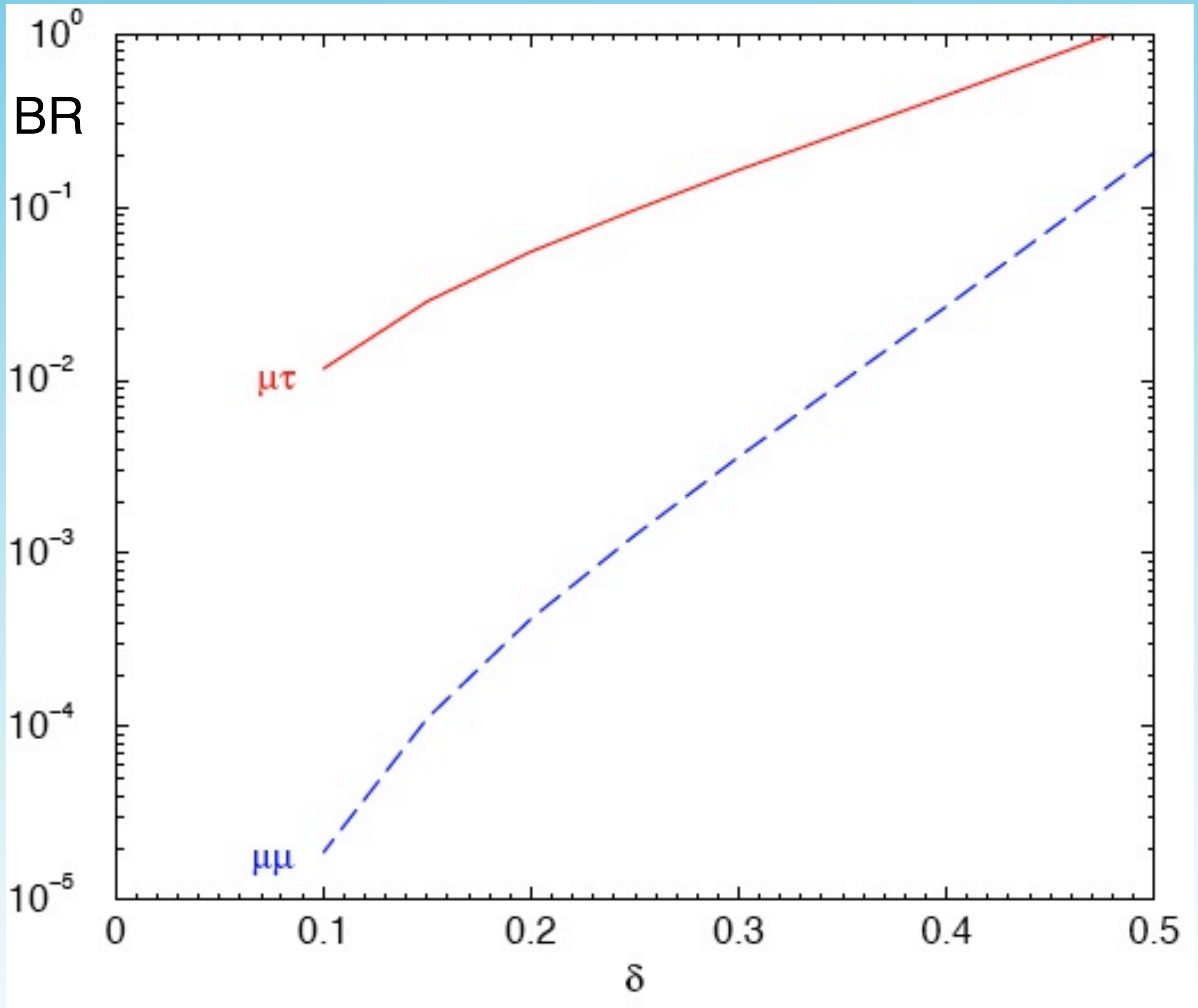
if: $\delta \neq 0$
mixing

we have $\tilde{\mu}$ in $\tilde{\tau}_1$

$$\tilde{\chi}_2^o \longrightarrow \tilde{\tau}_1\, \mu$$

$\tilde{\tau}_1 \longrightarrow \tilde{\chi}_1^o\, \tau$ ———

$\tilde{\tau}_1 \longrightarrow \tilde{\chi}_1^o\, \mu$ - - -



Phys. Rev. D 63, 115006 (2000)

# susy -2

## Signal: $E_{\text{miss}}$ $\mu$ $\tau_{\text{had}}$ j

$$\begin{aligned} pp \to \tilde{q}\tilde{q} \quad &\to \quad q\tilde{\chi}_2^0\, q\tilde{\chi}_2^0 \\ &\to \quad qq\mu\tau\tilde{\chi}_1^0\, \mu\tau\tilde{\chi}_1^0 \end{aligned}$$

Selection cuts:

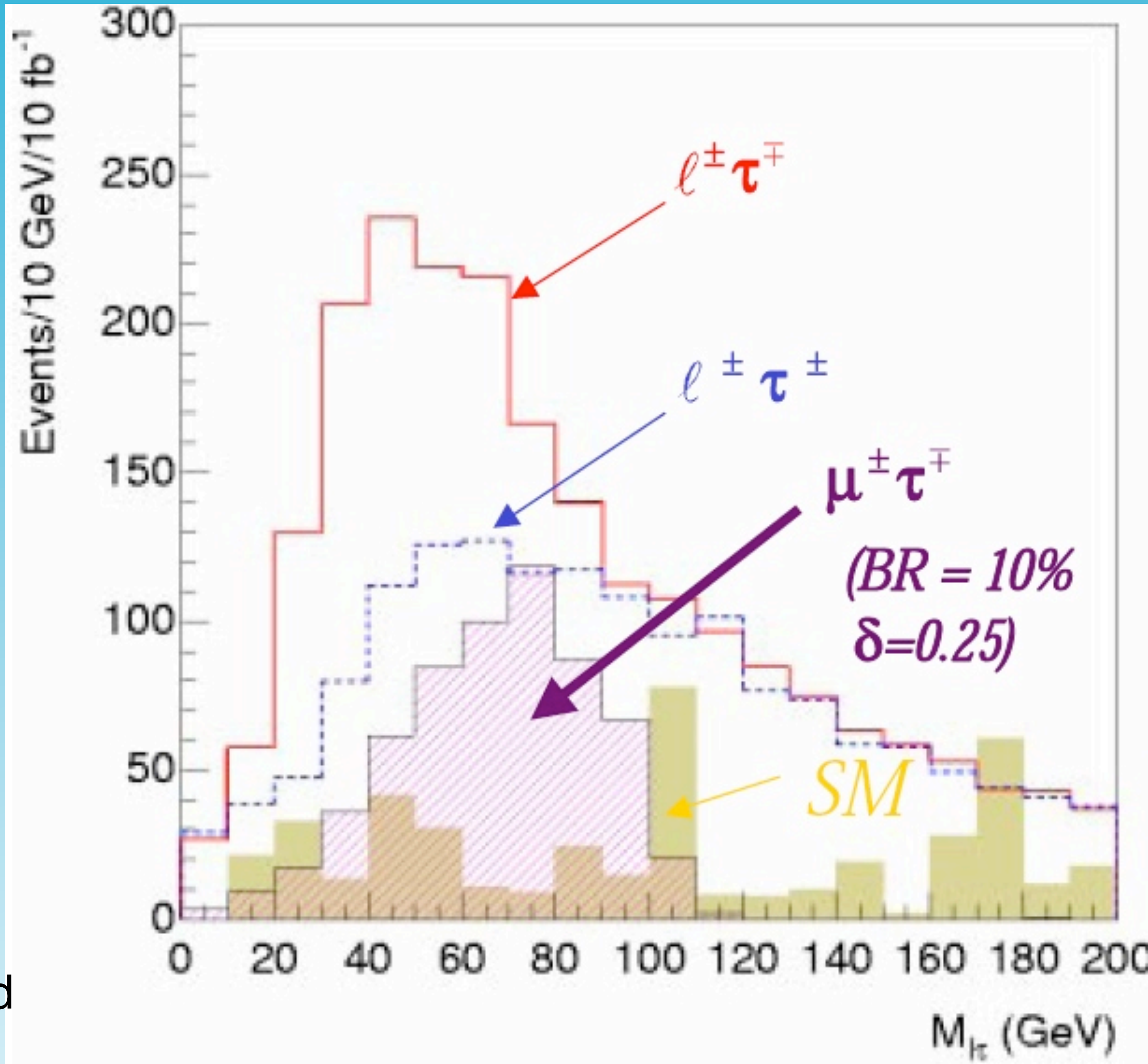
$N_j \geq 4 \quad 1P_T > 100\text{GeV}\ 3P_T > 50\text{GeV}$

$M_{eff} \equiv E_T\text{miss} + \Sigma P_T > 800\text{GeV}$

$E_T\text{miss} > 0.2 M_{eff}$

$|\eta| < 2.5$

$R > 0.4$



isajet +ATLAS fast simulation + realistic smearing + full tau simulation @ low luminosity

Backgrounds:

- SM background is very small
- Normal SuSY signal becomes background to LFV in SuSY

$$\tilde{\chi}_2^o \to \tau\,\tau\,\tilde{\chi}_1^o \to \mu\,\tau\,\nu_\mu\,\nu_\tau\,\tilde{\chi}_1^o$$

- How can we extract the LFV events?

Phys. Rev. D 63, 115006 (2000)

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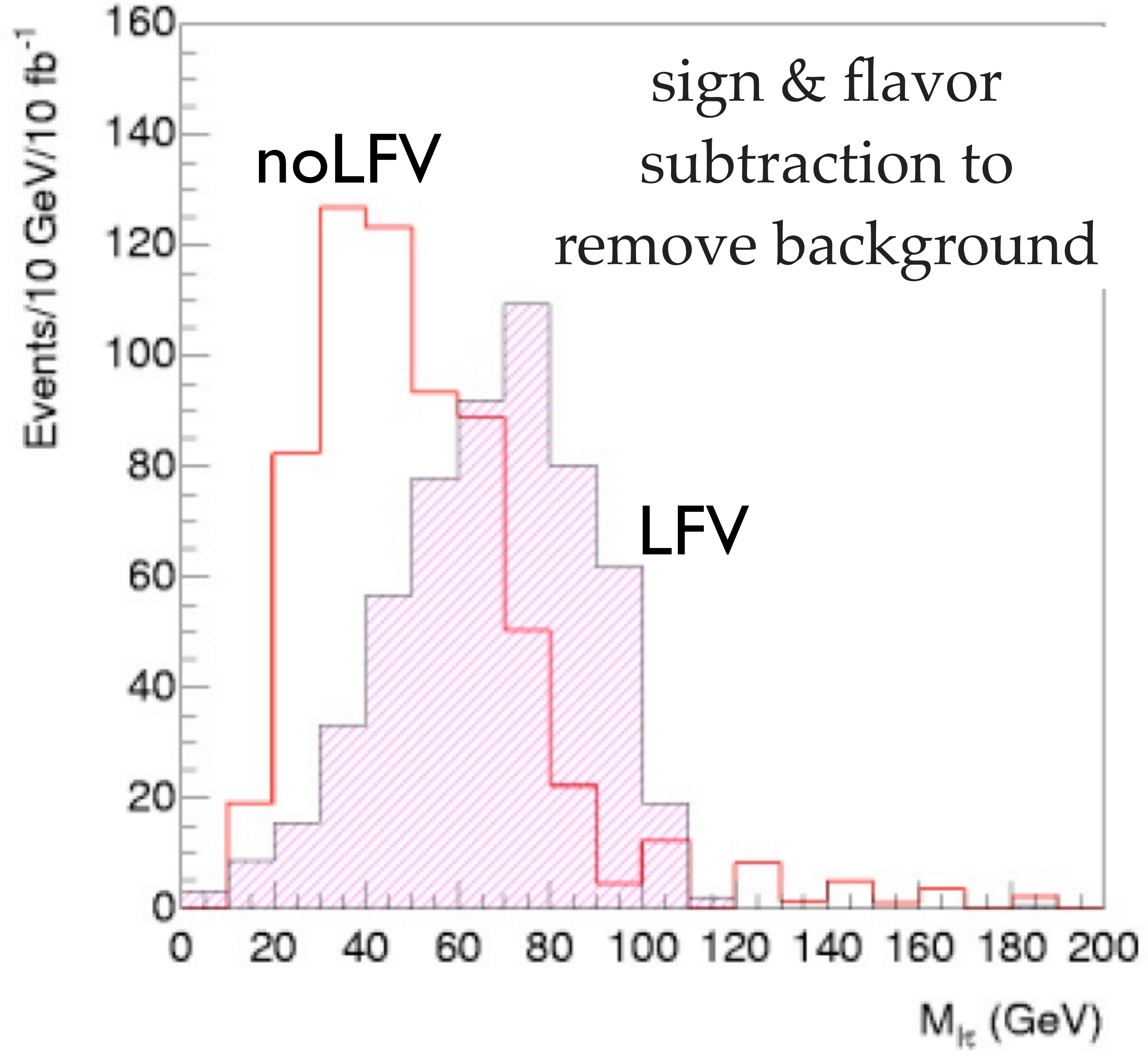
# susy -3

LFV gives harder mass distribution and more muons compared to nonLFV decay:

$$\tilde{\chi}_2^o \rightarrow \tau\ \tau\ \tilde{\chi}_1^o \rightarrow \mu\ \tau\ \nu_\mu\ \nu_\tau\ \tilde{\chi}_1^o$$
$$\tilde{\chi}_2^o \rightarrow \tau\ \tau\ \tilde{\chi}_1^o \rightarrow e\ \tau\ \nu_e\ \nu_\tau\ \tilde{\chi}_1^o$$

$$E \equiv N(\mu^\pm\, \tau^\mp) - N(e^\pm\, \tau^\mp)$$

in case of nonLFV, expect $E = 0$.
We can do a counting experiment.



sign & flavor subtraction to remove background

For 10fb$^{-1}$ & BR=0.1 → $E = 476 \pm 39$.

or if 5σ signal is observed @10fb$^{-1}$ → BR=0.023 or $\delta \sim 0.1$

or $\delta < 0.1$ → BR< $10^{-9}$

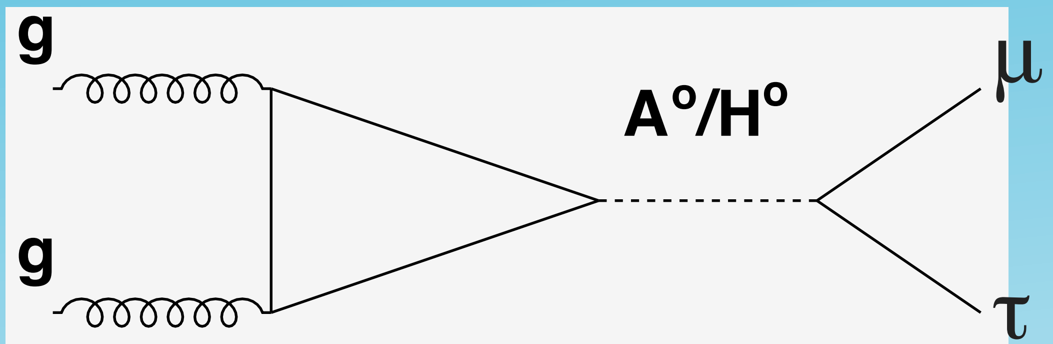
# 2HDM -1

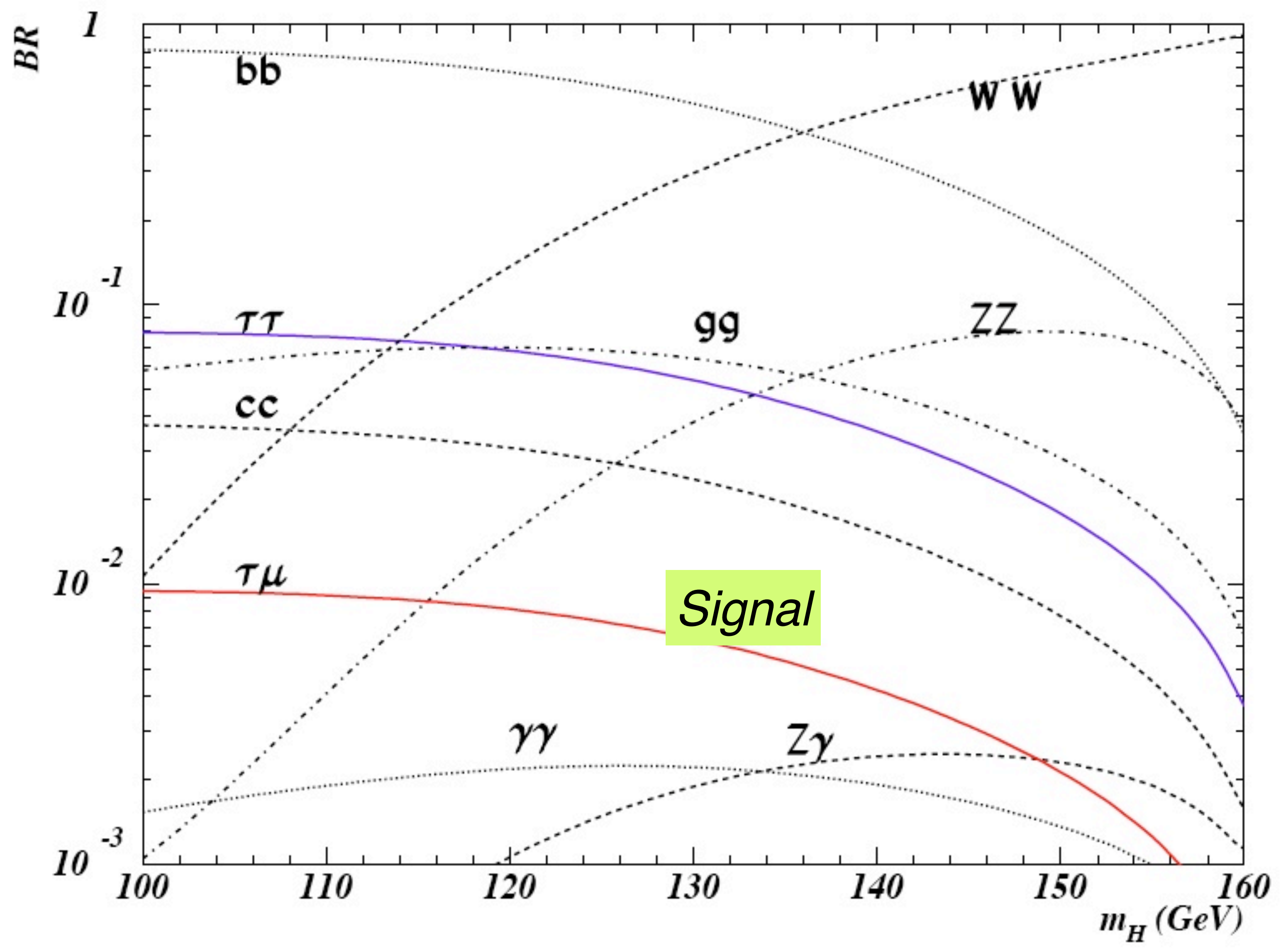
Phys. Rev. D 67, 035001 (2003)

## Type III 2HDM: LFV exists @ tree level

$$\mathrm{BR}(A^o/H^o \rightarrow \tau\mu) = \kappa^2_{\tau,\mu}\left(\frac{2m_\mu}{m_\tau}\right)\mathrm{BR}_{SM}(H^o \rightarrow \tau\tau)$$

$\kappa_{\mu\,\tau} \approx 1$ compatible w/ μ g-2 results





*Considered Backgrounds:*

$$W^\pm Z \rightarrow \mu^\pm \nu_\mu \tau^+ \tau^-$$

$$W^+W^- \rightarrow \mu^+ \nu_\mu \tau^- \bar{\nu}_\tau$$

$$t\bar{t} \rightarrow \mu^\pm \nu_\mu \tau^\pm \nu_\tau b\bar{b}$$

$$Z(\gamma^*) \rightarrow \tau^+\tau^- \rightarrow \mu\nu_\mu\nu_\tau\tau$$

$$W^\pm + \mathrm{jets} \rightarrow \mu^\pm \nu_\mu + \mathrm{jets}$$

→ $A^o/H^o \rightarrow \tau^+\tau^- \rightarrow \mu\nu_\mu\nu_\tau\tau$

*Signal Final states:*

- Hadronic final state:
  τ jet, isolated μ & missing $E_T$
- Leptonic (e) final state:
  ~~hadron activity~~, isolated e, μ & missing $E_T$

Phys. Rev. D 67, 035001 (2003)

# 2HDM -2

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$\sigma$ bg is $10^4$ $\sigma$ signal

Pythia + ATLAS fast simulation, 30 $\text{fb}^{-1}$

Cuts:

- 1 isolated $\mu$: $p_T^\mu > 20$ GeV, $|\eta^\mu| < 2.5$
- 1 hadronic $\tau$-jet: $p_T^\tau > 20$ GeV, $|\eta^\tau| < 2.5$
- b-jet veto and jet veto: 60% b-tagging, 1% mis-tagging efficiency.
- $\tau$-jet ID efficiency of 30% assumed
- Signal efficiency: $\sim$ 15%
- $W^\pm$+jet background efficiency: 0.4%
- $Z^0 \to \tau\tau$: $\sim$ 3%

$$\frac{p_T^{\tau-\text{jet}}}{p_T^\tau} > 0.6,$$

$$\Delta R(p_T^{\tau-\text{jet}}, p_T^\tau) < 0.2\,\text{rad}.$$

Single charged track within $\Delta R < 0.3$ of $\tau$ jet

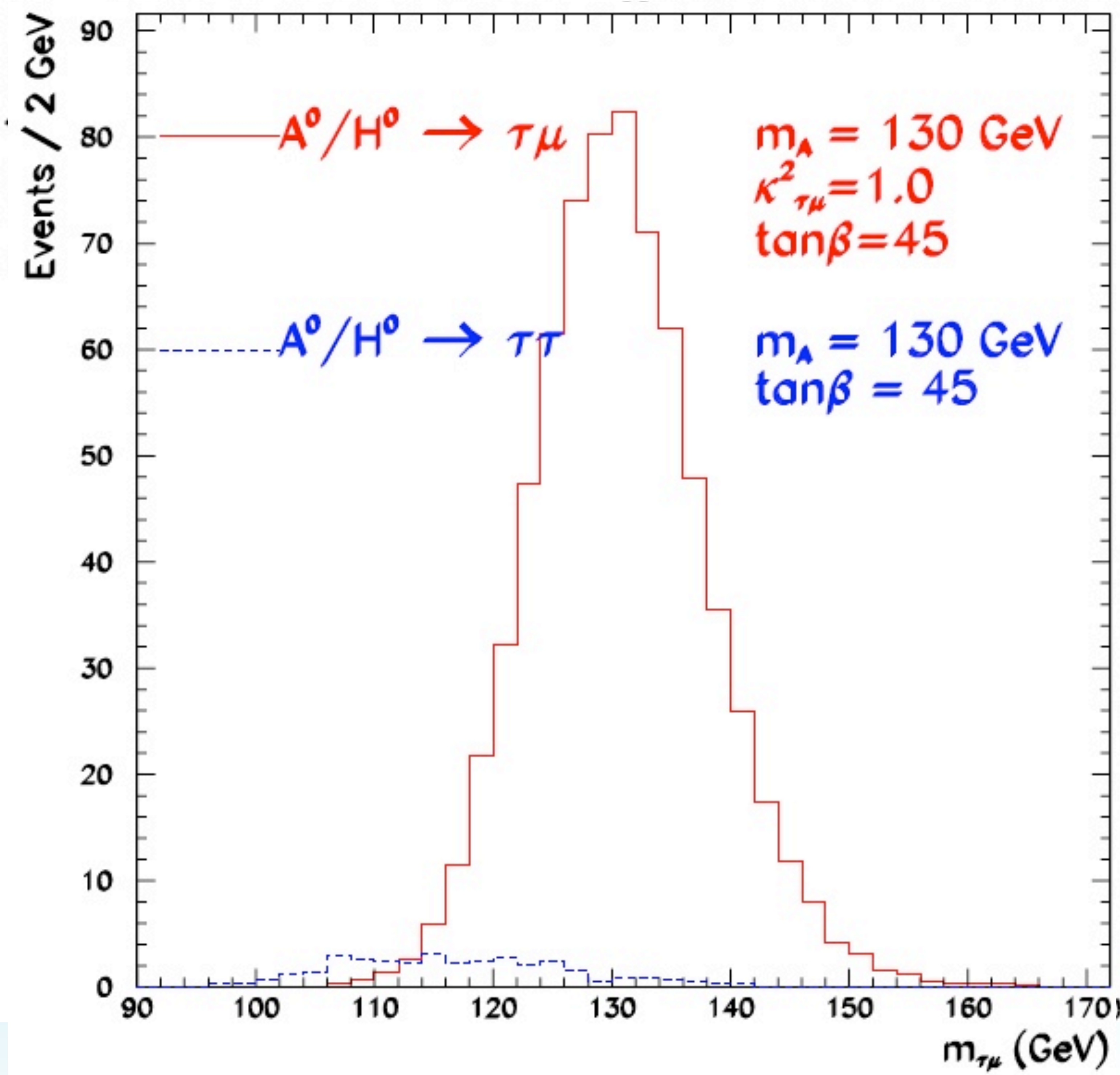
Selection of 1-prong hadronic $\tau$ decays

$$\delta\phi\left(p_T^\mu, p_T^{\tau\text{-jet}}\right) > 2.75\ \text{rad},$$

$$\delta\phi\left(p_T^{\text{miss}}, p_T^{\tau\text{-jet}}\right) < 0.6\ \text{rad}.$$

$\Delta p_T = p_T^\mu - p_T^{\tau\text{-jet}} > 0$ $p_T^\tau > 50$ GeV

Selection optimized for LFV mode:



Phys. Rev. D 67, 035001 (2003)

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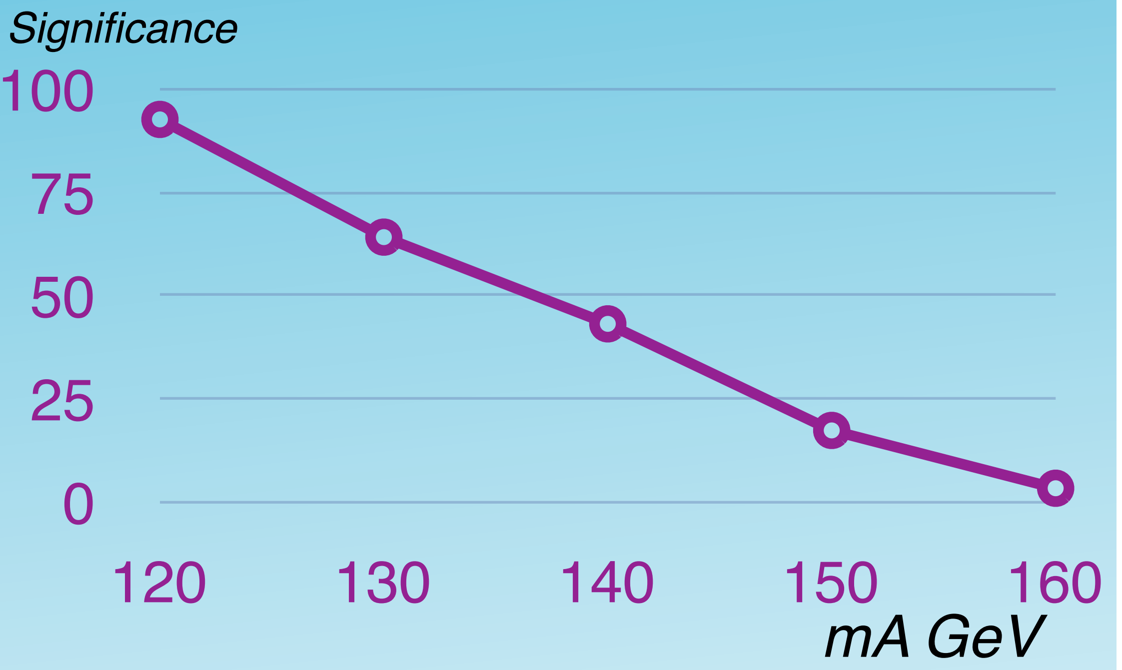
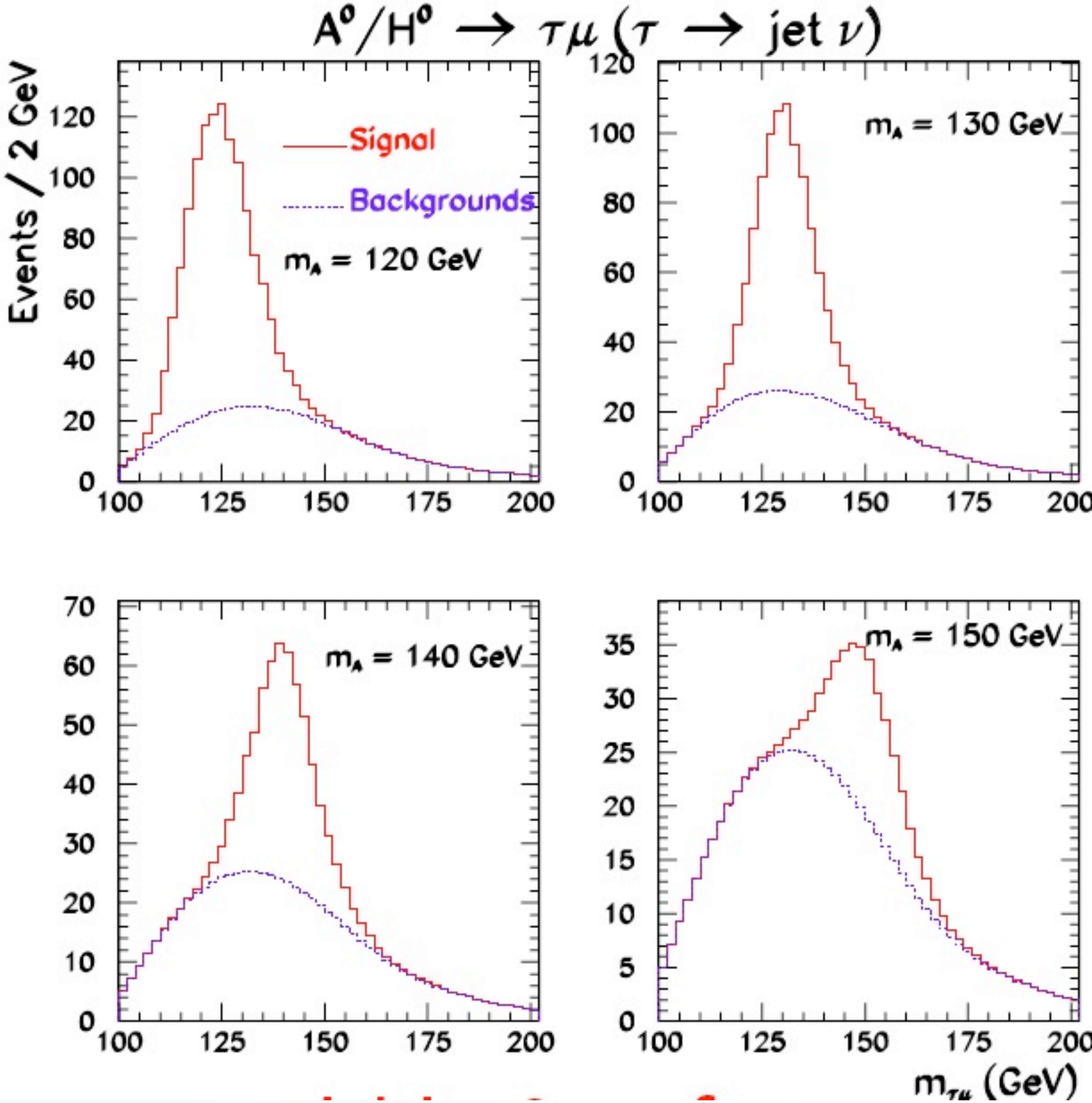
# 2HDM -3

signal is well in the reach of LHC/ATLAS:

| MA(GeV) | 120 | 130 | 140 | 150 | 160 |
|---|---|---|---|---|---|
| s/√B combined | 92.7 | 64.2 | 43.2 | 17.4 | 3.4 |





if ~~signal~~, 95% CL can be obtained after few years of low luminosity

J. Phys. G 32 (2006) 73-92

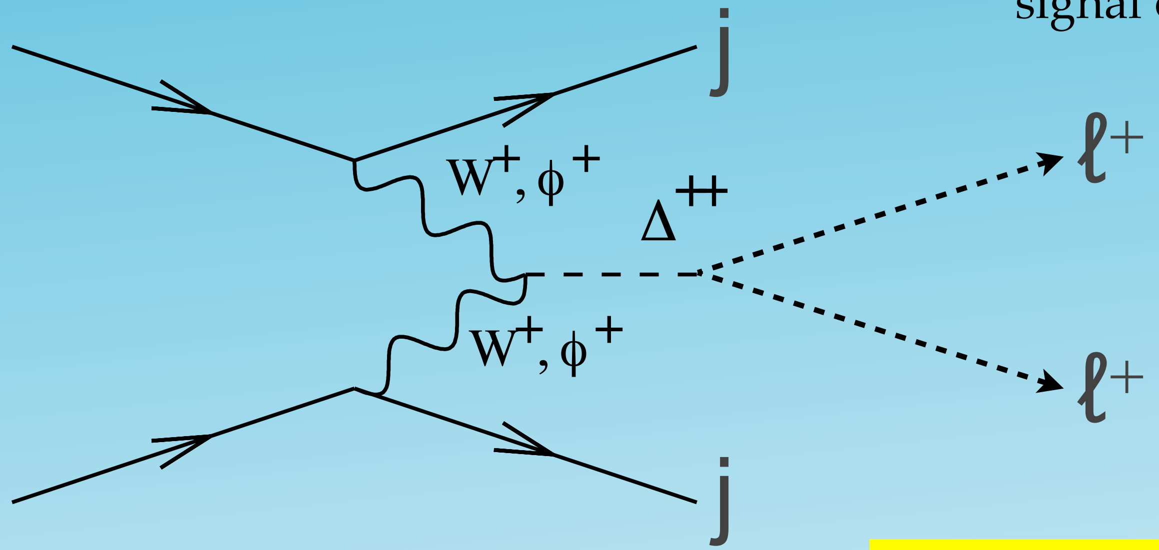
**ATLAS**

# LNV -1

- Doubly charged Higgs, single production
  - in Left Right symmetric models $m_{WR}$>640GeV
  - assuming equal left/right gauge couplings: g=0.64
  - fast MC used @ $\mathcal{L}=100fb^{-1}$/yr

| $M(W_R^+)$ | $M(\Delta_R^{++})$ | | | | |
|---|---|---|---|---|---|
| | 300 | 500 | 800 | 1000 | 1500 |
| 650 | 7.9 | 4.6 | 2.2 | 1.4 | 0.45 |
| 750 | 4.7 | 2.8 | 1.4 | 0.87 | 0.31 |
| 850 | 2.9 | 1.8 | 0.90 | 0.58 | 0.21 |
| 950 | 1.9 | 1.2 | 0.61 | 0.40 | 0.15 |
| 1000 | 1.6 | 0.98 | 0.50 | 0.33 | 0.12 |
| 1050 | 1.3 | 0.81 | 0.42 | 0.28 | 0.11 |
| 1500 | 0.30 | 0.20 | 0.11 | 0.074 | 0.029 |

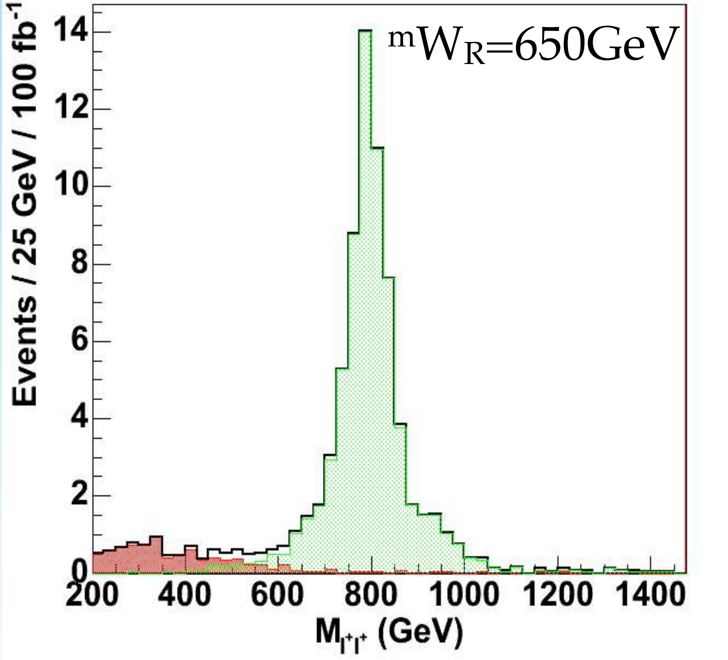
signal σ in fb

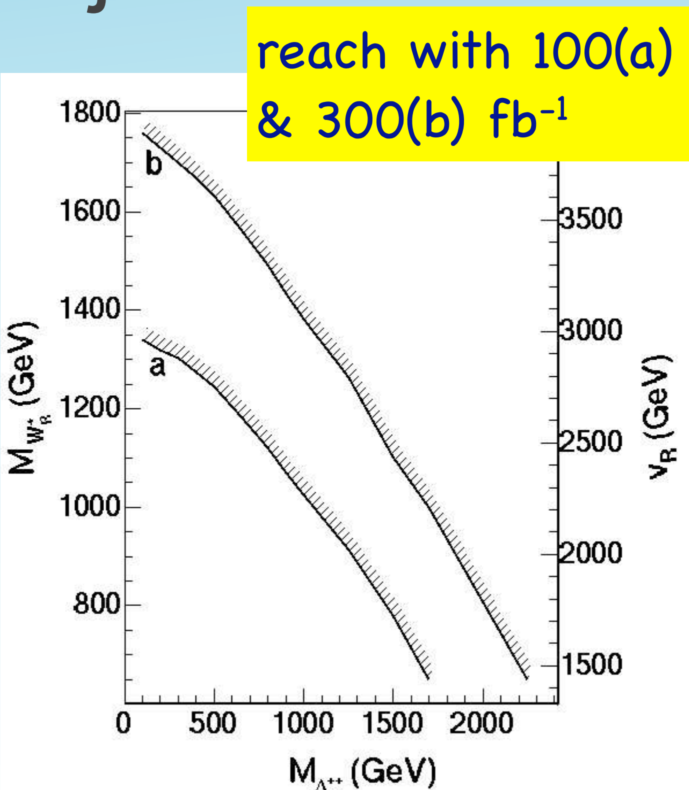


- Selection
  - e/μ in $|\eta|<2.5$ & $\varepsilon_{reco}=90\%$
  - $p^{\ell}_T>50$ & $p^{j1}_T>200$ & $p^{j2}_T>200$
  - $|\eta^{j1}-\eta^{j2}|>2$
- SM Background

| Background | Number of Events | $\sigma \times BR$ (fb) |
|---|---|---|
| $pp \to Wt\bar{t}$ | 200 000 | 23 |
| $qq \to W^+W^+ qq$ | 100 000 | 37 |
| $qq \to WZqq$ | 27 000 | 28.6 |
| $qq \to t\bar{t}$ $P_t$ 10-200 GeV | 8 000 000 | 90 800 |
| $qq \to t\bar{t}$ $P_t$ 200 GeV-∞ | 2 000 000 | 14 100 |

min 10 events required

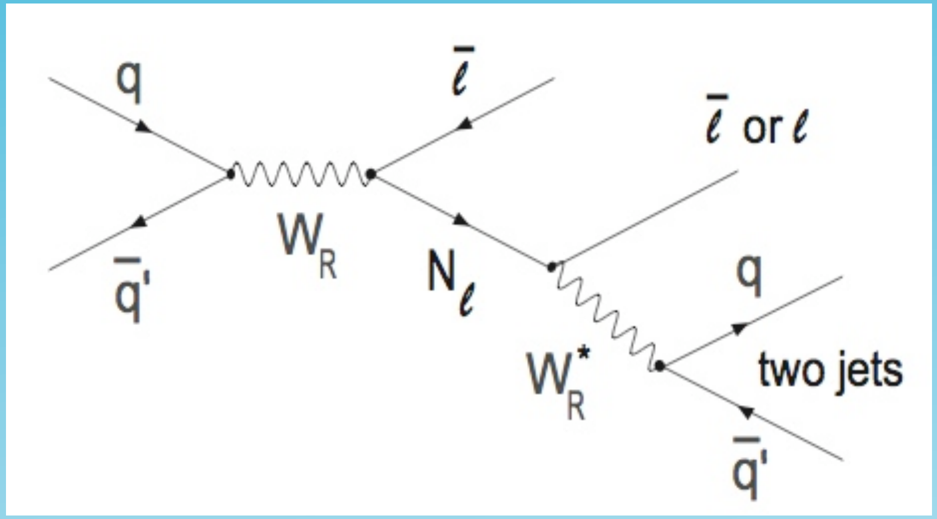


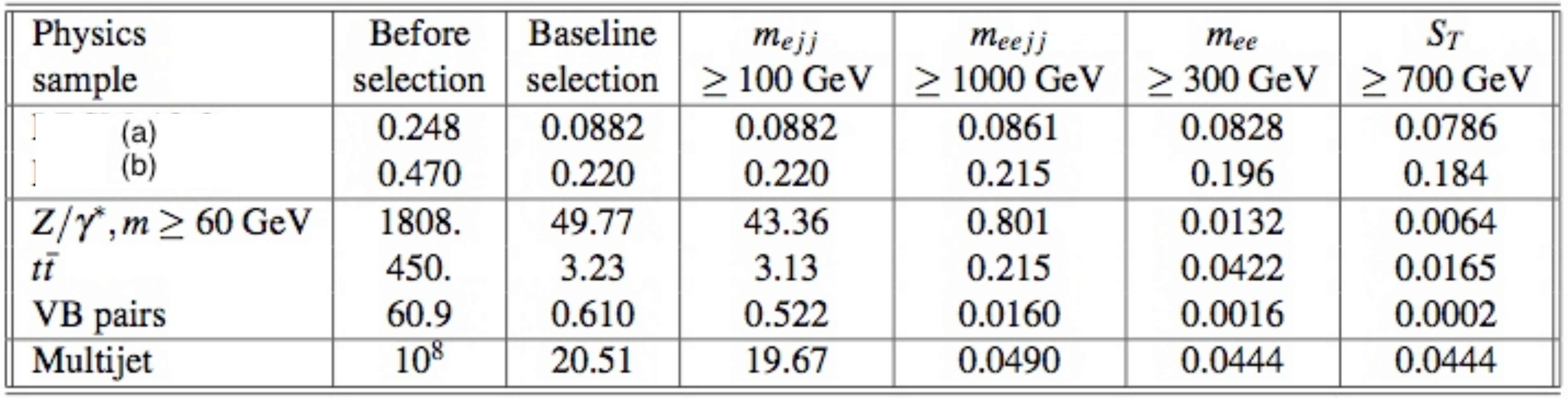

reach with 100(a) & 300(b) $fb^{-1}$

# LNV -2

arXiv:0901.0512v4,
("CSC book") CERN OPEN-2008-020

- LR symmetric model w/ $W_R$ & $N_{majorana}$
  - Full MC used (14TeV)
  - LO $\sigma(pp \to W_R X)$; $W_R \to \ell N_\ell \to \ell\ell\, jj$
    - 24.8pb ($W_R$=1800,$N_e$=$N_\mu$=300GeV) (a)
    - 47.0pb ($W_R$=1500,$N_e$=$N_\mu$=500GeV) (b)
  - Baseline Selection
    - $p_T \geq 20$ GeV, $|\eta^\ell|<2.5$, $|\eta^j|<4.5$,
  - SM Background
    - $t\bar{t}$, $Z/\gamma^*$ & vector boson pair production + multijets for $\ell$=e





| Physics sample | Before selection | Baseline selection | $m_{ejj} \geq 100$ GeV | $m_{eejj} \geq 1000$ GeV | $m_{ee} \geq 300$ GeV | $S_T \geq 700$ GeV |
|---|---|---|---|---|---|---|
| (a) | 0.248 | 0.0882 | 0.0882 | 0.0861 | 0.0828 | 0.0786 |
| (b) | 0.470 | 0.220 | 0.220 | 0.215 | 0.196 | 0.184 |
| $Z/\gamma^*, m \geq 60$ GeV | 1808. | 49.77 | 43.36 | 0.801 | 0.0132 | 0.0064 |
| $t\bar{t}$ | 450. | 3.23 | 3.13 | 0.215 | 0.0422 | 0.0165 |
| VB pairs | 60.9 | 0.610 | 0.522 | 0.0160 | 0.0016 | 0.0002 |
| Multijet | $10^8$ | 20.51 | 19.67 | 0.0490 | 0.0444 | 0.0444 |

➡Lepton sign investigated after this publication.

discovery limits
a:150pb$^{-1}$ & b:40pb$^{-1}$

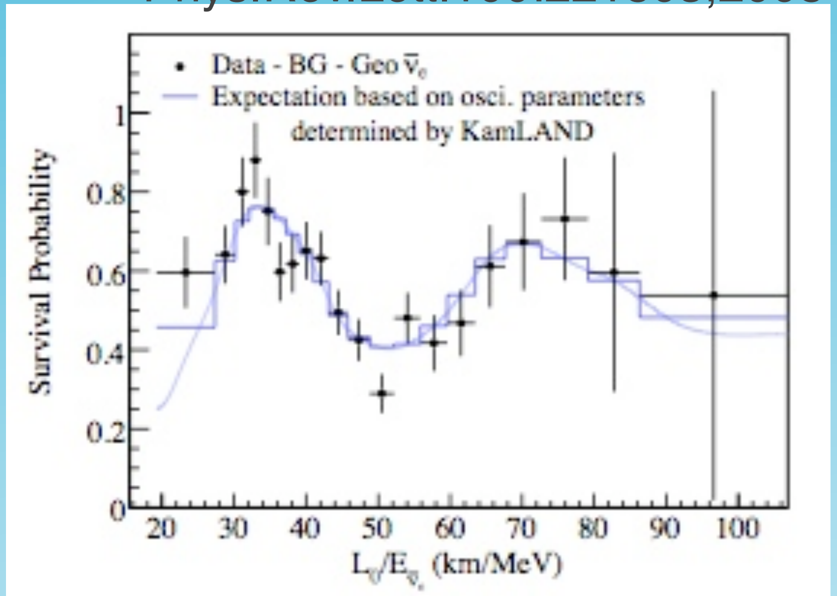
# Summary & Outlook

- ATLAS is currently running to record collision data
- LFV is studied within SM and via BSM
  - Yearly yields to discover LFV
    - susy: exp 476 ± 39 vs bg 0
    - 2HDM: $3.4 < S/\sqrt{B} < 93$
    - SM-like: exp 46 ± 2 vs bg 1
  - or push BR($\tau \rightarrow \mu\gamma$) limit to lower values
- LNV studied in BSM models
  - $\Delta^{++}$ mass up to 1.8TeV depending on $W^{+}$ mass
  - Early discovery possible in LR models, but SS vs OS lepton comparisons not public.
- Some of these analyses shown can be also done with 200 $pb^{-1}$ at $\sqrt{s}$=10TeV (the results are not yet public)

# Thank you for listening

- Further references
  - Neutrino oscillation papers
    - K2K: hep-ex/0411038, Phys.Rev.Lett.94:081802,2005
    - Kamland: hep-ex/0406035, Phys.Rev.Lett.94:081801,2005
      arXiv:0801.4589 Phys.Rev.Lett.100:221803,2008
  - Current LFV limits (thanks to S. Banerjee)
    - BaBar: arXiv:0908.2381 (2009), BR ($\tau^\pm \rightarrow \mu^\pm\gamma$) < $4.4\text{x}10^{-8}$ @ 90% CL
    - Belle: arXiv:0708.3272 (2007), BR($\tau^\pm \rightarrow \mu^\mp \mu^\pm \mu^\pm$) < $3.2\text{x}10^{-8}$ @ 90% CL
  - J.Ellis et.al. Eur. Phys. J. C14, 319, (2000).
- ATLAS public web pages :
  - http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html
  - http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EXOTICS

Phys.Rev.Lett.100:221803,2008



Backup slides

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# $\tau \longrightarrow \mu\,\gamma$

E. Barberio
unpublished

## Source: $Z \longrightarrow \tau\,\tau$

*Pythia + Photos + Atlas Fast simulation was used.*

Compared to W channel, 10x less signal
1 tau for tagging, other for signal

*generator cuts:*

$$\cos\theta_{||} < 0.5(Mz)$$
$$P_T\text{miss} < 60\text{GeV}$$
$$N_{\text{jet}} < 2$$
$$0.5 < m(\tau\gamma) < 3.0\text{GeV}$$

*analysis cuts:*

$$p_T^{\mu} > 6\text{ GeV}$$
$$E_T^{\mu}(e,\gamma) > 15\text{ GeV}$$

selection efficiency ~14%

## Studied Backgrounds:

$W \longrightarrow \mu\nu\,\gamma$

$W \longrightarrow \tau\nu\,\gamma$

$\tau \longrightarrow \mu\nu_\mu\nu_\tau$

$Z \longrightarrow \mu^+\mu^-\,\gamma$

$Z \longrightarrow \tau^+\tau^-\,\gamma$

$\tau \longrightarrow \mu\nu_\mu\nu_\tau$

$t\bar{t}\,\gamma$

$b\bar{b}\,\gamma$

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low luminosity

1.6 < M < 2.0 GeV

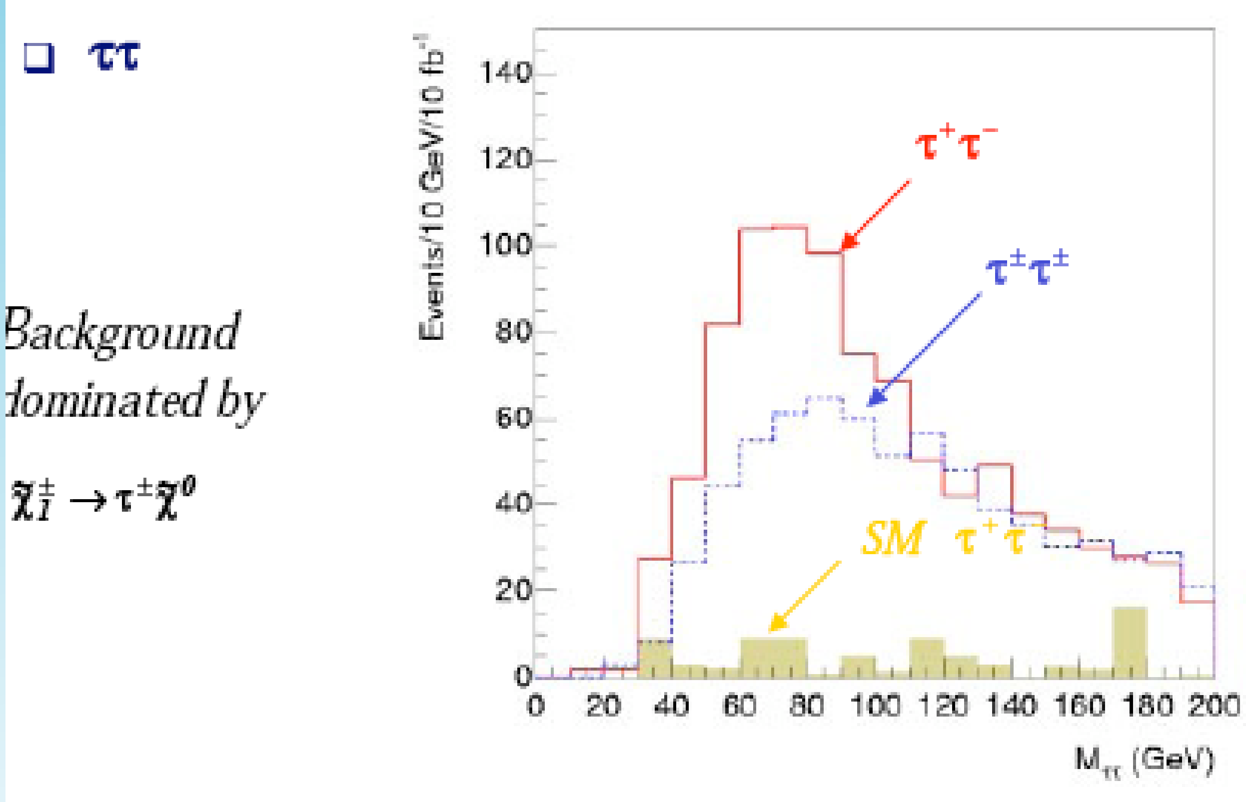
~12 bg events/year for $m_\tau$

~10 signal events/year

# ATLAS & CMS detectors

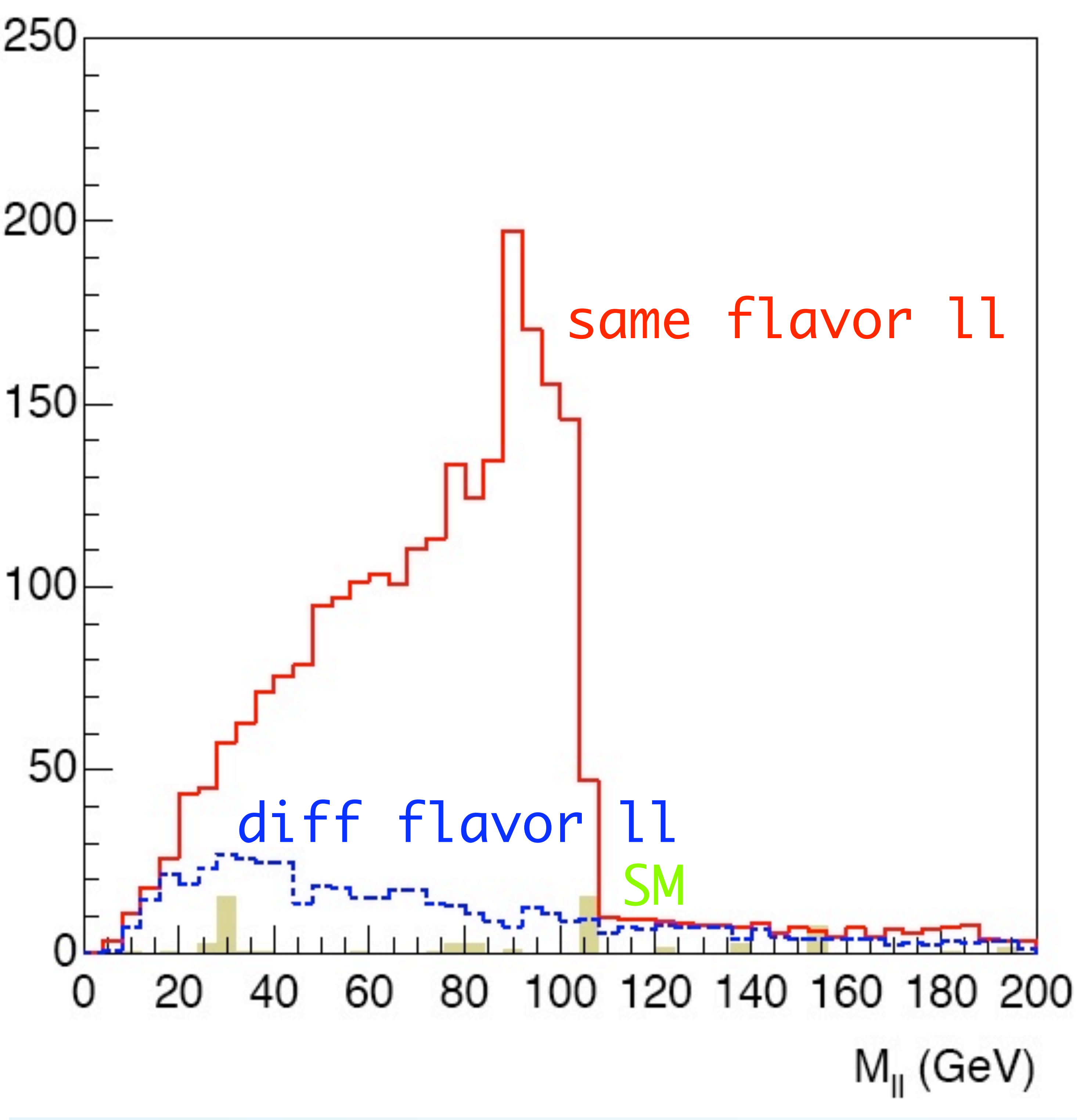
| | ATLAS | CMS |
|---|---|---|
| length x diameter (m) | 44 x 22 | 22 x 15 |
| Magnetic Field (Tesla) | 2 | 4 |
| Weight (Tons) | 7 000 | 12 500 |
| eta coverage | 2.7>muons, 2.5>tracking 4.9>calo | 2.4>muons, 2.5>tracking 5.0>calo |
| Inner detector | Silicon pixels, Silicon strips, Transition Radiation Tracker. | Silicon pixels, Silicon strips. |
| Electromagnetic Calo | Lead plates as absorbers with liquid argon as the active medium | Lead tungstate ($PbWO_4$) crystals both absorb and respond by scintillation |
| Hadronic Calo | Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions. | Stainless steel and copper absorber with plastic scintillating tiles as detectors |
| Muon System | Large air-core toroid magnets with muon chamber form outer part of the whole ATLAS | Muons measured already in the central field, further muon chambers inserted in the magnet return yoke |

# susy - details



❑ ττ

Background dominated by $\tilde{\chi}_1^\pm \to \tau^\pm \tilde{\chi}^0$

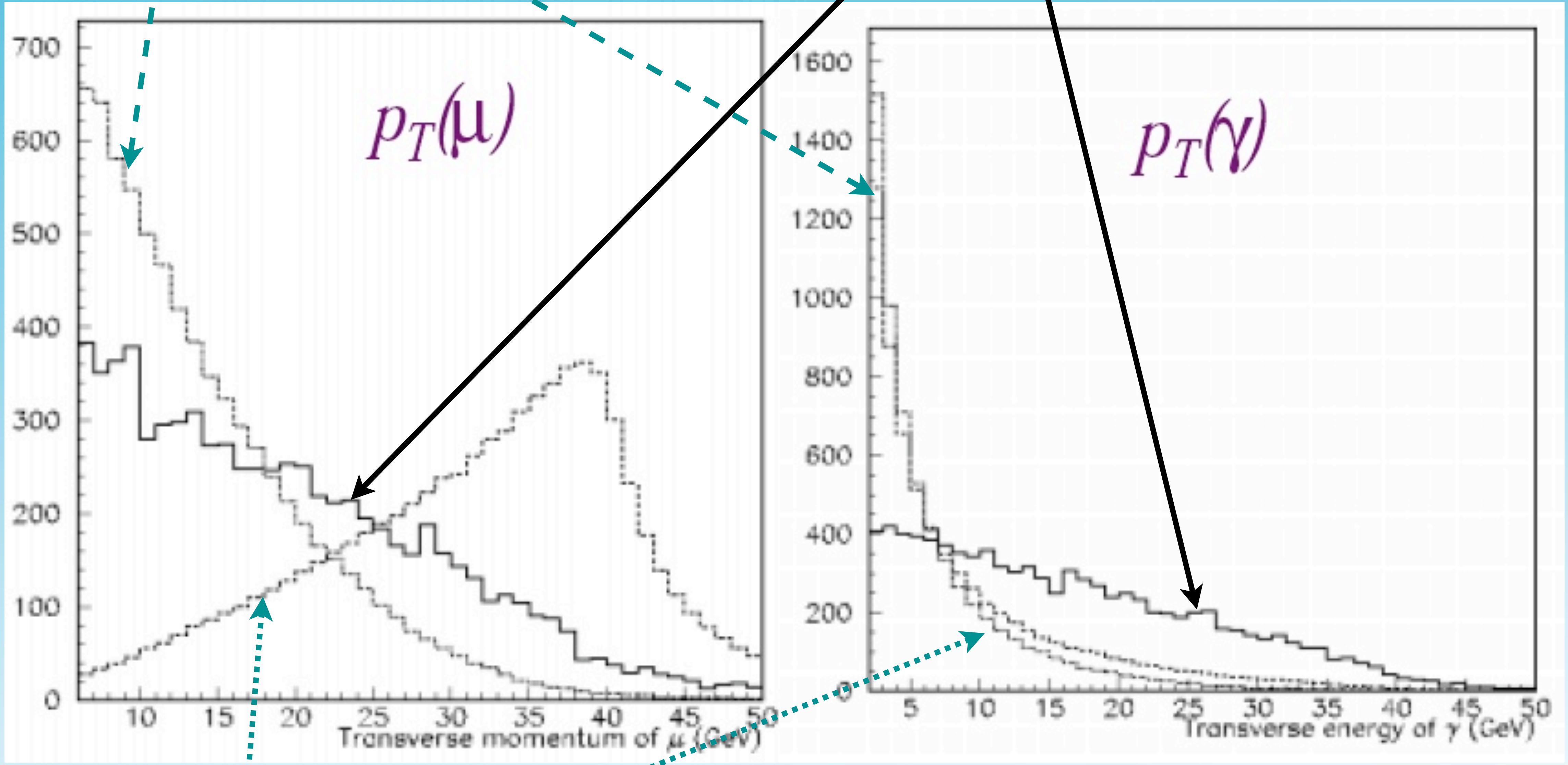


# $\tau \rightarrow \mu\,\gamma$ details

kinematic distributions

$W \rightarrow \mu\,\nu_\mu\gamma$

$\tau \rightarrow \mu\,\gamma$



$W \rightarrow \tau\,\nu_\tau \rightarrow \mu\,\nu_\mu\,\nu_\tau\,\gamma$