The Test of “See-saw” at the LHC

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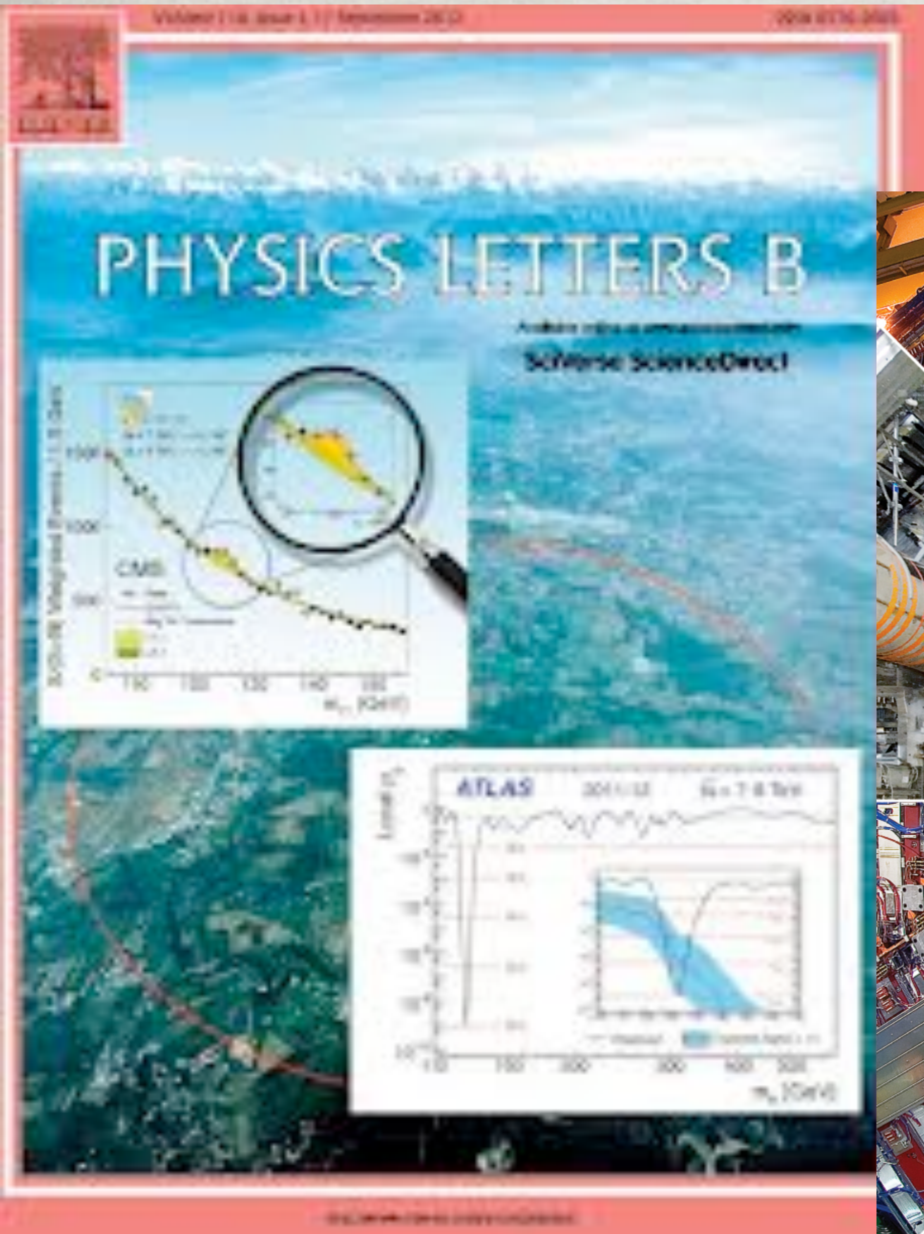
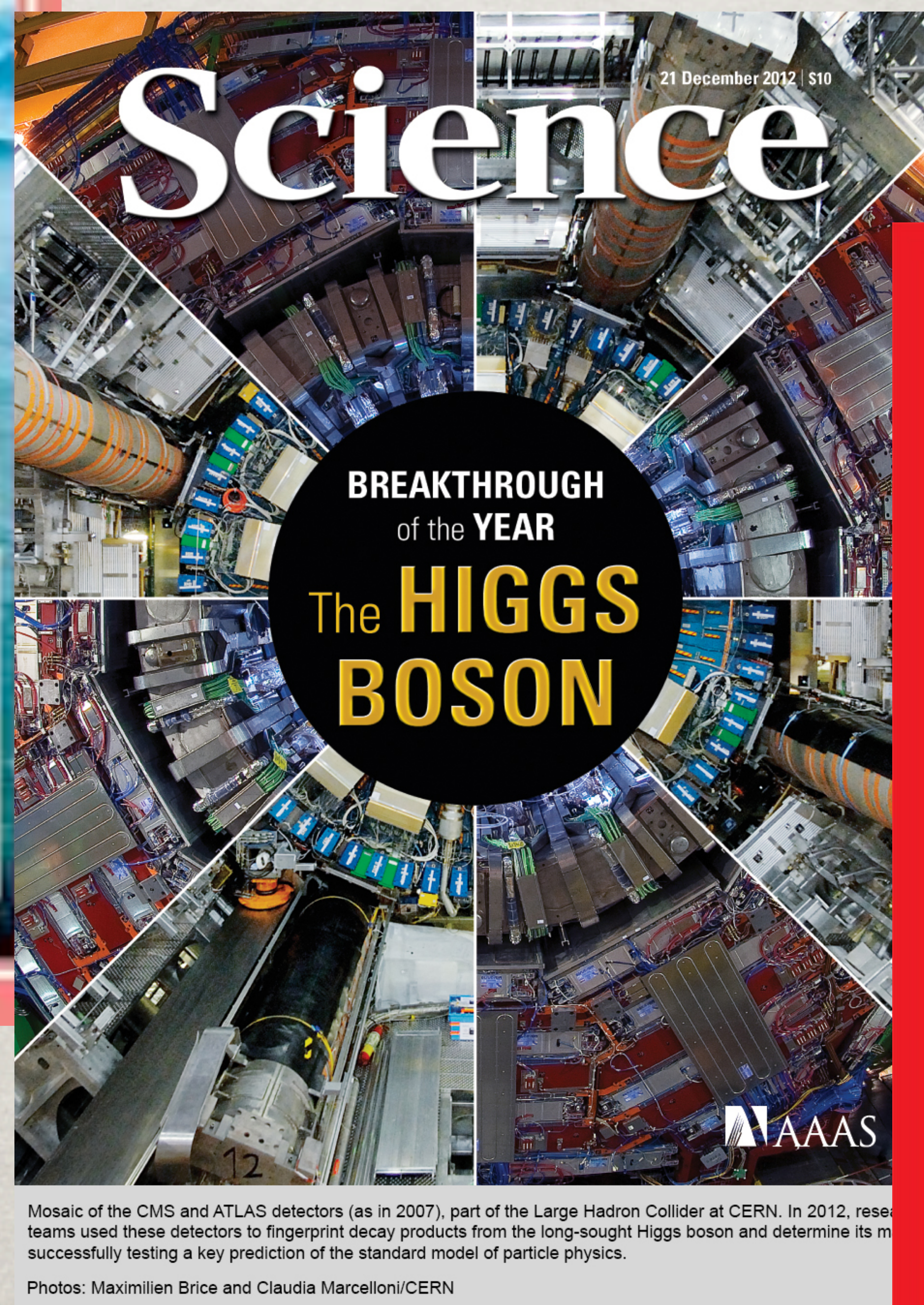
From Majorana to LHC
Trieste, Oct. 3-5, 2013

LHC Rocks!

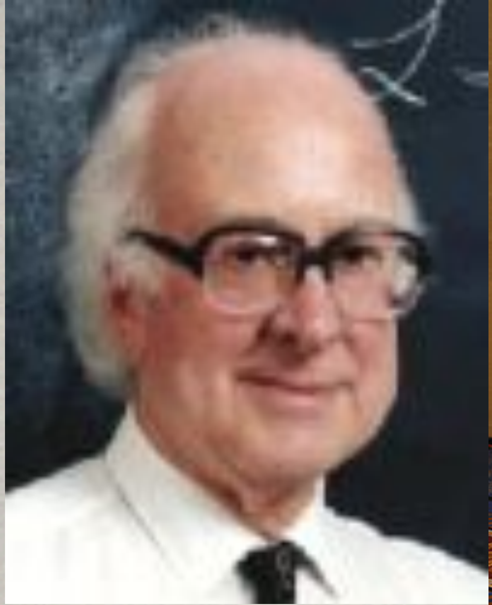
on the 4th of July, 2012:

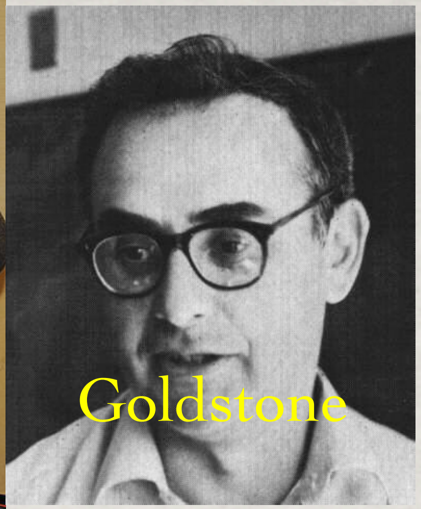
Salute To ATLAS/CMS !

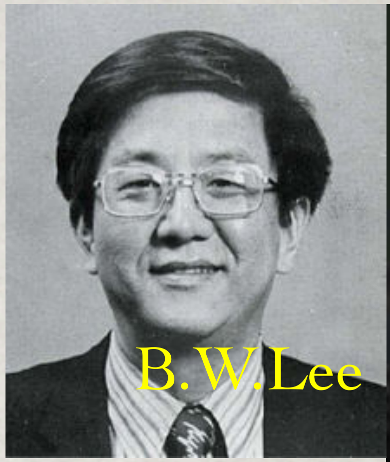


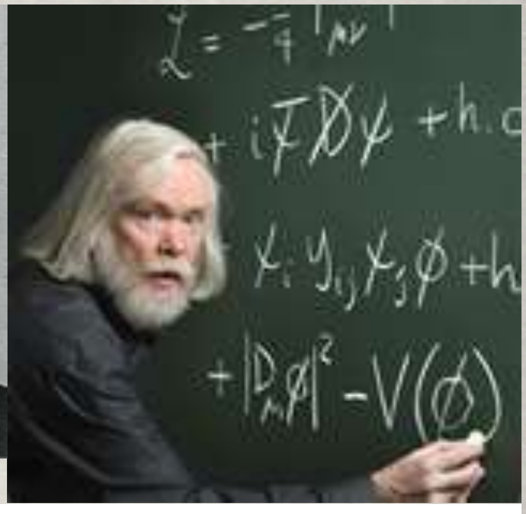


Higgs Phenomenology (70's)



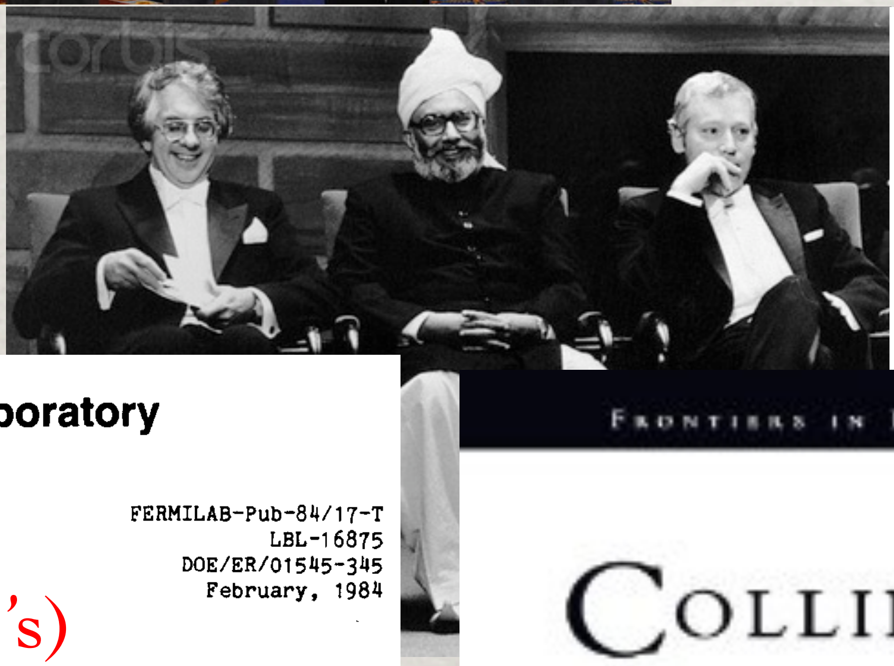






The Higgs mechanism (1964)

The SM (1960-1967)



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as

Fermi National Accelerator Laboratory

FERMILAB-Pub-84/17-T
LBL-16875
DOE/ER/01545-345
February, 1984

The "EHLQ" (80's)

Supercollider Physics

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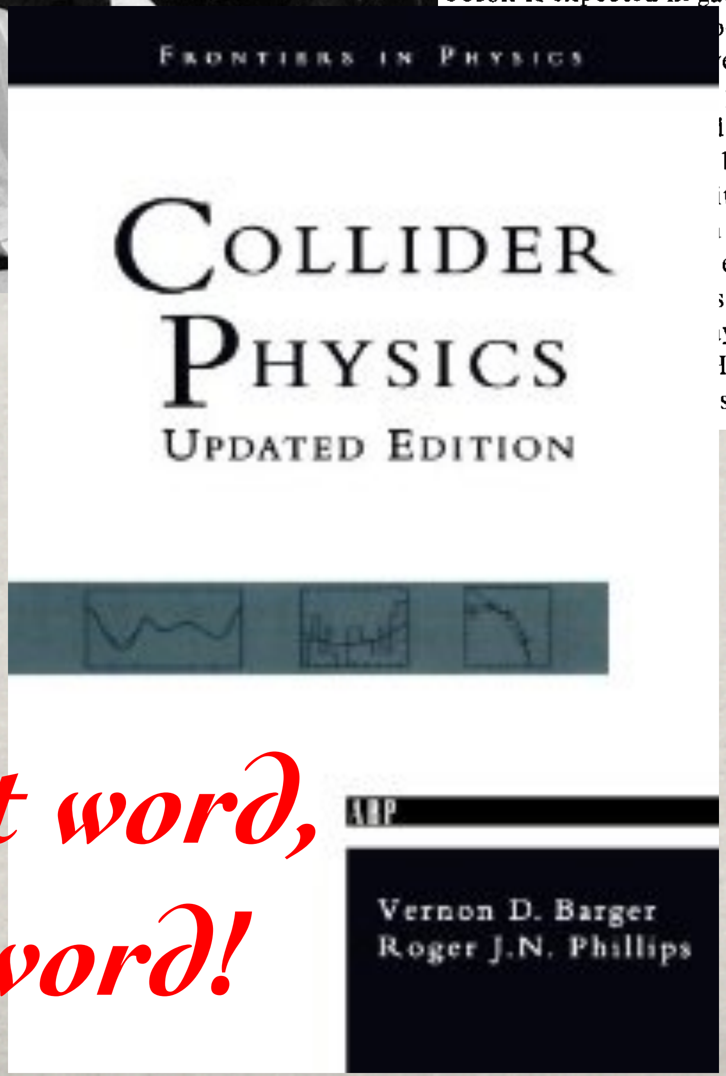
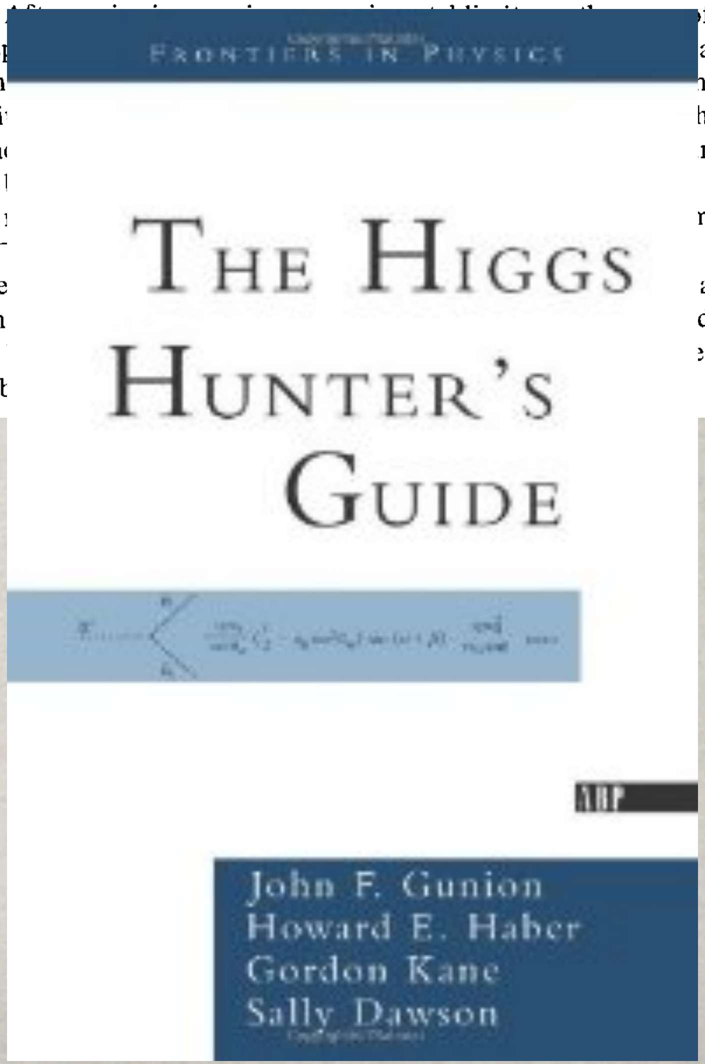
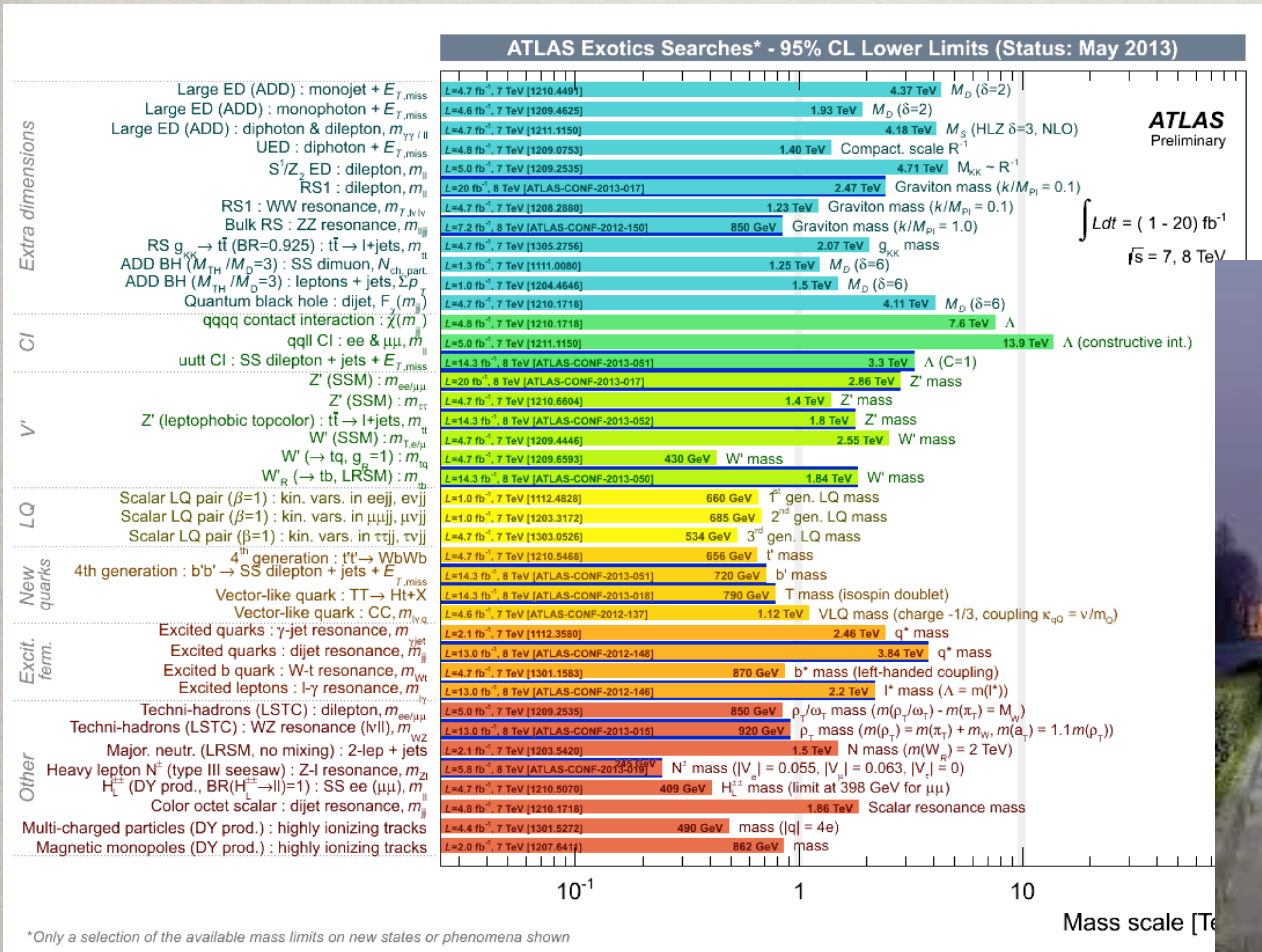




Theories say the first word,
Expts say the last word!

Marching into TeV scale physics:

But, no sign for BSM physics (yet)



Under the Higgs lamp post

Neutrinos are Hot!

Active programs, rich physics

Now we know a LOT:

$$
\begin{aligned}
7.27 \times 10^{-5}\,\mathrm{eV}^2 &< \Delta m^2_{21} < 8.01 \times 10^{-5}\,\mathrm{eV}^2, \\
2.38\,(2.29) \times 10^{-3}\,\mathrm{eV}^2 &< |\Delta m^2_{31}| < 2.68\,(2.58) \times 10^{-3}\,\mathrm{eV}^2, \\
0.29 &< \sin^2\theta_{12} < 0.35, \\
0.38\,(0.39) &< \sin^2\theta_{23} < 0.66\,(0.65), \\
0.019\,(0.020) &< \sin^2\theta_{13} < 0.030\,(0.030),
\end{aligned}
$$

Σm_ν [eV]	95% limits
	< 0.230

Jan Hamann

Still need to know:

- $m_1 - m_3$ mass hierarchy
- CP phases
- Dirac/Majorana

And what theory at work?

Weinberg's operator:

$$\frac{1}{\Lambda}\,(y_\nu LH)(y_\nu LH)$$

charaterized the "seesaw".

See-saw implies the synergy:
among low-energy, high-energy, and cosmology!

Illustrative models:

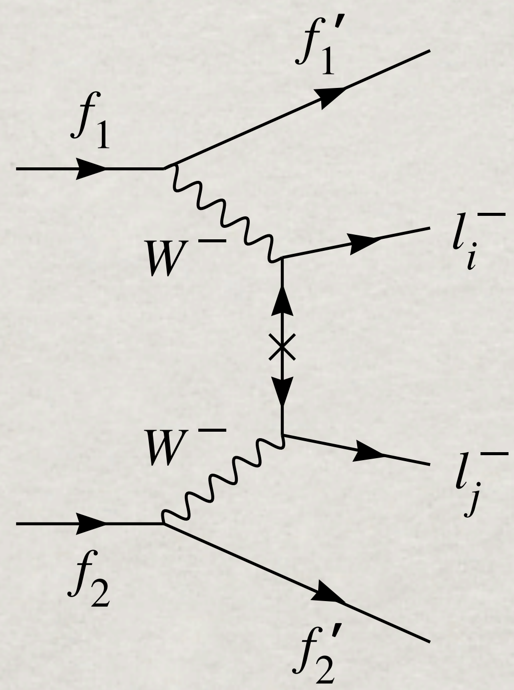
- Neutral fermion N (type I)
- Charged scalar $H^{\pm\pm}$, $H^{\pm}$ and W_R (type II)
- Charged fermion triplet $T^{\pm}$, T^0 (type III)

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

†Yanagita (1979); Gell-Mann, Ramond, Slansky (1979),
S.L. Glashow (1980); Mohapatra, Senjanovic (1980) ...

The search for ΔL=2 processes

(1). Neutrino-less double β Decay



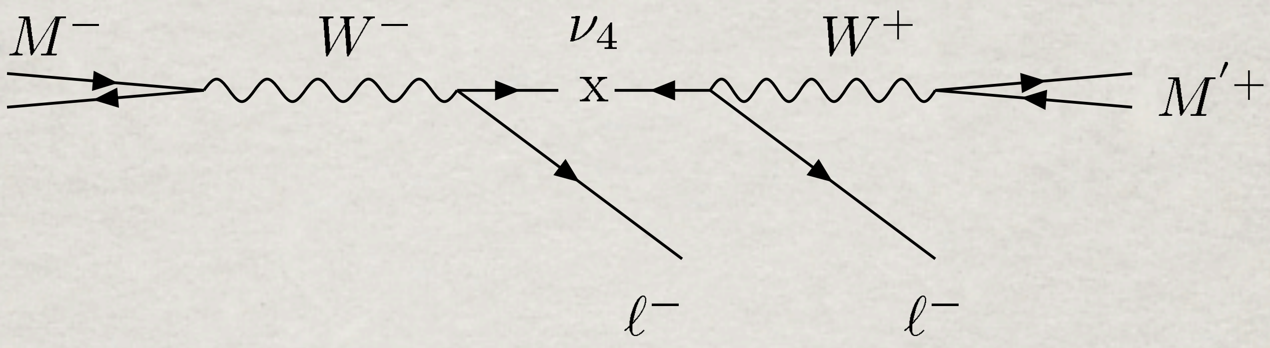
$$U_{iN} \frac{\not{p}+m_N}{p^2-m_N^2+i\epsilon} U_{jN}.$$

The transition rates are proportional to

$$|\mathcal{M}|^2 \propto \begin{cases} \langle m \rangle_{ee}^2 = \left| \sum_{i=1}^{3} U_{ei} U_{ei} m_i \right|^2 & \text{for light } \nu \quad \Rightarrow \langle m \rangle_{ee} \sim \mathcal{O}(0.1 \text{ eV}) \\ \dfrac{\left| \sum_i^n V_{ei} V_{ei} \right|^2}{m_N^2} & \text{for heavy } N \ \Rightarrow |V_{eN}|^2 / m_N < 5 \times 10^{-8} \text{ GeV}^{-1} \end{cases}$$

Very challenging!

(2). Extension to N Resonance Signals



The transition rates are proportional to[†]

$$|\mathcal{M}|^2 \propto \frac{\Gamma(N \to i)\ \Gamma(N \to f)}{m_N \Gamma_N}$$ for resonant N production.

- Active searches:*

  $\tau,\ K,\ D,\ B$ decays: $M^+ \to \ell_i^+ \ell_j^+ M^-$ via N

- Other processes to look for:

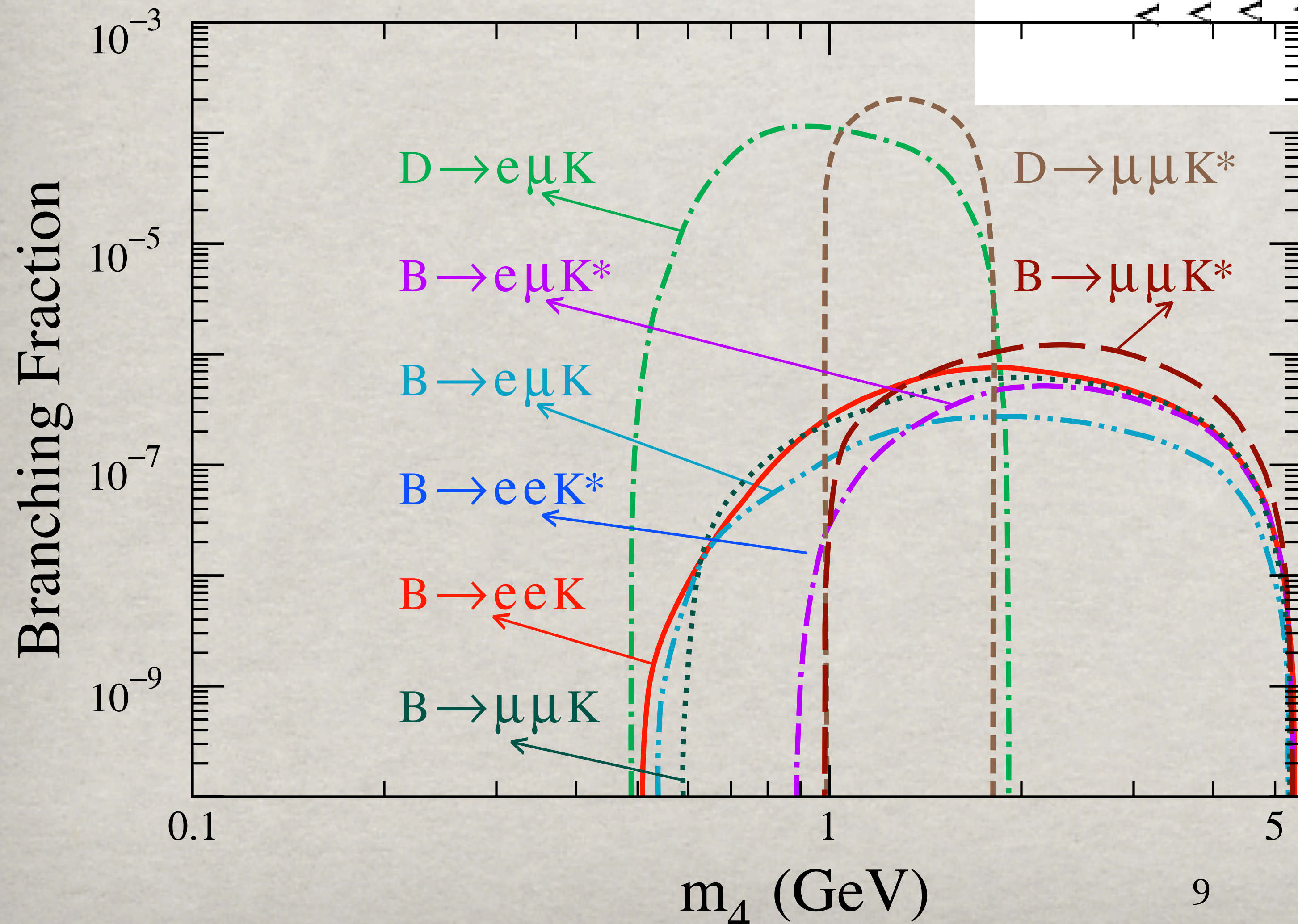
$$D^+,\ B^+ \to \ell^+ \ell^+ K^*,$$
$$B^+ \to \tau^+ e^+ M^-,\ \tau^+ \mu^+ M^-,\ \tau^+ \tau^+ M^-.$$

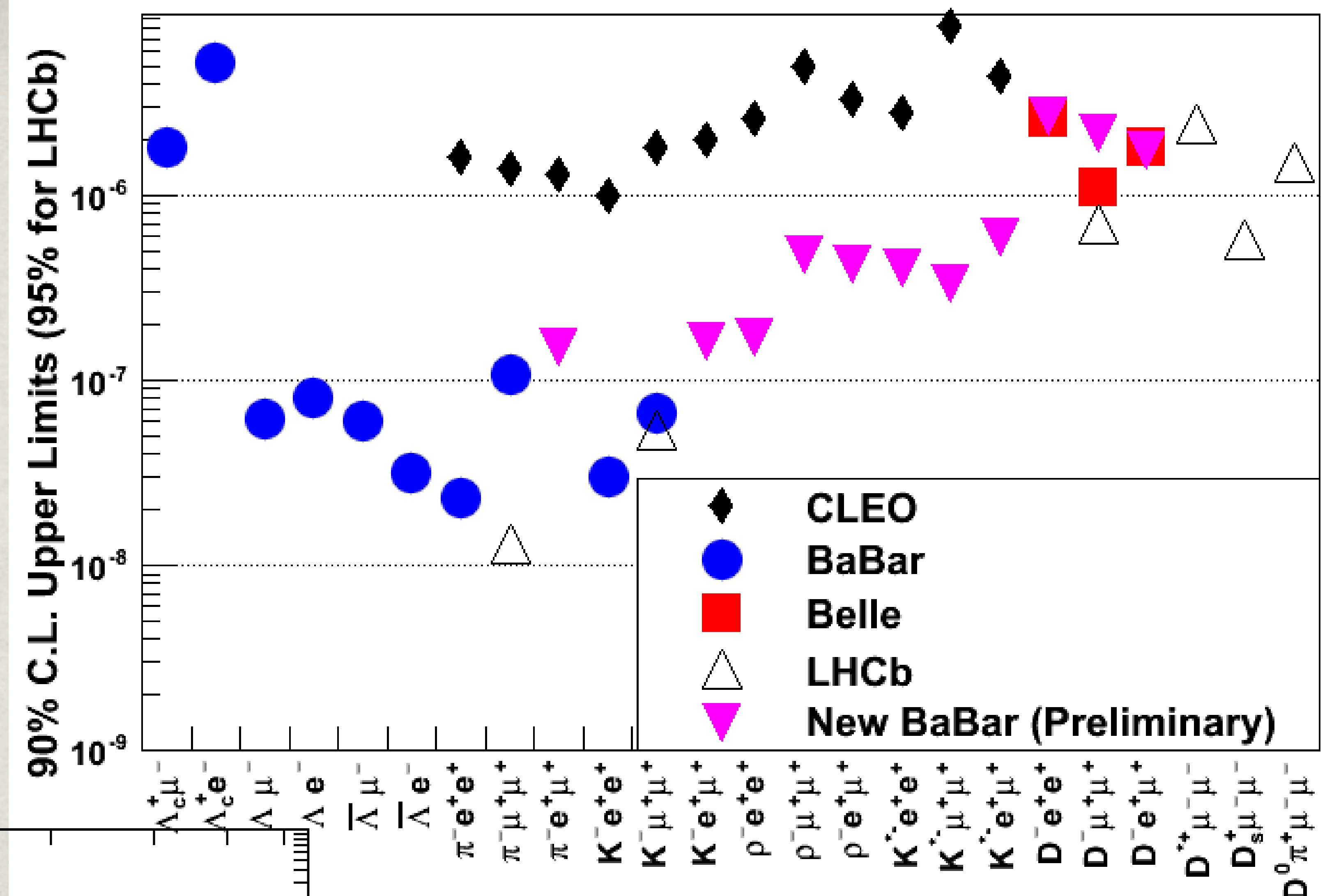
at Super-B, LHCb.

[†]A. Atre, T. Han, S. Pascoli, B. Zhang, arXiv.0901.3589.

*LHCb Collaboration: arXiv:1201.5600 [hep-ex]; PDG listing.

Atre, TH, Pascoli, Zhang:
arXiv:0901:3589





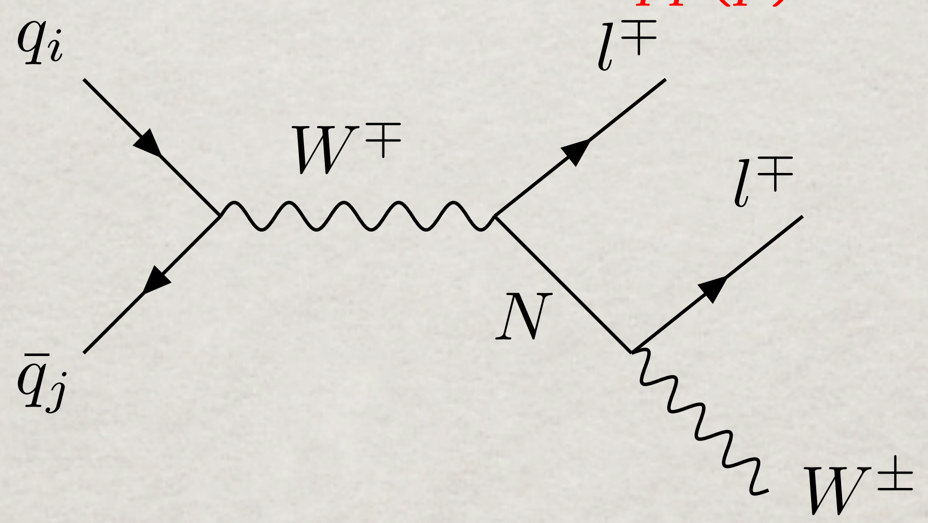
BaBar: arXiv:1310:0876

The Search at the LHC

A few illustrative cases:

(1). Type I Seesaw: N

At hadron colliders: § $pp(\bar{p}) \to \ell^{\pm}\ell^{\pm}jjX$



$$\sigma(pp \to \mu^{\pm}\mu^{\pm}W^{\mp}) \approx \sigma(pp \to \mu^{\pm}N)Br(N \to \mu^{\pm}W^{\mp}) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V^{\ell N}\right|^2} V_{\mu N}^2\ \sigma_0.$$

Suffer from mixing suppression.
(see talks by F. Del Aguila; P.S.Bhupal Dev)

§ Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

† T. Han and B. Zhang, hep-ph/0604064, PRL (2006).

Type I Seesaw: A case with B-L

Fields	Vertices	Couplings	Approximations
Z'	$\bar{q}_i q_i Z'$	$-iQ^q_{BL} g_{BL} \gamma^\mu$	$-$
	$q_1 = u, q_2 = d$	$Q^q_{BL} = \frac{1}{3}$	
	$\bar{\ell}\ell Z'$	$-iQ^\ell_{BL} g_{BL} \gamma^\mu$	$-$
	$\ell = e, \mu, \tau$	$Q^\ell_{BL} = -1$	
	$\overline{N_{m_1}} N_{m_2} Z'$	$-i(U_C^T U_C^* - V^T V^*)_{m_1 m_2} Q^\ell_{BL} g_{BL} \gamma^\mu P_R$	$i I_{m_1 m_2} g_{BL} \gamma^\mu P_R$
	$\overline{\nu_{m_1}} \nu_{m_2} Z'$	$-i(U^\dagger U - V_C^\dagger V_C)_{m_1 m_2} Q^\ell_{BL} g_{BL} \gamma^\mu P_L$	$i I_{m_1 m_2} g_{BL} \gamma^\mu P_L$
N_m	$\overline{N^c_m} \ell^- W^+$	$-i\frac{g}{\sqrt{2}} V^*_{\ell m} \gamma^\mu P_L$	$-$
	$N^T_m \ell^- W^+$	$-i\frac{g}{\sqrt{2}} V^*_{\ell m} C \gamma^\mu P_L$	$-$
	$\overline{\nu_{m_1}} N^c_{m'_2} Z$	$-i\frac{g}{2c_W} U^{\nu N}_{m_1 m'_2} \gamma^\mu P_L$	$-$
	$\overline{\nu_{m_1}}\, \overline{N_{m'_2}}^T Z$	$-i\frac{g}{2c_W} U^{\nu N}_{m_1 m'_2} \gamma^\mu P_L C$	$-$

In general, $M_\nu = m_D\, M_N^{-1}\, m_D^T$,

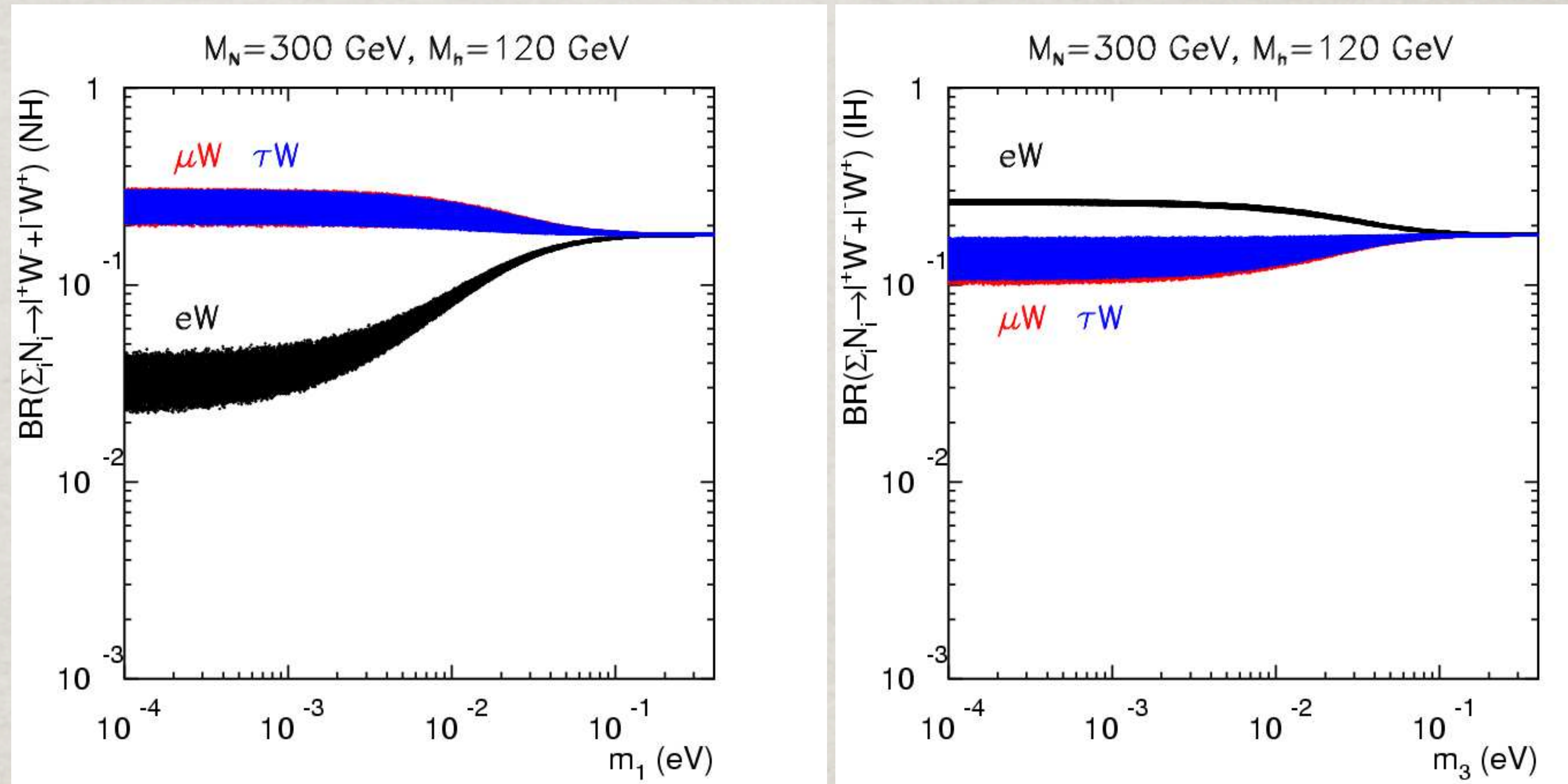
Casas-Ibarra parameterization:

$$m_D = V_{PMNS}\, m^{1/2}\, \Omega\, M^{1/2}, \qquad V_{\ell N} = V_{PMNS}\, m^{1/2}\, \Omega\, M^{-1/2}.$$

P. Fileviez-Perez, TH, T. Li, arXiv:0907.4186.

Type I Seesaw: A case with B-L

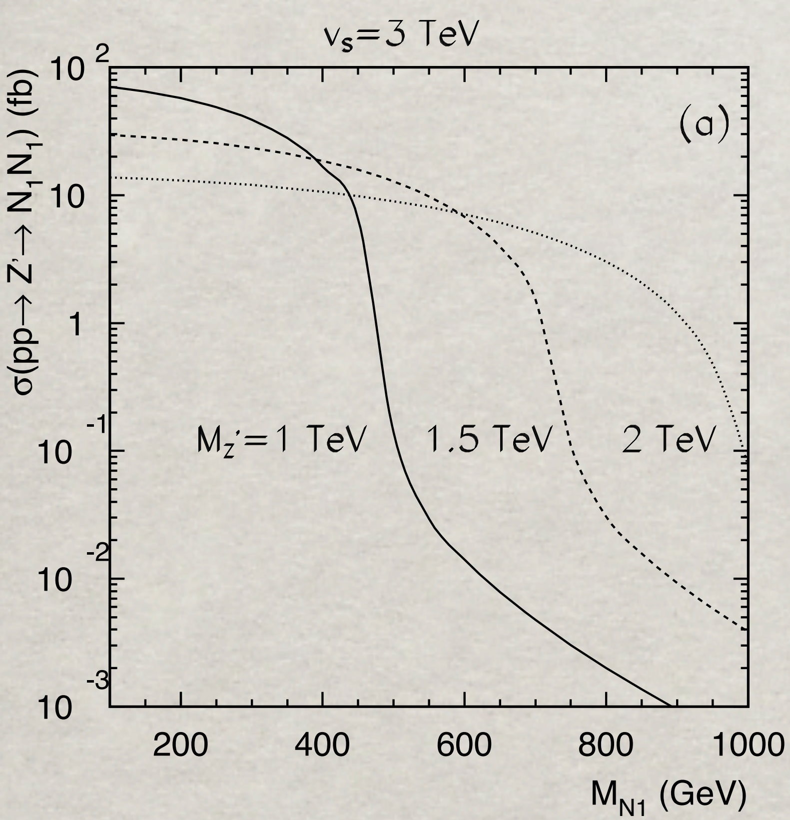
Assuming degenerate N's: $M \sum_{N=1,2,3} (V^*_{\ell N})^2 = (V^*_{PMNS}\, m\, V^\dagger_{PMNS})_{\ell\ell} \equiv (M_\nu)_{\ell\ell}\,, \quad (\ell = e, \mu, \tau).$



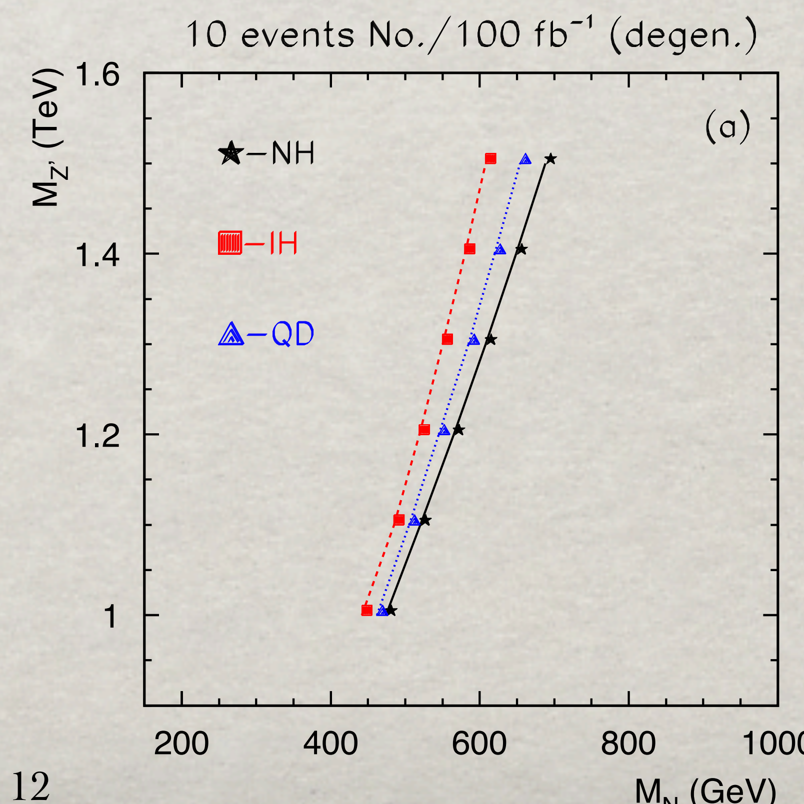
$$M_\nu^{ee} \ll M_\nu^{\mu\mu}, M_\nu^{\tau\tau} \quad \text{for NH},$$

$$M_\nu^{ee} > M_\nu^{\mu\mu}, M_\nu^{\tau\tau} \quad \text{for IH},$$

$$M_\nu^{ee} \approx M_\nu^{\mu\mu} \approx M_\nu^{\tau\tau} \quad \text{for QD}.$$



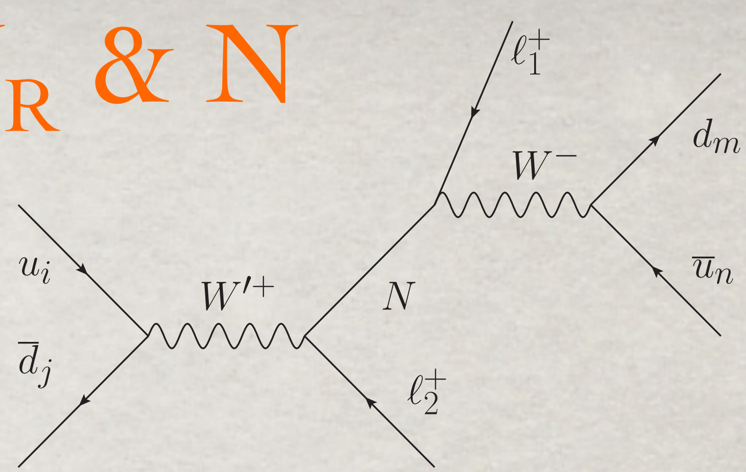
pp → Z' → NN



pp → Z' → NN
→ $l^+l^+ W^-W^-$

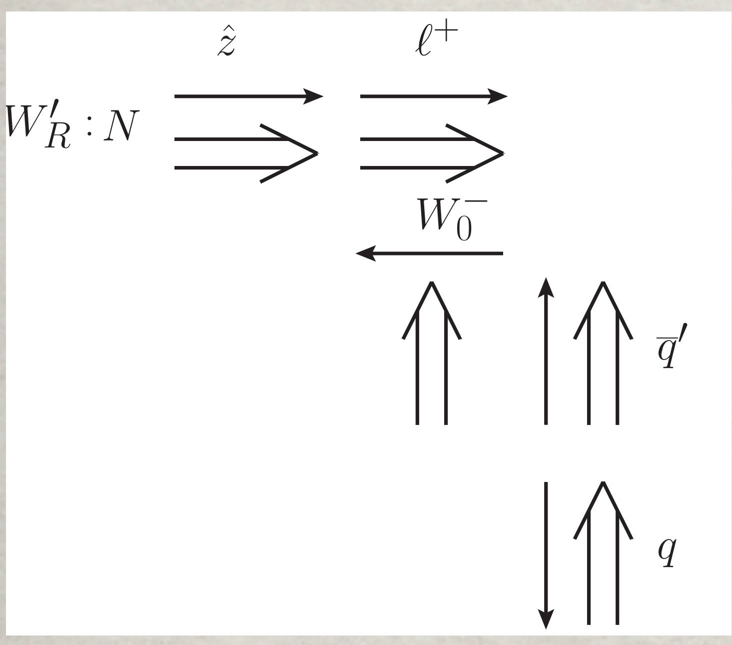
P. Fileviez-Perez, TH, T. Li, arXiv:0907.4186.

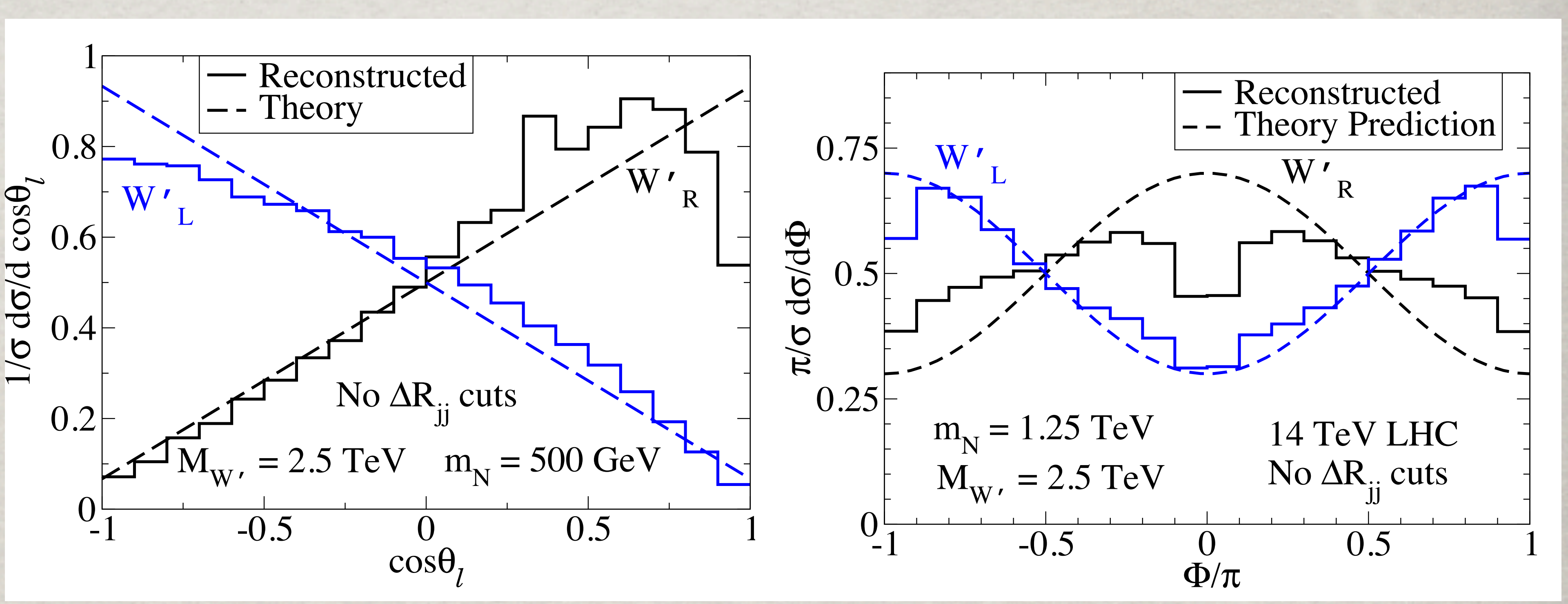
(2). Type II Seesaw: W_R & N



A clean channel with rich physics:†

- Significantly enhanced rate at W_R resonance; ¶
- If observed, determine N's nature: $\Delta L = 2$, azimuthal angle ...
- and determine W' chiral coupling to $\ell - N_{R,L}$ and $q - \bar{q}$.





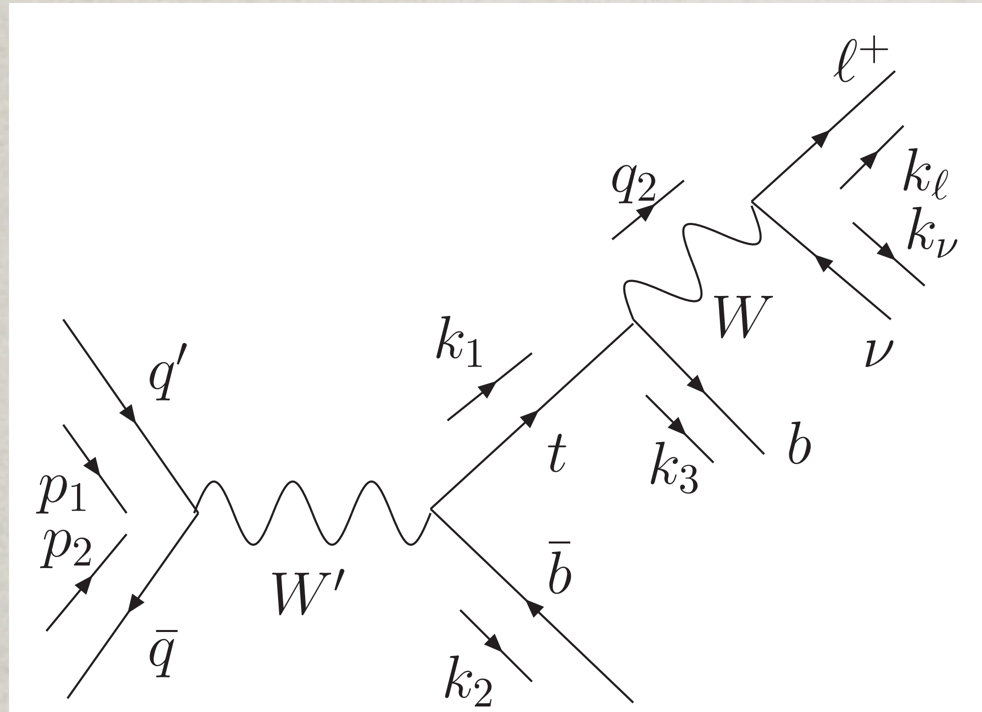
Keung & Senjanovic, PRL (1983).

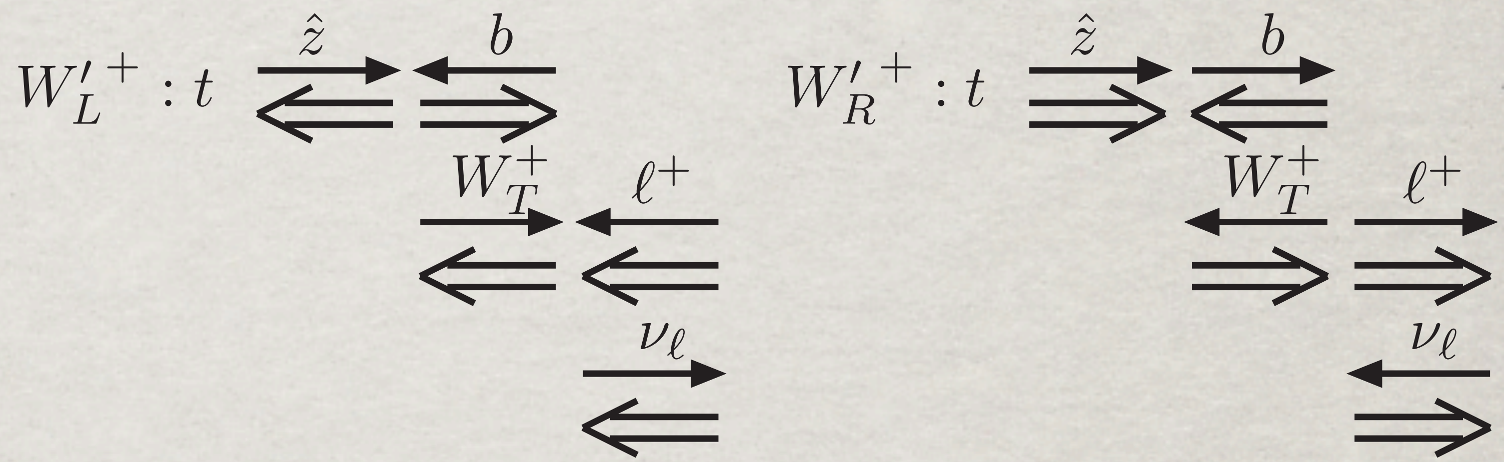
$$\cos\Phi = \frac{\hat{p}_N \times \vec{p}_{\ell_2}}{|\hat{p}_N \times \vec{p}_{\ell_2}|} \cdot \frac{\hat{p}_N \times \vec{p}_q}{|\hat{p}_N \times \vec{p}_q|}$$

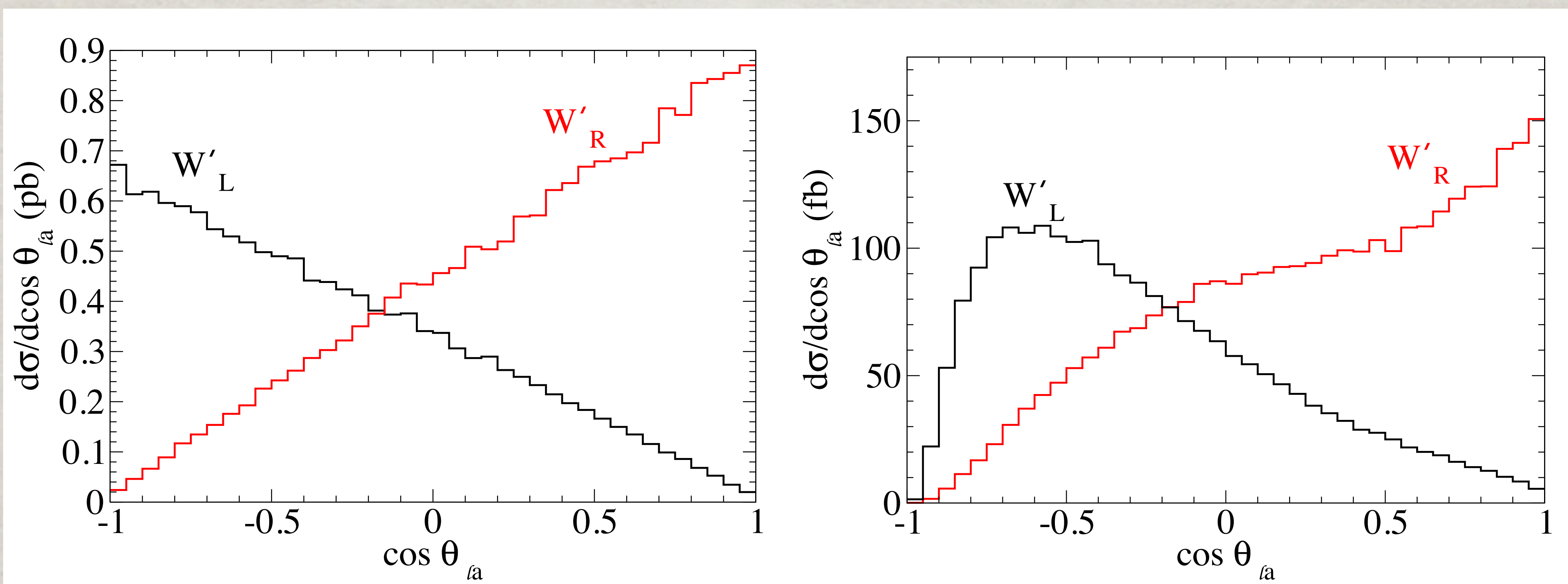
†ATLAS, arXiv:1203.5420 [hep-ex]

†T. Han, I. Lewis, R. Ruiz, Z. Si, *arXiv:1211.6447*.

Type II Seesaw: $W_R \rightarrow t\ b$



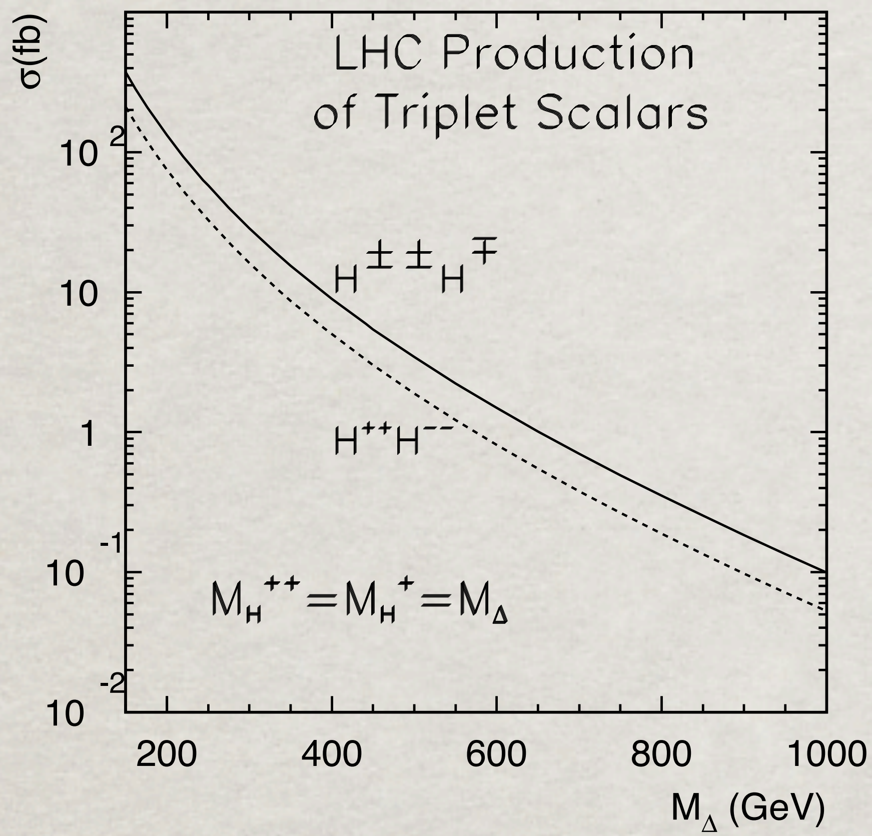


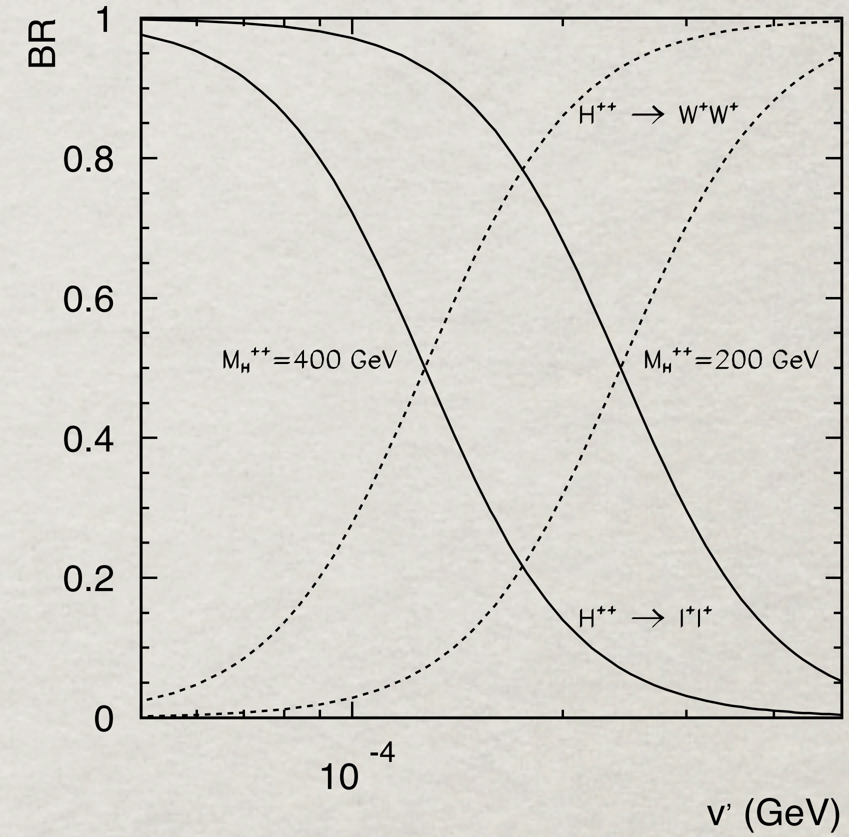


(a) (b)

Type II Seesaw: H±± & H±

$H^{++}H^{--}$ production at hadron colliders:





Unique decays:

$$\Gamma(\phi^{++} \to \ell^+\ell^+) \propto Y_{ij}^2 M_\phi, \quad \Gamma(\phi^{++} \to W^+W^+) \propto \frac{v'^2 M_\phi^3}{v^4},$$

with $Y_{ll}v' \approx m_\nu\ (eV) \Rightarrow v' \approx 2 \times 10^{-4}$ GeV the division.

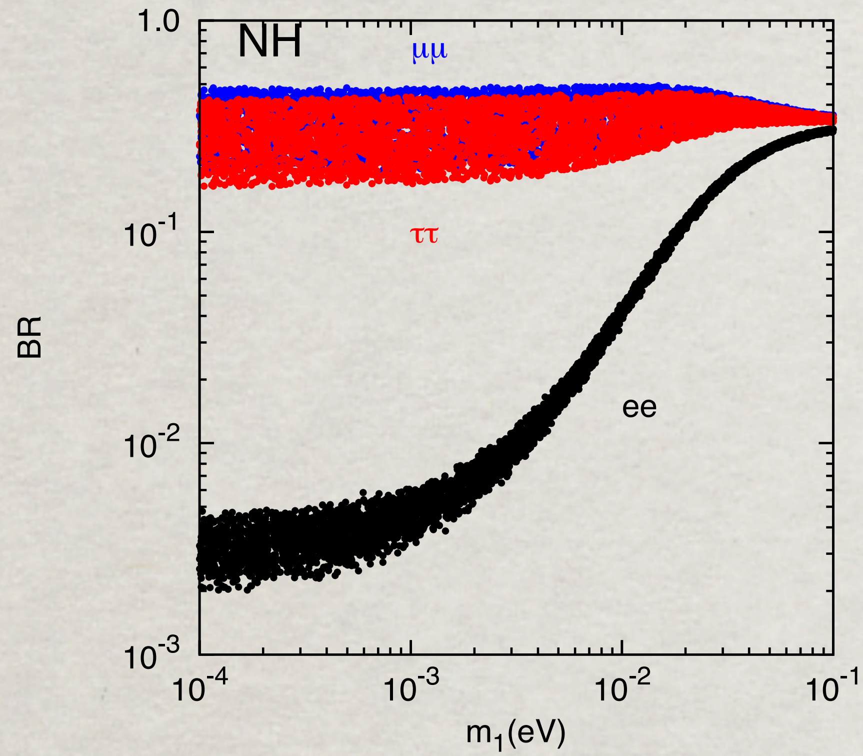
Will concentrate on the leptonic modes. †

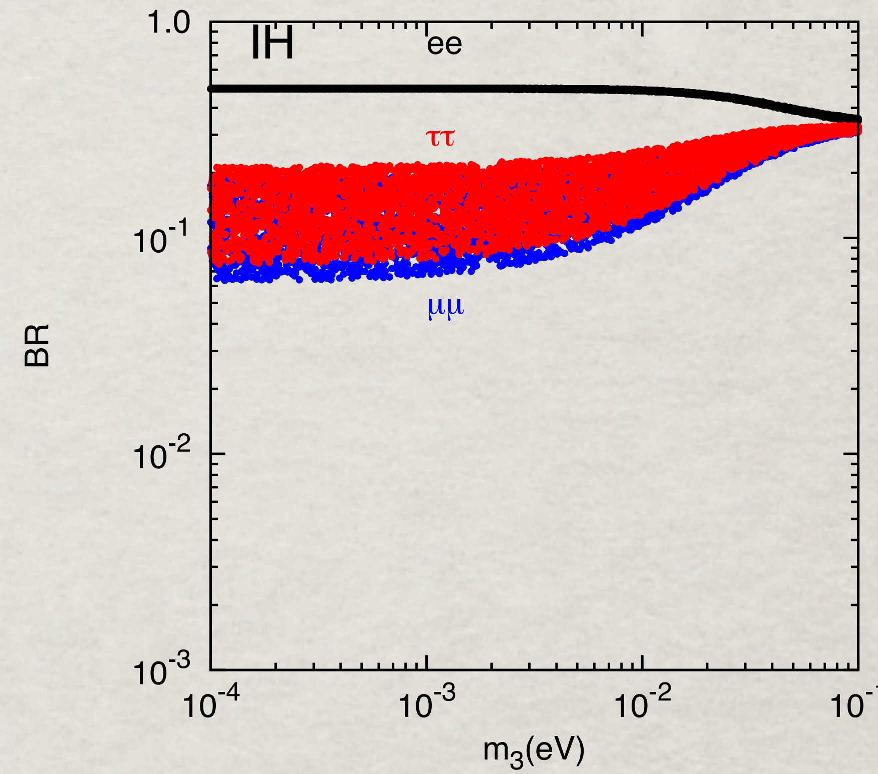
Current LHC bound: $M_{H^{++}} > 400$ GeV for $BR(\mu\mu) = 100\%$.

†Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]; ATLAS/CMS: 4.7 fb^{-1}

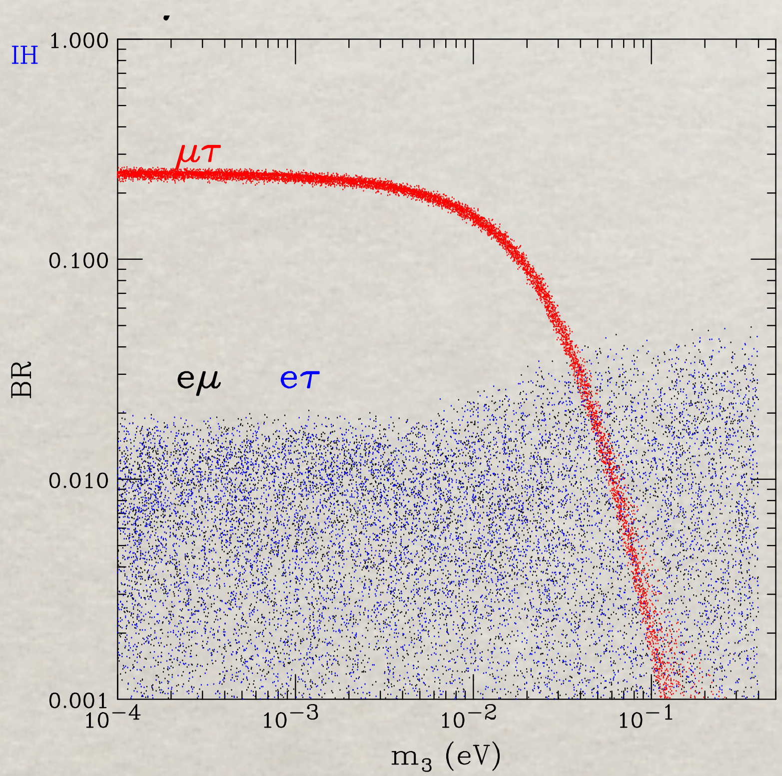
Type II Seesaw: H±± & H±

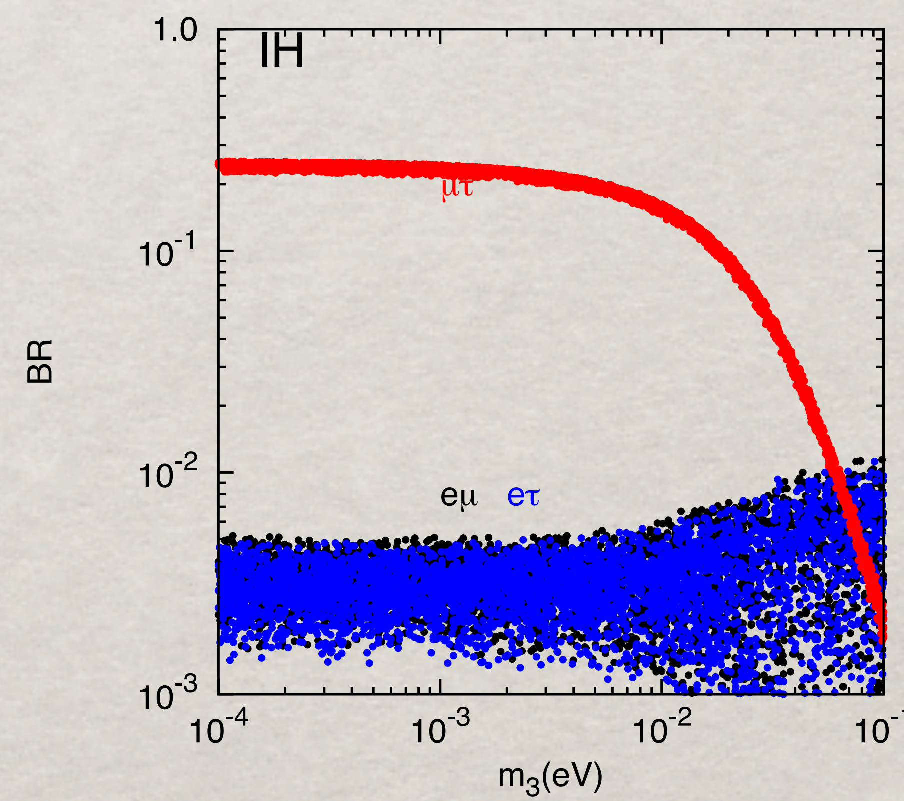
$H^{\pm\pm}, H^{\pm}$ decays predicted by the light neutrino spectrum:





Before DayaBay





with DayaBay

†TH, Gui-Yu Huang, Tong Li, to appear.

Type II Seesaw: $H^{\pm\pm}$ & $H^{\pm}$

Summarize the discovery modes:

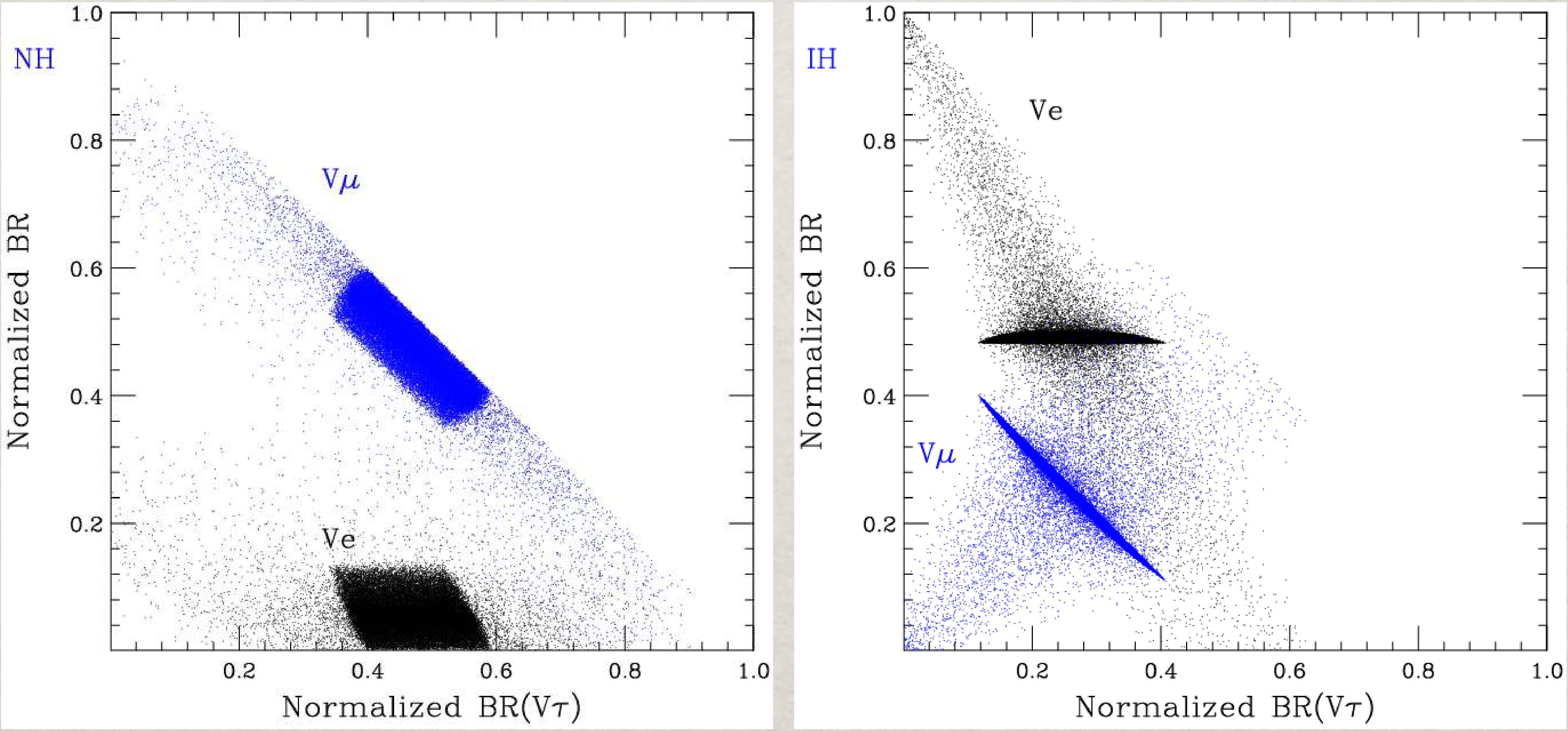
Spectrum	Relations
Normal Hierarchy ($\Delta m^2_{31} > 0$)	BR($H^{++} \to \tau^+\tau^+$), BR($H^{++} \to \mu^+\mu^+$) $\gg$ BR($H^{++} \to e^+e^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\mu^+$), BR($H^{++} \to e^+\tau^+$) BR($H^+ \to \tau^+\bar{\nu}$), BR($H^+ \to \mu^+\bar{\nu}$) $\gg$ BR($H^+ \to e^+\bar{\nu}$)
Inverted Hierarchy ($\Delta m^2_{31} < 0$)	BR($H^{++} \to e^+e^+$) $>$ BR($H^{++} \to \mu^+\mu^+$), BR($H^{++} \to \tau^+\tau^+$) BR($H^{++} \to \mu^+\tau^+$) $\gg$ BR($H^{++} \to e^+\tau^+$), BR($H^{++} \to e^+\mu^+$) BR($H^+ \to e^+\bar{\nu}$) $>$ BR($H^+ \to \mu^+\bar{\nu}$), BR($H^+ \to \tau^+\bar{\nu}$)
Quasi-Degenerate ($m_1, m_2, m_3 > \lvert\Delta m_{31}\rvert$)	BR($H^{++} \to e^+e^+$) $\sim$ BR($H^{++} \to \mu^+\mu^+$) $\sim$ BR($H^{++} \to \tau^+\tau^+$) $\approx$ 1/3 BR($H^+ \to e^+\bar{\nu}$) $\sim$BR($H^+ \to \mu^+\bar{\nu}$) $\sim$BR($H^+ \to \tau^+\bar{\nu}$) $\approx$ 1/3

† Pavel Fileviez Perez, Tao Han, Gui-Yu Huang, Tong Li, Kai Wang, arXiv:0803.3450 [hep-ph]

(3). Type III (& I) Seesaw: $T^{\pm}$ & T^0

Lepton flavor combination determines the ν mass pattern: †

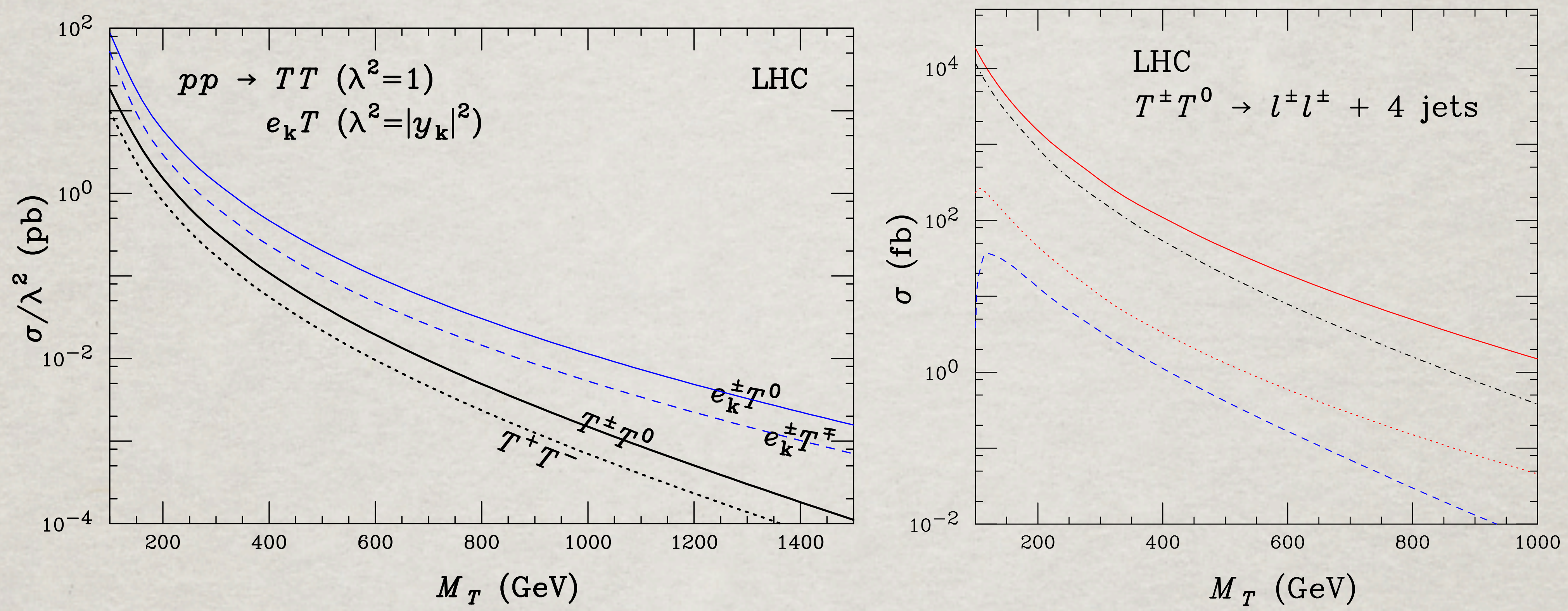
$$m_\nu^{ij} \sim -v^2 \frac{y_T^i y_T^j}{M_T}, \quad BR(T^{\pm,0} \to W^\pm \ell,\ Z\ell) \sim y_T^2 \sim V_{PMNS}^2 \frac{M_T m_\nu}{v^2}.$$



Lepton flavors correlate with the ν mass pattern.

†Abdesslam Arhrib, Borut Bajc, Dilip Kumar Ghosh, Tao Han, Gui-Yu Huang, Ivica Puljak, Goran Sejanovic, arXiv:0904.2390.

Type III (& I) Seesaw: $T^{\pm}$ & T^0



- Single production $T^{\pm}\ell^{\mp}$, $T^0\ell^{\pm}$:

Kinematically favored, but highly suppressed by mixing.

- Pair production with gauge couplings.

Example: $T^{\pm} + T^0 \to \ell^+ Z(h) + \ell^+ W^- \to \ell^+ jj(b\bar{b}) + \ell^+ jj$.
Low backgrounds.

- LHC studies with Minimal Flavor Violation implemented. ‡

†Similar earlier work: Franceschini, Hambye, Strumia, arXiv:0805.1613.

‡O. Eboli, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia, arXiv:1108.0661 [hep-ph].

Summary

- It is of fundamental importance to test the Majorana nature of ν's.
- Type I See-saw:
  - $\tau,\ K,\ D,\ B$ rare decays sensitive to

    $140\ \text{MeV} < m_4 < 5\ \text{GeV},\ 10^{-9} < |V_{\ell 4}|^2 < 10^{-2};$
  - LHC sensitive: $10\ \text{GeV} < m_4 < 400\ \text{GeV},\ 10^{-6} < |V_{\mu 4}|^2 < 10^{-2}.$
  - May be helped with B-L Z'.
- Type II See-saw: for a scalar triplet $\Phi^{\pm\pm}$
  - LHC sensitive: $M_\phi \sim 600 - 1000$ GeV ($\ell^\pm\ell^\pm$ *or* $W^\pm W^\pm$).
  - Distinguish Normal/Inverted Hierarchy; Probe Majorana phases.
  - With $W'^\pm \to N\ell^\pm$, reach $M_N < M_{W'} \sim 4 - 5$ TeV.
- Type III See-saw: for a lepton triplet $T^\pm,\ T^0$
  - LHC sensitive: $M_T \sim 800$ GeV.
  - Also distinguish Normal/Inverted Hierarchy.

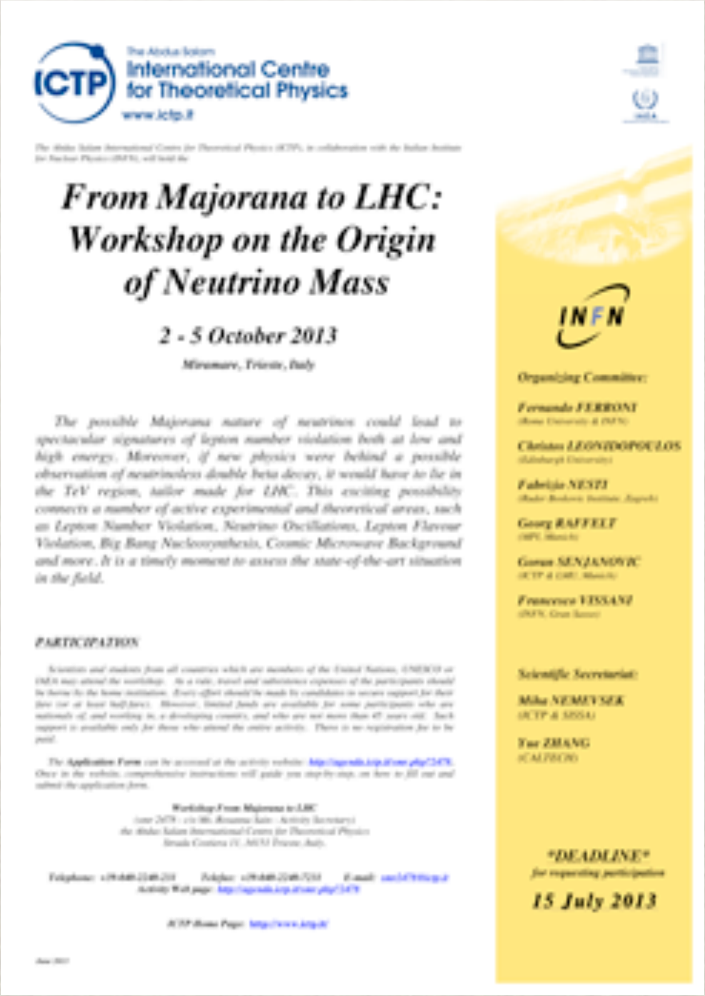
The See-saw models for m_ν may be the best playground

for synergies among the frontiers:
intensity, energy and astrophysics/cosmology.

Last, not least

Many Thanks to the organizers:

F. Ferroni
C. Leonidopoulos
F. Nesti
G. Raffelt
G. Senjanovic
F. Vissani


The Abdus Salam International Centre for Theoretical Physics
www.ictp.it

From Majorana to LHC: Workshop on the Origin of Neutrino Mass

2 - 5 October 2013

Miramare, Trieste, Italy

The possible Majorana nature of neutrinos could lead to spectacular signatures of lepton number violation both at low and high energy. Moreover, if new physics were behind a possible observation of neutrinoless double beta decay, it would have to lie in the TeV region, tailor made for LHC. This exciting possibility connects a number of active experimental and theoretical areas, such as Lepton Number Violation, Neutrino Oscillations, Lepton Flavour Violation, Big Bang Nucleosynthesis, Cosmic Microwave Background and more. It is a timely moment to assess the state-of-the-art situation in the field.

PARTICIPATION

[illegible]

Workshop From Majorana to LHC

INFN

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(CALTECH)

DEADLINE
for requesting participation
15 July 2013

It has been a lot of fun!

Special thanks to Goran!

Best wishes to your new endeavor!