

Fisica oltre il Modello Standard alle alte energie

Modelli Compositi delle particelle elementari, modelli con multipletti di isospin superiore
e stati di carica esotica (leptoni di carica doppia L^{++} e quarks di carica $Q=5/3$ e,
Neutrini di Majorana compositi)

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Outline della presentazione

- ◆ Breve introduzione/motivazione ai modelli compositi effettivi delle particelle elementari (interazioni di gauge, interazioni di contatto, modelli con multipletti di iso-spin superiore, stati di carica esotica)
- ◆ Attività del gruppo di fenomenologia in sinergia con il gruppo sperimentale negli ultimi anni
- ◆ Qualche esempio di progetti/tesi:
 - * Doubly Charged Leptons (where it all started!!)
 - * Heavy composite Majorana neutrino (pheno + CMS analysis);
 - * Phenomenology of production at LHC of heavy $Q(5/3)$
- ◆ Conclusioni/Sviluppi

Il Modello Standard descrive le interazioni fondamentali delle particelle elementari

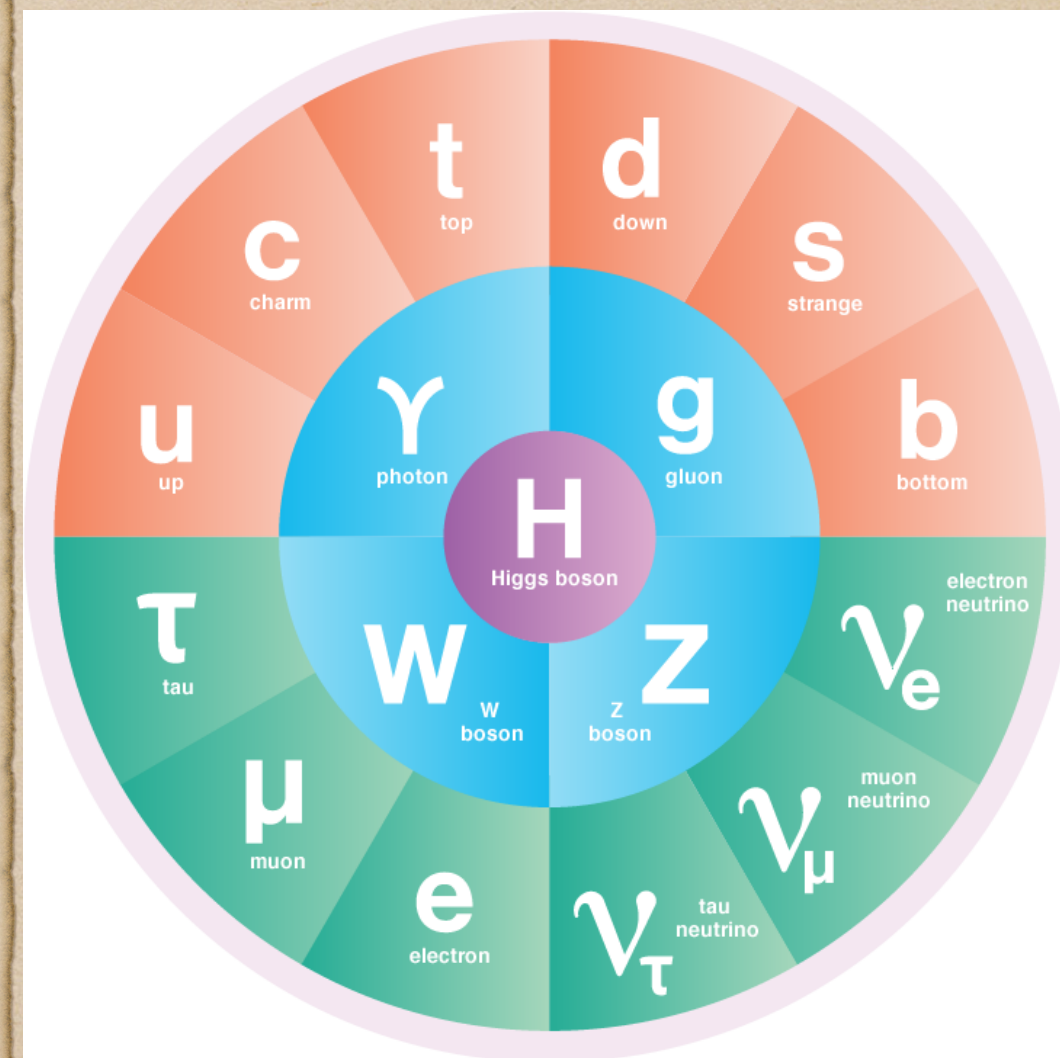
- ◆ Accordo eccellente con moltitudine di dati empirici fino a scale di lunghezza molto "piccole"
- ◆ E' una teoria di campo basata sul principio dell'invarianza di Gauge che incorpora meccanica quantistica e relatività ristretta
- ◆ Coinvolge aspetti della teoria dei gruppi.
- ◆ Raggiunge in alcuni casi precisioni fantastiche, anche dell'ordine di una parte su 10^{10}

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Lagrangiana del Modello Standard

- ◆ Meccanica Quantistica Relativistica (MQR) Modello Standard ➤
Fenomeni microscopici
- ◆ Relatività Generale ➤ (Gravitazione, Cosmologia) ma inconciliabile con MQ

- ◆ Gli elementi base della MQ sono i campi, onde o particelle.
- ◆ Le particelle appaiono (ad oggi) elementari fino alle scale più piccole accessibili in laboratorio
- ◆ Proprietà: massa, spin, carica etc..
- ◆ Altro elemento fondamentale del modello standard sono le SIMMETRIE: Invarianza di gauge e la connessione con la teoria matematica dei gruppi
- ◆ Bosone di Higgs ultima scoperta (2012)



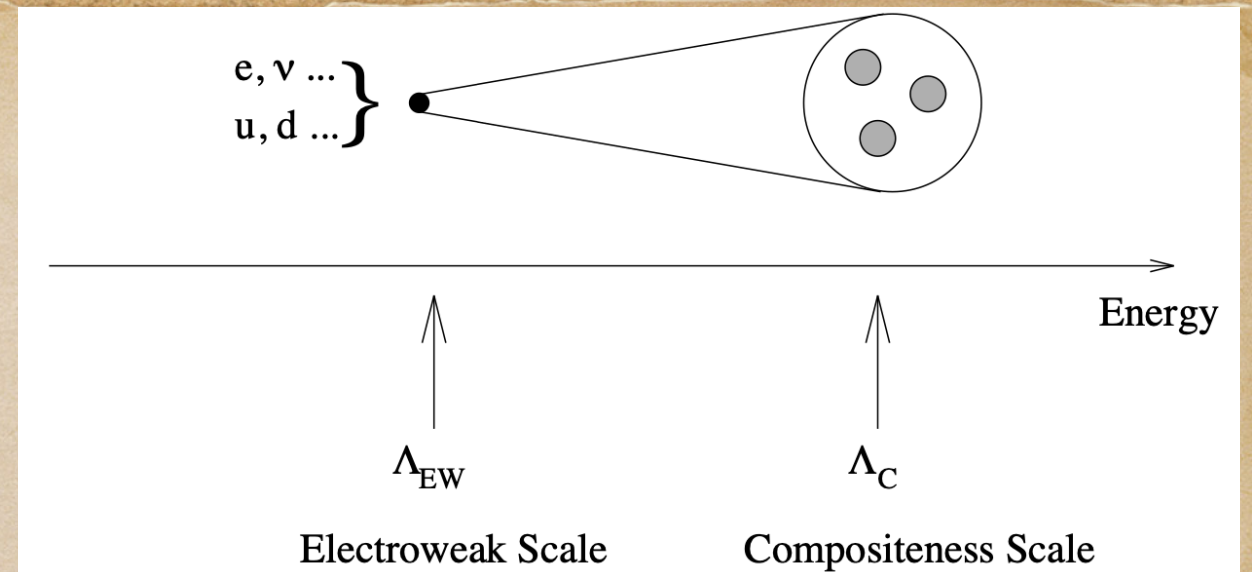
Fisica oltre il modello standard ?

- ◆ Pur se in accordo impressionante con gli esperimenti il Modello Standard è dal punto di vista teorico è ritenuto non completamente soddisfacente.
- ◆ Dipende da molti parametri liberi (19) come masse delle particelle, costanti di accoppiamento etc..
- ◆ Non prevede la massa dei neutrini
- ◆ Non comprende le interazioni gravitazionali
- ◆ Non fornisce un candidato per la materia oscura

Possibili estensioni del Modello Standard

- ◆ **Super-simmetria** (simmetria dello spazio tempo che collega fermioni e bosoni). Ogni particella di spin s è accompagnata da un super-partner di spin $s-1/2$)
- ◆ Modelli Compositi (i quarks e i leptoni non sono puntiformi ma hanno una struttura interna)
- ◆ **Extra-dimensioni** (lo spazio tempo acquista dimensioni spaziali aggiuntive)

Composite Models



- ◆ The idea is that at some **high energy scale Λ** a further level of **compositeness** of the so called “elementary” particles **will show up**. It goes back quite some time.
- ◆ P.A.M Dirac, Sci. Am. 208, 45 (1963); Terazawa et al., PRD 15, 480 (1977); Eichten, Lane, Peskin, PRL 50, 811 (1983); Cabibbo, Maiani, Srivastava, PLB 139, 459 (1984);
- ◆ Quite natural expectations in such framework are:
 - ◆ **excited states (e^*, q^* etc..)** of mass **m^*** ;
 - ◆ **contact interactions** which are the residual forces stemming from the new and unknown dynamic of the ‘**preonic**’ constituents

- ◆ Over the years phenomenology and experimental searches concentrated to the isospin $I_W = 0, \frac{1}{2}$ multiplets.
- ◆ Higher weak isospin multiplets ($I_W = 1, \frac{3}{2}$) contain exotic states (doubly charged leptons, and quarks of charge $Q = 5/3 e$) [Pancheri-Srivastava, *Phys.Lett.* 146B (1984) 87-94];
- ◆ Somehow the phenomenology of these exotic states remained mostly unexplored; All phenomenology concentrated with the doublet/scalar case.
- ◆ We have been filling the gap!

Lepton sector

I_W	Multiplet	Q	Y	Coupled to
0	E^-	-1	-2	e_R through B_μ
$\frac{1}{2}$	$\begin{pmatrix} E^0 \\ E^- \end{pmatrix}$	$\begin{matrix} 0 \\ -1 \end{matrix}$	-1	$\ell_L = \begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}$ through W^μ and B^μ
1	$\begin{pmatrix} E^0 \\ E^- \\ E^{--} \end{pmatrix}$	$\begin{matrix} 0 \\ -1 \\ -2 \end{matrix}$	-2	e_R through $\mathbf{W}_\mu$
$\frac{3}{2}$	$\begin{pmatrix} E^+ \\ E^0 \\ E^- \\ E^{--} \end{pmatrix}$	$\begin{matrix} 1 \\ 0 \\ -1 \\ -2 \end{matrix}$	-1	$\ell_L = \begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}$ through W^μ

Quark sector

I_W	Multiplet	Q	Y	Coupled to
0	$(i) \quad U$ $(ii) \quad D$	$2/3$ $-1/3$	$4/3$ $-2/3$	u_R through B^μ and $G^{\mu,a}$
$\frac{1}{2}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$	$1/3$	$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ through W^μ B^μ and $G^{\mu,a}$
1	$(i) \begin{pmatrix} U^+ \\ U \\ D \end{pmatrix}$ $(ii) \begin{pmatrix} U \\ D \\ D^- \end{pmatrix}$	$\begin{pmatrix} 5/3 \\ 2/3 \\ -1/3 \end{pmatrix}$ $\begin{pmatrix} 2/3 \\ -1/3 \\ -4/3 \end{pmatrix}$	$4/3$ $-2/3$	u_R through W^μ d_R through W^μ
$\frac{3}{2}$	$\begin{pmatrix} U^+ \\ U \\ D \\ D^- \end{pmatrix}$	$5/3$ $2/3$ $-1/3$ $-4/3$	$1/3$	$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$ through W^μ

Magnetic type gauge Interactions

$$\mathcal{L}_{\text{int}}^{(I_W=3/2)} = \frac{gf_{3/2}}{\Lambda} \sum_{M,m,m'} C\left(\frac{3}{2}, M | 1, m; \frac{1}{2}, m'\right) \times$$

$$\left(\bar{\Psi}_M \sigma_{\mu\nu} q_{Lm'} \right) \partial^\nu (W^m)^\mu + h.c.$$

(dim=5 operators)

$$\mathcal{L}_{\text{int}}^{(I_W=1)} = \frac{gf_1}{\Lambda} \sum_{m=0,\pm 1} \left[\left(\bar{U}_m \sigma_{\mu\nu} u_R \right) + \right.$$

$$\left. \left(\bar{D}_m \sigma_{\mu\nu} d_R \right) \right] \partial^\nu (W^m)^\mu + h.c.$$

⇒ Exotic states couple only to $SU(2)$ gauge field (W^μ)

⇒ Implementation in CalcHEP generator

⇒ Parameter Space: $[\Lambda, m^*]$

Contact interactions

$$\mathcal{L}_{\text{CI}} = \left(\frac{g_*^2}{2\Lambda^2} \right) j^\mu j_\mu,$$

$$j_\mu = (\eta \bar{f}_L \gamma_\mu f_L + \eta' \bar{f}_L \gamma_\mu f_L^* + \eta'' \bar{f}_L^* \gamma_\mu f_L^* + \text{H.c.}) \\ + (L \rightarrow R),$$

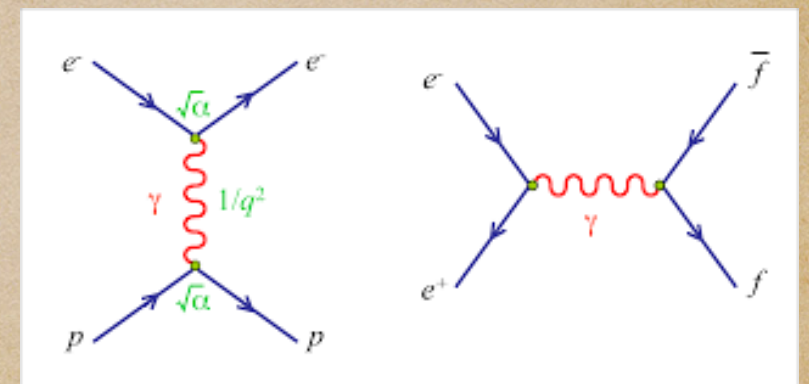
(dim=6 operators)

- ◆ Standard normalisation is: $g_*^2 = 4\pi$
- ◆ Fermion interactions are obtained as an effective field theory after the high energy modes ($\approx \Lambda$) have been integrated out
- ◆ Implementation in the CalcHEP generator

$\Rightarrow$ Parameter Space: $[\Lambda, m^*]$

Flusso di lavoro tipico di una TL magistrale in teoria/ fenomenologia delle particelle elementari con applicazioni alle ricerche agli acceleratori (LHC).

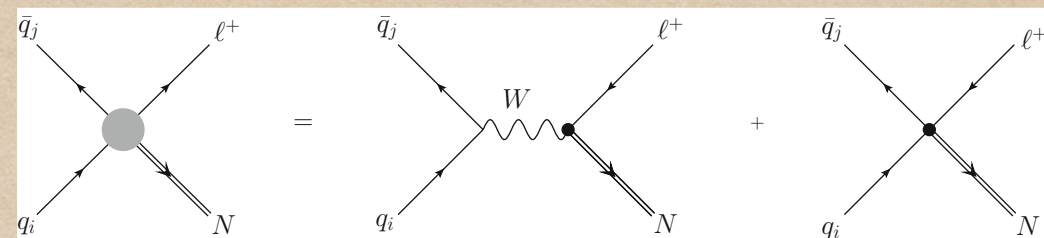
- ◆ Studio di un modello teorico di riferimento di qualche scenario BSM che tipicamente offre delle previsioni distinte (diverse) da quelle del modello standard: $\rightarrow \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$
 - ◆ Studio di letteratura di riferimento e scelta un processo fisico che possa mettere in evidenza delle differenze dalle previsioni del MS.
- ◆ Calcolo di ampiezze di scattering dei processi individuati tramite la tecnica dei diagrammi di Feynman (corso di Fisica Teorica).
- ◆ Esistenza di tools per automatizzare il calcolo (generatori, quali CalcHEP, MadGraph) e.g. quadrati delle ampiezze e sezioni d'urto
 - * Simulazione veloce della risposta del rivelatore (Delphes);
 - * Stima dei fondi del MS più importanti
 - * Determinazione della sensibilità ai parametri del modello



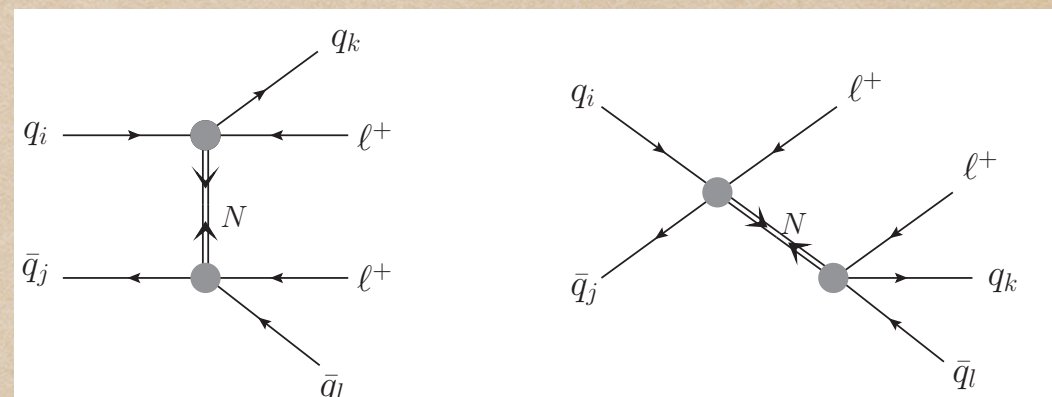
Heavy Composite Majorana Neutrino (HCMN) production @ LHC

Eur. Phys. J. C (2016) 76:593, Leonardi, Alunni, Romeo, Fanò, and Panella

- ◆ First complete study of searches @ LHC of exotic composite Majorana Neutrino; $pp \rightarrow \ell N_\ell$

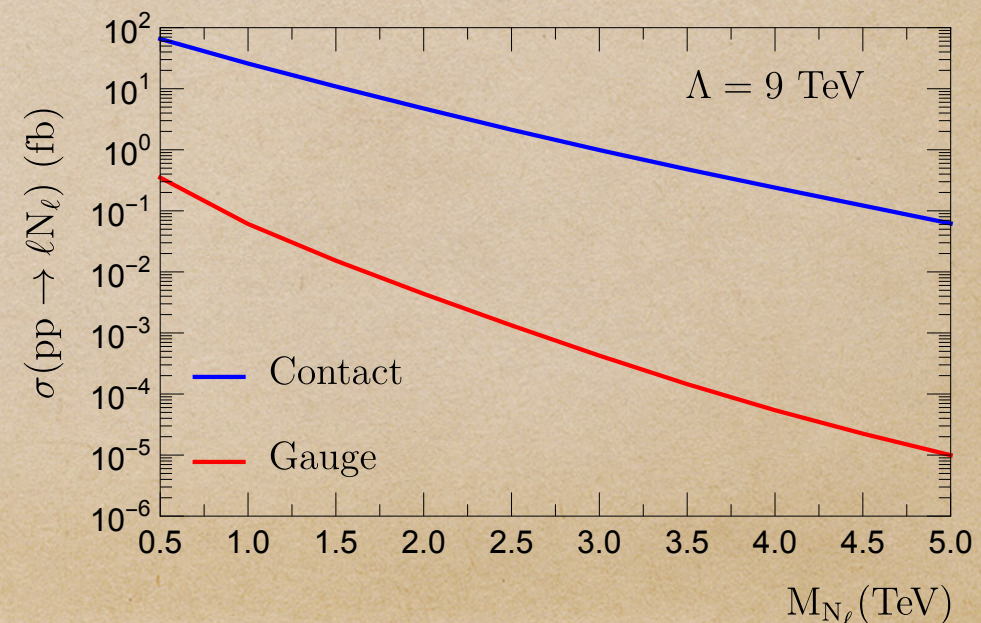


- ◆ Gauge AND contact interactions;
- ◆ implementation of model (interactions) in the generator (CalcHEP);
- ◆ N_ℓ interacts via both gauge and contact interactions:



- ◆ $N_\ell \rightarrow \ell q \bar{q}', N_\ell \rightarrow \nu \bar{\nu} q \bar{q}', N_\ell \rightarrow \ell \ell \nu \nu$

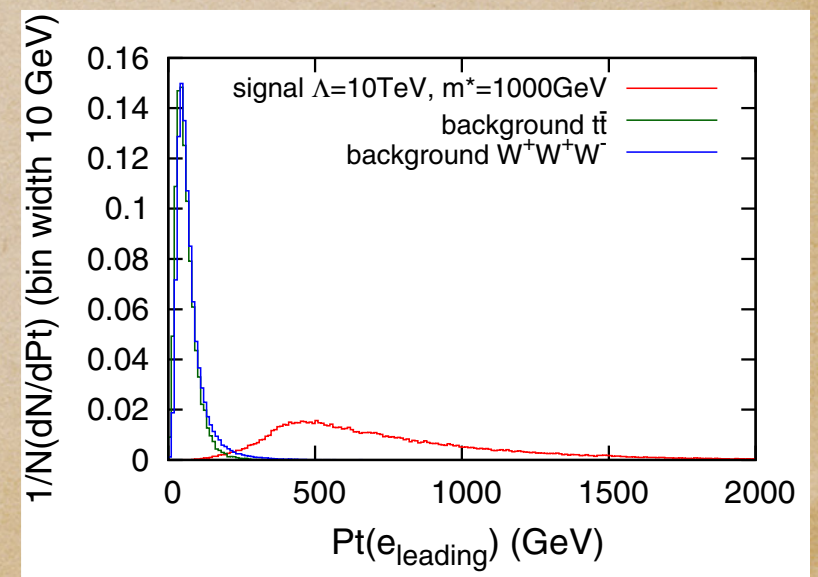
- ◆ final signature : $\Rightarrow pp \rightarrow \ell \ell jj$



Invariant mass distribution

- ◆ Signal: $pp \rightarrow \ell N \rightarrow \ell \ell jj$
- ◆ main SM background and is t t -bar and WWW production:
 $pp \rightarrow t\bar{t} \rightarrow \ell^+ \ell^+ \nu \nu jets$ $pp \rightarrow W^+ W^+ W^- \rightarrow \ell^+ \nu \ell^+ \nu jj$
- ◆ Kinematic study to optimize Statistical Significance
 - * Angular, p_T , reconstructed invariant mass ($M_{\ell \ell jj}$) distributions
 - * Fast simulation of detector reconstruction with DELPHES
 - * Most efficient cut:

$$\left\{ \begin{array}{l} p_T(e_{\text{leading}}^+) \geq 200 \text{ GeV}, \\ p_T(e_{\text{second-leading}}^+) \geq 100 \text{ GeV}. \end{array} \right.$$



Contour maps of S @ 5- and 3- σ within statistical error

- Signal events:

$$N_s = L\sigma_s\epsilon_s$$

- background events:

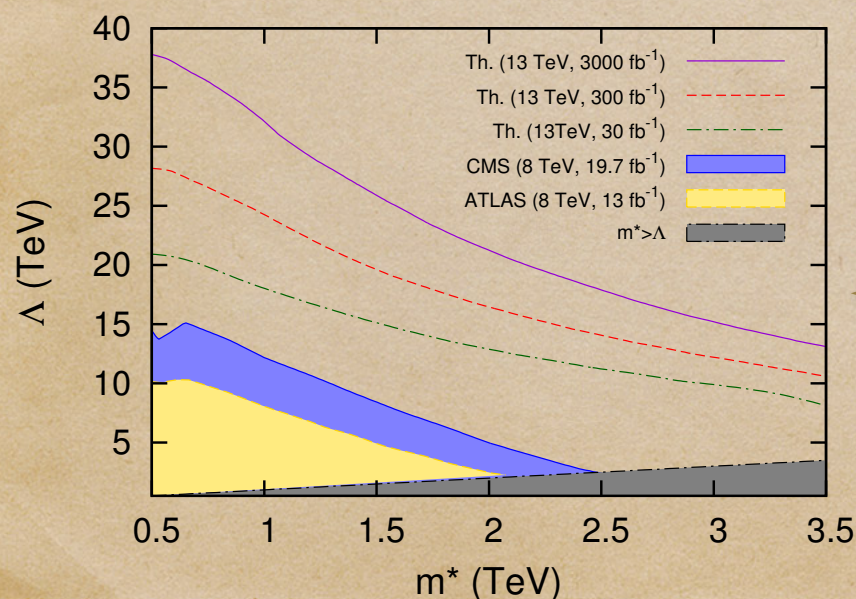
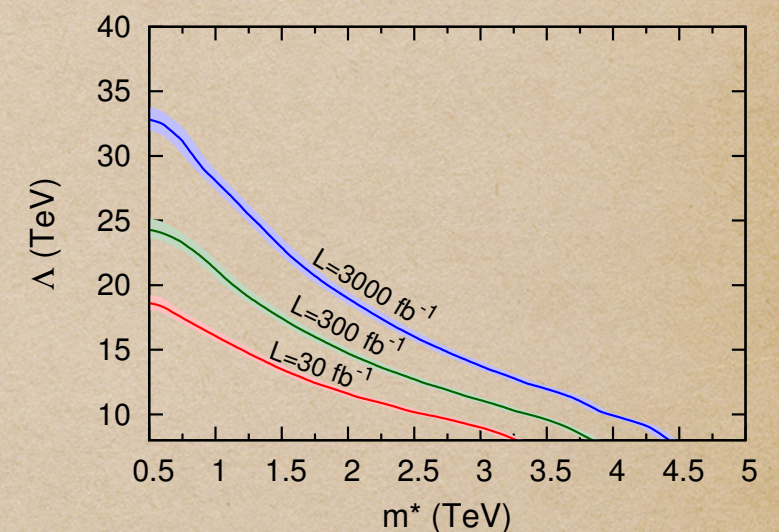
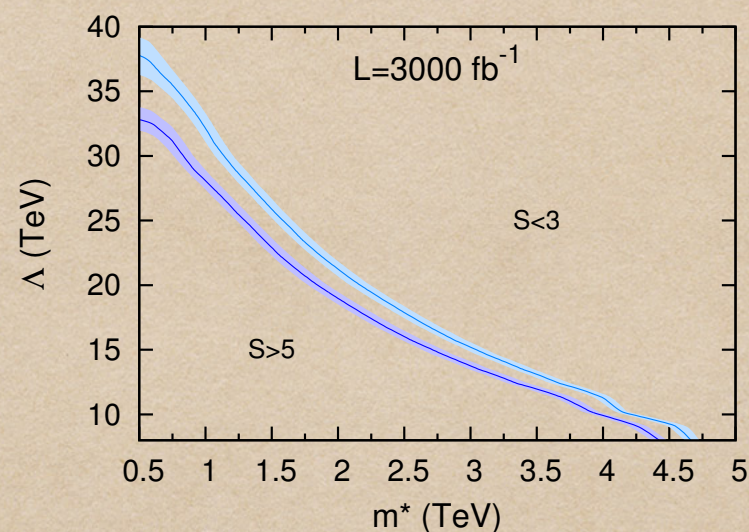
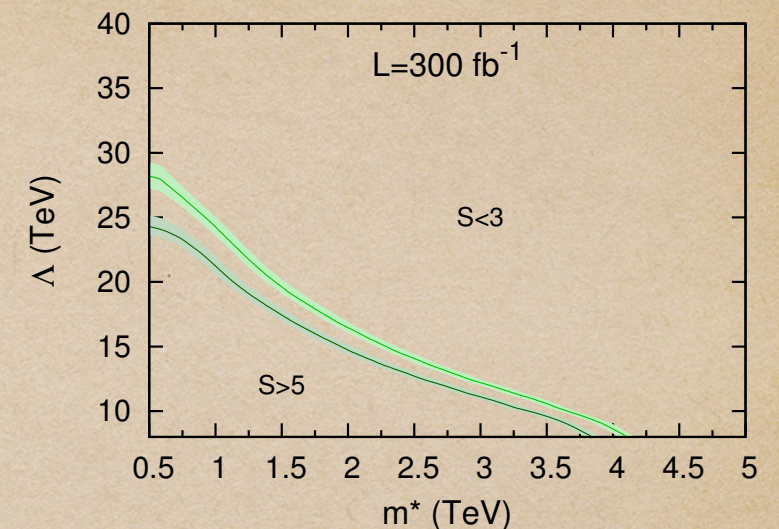
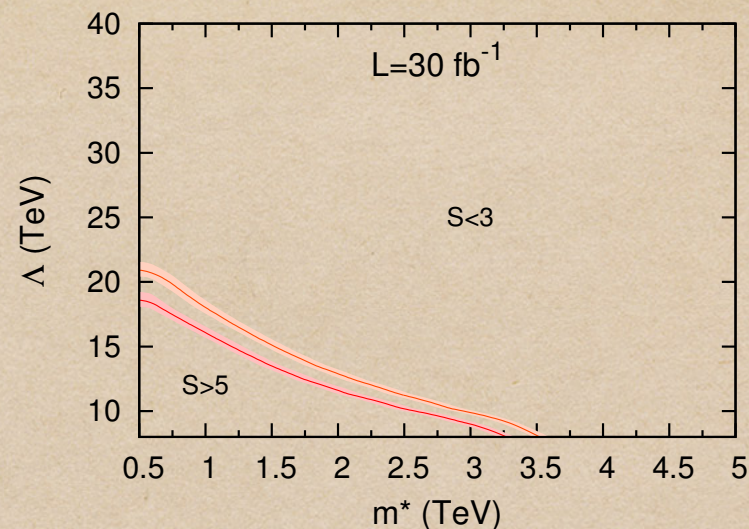
$$N_b = L\sigma_b\epsilon_b$$

- Statistical Significance S :

$$S = \frac{N_s}{\sqrt{N_s + N_b}}$$

- $L = (30, 300, 3000) \text{ fb}^{-1}$

- $\sqrt{s} = 13 \text{ TeV}$



Current exclusion regions at 95% C.L. from CMS and ATLAS (Run I) vs the discovery reach expected at Run II @ 3- σ from the $eejj$ signature due to a heavy composite Majorana neutrino

Experimental search of HCMN signature [CMS-PAS-16-026]

- ◆ Implementation of the Majorana neutrino with gauge and contact interactions in the CalcHEP generator
- ◆ Preparation of private signal samples with the theoretical model implemented in CalcHEP
- ◆ CMS analysis of data collected in Run II (2015) corresponding to 2.3 fb^{-1} integrated luminosity.
- ◆ Presented @ ICHEP 2016
- ◆ PhD thesis of R. Leonardi e L. Alunni

Available on the CERN CDS information server

CMS PAS EXO-16-026

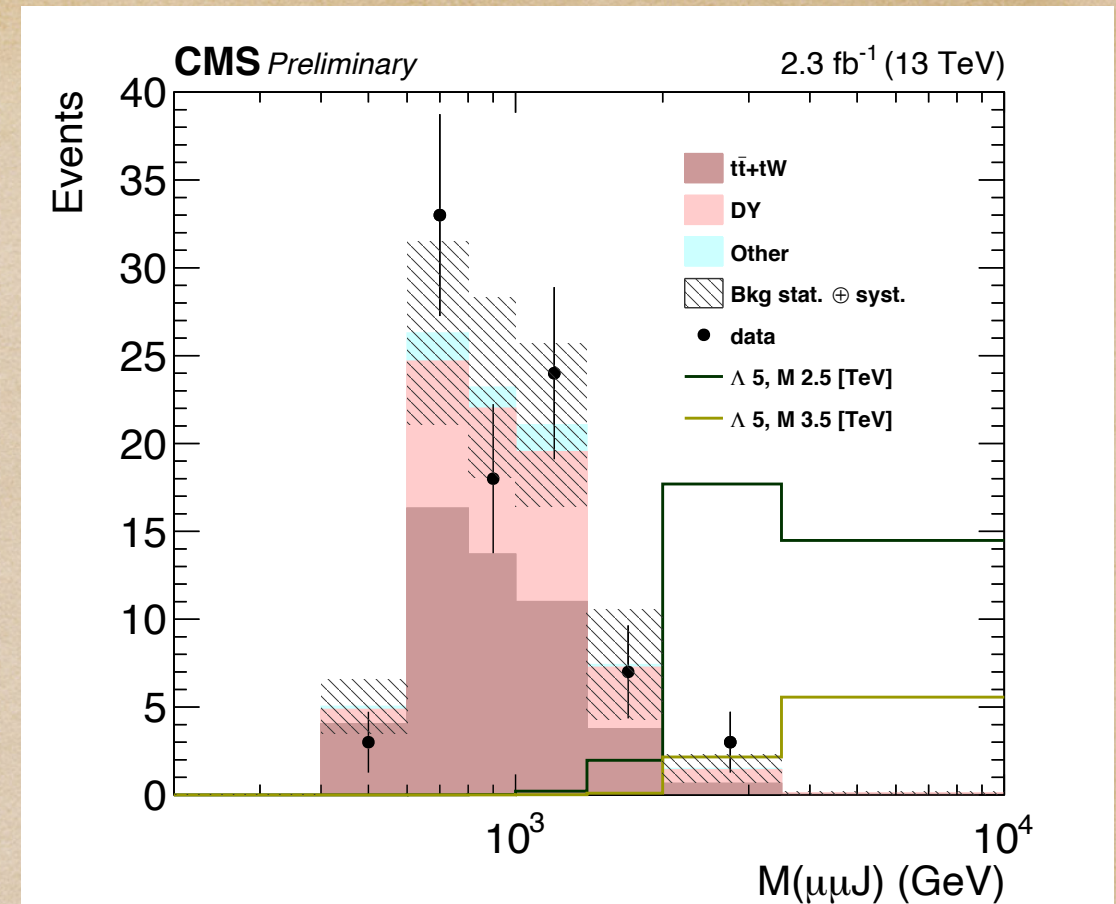
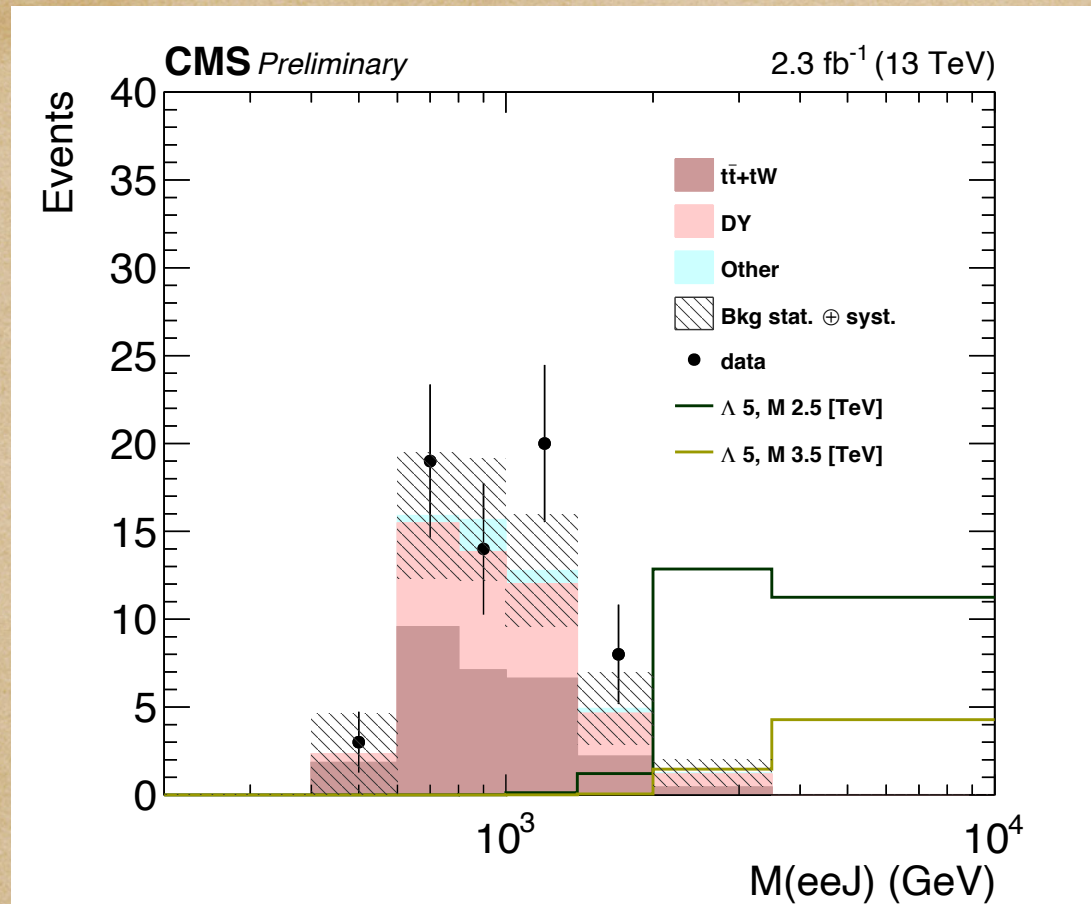
CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch

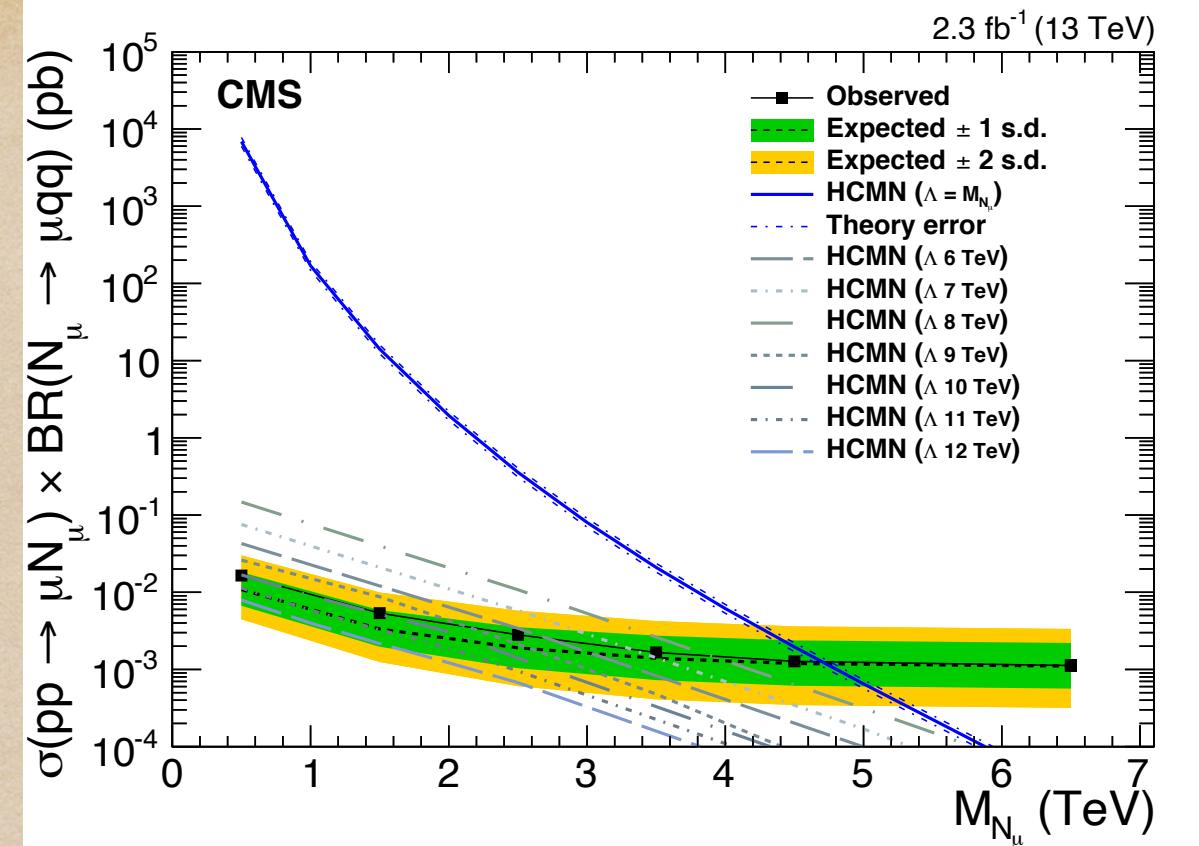
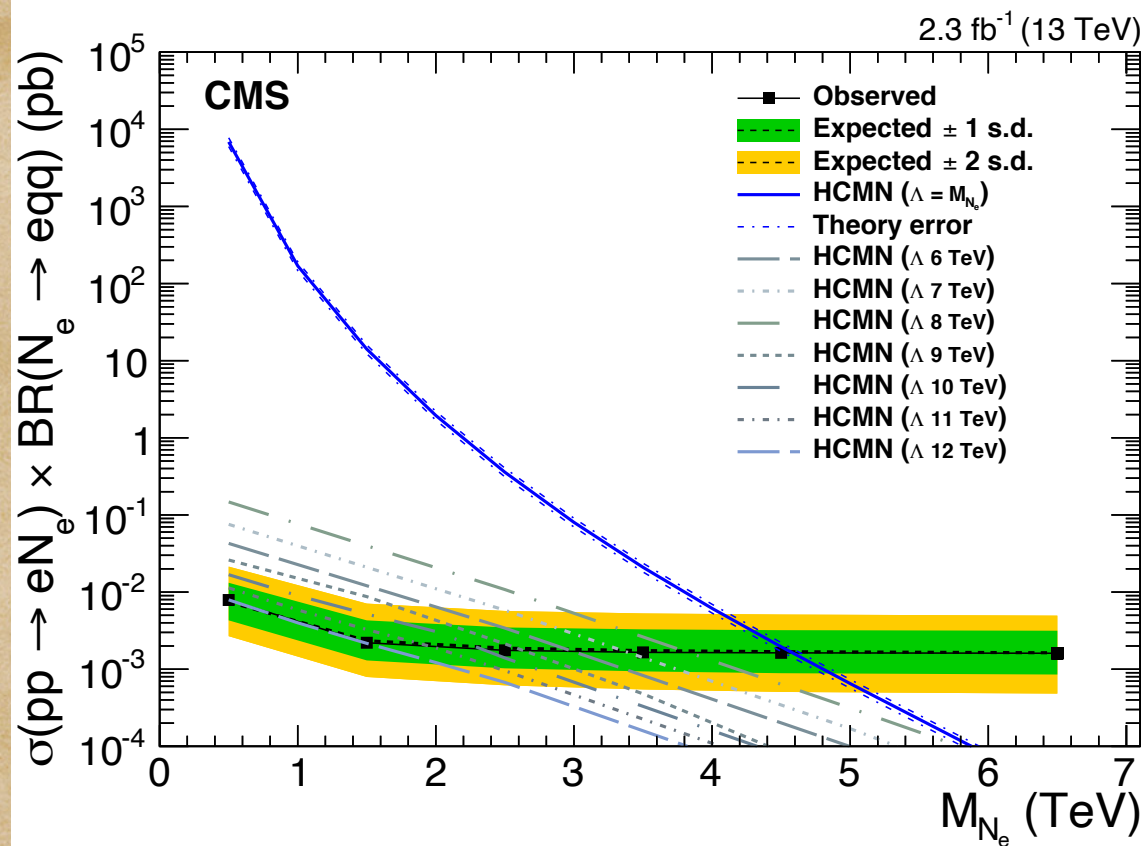
2016/08/04

Search for heavy composite Majorana neutrinos produced in association with a lepton and decaying into a same-flavour lepton plus two quarks at $\sqrt{s} = 13 \text{ TeV}$ with the CMS detector

The CMS Collaboration



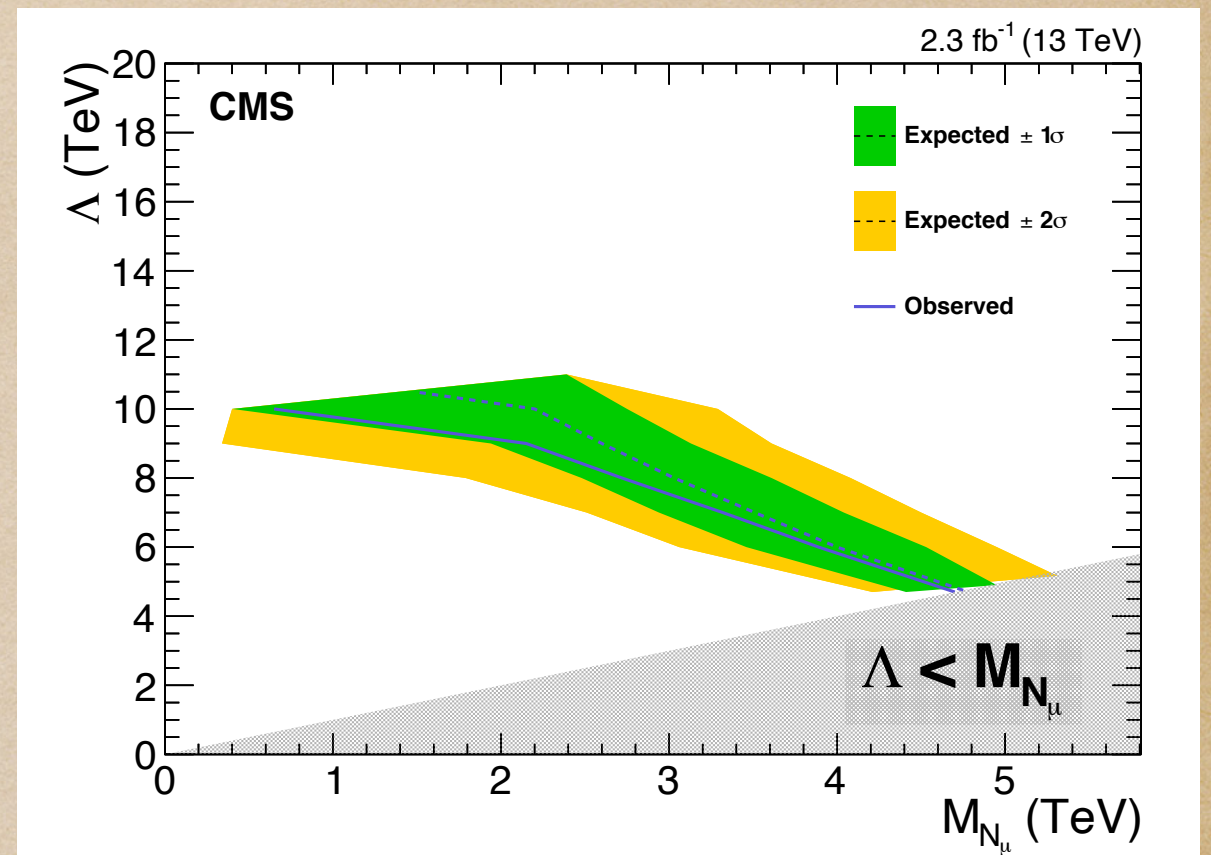
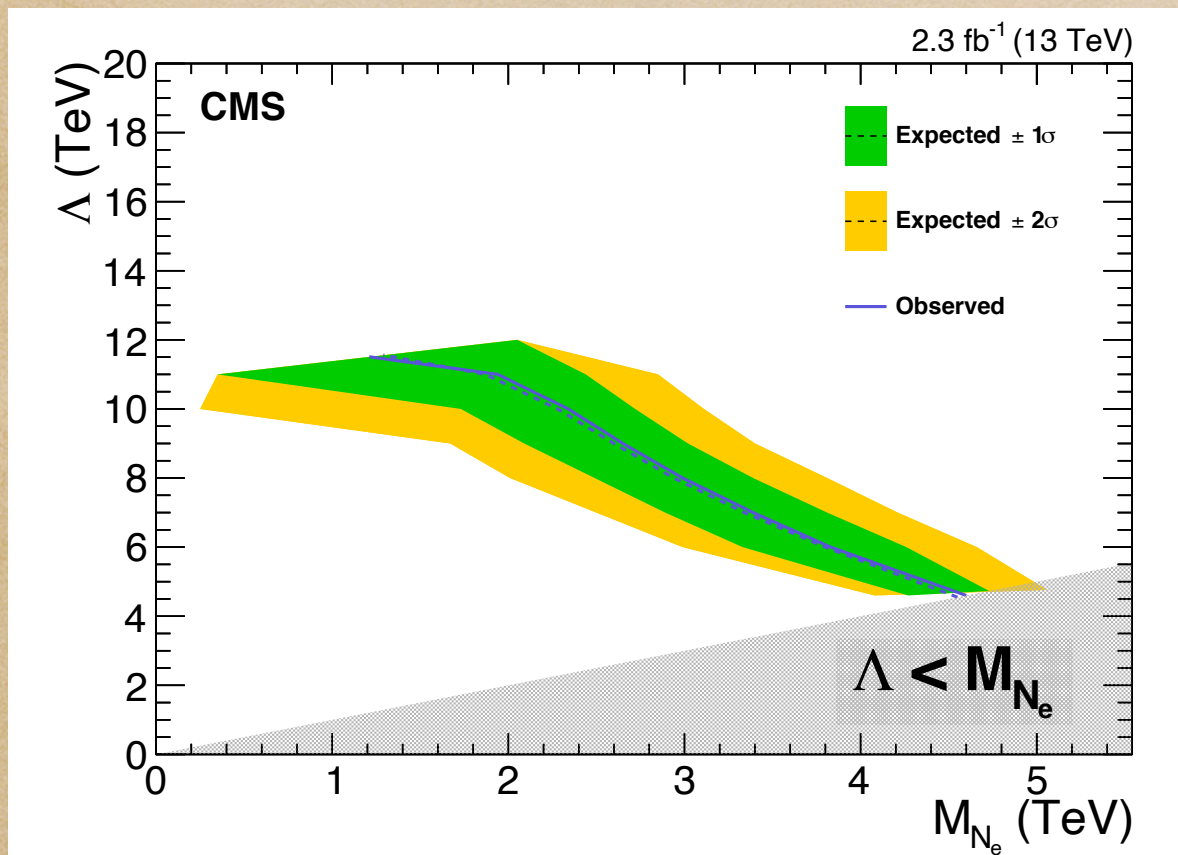
- ◆ **Distribution on M_{IJ} for:** data (black dots) and standard model expectations (stack plots) and signal (lines) from (eeqq and $\mu\mu qq$ analyses) @ $\Lambda = 5$ TeV.
- ◆ No significant deviations from SM expectations are observed: $\rightarrow$ Set upper limits.



- ◆ Observed 95% C.L. upper limits on $\sigma(pp \rightarrow \ell N) \times B(N \rightarrow \ell qq)$ (black solid line) from (eeqq and $\mu\mu qq$ analyses);
- ◆ For $\Lambda = M_N = m^*$ (blue line) limits are: $M_N > 4.60, (4.70)$

TeV

Exclusion regions of 2-dim parameter space (Λ, M_N)



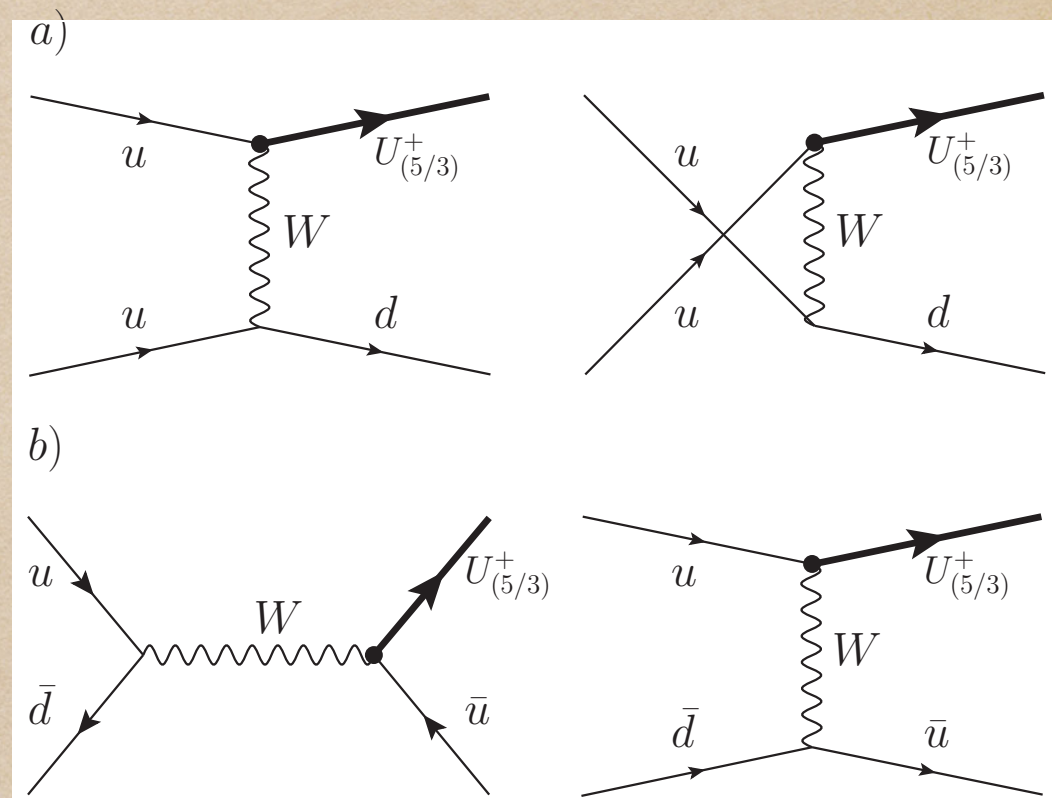
- Observed 95% C.L. Exclusion regions (below the curve) on the 2-dim parameter space (Λ, M_N), from (eeqq and $\mu\mu qq$ analyses);

HCMN (theory+exp) conclusioni e sviluppi futuri

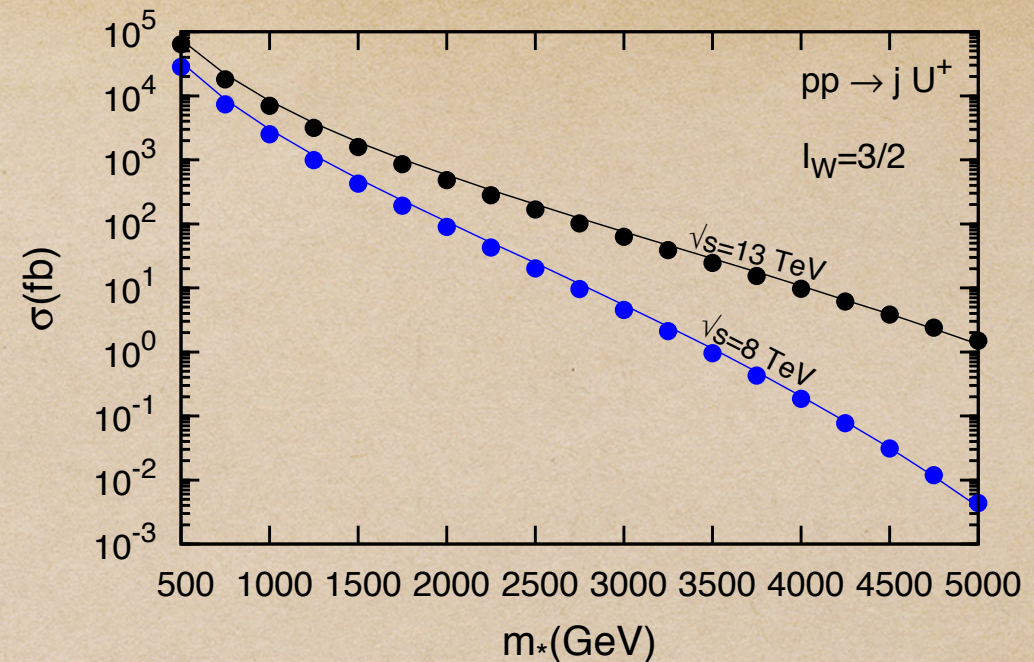
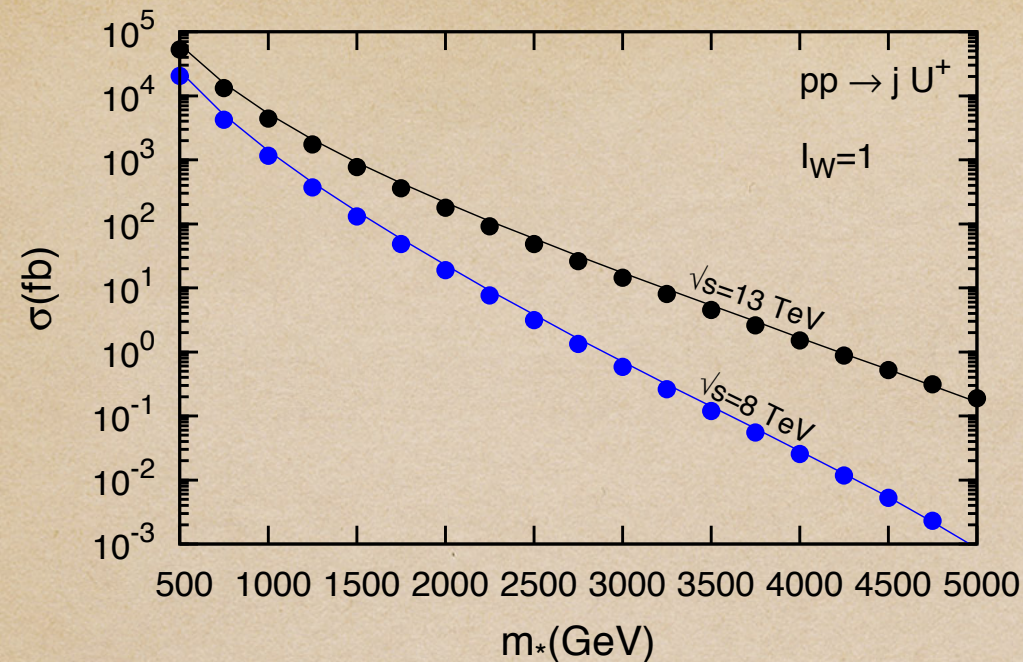
- ♦ LAVORO TEORICO [Eur. Phys. J. C (2016) 76:593] Quite interesting results (high mass reach);
 - * Inclusion of contact interactions in theoretical model and full exploration of the two-dimensional parameter space (Λ, m^*) ;
- ♦ CMS analysis (CMS-PAS EXO-16-026) (published in PLB):
 - * if $\Lambda = m^* (\approx M_N)$ current limits are: $M_N > 4.60$ TeV (eeqq channel) and $M_N > 4.70$ TeV ($\mu\mu qq$ channel)
- Aggiornamento dei risultati dell'analisi con la maggiore statistica del RUN II; ("Reload" of CMS-PAS EXO-16-026, currently undergoing), Tesi di dottorato di Matteo Presilla 2021 (Università di Padova). Analisi di CMS in corso di pubblicazione (2021).-
- Lo stesso modello composito si sta attualmente studiando nell'ambito del doppio decadimento beta senza neutrini ($0\nu\beta\beta$). Collaborazione con il GSSI (F. Vissani et al). Inclusione delle interazioni di contatto. Derivazione dei vincoli imposti dallo limite inferiore (sperimentale) sulla vita media dello $0\nu\beta\beta$ ai parametri del modello $[\Lambda, M]$.

Produzione di $U^+_{(5/3)}$ @ LHC

- ♦ Studio di fattibilità di ricerche @ LHC di quark composti di carica;
- ♦ Si sono considerate dapprima le interazione di tipo magnetico;
- ♦ Implementazione del modello (interazioni) nel generatore (CalcHEP);
- ♦ $U^+_{(5/3)}$ interagisce solo tramite il bosone di gauge W . Decadimento: $U^+_{(5/3)} \rightarrow Wu \rightarrow Wjet$
- ♦ Considerare il decadimento leptonic del bosone: $W \rightarrow \ell\nu$
- ♦ Segnatura finale: $pp \rightarrow \ell \cancel{p_T} jj$



$$U^+_{5/3} \rightarrow W j \rightarrow \ell \nu j \rightarrow \ell \cancel{p_T} j$$



- Modello implementato in CalcHEP (●, ●)
- Verifiche fra calcoli numerici/analitici (solid lines)

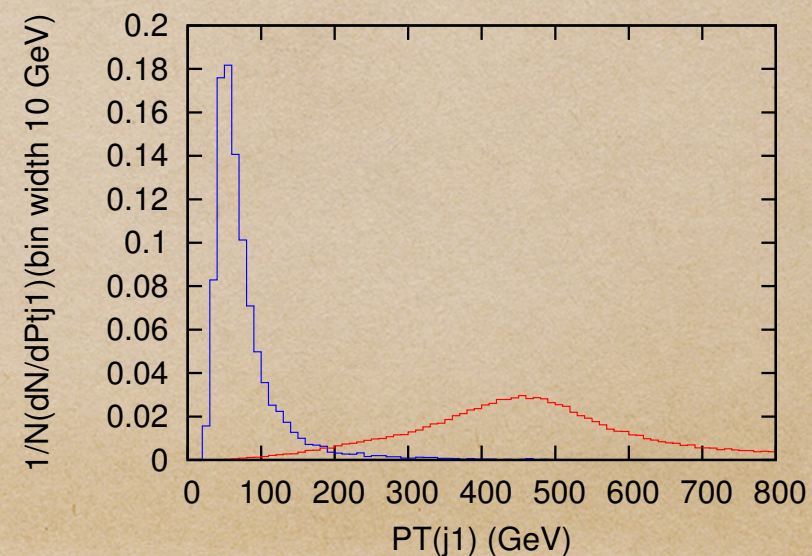
$$\sigma = \sum_{a,b} \int_{\frac{m_*^2}{s}}^1 \int_{\tau}^1 d\tau \frac{dx}{x} f_a(x, \hat{Q}) f_b\left(\frac{\tau}{x}, \hat{Q}\right) \hat{\sigma}(\tau s, m_*).$$

- Sezioni d'urto molto promettenti !!
- $\sigma \approx O(10^2)$ fb per masse $m^* \approx 2500$ GeV @ 13 TeV

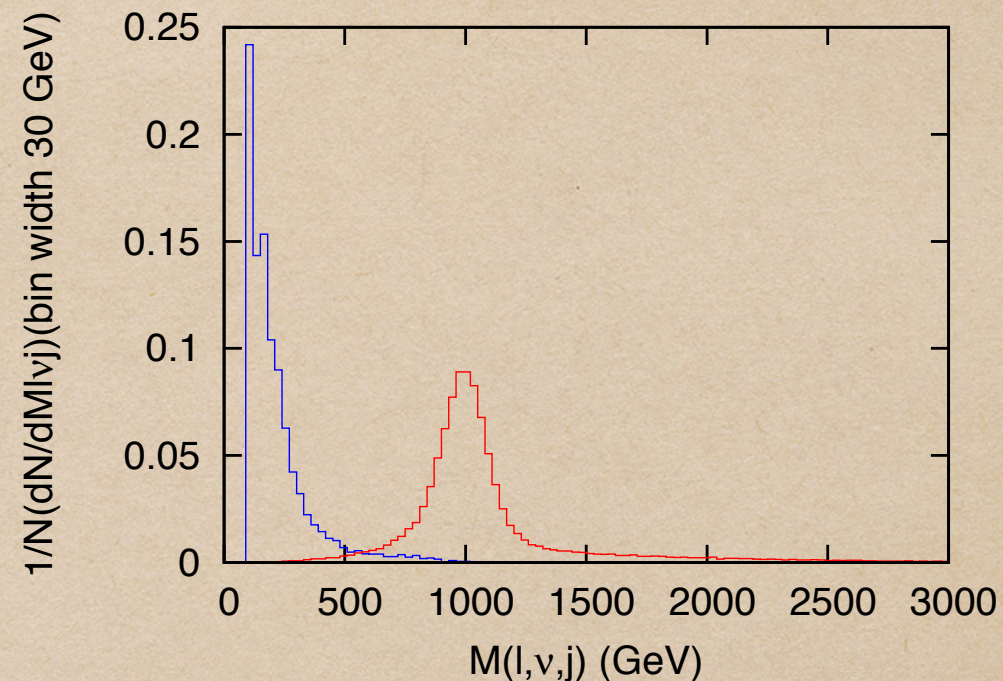
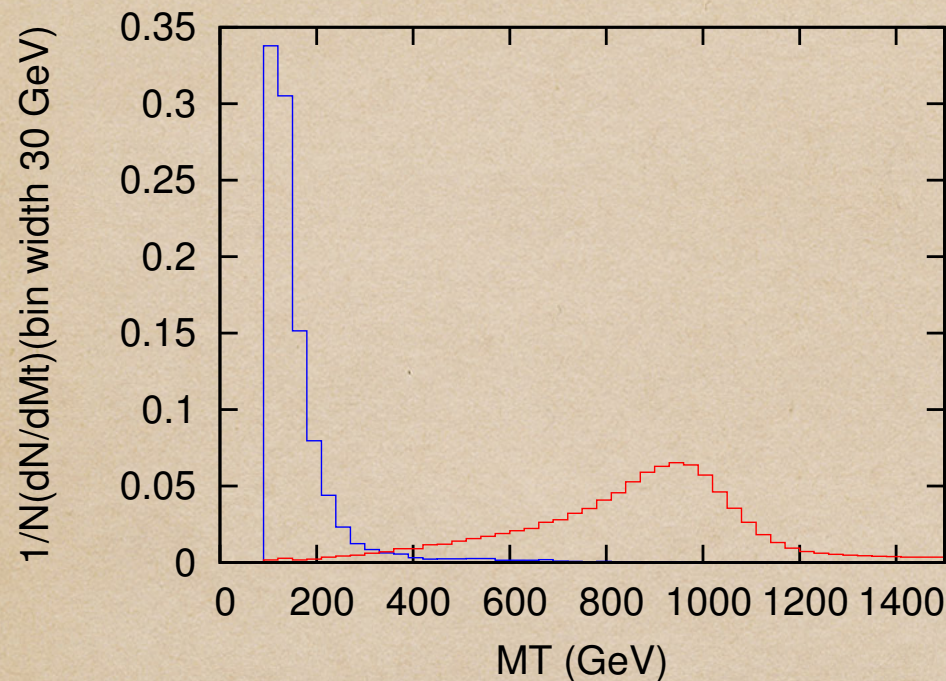
Segnale e fondo SM (background)

- ♦ Signal:
 $pp \rightarrow U^+ u \rightarrow \ell \cancel{p_T} jj$
- ♦ main SM background is Wjj production with $W \rightarrow \ell \nu$:
 $pp \rightarrow Wjj \rightarrow \ell \cancel{p_T} jj$
- ♦ Kinematic study to optimize Statistical Significance:
 - * Angular, p_T , Transverse -mass (M_T) and reconstructed invariant mass ($M_{\ell \nu j}$) distributions
 - * Fast simulation of detector reconstruction with DELPHES

- * Most efficient cut:
$$\begin{cases} p_T(j_{\text{leading}}) \geq 180 \text{ GeV}, \\ p_T(j_{\text{second-leading}}) \geq 100 \text{ GeV}. \end{cases}$$



Transverse -mass (M_T) and reconstructed invariant mass ($M_{\ell\nu j}$) distributions highly correlated with m^* ($\Lambda = 10 \text{ TeV}$, $m^* = 1000 \text{ GeV}$)



$$M_T^2 = \left(\sqrt{p_{TW}^2 + M_W^2} + p_{Tj1} \right)^2 - (\mathbf{p}_{TW} + \mathbf{p}_{Tj1})^2$$

$\Rightarrow$ Longitudinal neutrino momentum, hence $M_{\ell\nu j}$, can be reconstructed:

$\Rightarrow M_T$ distribution shows a clear peak with a relatively sharp end-point at $M_T \approx m^*$

$$M_W^2 = (p_\ell + p_\nu)^2$$

$$(1 - B^2)(p_L^\nu)^2 - 2AB p_T^\ell p_L^\nu + (p_T^\ell)^2(1 - A^2) = 0$$

$$A = \frac{M_W^2 + 2\mathbf{p}_T^\ell \cdot \mathbf{p}_T^\nu}{2E_\ell p_T^\nu}, \quad B = \frac{p_L^\ell}{E_\ell}$$

$$p_L^\nu = \frac{1}{1 - B^2} \left[AB \pm \sqrt{A^2 + B^2 - 1} \right] p_T^\ell$$

Efficiències

- Signal events:

$$N_s = L\sigma_s\epsilon_s$$

- background events:

$$N_b = L\sigma_b\epsilon_b$$

- Statistical Significance:

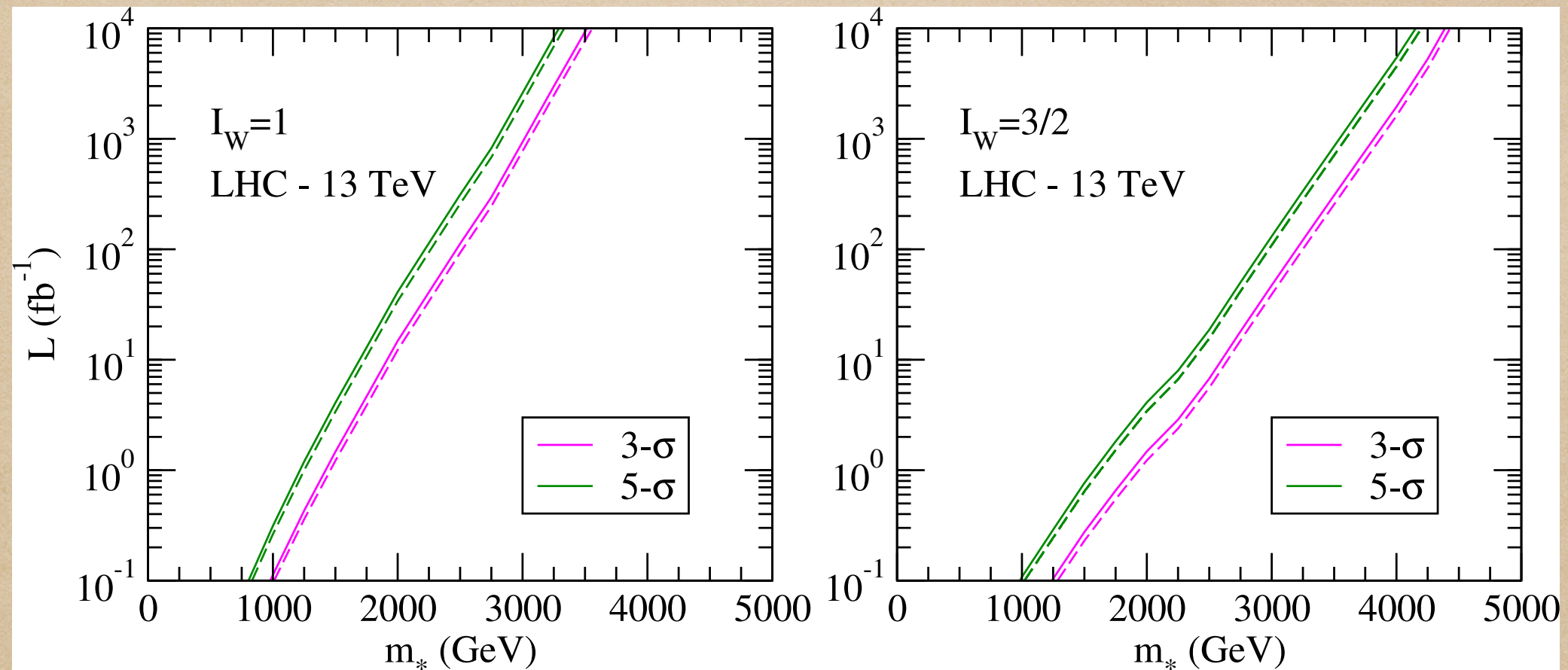
$$S = \frac{N_s}{\sqrt{N_s + N_b}}$$

- Luminosity:

$$L = \frac{S^2}{\sigma_s\epsilon_s} \left[1 + \frac{\sigma_b\epsilon_b}{\sigma_s\epsilon_s} \right]$$

Background			
	σ_b before cut (fb)	σ_b after cut (fb)	(ϵ_b)
	8200000	14678	0.00179
Signal ($I_W = 1$)			
m_* (GeV)	σ_s before cut (fb)	σ_s after cut (fb)	(ϵ_s)
500	7782	5416.74	0.69606
1000	1277	1064.33	0.83346
1500	344.6	298.489	0.86619
2000	107.7	95.1185	0.88318
2500	39.05	34.7037	0.8887
3000	13.5	12.0555	0.893
3500	4.281	3.84352	0.89781
4000	1.424	1.28213	0.90037
4500	0.4957	0.446665	0.90108
5000	0.1799	0.162518	0.90338
Signal ($I_W = 3/2$)			
m_* (GeV)	σ_s before cut (fb)	σ_s after cut (fb)	(ϵ_s)
500	11080	5819.11	0.52519
1000	2240	1649.89	0.73656
1500	806.3	646.065	0.80126
2000	343.2	283.964	0.8274
2500	159.9	134.147	0.83894
3000	60.25	51.8626	0.86079
3500	23.55	20.0983	0.85343
4000	9.347	7.57986	0.81094
4500	3.191	2.60797	0.81729
5000	1.043	0.845737	0.81087

Luminosity curves @ 5- and 3- σ within statistical error



- Mass reach @ 3- σ for $L = (30, 300, 3000) \text{ fb}^{-1}$
- $I_W = 1$ $m_* \geq (2230, 2780, 3280) \text{ GeV}$
- $I_W = 3/2$ $m_* \geq (2930, 3540, 4140) \text{ GeV}$

Q(5/3) conclusioni e possibili continuazioni

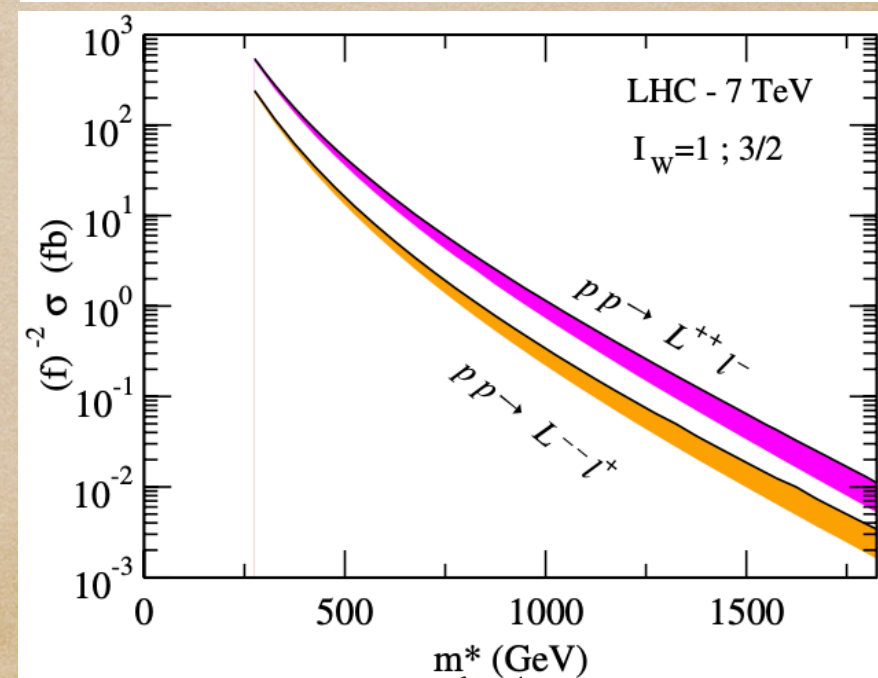
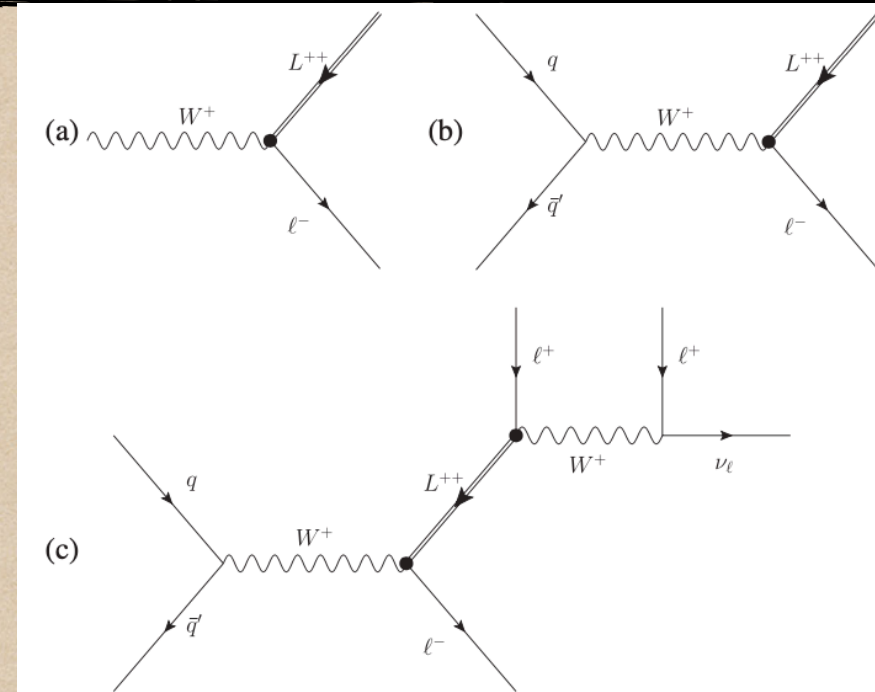
- ◆ Risultati molto incoraggianti (sensibilità a range masse molto ampio);
- ◆ Studi più dettagliati sono giustificati:
 - * Esplorazione completa dello spazio dei parametri (Λ, m_*);
 - * (DA FARE) includere interazioni di contatto;
- ◆ Iniziare una nuova analisi dei dati di LHC? (Sarebbe la prima in assoluto per quark eccitati di carica 5/3 in modelli compositi);
- ◆ Possibile collaborazione con il gruppo CMS group;

Phenomenology of excited doubly charged heavy leptons @ LHC

Phys. Rev. D (2012) 85, 095018, S. Biondini,

O. Panella, G. Pancherì, Y.N. Srivastava, and L. Fano`.

- ◆ **First complete study** of searches @ LHC of exotic heavy composite states (L^{++}): $pp \rightarrow L^{--} \ell^-$
- ◆ Magnetic type Gauge interactions;
- ◆ **implementation of model (interactions) in the generator (CalcHEP);**
- ◆ L^{++} interacts only via gauge interactions: (i) $L^{++} \rightarrow \ell^+ \ell^+ \nu_\ell$
- ◆ or (ii) $L^{++} \rightarrow \ell^+ \ell^- q \bar{q}'$
- ◆ **final signature** : $\longrightarrow pp \rightarrow \ell^- \ell^+ \ell^+ \nu_\ell$

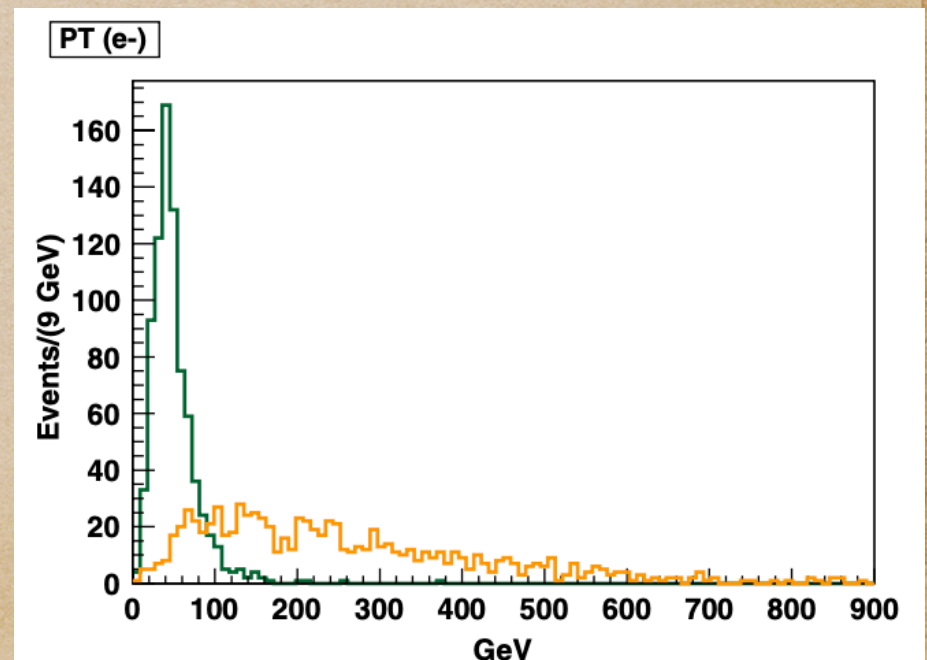


Note: also $pp \rightarrow \ell^+ \ell^- jj$ signature is possible !!

Segnale and fondo SM

- ♦ Signal: $pp \rightarrow \ell^- L^{++} \rightarrow \ell^- \ell^+ \ell^+ \nu_\ell$
- ♦ main SM background and is $t t\text{-bar}$ and WW production:
 $pp \rightarrow W^+ Z \rightarrow \ell^+ \ell^- \ell^+ \nu_\ell$
- ♦ Kinematic study to optimize Statistical Significance $s = \frac{N_{\text{sig.}}}{\sqrt{N_{\text{sig.}} + N_{\text{bg.}}}}$
 - * Angular, p_T , reconstructed invariant mass $M_{\ell\ell}$ distributions
 - * Fast simulation of detector reconstruction with DELPHES
 - * Most efficient cuts:

$$\left\{ \begin{array}{l} p_T(e^-) > 80 \text{ GeV} \\ |\eta(e_1^+)| < 2 \end{array} \right.$$

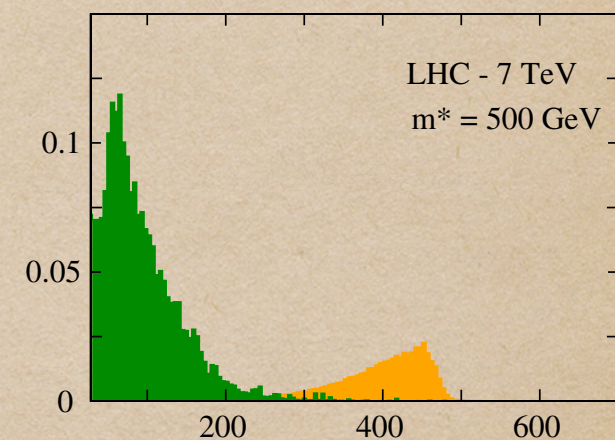
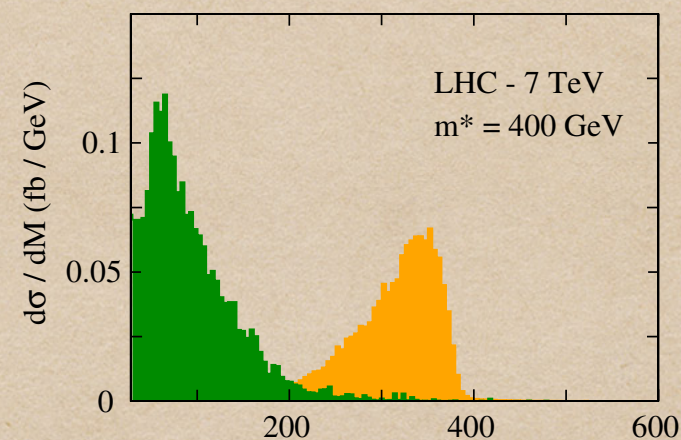


Like sign dileptons invariant mass distribution and Luminosity curves

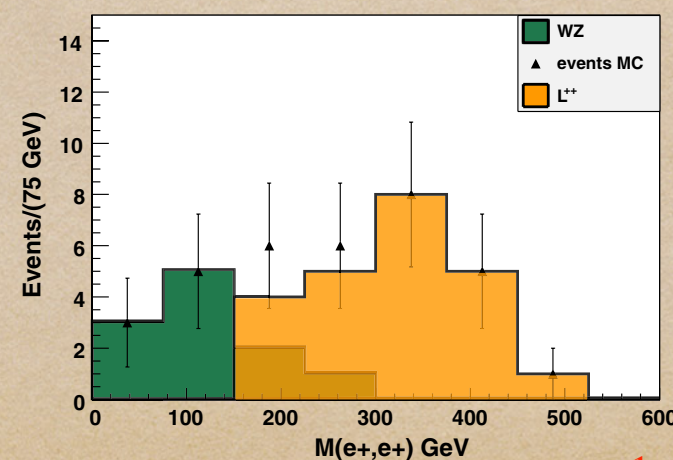
- Strong correlation of Like sign dilepton invariant mass with the mass of the excited doubly charged Lepton:

$$\left[m_{(\ell^+, \ell^+)}^2 \right]_{\max} = \frac{(m^{*2} - m_W^2)(m_W^2 - m_\nu^2)}{m_W^2} \rightarrow \left[m_{(\ell^+, \ell^+)}^2 \right]_{\max} = m^{*2} - m_W^2$$

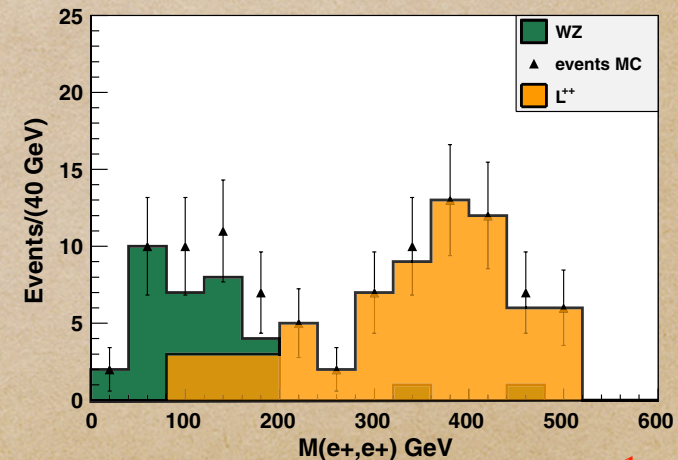
@ Generator level



Reconstructed
(Delphes)



$\sqrt{s} = 7 \text{ TeV}, L = 10 \text{ fb}^{-1}$



$\sqrt{s} = 7 \text{ TeV}, L = 30 \text{ fb}^{-1}$

Luminosity Curves

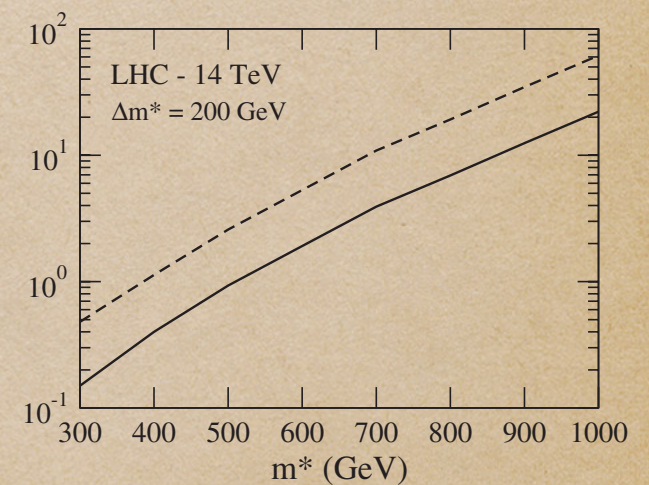
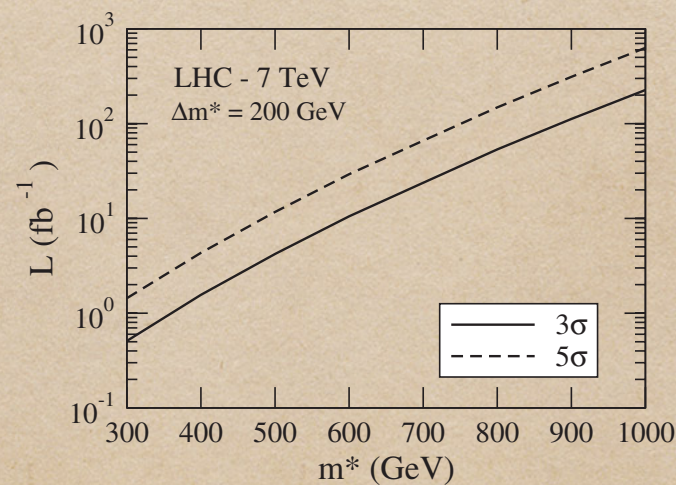
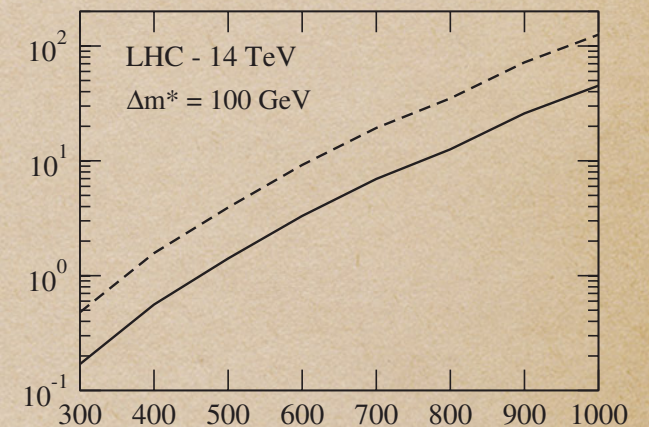
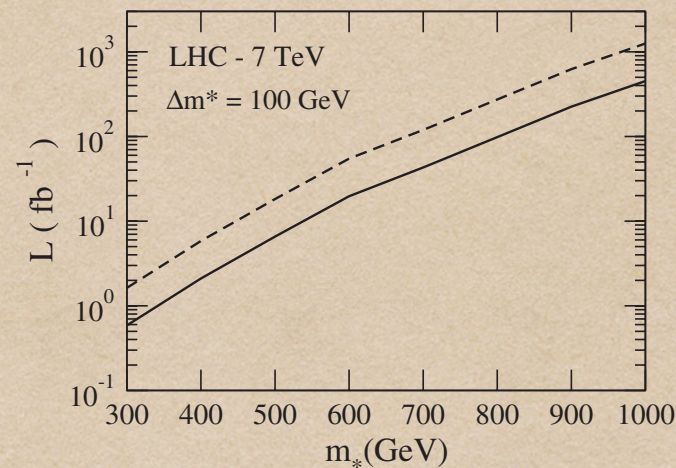
- With $N_s = \sigma_s L$ and $N_b = \sigma_b L$ the Statistical Significance s is computed: $s = \frac{N_s}{\sqrt{N_s + N_b}}$

$$N_s = L \int_{m^* - \Delta m^*}^{m^*} dm_{(\ell^+, \ell^+)} \frac{d\sigma_s}{dm_{(\ell^+, \ell^+)}}$$

$$N_b = L \int_{m^* - \Delta m^*}^{m^*} dm_{(\ell^+, \ell^+)} \frac{d\sigma_b}{dm_{(\ell^+, \ell^+)}}$$

Solve for L @ given statistical significance:

$$L = s^2 \left(\frac{\sigma_s + \sigma_b}{\sigma_s^2} \right)$$



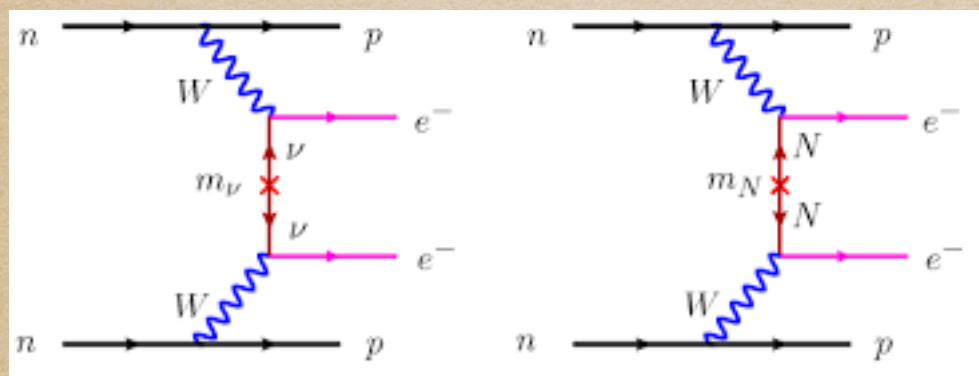
High Mass reach!!

L^{++} production @LHC conclusions and outlook

- ◆ First Pheno-Exp synergy paper [Phys. Rev. D (2012) 85, 095018]. Found quite interesting results (high mass reach);
 - * First implementation of the composite magnetic type ($\sigma_{\mu\nu}$) gauge interactions (dim=5 operators) in the CalcHEP generator.
 - * Left open the inclusion of contact interactions in theoretical model and full exploration of the two-dimensional parameter space (Λ, m^*);
- In subsequent paper (second pheno-exp synergy paper) Contact interactions for the composite model are implemented for the first time in the CalcHEP generator [Phys. Rev. D90, 035001 (2014)], R. Leonardi, O. Panella, and L. Fanò, master thesis of Roberto Leonardi]
- Production of doubly charged leptons is studied in view of larger cross sections induced by dominant contact interactions;

Possibili progetti di tesi (I)

- ◆ Modelli compositi nel doppio decadimento beta senza neutrini ($0\nu\beta\beta$):
 - * Inclusione dei termini di interazioni di contatto;

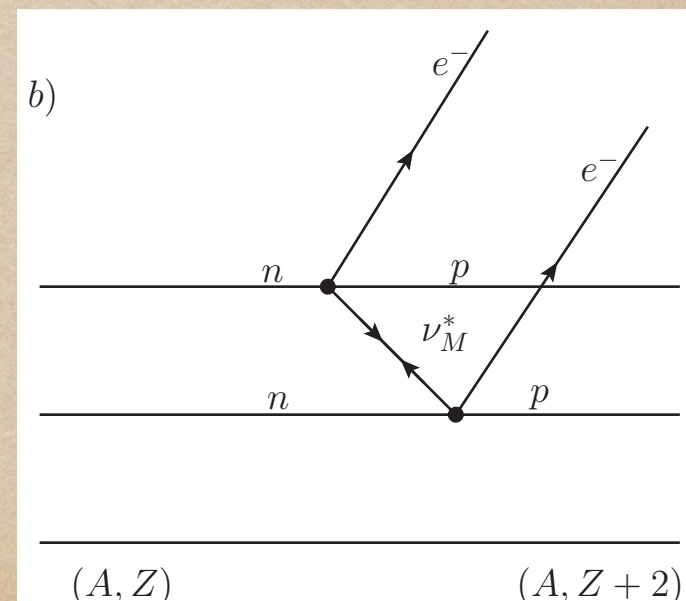


(interazioni di contatto)

$0\nu\beta\beta$

$$T_{\text{half-life}} \geq 10^{26} \text{ yr}$$

Risultati preliminari incoraggianti



Possibili progetti di tesi (II)

LEPTON NUMBER VIOLATING DECAYS OF K, B MESONS

- $K^+ \rightarrow \pi^- e^+ e^+$ $\mathcal{B} < 2.2 \times 10^{-10}$
- $K^+ \rightarrow \pi^- \mu^+ \mu^+$ $\mathcal{B} < 4.2 \times 10^{-10}$
[Phys. Lett. B, 797, 2019, 134794](#) (NA62 Collab)
- Stessi diagrammi di Feynman
 $pp \rightarrow jj\ell^+\ell^+$
- Possibilità di studiare complementarità con bound derivati da CMS per modello composito con neutrini di Majorana.
- Anche approccio bottom up EFT [Phys. Lett. B 479, 2000, 33-36](#) (K. Zuber, See-Saw model)

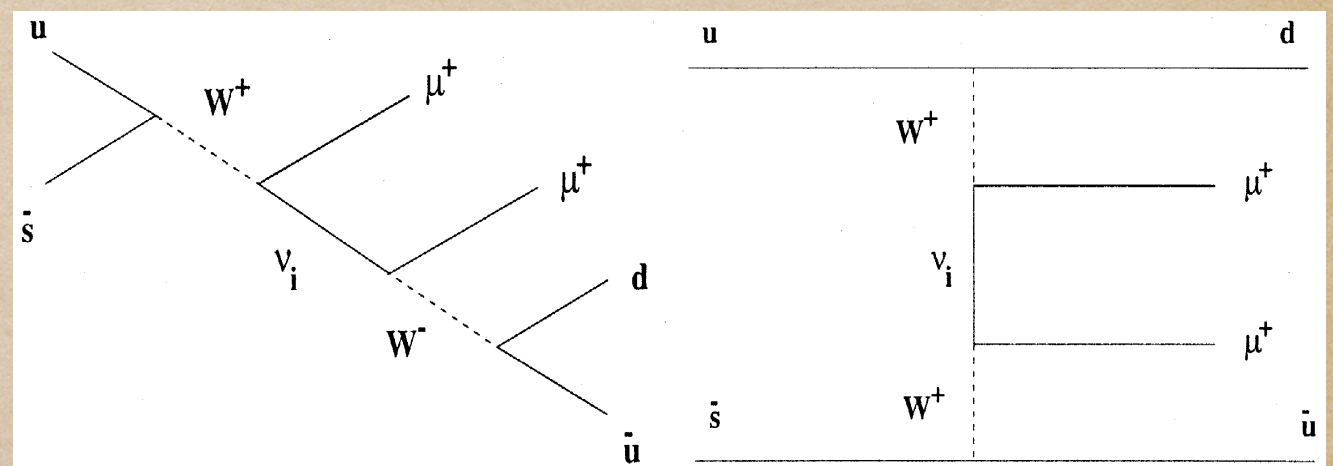


Fig. 1. Feynman diagrams in lowest order contributing to the rare kaon decay $K^+ \rightarrow \pi^- \mu^+ \mu^+$. Shown are the tree (left) and box diagram (right).

Tesi di Laurea Magistrale/Dottorato su fenomenologia modelli compositi e oltre

- ♦ S. Biondini [LM-2011] “Phenomenology of excited doubly charged heavy leptons at LHC”, [Physical Review D, 85, 095018, (2012)] e lavoro su “Exotic leptons at future linear colliders”, [Physical Review D 92, 015023 (2015)]
→ PhD @ Monaco (TUM)
- ♦ R. Leonardi [LM-2013] “Doubly charged leptons with contact interactions” PRD 90, 035001 (2014)
- ♦ R. Leonardi (gruppo IV+CMS) e L. Alunni (CMS), dottorato XXIX ciclo. (Heavy Composite Majorana Neutrinos - HCMN-). [Eur. Phys. J. C (2016) 76:593, CMS-PAS-16-026]
- ♦ R. Leonardi (gruppo IV+CMS) dottorato XXIX ciclo. “Phenomenology @ LHC of exotic quarks of charge $Q=5/3e$ ” Production of exotic composite quarks of charge $Q=5/3e$ at the LHC [Ph. D. thesis of R. Leonardi (Dicembre 2016), Phys. Rev. D 96 (2017) 0750034].
- ♦ M. Presilla [LM, Febbraio 2017] (Mirror type model of composite Majorana neutrinos. Fenomenologia con due auto-stati di massa N_1 e N_2) + dottorato@Padova
- ♦ L. Mattioli [LM, Dicembre 2018] (Casimir-Polder interactions with massive photons: implications for BSM Physics. (Phys. Rev. D 100 (2020) 116023; dottorato@Varsaw Univ.
- ♦ C. Carrivale [LM, xxxx 2021] Vector Boson Scattering @LHC e Effective Field Theories. Il caso di $W^+W^+ \rightarrow W^+W^+$. In collaborazione con CMS. Vedi presentazione di Livio Fanò.

Tesi di Laurea Triennale su attività di fisica matematica, meccanica quantistica.

Collaborazione con Pinaki Roy (Indian Statistical Institute, Kolkata)

- ♦ A. M. Frassino, [LT-2010] Successivamente completato progetto di ricerca “The Casimir Effect in Minimal Length Theories based on a Generalised Uncertainty Principle”: Physical Review D, 85, 045030 (2012).
→PhD @ Francoforte + post-doc @ Geneva Univ. + post-doc@Barcelona Univ.
- ♦ S. Biondini, [LT-2010]: “New exact Solution of the one dimensional Dirac equation for the Woods-Saxon potential within the effective mass case” Journal of Physics A, 43, 325302 (2010). →PhD @ Monaco
+post-doc@Berna, Groningen, Basilea
- ♦ L. Menculini, [LT-2012]: “Exact solutions of the (2+1) dimensional Dirac equation in a constant magnetic field in the presence of a minimal length” Physical Review D 87, (2013), 065017; + “Quantum phase transitions of the Dirac oscillator in a minimal length scenario” Physical Review D 91 (2015) 4, 045032.
→PhD @ Perugia (G. Grignani)
- ♦ M. Presilla [LT-2015] “Quantum phase transitions of the Dirac oscillator in the Anti-Snyder model” Physical Review D 92 (2015) 4, 045019, + “Solutions of the Bogoliubov-de Gennes equation with position dependent Fermi-velocity and gap profiles”, Phys. Lett. A, 381 (2017) 713-719. →PhD @ Padova (CMS)
- ♦ V. D. Paccioia [LT-2019] “Angular momentum Quantum Backflow in the non-commutative plane” Physical Review A 102 (2020), 062218,

Recap of Recent Activities (I)

(from a New Physics Lagrangian to the constraints on the model parameters from actual LHC data)

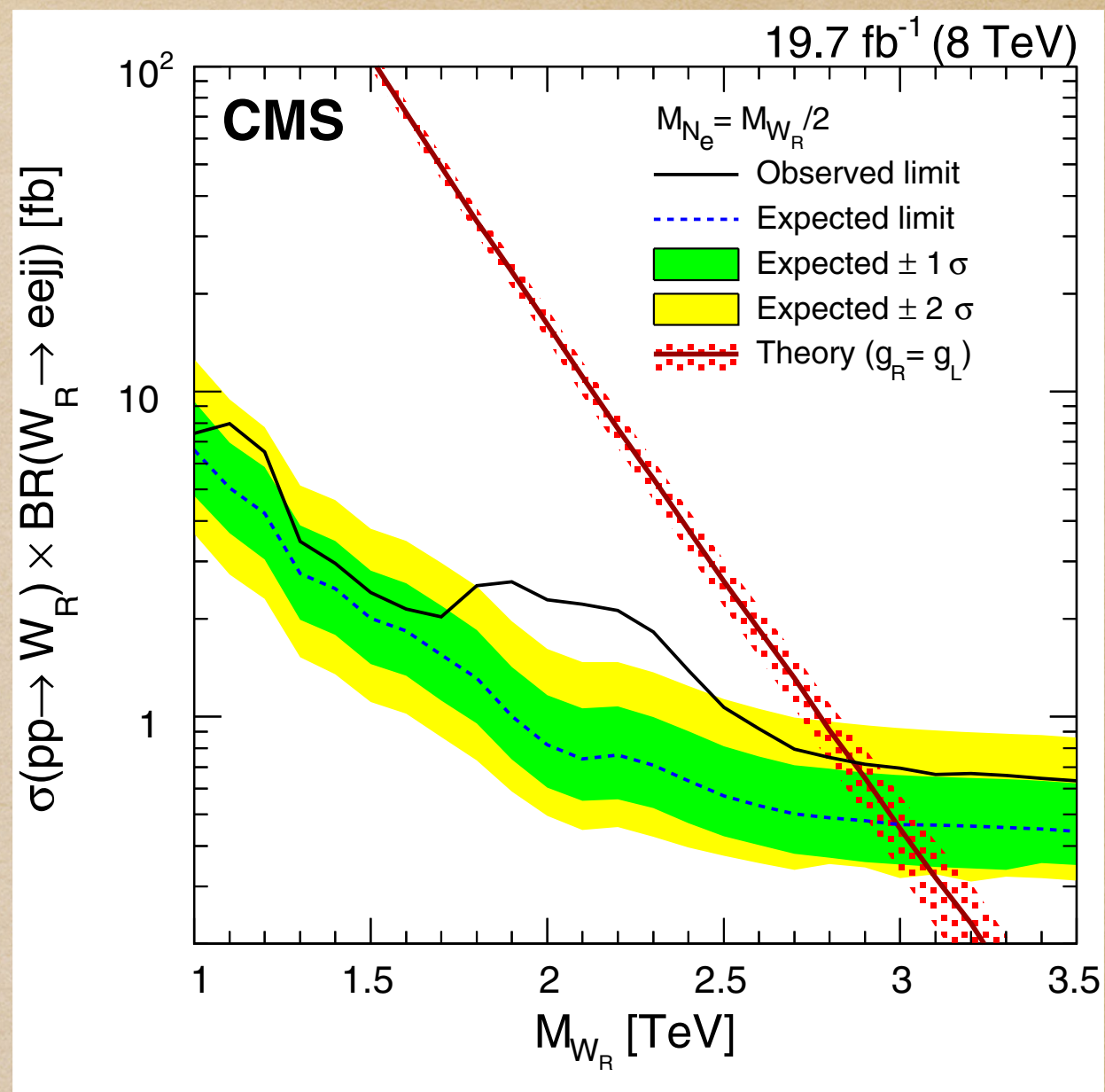
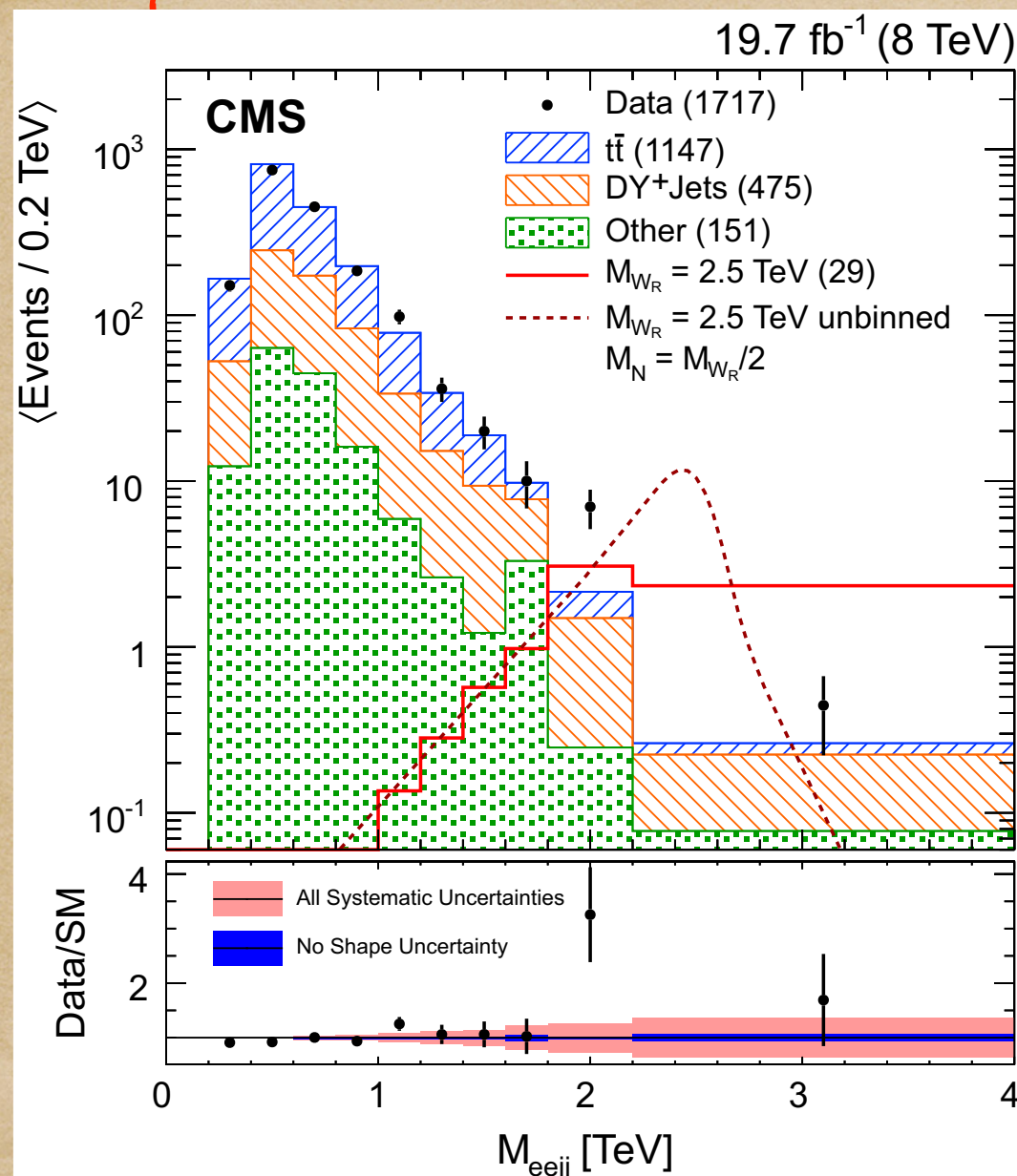
- ♦ Phenomenology of doubly charged leptons at LHC ; [Master thesis of S. Biondini (2011), PRD 85, 095018 (2012), S. Biondini, O. Panella, G. Pancheri, Y. N. Srivastava and L. Fanò ;
- ♦ Doubly charged heavy leptons at LHC via Contact interactions; [Master thesis of R. Leonardi, (2013), R. Leonardi, O. Panella, Lívio Fanò, PRD 90, 035001 (2014)]
- ♦ Heavy composite Majorana neutrinos —from a theoretical model [EPJC, 76, 593 (2016)] to a REAL experimental analysis (CMS-PAS-16-026) [Ph. D. thesis of R. Leonardi and L. Alunni-Solstizi (XXIX ciclo, December 2016)];
- ♦ Search for a heavy composite Majorana Neutrino in the final state with two leptons and two quarks at $\sqrt{s} = 13$ TeV, Phys. Lett. B. 775 (2017), 315-337, CMS Collaboration, A. M. Sirunyan et al. — guest author of this CMS paper!!—]
- ♦ Production of exotic composite quarks of charge $Q=5/3e$ at the LHC [Ph. D. thesis of R. Leonardi (Dicembre 2016), Phys. Rev. D96 (2017) 0750034];

Recap of Recent Activities (II)

(from a New Physics Lagrangian to the constraints on the model parameters from actual LHC data)

- ♦ **Leptogenesis and Composite Heavy neutrinos with gauge mediated interactions** ; [S. Biondini and O. Panella(2011), Eur. Phys. Journal C77 (2017), 644]
- ♦ **Search for heavy composite Majorana neutrinos at the HL- and the HE-LHC**, P. Azzí, C.Cecchi, L. Fanò, A Gurrola; W, Johns, R Leonardi, E. Manoni, M. Narain, O. Panella, M. Presilla, F. Romeo, S. Sagir, P. Sheldon, F. Simonetto, E usai, W. Zhang (CMS). **Report from Working Group 3: BSM physics at the HL-LHC and HE-LHC**, Xavier Cid Vidal et al. CERN Yellow Report Monogr. 7 (2019) 585-865]
- ♦ **New Mirror model of LNV with composite Majorana neutrinos** — model with two mass eigenstates implemented in CalcHEP and MadGraph [M. Presilla, R. Leonardi, and O. Panella, February 2017, **Report from Working Group 3: BSM physics at the HL-LHC and HE-LHC**, Xavier Cid Vidal et al. CERN Yellow Report Monogr. 7 (2019) 585-865]
- ♦ **Perturbative Unitarity Bounds for effective composite models** — [S. Biondini, R. Leonardi, O. Panella and M. Presilla, Phys. Lett. B795 (2019) 644-649, Erratum, arXiv:1903.12285]. **STesi di dottorato Matteo Presilla (Università di Padova).**

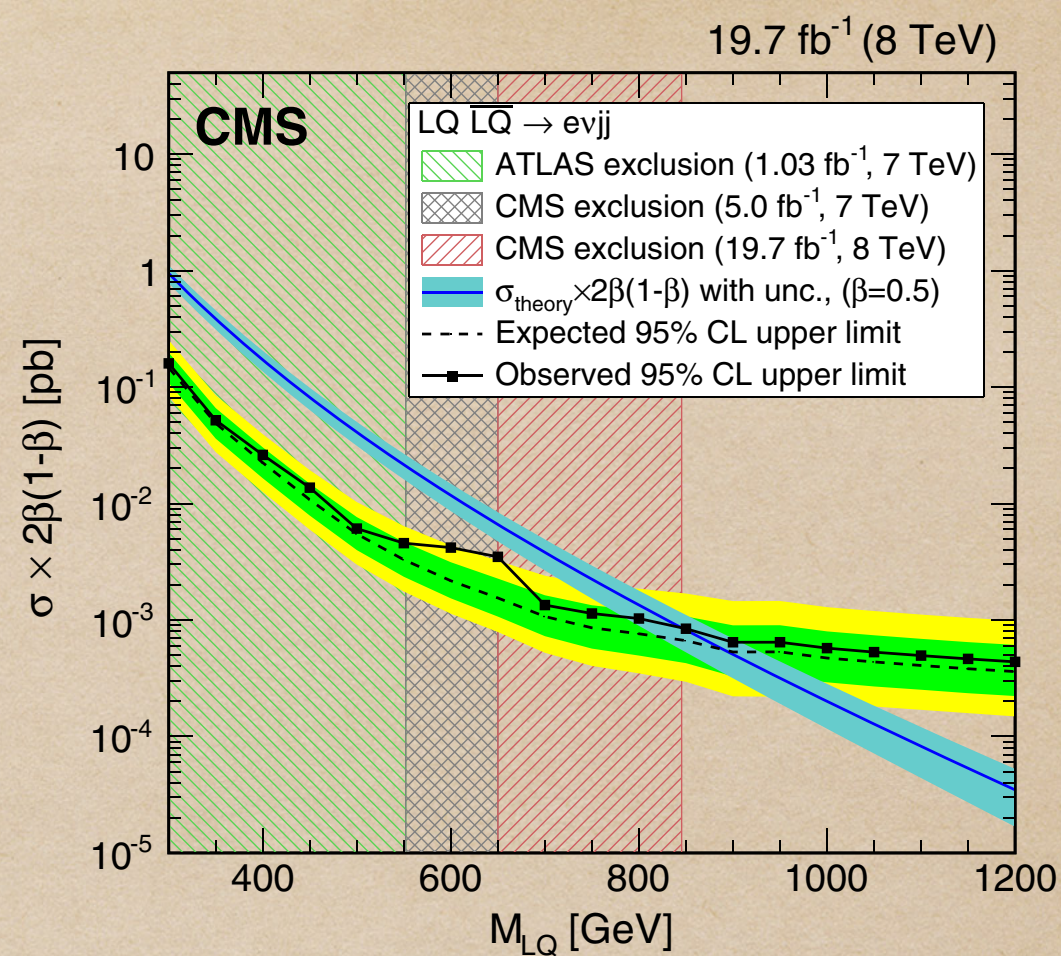
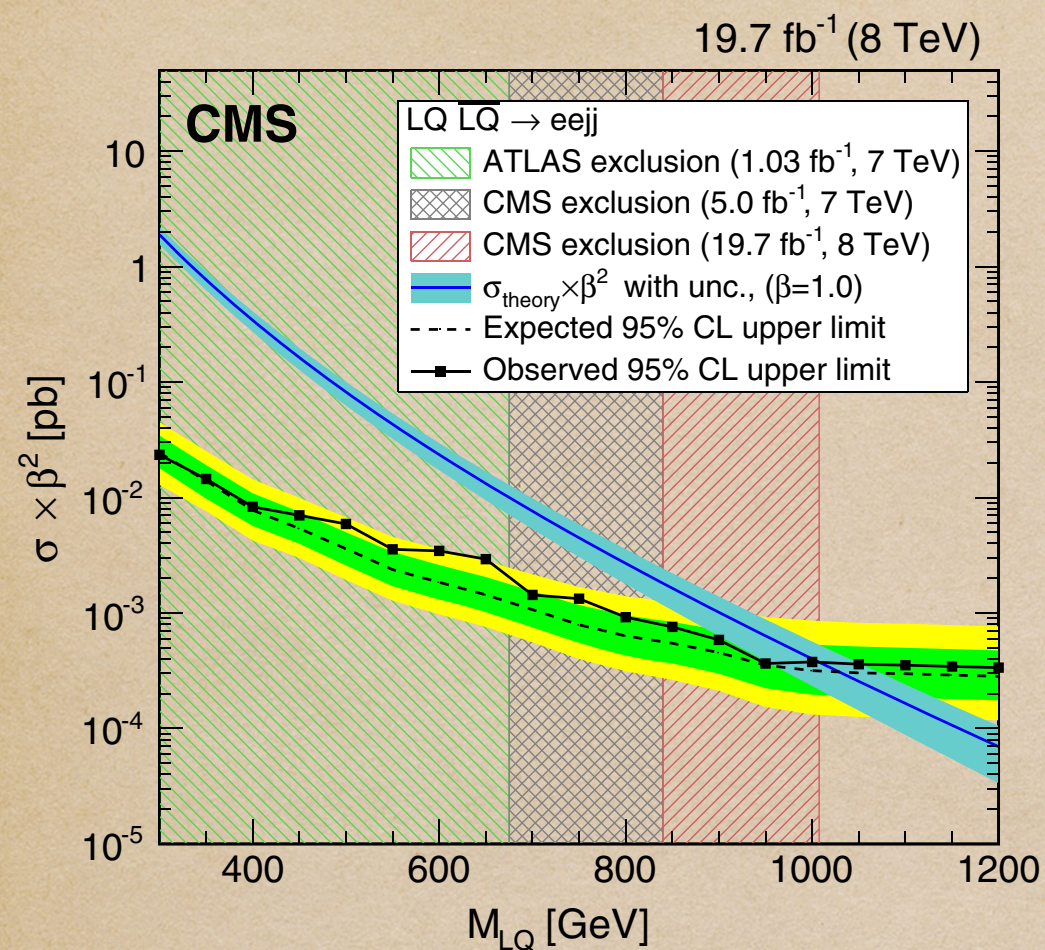
Experimental motivations from LHC searches @ Run I



- ◆ (CMS Collab.) EPJC 74:3149 (2014) “Search for heavy neutrinos and W_R bosons ...” ($\ell\ell jj$ - final state)
- ◆ 2.8σ excess found in the interval $1.8 \text{ TeV} < M_{eejj} < 2.2 \text{ TeV}$
- ◆ Same excess not observed in the $(\mu\mu jj)$ channel!!

(back in 2016/17)

Experimental motivations from LHC searches @ Run I



- ◆ CMS Collab. Phys. Rev. D 93 (2016) 032004, “Search for pair production of lepto-quarks ...” ($\ell\ell jj$ and $\ell\nu jj$ - final states)
- ◆ 2.3σ (2.6σ) excess found
- ◆ Same excess not observed in the ($\mu\mu jj$) channel!!

(back in 2016/17)