A Pseudo-Dirac Bino and Neutrino Masses at the LHC

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Pilar Coloma, SI, *PRL. 117 no.11 111803, arXiv:1606.06372*
Julia Gehrlein, Patrick Fox, SI, *in preparation*

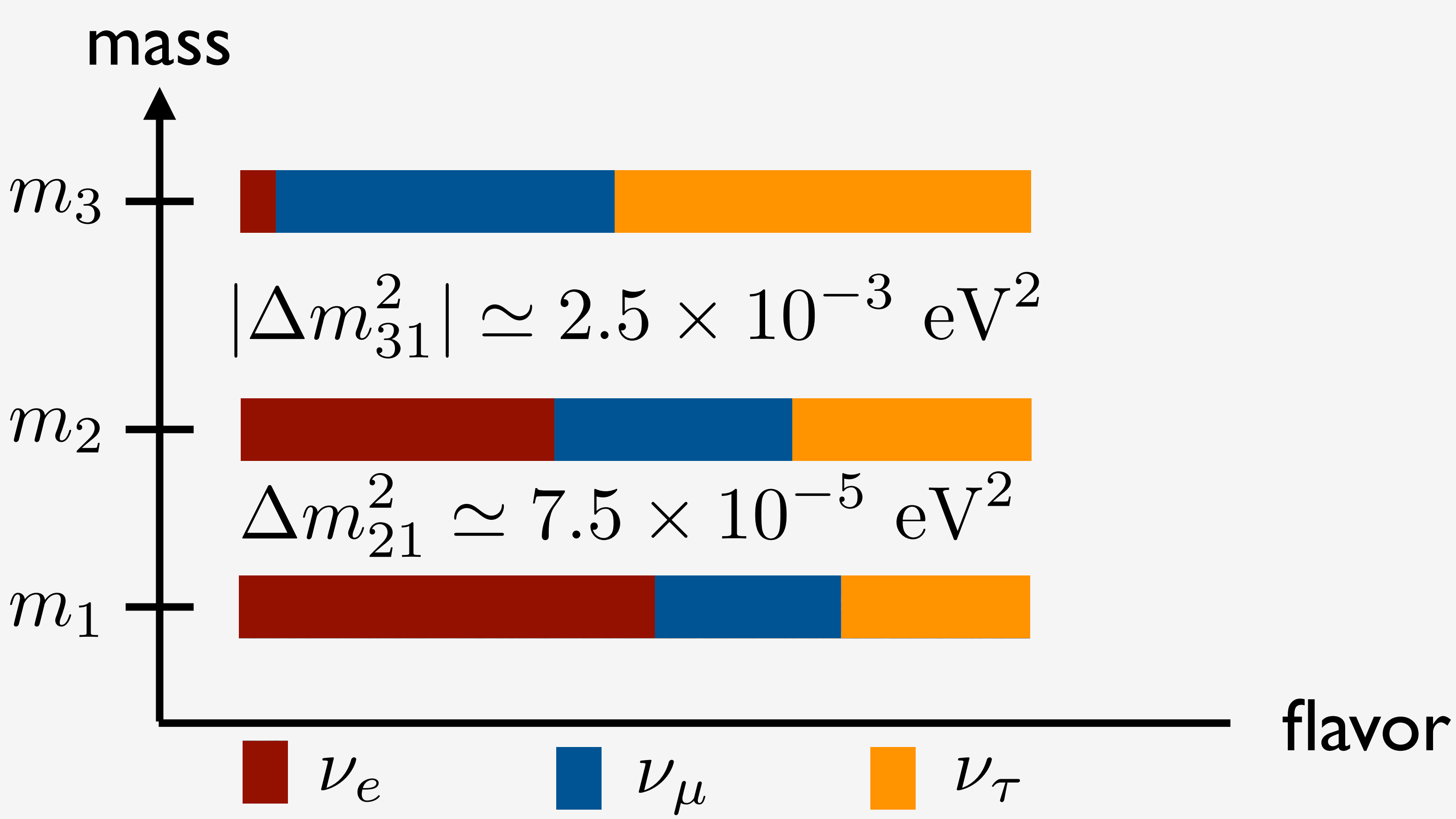
Neutrinos have mass

PDG review, www.nu-fit.org, ...

Mass eigenstates are different than flavor eigenstates

↕

Neutrinos are massive particles



Mixing angles

$\theta_{23} \sim 45^\circ$

$\theta_{13} \sim 9^\circ$

$\theta_{12} \sim 33^\circ$

Origin of the masses is not known

Massless in the SM — no right-handed neutrinos

SM singlet fermions

1- Can have Dirac masses

$$y_\nu \bar{\ell}\,\tilde{\phi}\,\nu_R \to m_\nu \overline{\nu_L}\nu_R \quad \Longleftrightarrow \quad y_\nu \sim 10^{-12}$$

Fermion masses are technically natural…

'We' don't like very small numbers

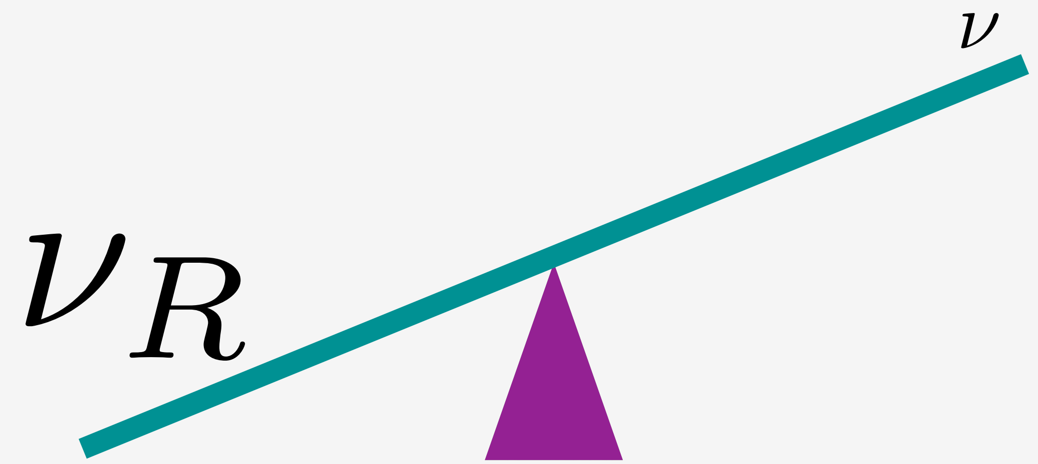
Origin of the masses is not known

2- Or Majorana masses — Seesaw mechanism

$$y_\nu \bar{\ell}\,\tilde{\phi}\,\nu_R + \frac{1}{2} M_R \nu_R^c \nu_R \quad \longrightarrow \quad m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

$$y_\nu \sim \mathcal{O}(1)$$

$$M_R \sim \mathcal{O}(10^{14}\ \mathrm{GeV})$$



Majorana particles are their own antiparticles

Lepton number is violated

Particle numbers are accidental symmetries of the SM…

Origin of the masses is not known

3- Or pseudo-Dirac masses — Inverse Seesaw Mechanism

Let's say lepton number is (approximately) conserved

SM singlets: $N, \; N'$

$L = 1 \quad L = \text{-}1$

$$Y_N \, \bar{\ell} \, \tilde{\phi} \, N + \epsilon Y_{N'} \, \bar{\ell} \, \tilde{\phi} \, N' + M_D \, \bar{N} N'^c + \mu \, \bar{N} N^c + \mu' \, \bar{N}' N'^c$$

lepton number violation

$$\psi = \begin{pmatrix} N \\ N'^\dagger \end{pmatrix}$$: pseudo-Dirac fermion

Origin of the masses is not known

3- Or pseudo-Dirac masses — Inverse Seesaw Mechanism

Light neutrino masses:

$$m_\nu \sim \frac{\epsilon Y_N^{\mathrm{T}} Y_{N'}\, v^2}{M_D} + \mathcal{O}\left(\frac{Y_N^{\mathrm{T}} \mu Y_N\, v^2}{M_D^2}\right)$$

For $Y_N \sim Y_{N'} \sim 1,$ $M_D \sim \mathrm{TeV}$ need: $\mu \sim \mathrm{keV}$ $\epsilon \sim 10^{-12}$

Why so small?

What we need

(Usually) SM singlet fermions as right-handed neutrinos

High mass scale

and/or

Small (lepton-number-violating) parameters

makes LHC searches very hard (impossible?)

Hall, Randall, *Nuc.Phys.B-352.2 1991*
Kribs, Poppitz, Weiner, arXiv: *0712.2039*
Frugiuele, Gregoire, arXiv:1107.4634

SI, McKeen, Nelson, arXiv: *1407.8193*
SI, John March-Russell, *arXiv:1604.00009*

My favorite model for everything!

$U(1)_R$ -symmetric SUSY

Pilar Coloma, SI, *PRL. 117 no.11 111803*

Has Dirac gauginos

Dirac gauginos are awesome - less tuning for heavier stops

Solves SUSY CP and flavor problems, …

$U(1)_{R\text{-}L}$ - symmetric SUSY

SUSY particles are charged under $U(1)_{R\text{-}L}$

Superfields	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$U(1)_R$	$U(1)_{R-L}$
L_i	1	2	-1/2	1	0
E_i^c	1	1	1	1	2
H_u	1	2	1/2	0	0
$W_{\tilde{B}}^{\alpha}$	1	1	0	1	1
$\Phi_S = \phi_S + \theta\, S$	1	1	0	0	0
$W'_{\alpha} = \theta\, D$	1	1	0	1	1

Spurion D-term

SUSY is broken in a hidden sector

Dirac bino mass

No Majorana gaugino masses due to the *R*-charges

Dirac masses come from the spurion D-term

$$\int d^2\theta \, c \frac{W'_\alpha}{\Lambda_M} W^\alpha_{\tilde{B}} \Phi_S \rightarrow \boxed{\frac{cD}{\Lambda_M}} \tilde{B} S$$

Λ_M : messenger scale

Dirac bino mass: M_D

$$\tilde{B} \equiv (1,1,0)_{+1}$$
$$S \equiv (1,1,0)_{-1}$$

$$\Rightarrow \quad \Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

: Dirac bino

$U(1)_{R\text{-}L}$ must be broken

…because (anomaly mediation)

(Small) Majorana mass for the bino

$$m_{\tilde{B}} = \frac{\beta(g_Y)}{g_Y} m_{3/2}$$

$m_{3/2}$: gravitino mass

Can also have a singlino Majorana mass

$$m_{\tilde{B}} \sim m_S \ll M_D$$

$U(1)_{R\text{-}L}$ is only approximately broken

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

: pseudo-Dirac bino

All the mass terms

$$-\mathcal{L} \supset \frac{f_i M_D}{\Lambda_M} \ell_i\, h_u \tilde{B} + \frac{d_i m_{3/2}}{\Lambda_M} \ell_i\, h_u S$$

$$+ M_D \tilde{B} S + m_{\tilde{B}} \tilde{B}\tilde{B} + m_S S S$$

→ $U(1)_{R\text{-}L}$ violating

This is an Inverse SeeSaw scenario!

$U(1)_{R\text{-}L}$ violation $\propto m_{3/2}$ → important for small neutrino masses

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

:We call this "biνo" (pronounced exactly like 'bino')

(like 'too' and 'two')

Neutrino masses

$$m_1 = 0$$

→ 1 neutrino is massless

$$m_2 = \frac{m_{3/2} v^2}{\Lambda_M^2}(1-\rho)$$

$$m_3 = \frac{m_{3/2} v^2}{\Lambda_M^2}(1+\rho)$$

→ Neutrino masses are prop to the gravitino mass

No dependence on M_D

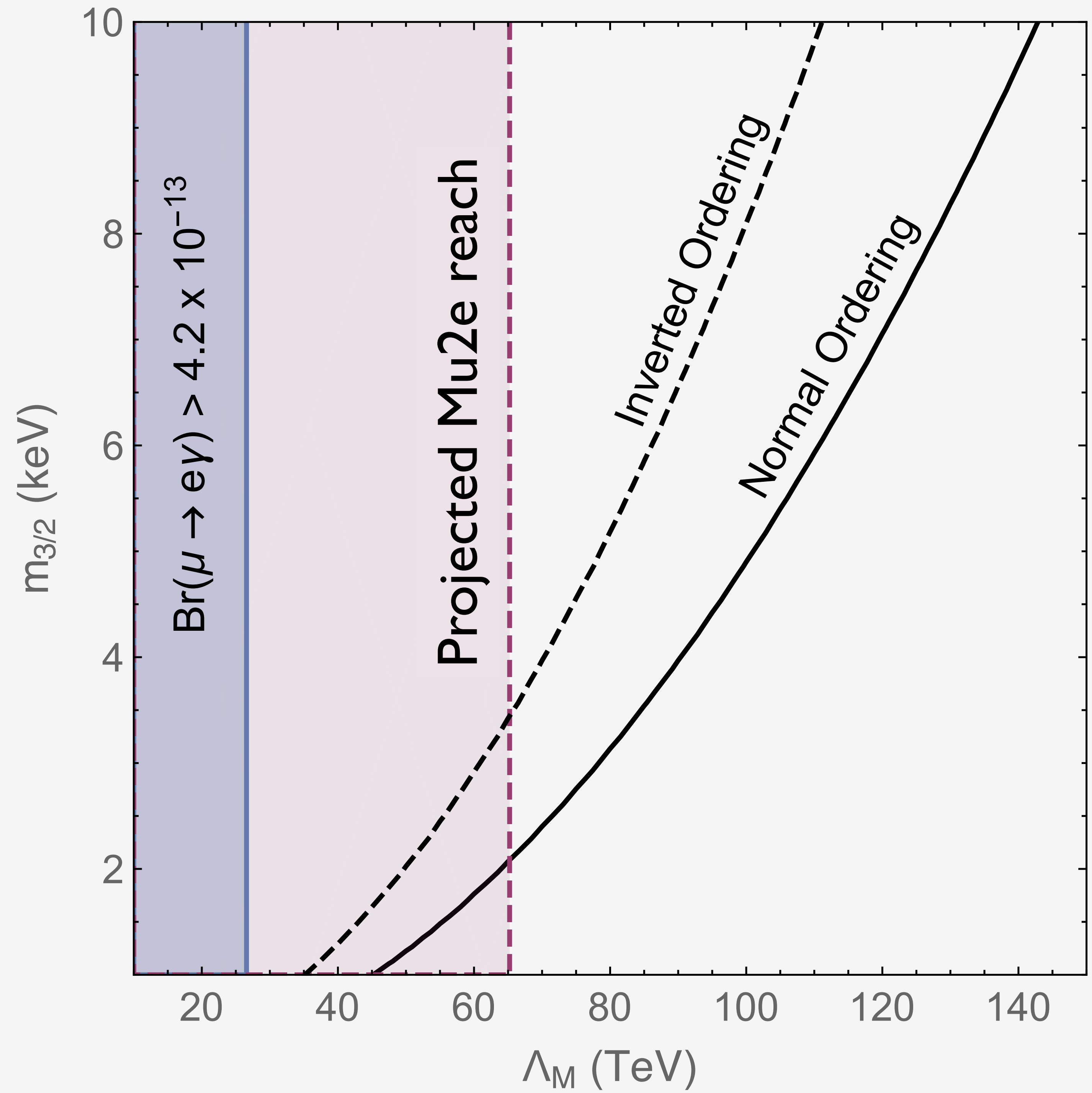
$\rho \simeq 0.7$ from mass splittings

Parameter space

Neutrino masses
+
Lepton flavor violation constraints

$$m_{3/2} \sim \mathcal{O}(\text{keV})$$

$$\Lambda_M \sim \mathcal{O}(100 \text{ TeV})$$



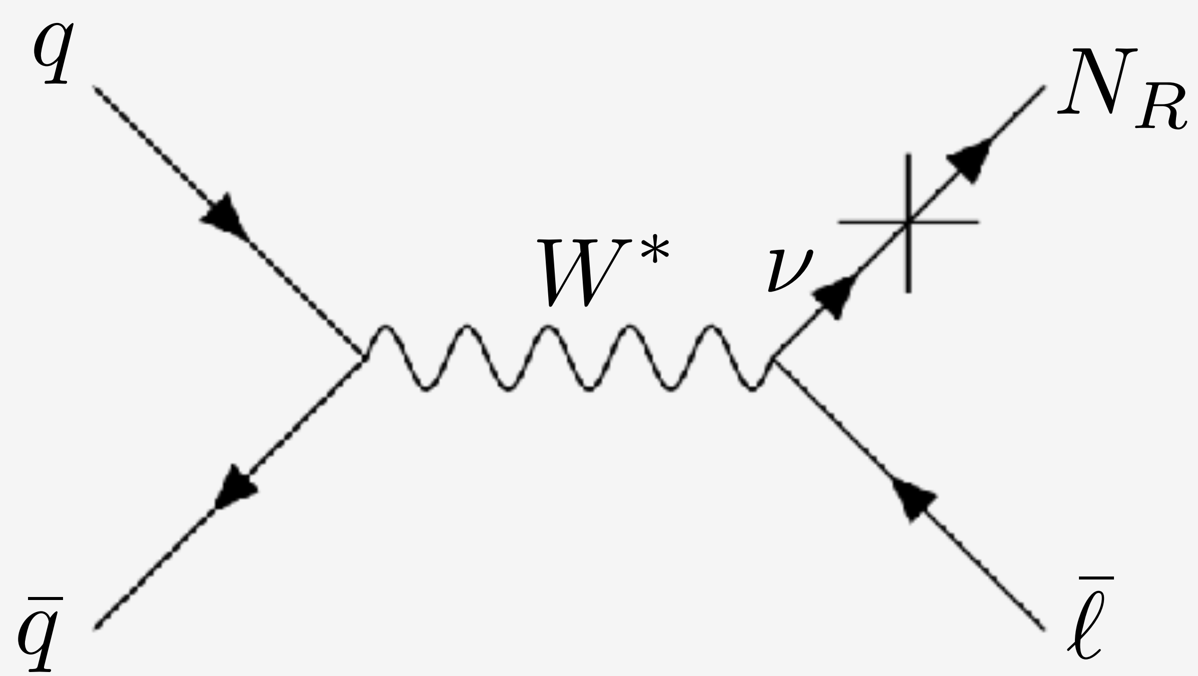
No constraints from neutrinoless double-beta decay

LHC Phenomenology of Biνo

Julia Gehrlein, Patrick Fox, SI, *in preparation*

LHC pheno: production

RH neutrinos are usually produced via mixing with the SM neutrinos



Pay a mixing price on top of EW interactions:

$$\theta^2 \sim 10^{-5}$$

There are better ways to produce a bino!

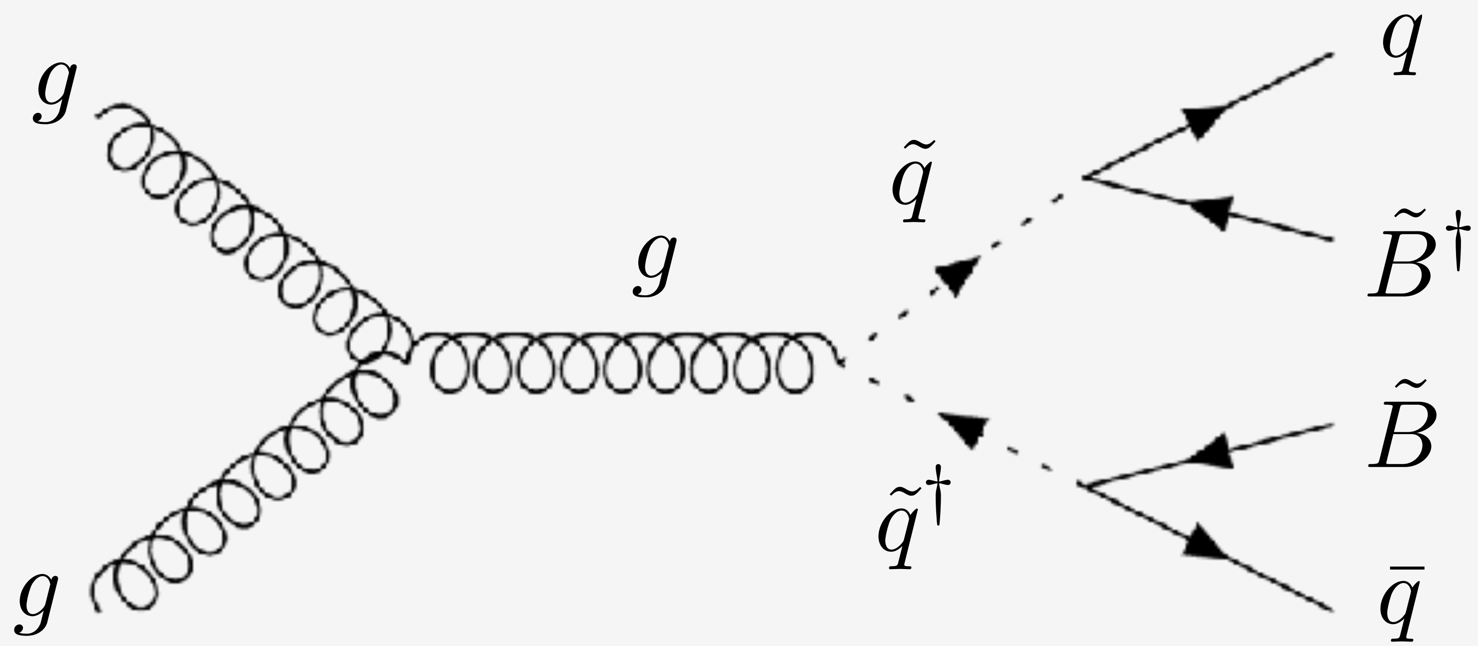
LHC pheno: production

Assumptions for the phenomenology:

- Lightest neutralino is a pure bino
- Gravitino is the LSP - a few keV
- Bino is the NLSP
- Degenerate squarks

LHC pheno: production

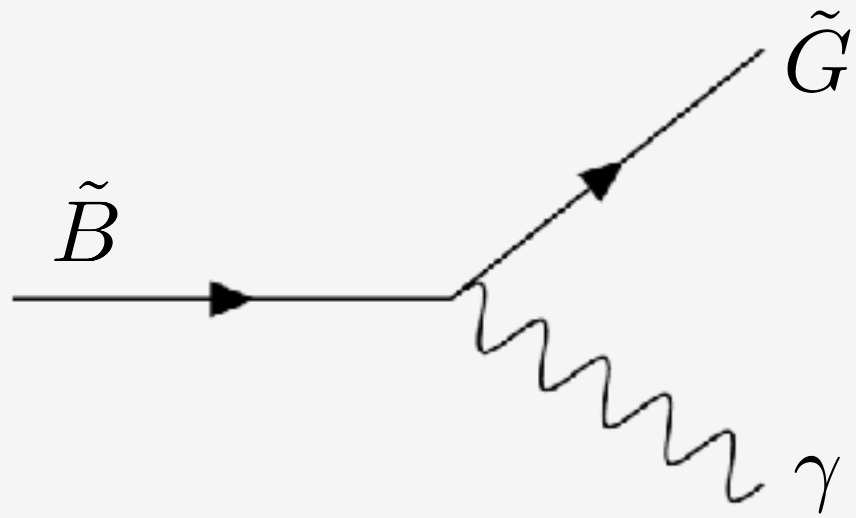
Can produce bino via squark decays:



Gluon fusion is the main production channel at 14 TeV LHC

LHC pheno: decays

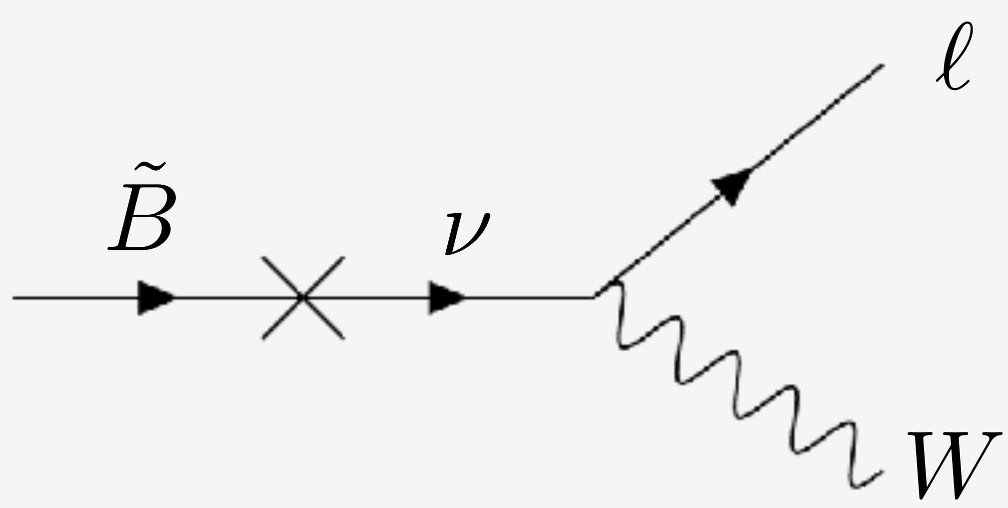
1) Decays to a gravitino and a photon



very small

$$\Gamma(\tilde{B} \to \tilde{G}\gamma) \sim \frac{M_D^5}{M_{Pl}^2 m_{3/2}^2} \sim 10^{-8} \text{ eV}$$

2-4) Decays to $W\ell,\ Z\nu,\ h\nu$



etc

total width:

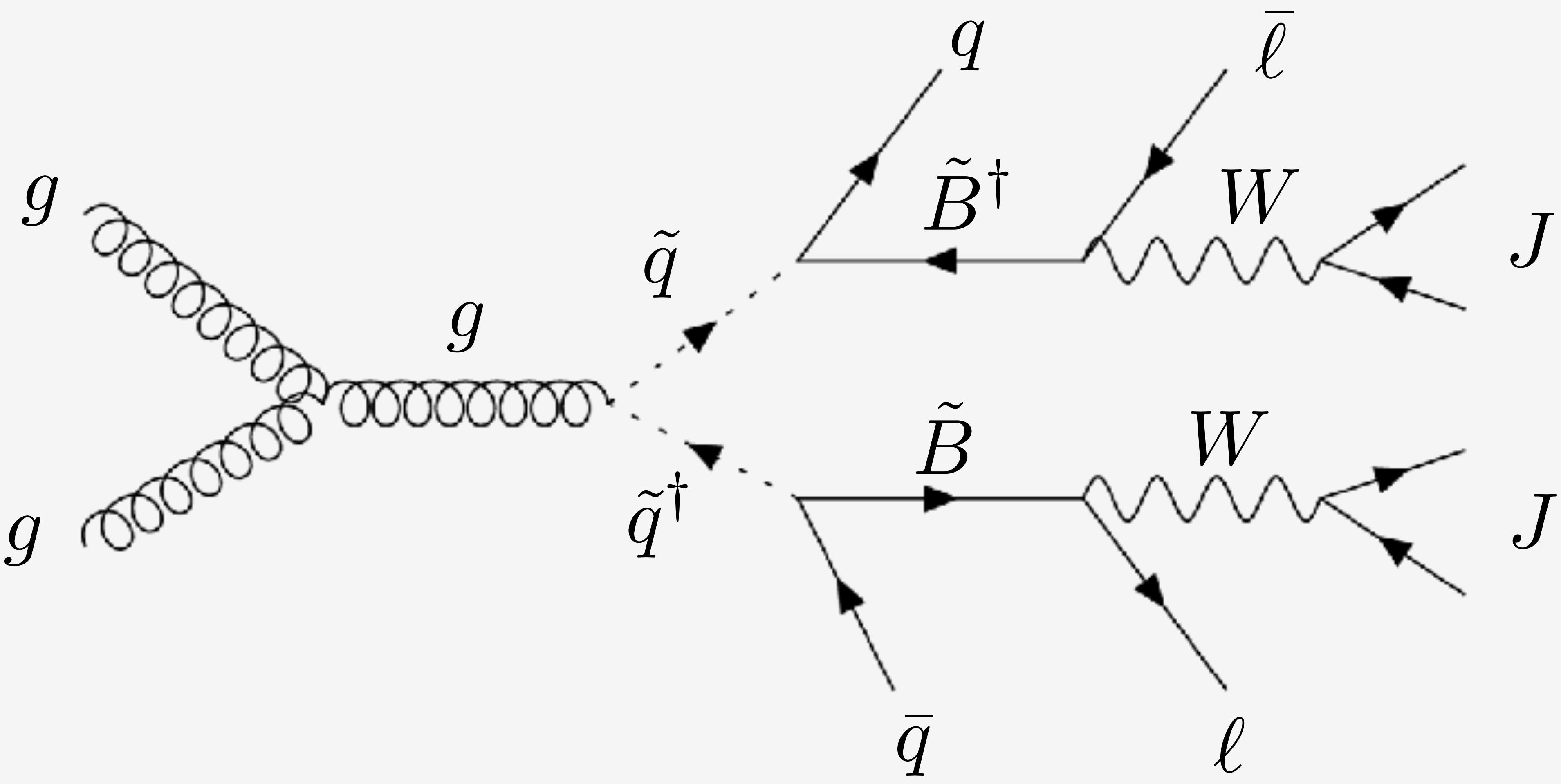
$$\Gamma_{tot} \sim \frac{M_D^3}{\Lambda_M^2} \sim O(\text{MeV})$$

LHC pheno: signals

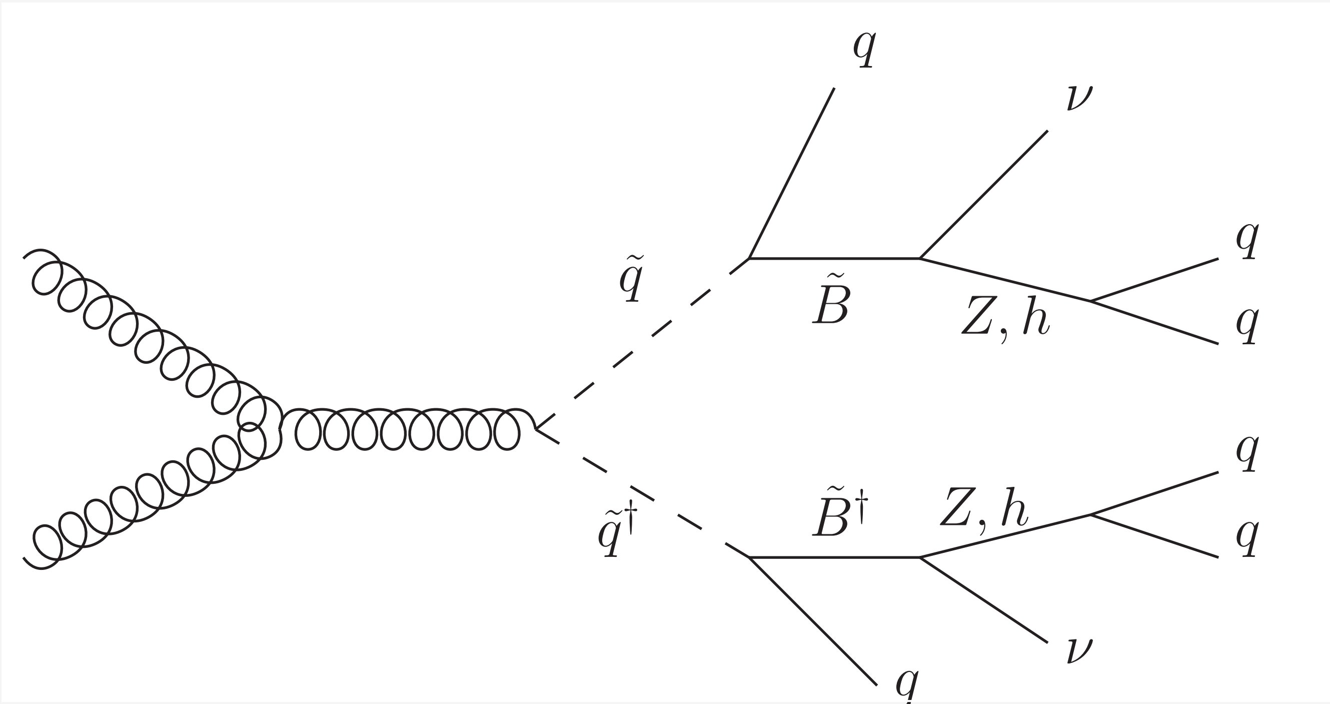
Bino decays promptly, no displaced vertices

A combination of jets, leptons and missing energy is expected

e.g.



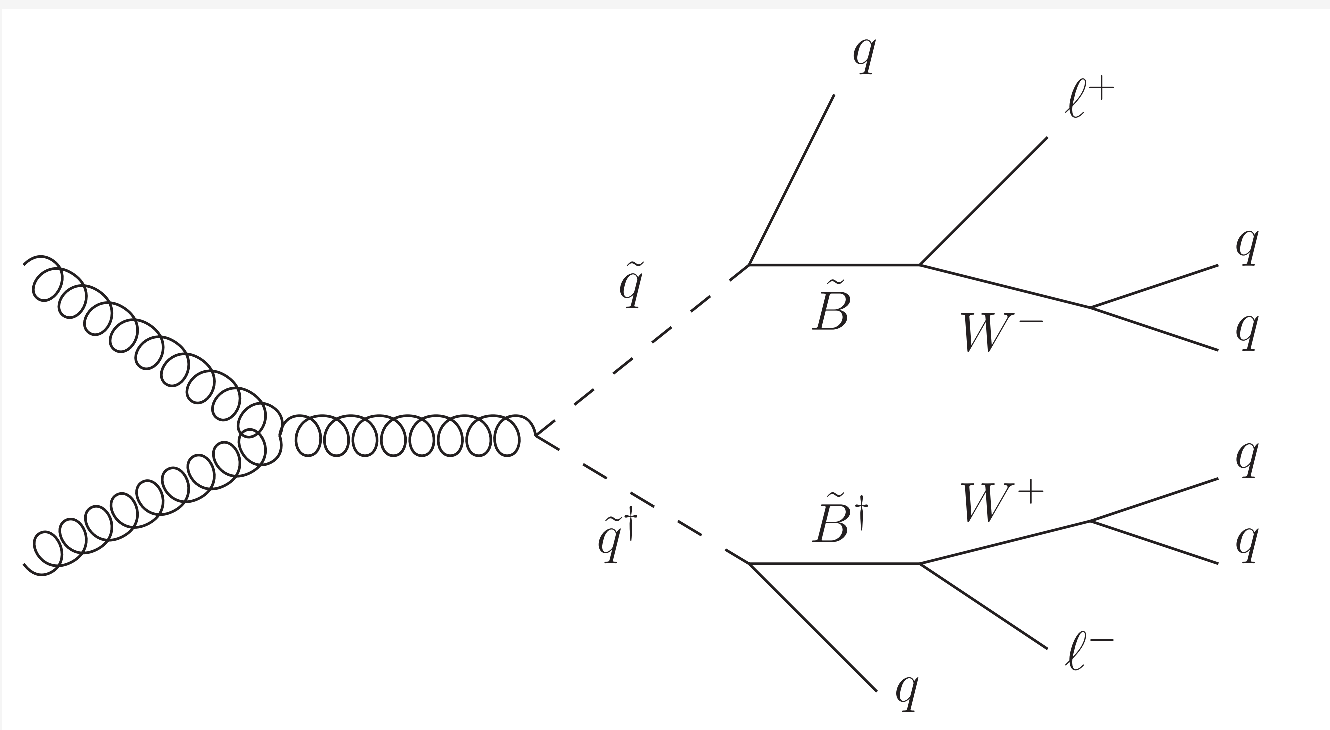
LHC pheno: signals



~ 20% branching ratio

ATLAS-CONF-2017-022

CMS-SUS-16-033

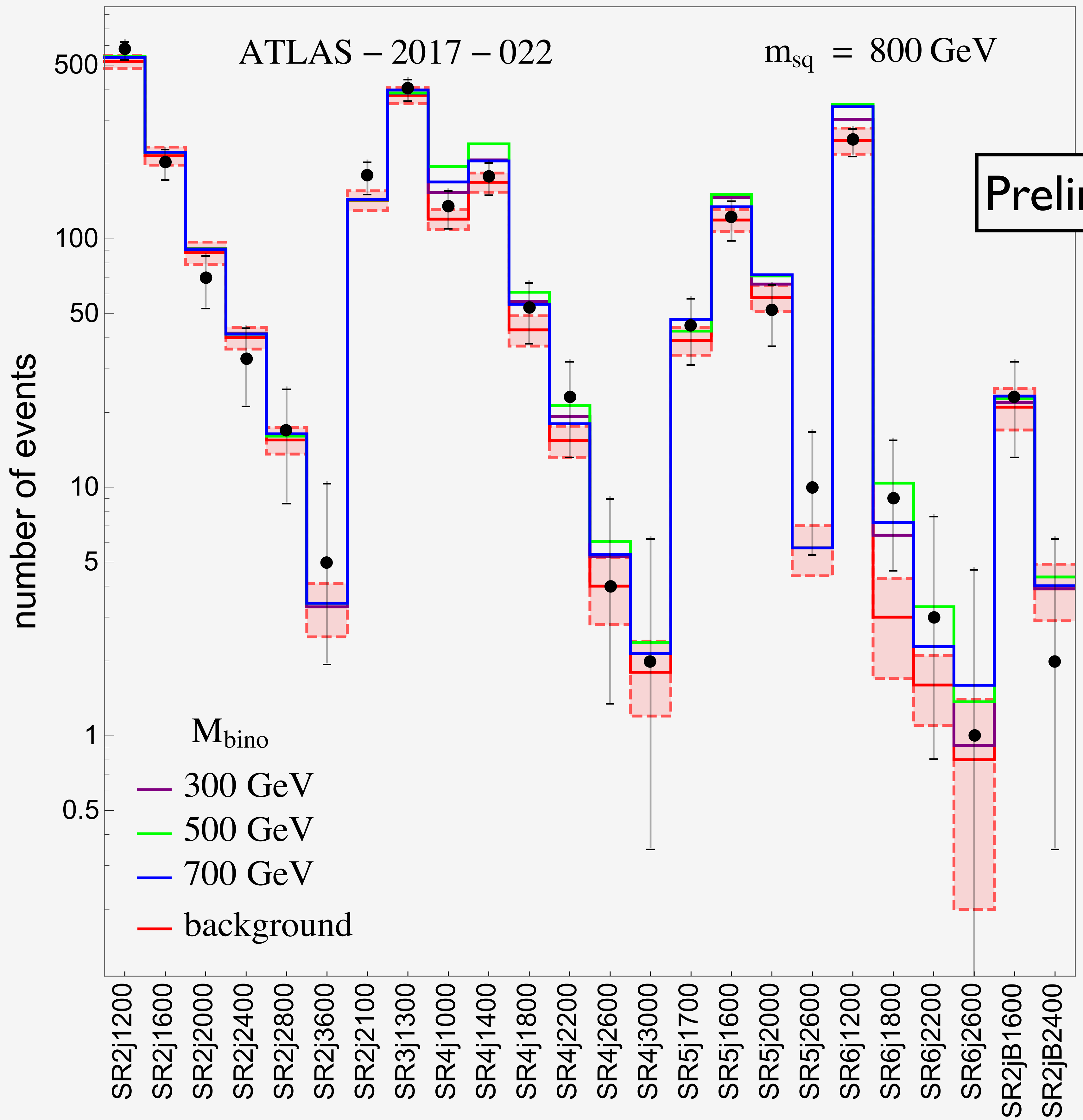


~ 3% branching ratio

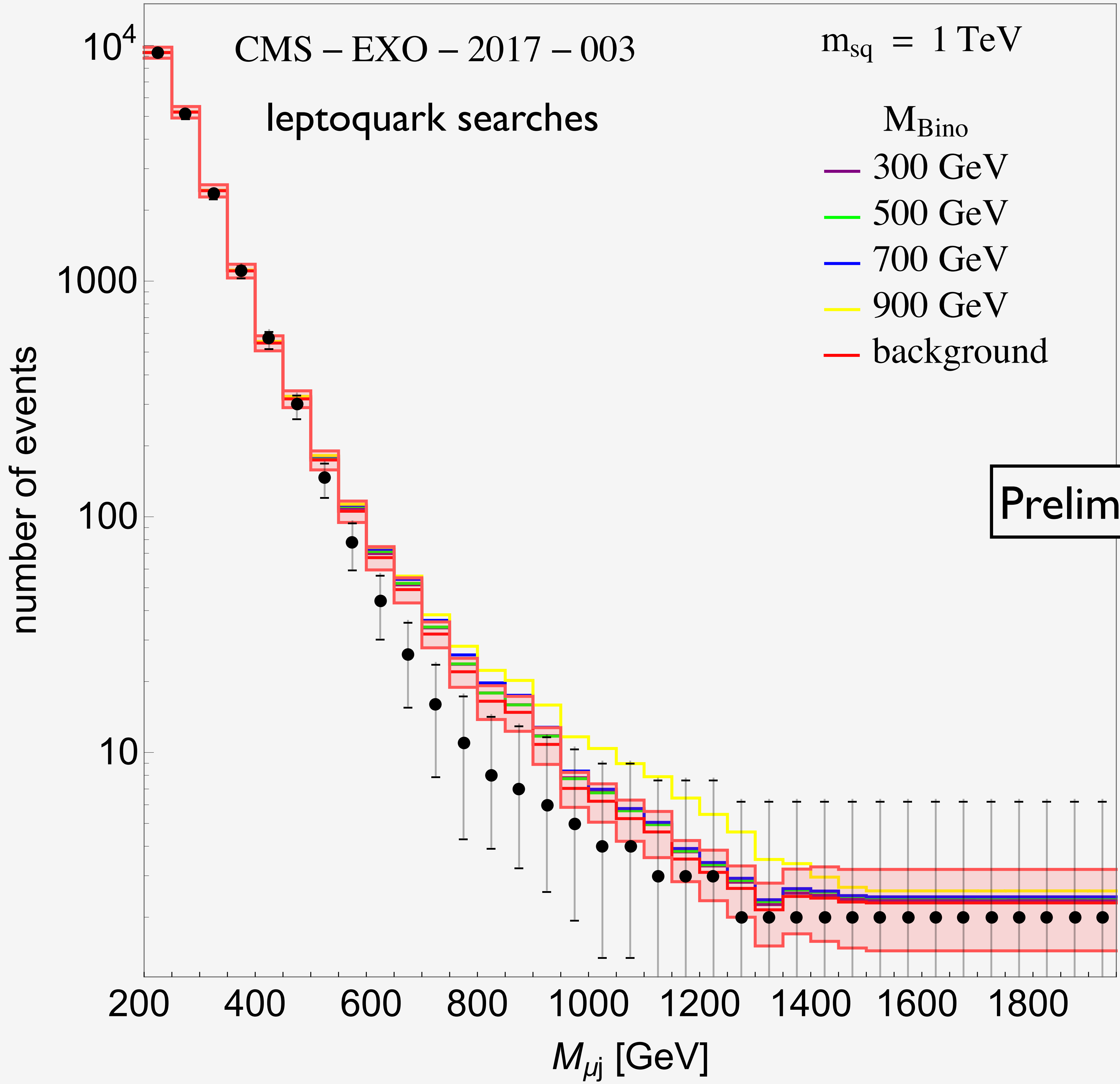
CMS-PAS-EXO-17-003

CERN-EP-2016-074 (ATLAS)

Huge thanks to Angelo Monteux for the analysis codes!

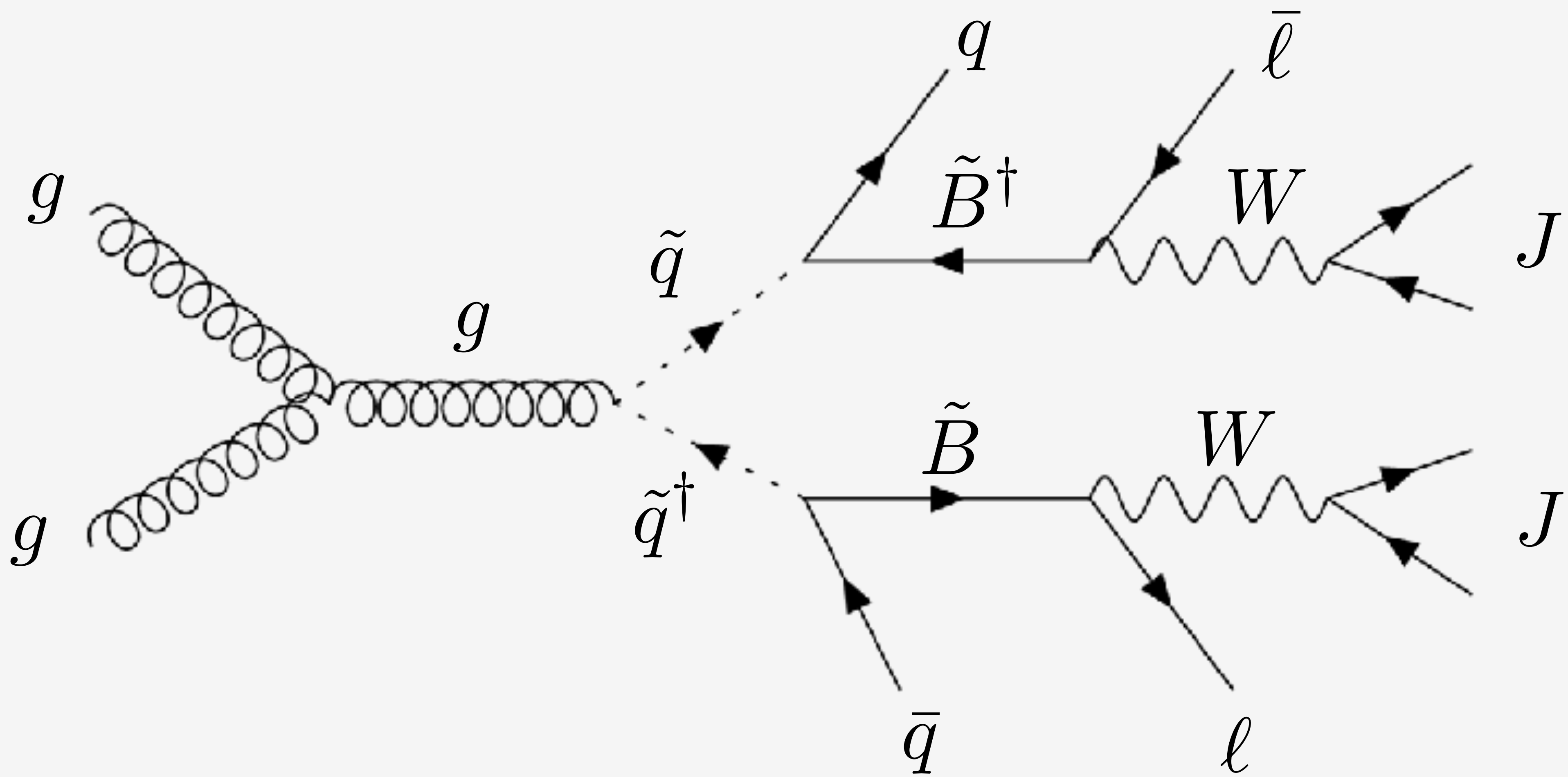


Preliminary results



Preliminary results

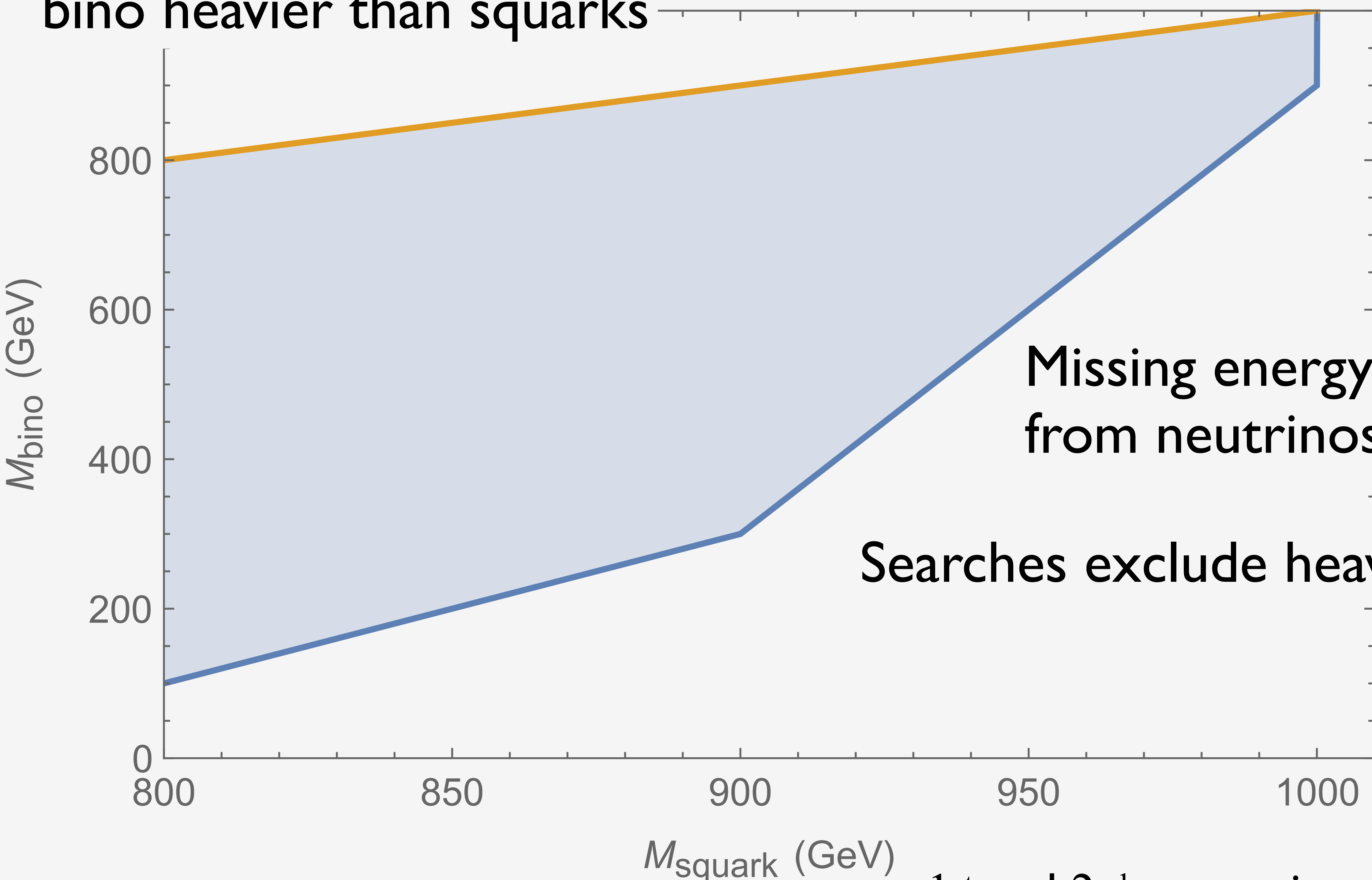
Smoking gun signal



electron : muon : tau
ratios are fully determined by the neutrino sector:
1:2:1

Preliminary results

bino heavier than squarks



1^{st} and 2^{nd} generation squarks