Ultra light heavy neutrinos at colliders

Bled 24

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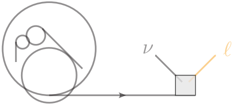
18 June 2024



[1] [w/ Si Hyun Jeon, Fernandez-Martinez, et al (*in progress*)]

Thank you for the invitation!

Plemelj

Sokhotski-Plemelj theorem (wiki)

Version for the real line [edit]

See also: Kramers–Kronig relations

Especially important is the version for integrals over the real line.

$$\lim_{\varepsilon\to 0^+} \frac{1}{x \pm i\varepsilon} = \mp i\pi\delta(x) + \mathcal{P}\left(\frac{1}{x}\right).$$

where $\delta(x)$ is the Dirac delta function where $\mathcal{P}$ denotes the Cauchy principal value. One may take the difference of these two equalities to obtain

$$\lim_{\varepsilon\to 0^+} \left[\frac{1}{x - i\varepsilon} - \frac{1}{x + i\varepsilon}\right] = 2\pi i\delta(x).$$

These formulae should be interpreted as integral equalities, as follows: Let f be a complex-valued function which is defined and continuous on the real line, and let a and b be real constants with $a < 0 < b$. Then

$$\lim_{\varepsilon\to 0^+} \int_a^b \frac{f(x)}{x \pm i\varepsilon}\, dx = \mp i\pi f(0) + \mathcal{P}\int_a^b \frac{f(x)}{x}\, dx$$

and

$$\lim_{\varepsilon\to 0^+} \int_a^b \left[\frac{f(x)}{x - i\varepsilon} - \frac{f(x)}{x + i\varepsilon}\right] dx = 2\pi i f(0)$$

Note that this version makes no use of analyticity.

Proof of the real version [edit]

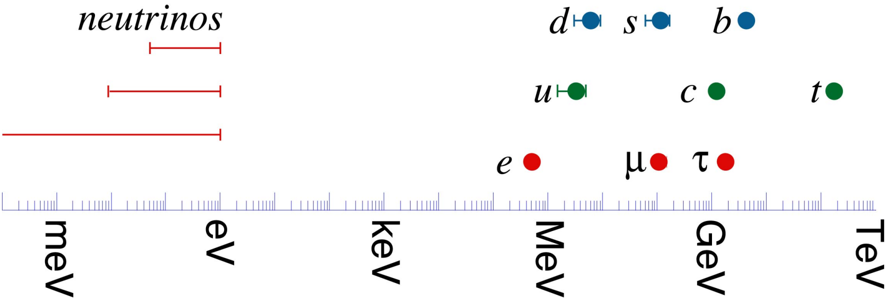
A simple proof is as follows.

$$\lim_{\varepsilon\to 0^+} \int_a^b \frac{f(x)}{x \pm i\varepsilon}\, dx = \mp i\pi \lim_{\varepsilon\to 0^+} \int_a^b \frac{\varepsilon}{\pi(x^2+\varepsilon^2)} f(x)\, dx + \lim_{\varepsilon\to 0^+} \int_a^b \frac{x^2}{x^2+\varepsilon^2} \frac{f(x)}{x}\, dx.$$

For the first term, we note that $\varepsilon/\pi(x^2+\varepsilon^2)$ is a nascent delta function, and therefore approaches a Dirac delta function in the limit. Therefore, the first term equals $\mp i\pi f(0)$.

apologies for the long delay!

Problem: according to the SM, $m_\nu = 0$. (Not enough ingredients but data obviously disagree!)

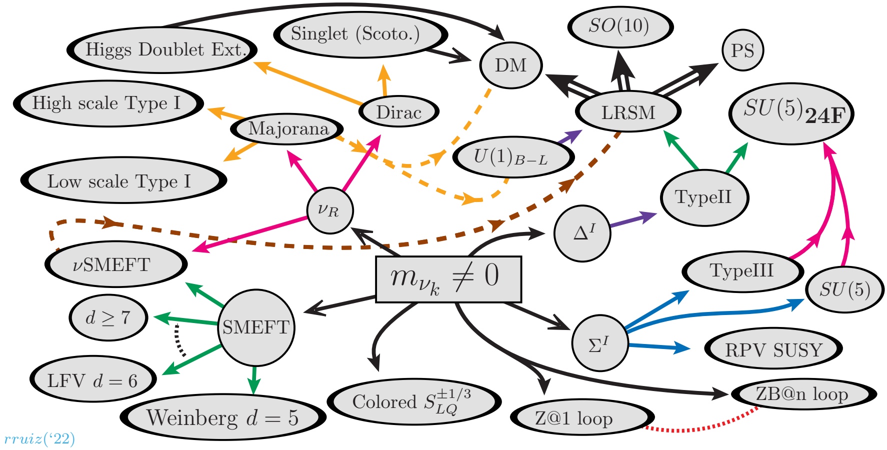


Discovery of neutrino masses $\Longrightarrow$ several open questions:

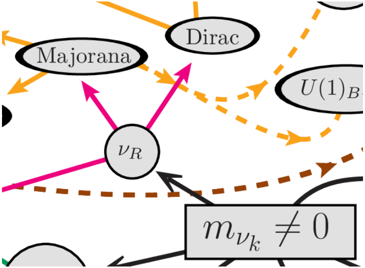
- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

These core ideas can be realized in ***many*** ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



adding right-handed neutrinos (the chiral states) to the SM[2]



[2] For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

adding ν_R to the SM

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu\ \text{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. = -y_\nu \begin{pmatrix}\overline{\nu_L} & \overline{\ell_L}\end{pmatrix} \begin{pmatrix}\langle\Phi\rangle + h \\ 0\end{pmatrix} \nu_R + H.c.$$

$$= \underbrace{-y_\nu\langle\Phi\rangle}_{=m_D}\overline{\nu_L}\nu_R + H.c. + \ldots$$

ν_R do not exist in the SM, so pretend that they do and $\nu_R = \nu_R^c$:

$$\implies \mathcal{L}_{\text{mass}} = \frac{-1}{2} \underbrace{\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}}_{\text{chiral state}} \underbrace{\begin{pmatrix} 0 & m_D \\ m_D & \mu_{\not{L}} \end{pmatrix}}_{\text{mass matrix (chiral basis)}} \begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

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After diagonalizing the mass matrix, identify ν_L (chiral eigenstate) in the SM as a linear combination of mass eigenstates:

$$\underbrace{|\nu_L\rangle}_{\text{chiral state}} = \cos\theta \underbrace{|\nu\rangle}_{\text{light mass state}} + \sin\theta \underbrace{|N\rangle}_{\text{heavy mass state (this is a prediction!)}}$$

the benchmark model

Generically paramerize active-sterile neutrino mixing via Atre, et al [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis}} \quad \text{(neglect heavier } N_{m'}\text{)}$$

The SM W coupling to **leptons** in the **flavor basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \nu_\ell\right] + \text{H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

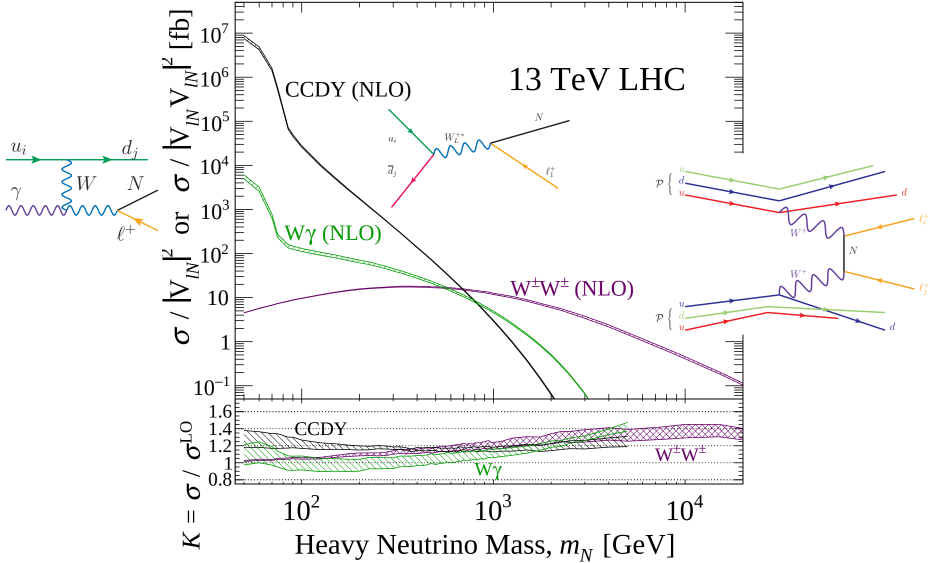
$\implies$ W coupling to N in the **mass basis** is

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\bar{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\implies$ N is **accessible through** $W/Z/h$ bosons

summary of high-mass searches at the LHC (2 slides)

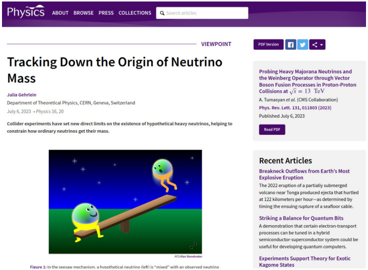
Plotted: Normalized production rate ($\sigma/|V|^{2\ (4)}$) vs m_N

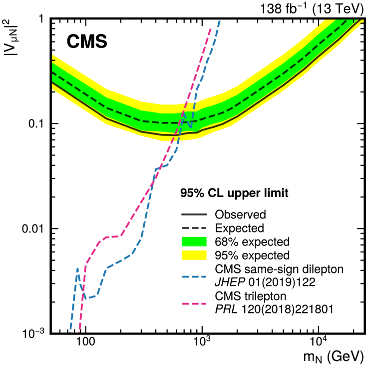


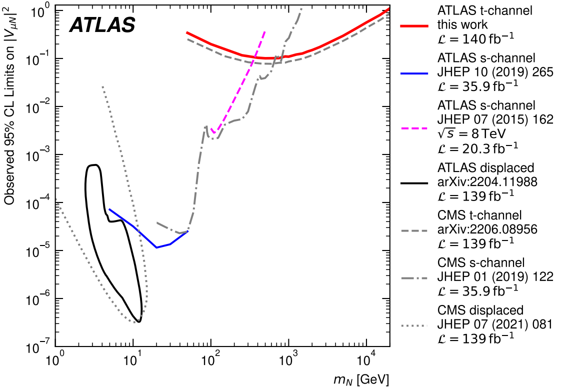
$\gamma W^{\pm}$ and $W^{\pm}W^{\pm}$ scattering drive high-mass scattering rates!

w/ Fuks, Neundorf, Peters, Saimpert [2011.02547; 2012.09882]

Search for $W^{\pm}W^{\pm} \to \ell^{\pm}\ell'^{\pm}$ quickly adopted by **ATLAS** and **CMS** experiments!







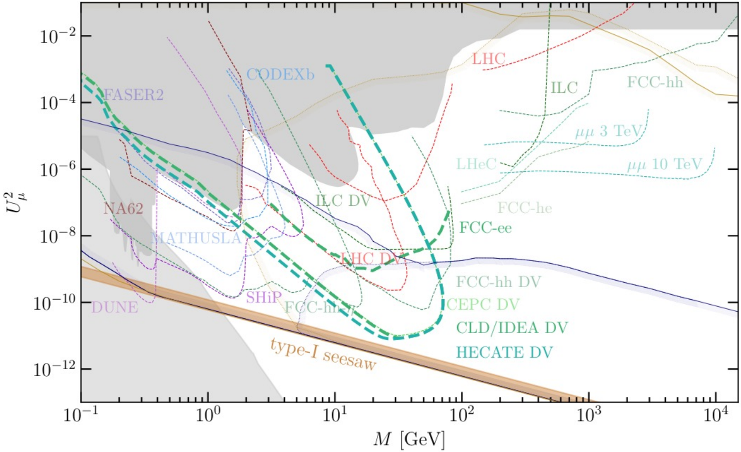
ATLAS (EPJC'23) [2305.14931]

$ee/e\mu$ **[2403.15016]**

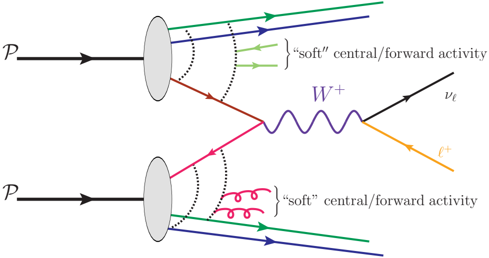
← **CMS (PRL'22) [2206.08956]**

summary of low-mass searches

Community Message: LHC+next-gen. facilities can probe *simplest* ($m_{\nu_1} = 0$) leptogenesis scenario w/ ν_R Abdullahi, et al [2203.08039]; w/ Alimena, et al [2203.05502]



challenges of a low-mass analyses



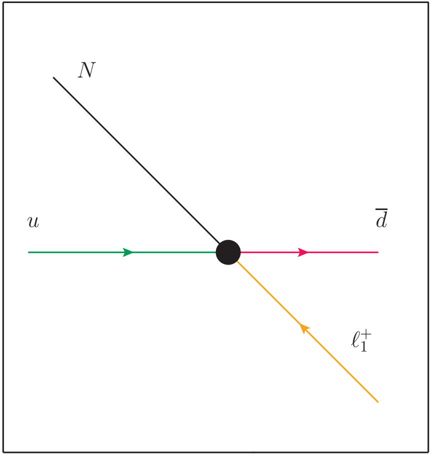
how good are our assumptions on phenomenological modeling?

Challenge: (sub)GeV-scale N carry lots of energy at $\sqrt{s} = 13/14$ TeV

$u\overline{d} \rightarrow W \rightarrow N\ell$ in W's c.m. frame

(= hard scattering frame)

Typical LHC production channel is $(1 \rightarrow 2)$-body decay of W boson



Classic exercise:

$$E_N^{(W)} = \frac{M_W}{2}\left(1 + \frac{m_N^2}{M_W^2}\right), \quad m_\ell = 0$$

Common analysis assumptions:

- $\langle\gamma_N^{(\mathrm{lab})}\rangle \approx \gamma_N^{(W)} = E_N/m_N$
- $\tau_N^{(lab)} \approx \gamma_N^{(W)}\tau_N, \quad \tau_N = \hbar/\Gamma_N$

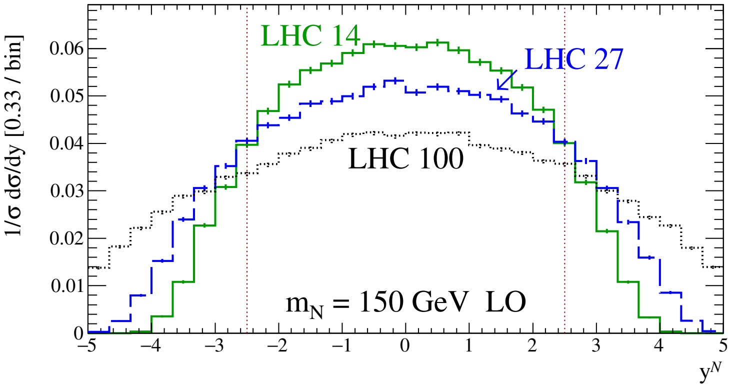
this assumes

$E_W^{(lab)} \sim M_W$ ($|\vec{p}_W^{(lab)}| \approx 0$) because M_W is large and $p_T^W \ll M_W$.

assuming that $|\vec{p}_W^{(lab)}| \approx 0$ is **bad** because $p_Z^W \gtrsim M_W$

Plotted: (normalized) rapidity of N in $pp(u\overline{d}) \to W \to N\ell$

here, $m_N = 150$ GeV but behavior still holds for $m_N \ll M_W$ [1812.08750]



take away: increasing collider energy $\sqrt{s}$ leads to growing $p_Z^W = (\xi_1 - \xi_2)\sqrt{s}$ since more asymm. values of ξ_i satisfy $(\xi_1\xi_2)s = M_W^2$

can we still reliably estimate the boost factor? ☺

The starting point is the **Collinear Factorization Thm**

Collins, Soper, Sterman ('85,'88,'89); Collins, Foundations of pQCD (2011)

$$d\sigma^{\rm LO}(pp \to W + X) = \sum_{a,b} \Delta_{ab} \otimes f_a \otimes f_b \otimes d\hat{\sigma}^{\rm LO}(ab \to W) + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{p}}{Q^{p+2}}\right)}_{\text{fun stuff}}$$

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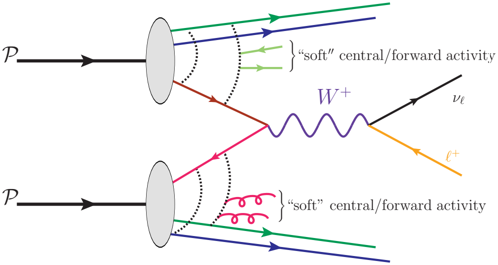
The average of an observable $\mathcal{O}$ can be obtained from the matrix element:

$$\langle \mathcal{O} \rangle = \frac{1}{\sigma} \times \int d\sigma \times \mathcal{O}$$

$$\implies \langle E_W^{(lab)} \rangle = \frac{1}{\sigma} \times \int d\sigma \times E_W^{(lab)}$$

$$\implies \langle E_W^{(lab)} \rangle|_{events} \approx \frac{1}{\sigma} \times \sum_i wgt_i \times E_W^{(lab)}$$



with $E_W^{(lab)} = (\xi_1 + \xi_2)\sqrt{s}$

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In practice, inclusive $pp \to W + X$ is a $2 \to 1$ process and hence special:

- $d\hat{\sigma}^{\rm LO} \sim \delta(\xi_1\xi_2 - M_W^2/s)$
- $\Delta_{ab} \sim \delta(1-z)$ **(parton shower is unitary)**

$\implies$ only one integral remains

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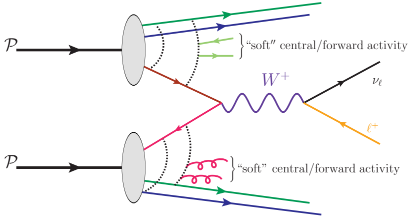
Old idea: approximate

e.g., Mangano [hep-ph/9711337]

$$f_{i/p}(\xi) \approx (\text{const.}) \left[\frac{(1-\xi)^\beta}{x}\right] x^{1+\delta}$$

- $\delta \approx 0.40$
- $\beta = 0, 1, 2, \ldots$
- const. $= \sum_k \mathcal{A}_k \alpha_s \log(\mu_f^k/\Lambda_{NP})$



Challenge: how to estimate p_Z^W at $\sqrt{s} = 13/14$ TeV?

interesting resolution by approximating PDF:
$f_{i/p}(\xi) \approx \text{const.} \frac{(1-\xi)^\beta}{x} x^{1+\delta}$

for $\beta = 2$, $\langle \gamma_W^{(\text{lab})} \rangle =$

$$\frac{-1-9\tau_0+9\tau_0^2+\tau_0^3-6\tau_0(1+\tau_0)\log(\tau_0)}{3\sqrt{\tau_0}[3-3\tau_0^2+(1+4\tau_0+\tau_0^2)\log(\tau_0)]},$$

where $\tau_0 = M_W^2/s$

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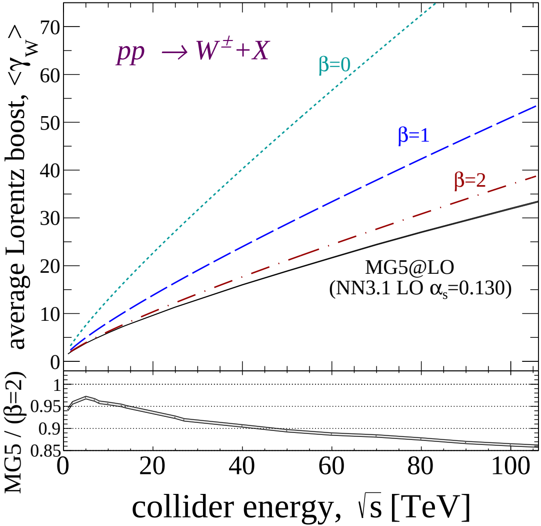
where $\tau_0 = M_W^2/s$

take away: varying β shows importance of $\xi = 1$ and large y (rapidity) regions

Plotted: avg. Lorentz boost of W $(\langle \gamma_W^{(\text{lab})} \rangle = \langle E_W^{(\text{lab})} \rangle / M_W)$



Challenge: how to estimate $\gamma_N^{(lab)}$ at $\sqrt{s} = 13/14$ TeV?

interesting resolution by approximating:
$\langle\gamma_N^{(\mathrm{lab})}\rangle = \langle\gamma_W^{(\mathrm{lab})}\rangle|_{\beta=2} \times E_N^{(W)}$

where
$E_N^{(W)} = \frac{M_W}{2}(1 + \frac{m_N^2}{M_W^2} - \frac{m_l^2}{M_W^2})$

Plotted: avg. Lorentz boost of N

$$\langle\gamma_N^{\rm (lab)}\rangle = \langle E_N^{\rm (lab)}\rangle / m_N$$

Challenge: how to estimate $\gamma_N^{(lab)}$ at $\sqrt{s} = 13/14$ TeV?

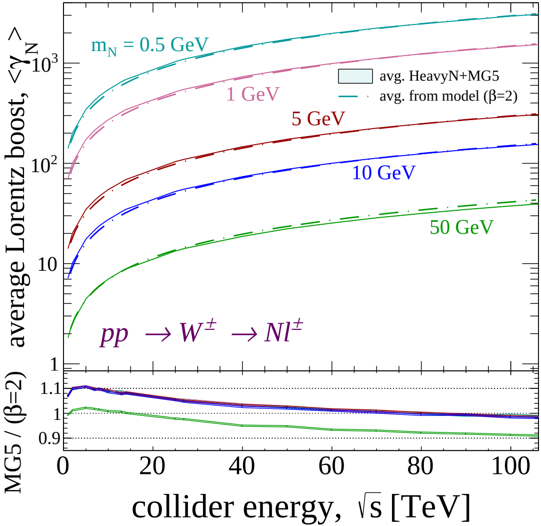
interesting resolution by approximating:

$$\langle\gamma_N^{\rm (lab)}\rangle = \langle\gamma_W^{\rm (lab)}\rangle|_{\beta=2} \times E_N^{(W)}$$

where

$$E_N^{(W)} = \frac{M_W}{2}\left(1 + \frac{m_N^2}{M_W^2} - \frac{m_l^2}{M_W^2}\right)$$

take away: boosts of ultra light N can be computed analytically

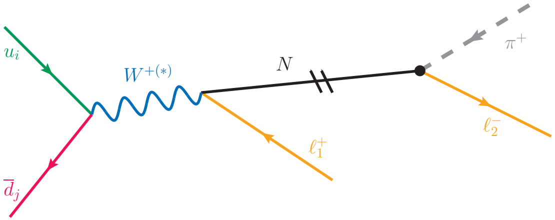


how good are our assumptions on phenomenological modeling?

decays of sub-GeV N

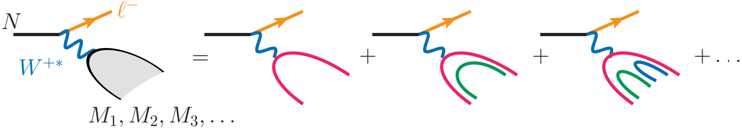
N with $m_N \in$ [150 MeV,5 GeV] decay to *hadrons*, not *free quarks*

(breakdown of the parton model)



important to remember difference between energy scale

$$E_N \sim \mathcal{O}(M_W) \gg \Lambda_{\rm NP} \text{ and mass scale } m_N \sim \mathcal{O}(\Lambda_{\rm NP})$$

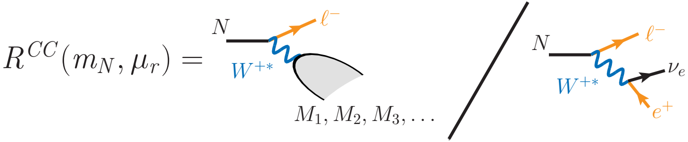


inclusive hadronic decays of sub-GeV N

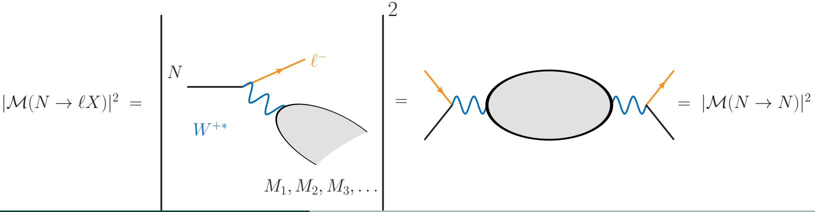
clever idea: to build inclusive hadronic width of N

$$\Gamma(N \to \ell + \text{had.}) = \sum_k \Gamma(N \to \ell + n_k M_k)$$

use formalism for computing $\Gamma(\tau \to \nu_\tau + \text{had.})$ Boyarsky, et al [1805.08567]



isolate "hadronic" component of $\mathcal{M}$, **simplify with optical theorem**,
solve loop via RG running $(d\mu^2 \to d\alpha_s)$: Braaten (PRL'88) + many others



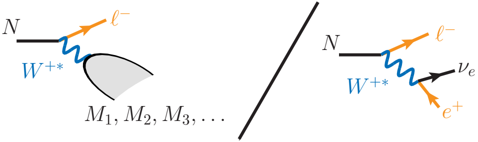
the problem?

the technical details, of course

inclusive hadronic decays of sub-GeV N

$\Gamma(\tau \to \nu_\tau + \text{had.})$ assumes $m_\nu = 0$ and $|(p_\tau - p_\nu)^2| < m_\tau^2$

Braaten (PRL'88) + many others

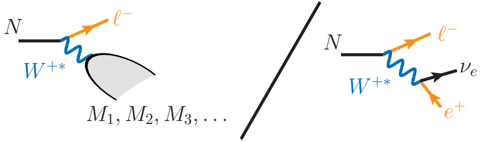
$R^{CC}(m_N, \mu_r) =$ 

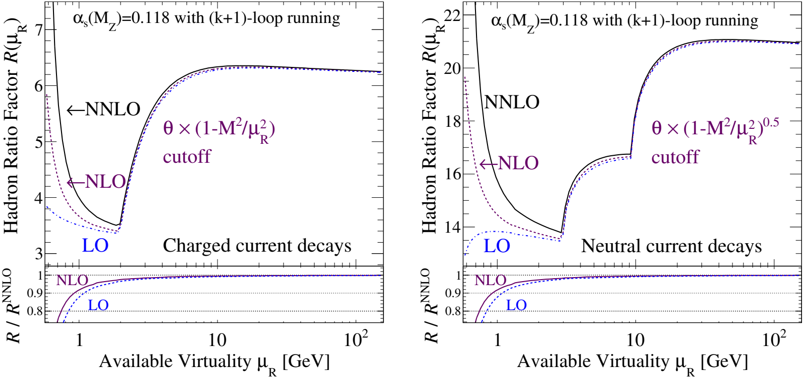
$\Gamma(N \to \ell + \text{had.})$ needs $m_N, m_\ell \neq 0$ and $|(p_N - p_\ell)^2| < (m_N - m_\ell)^2$

– replace m_τ dependence with m_N de Vries, et al [2010.07305]
– including missing phase space term for $m_\ell \neq 0$
– $m_N \to (m_N - m_\ell)$ replacement in boundary of phase space integral
– include neutral current contributions Coloma, et al [2007.03701]
– include threshold effects for meson masses(adhoc) Coloma, et al [2007.03701]
– check consistency with pQCD result in large m_N limit

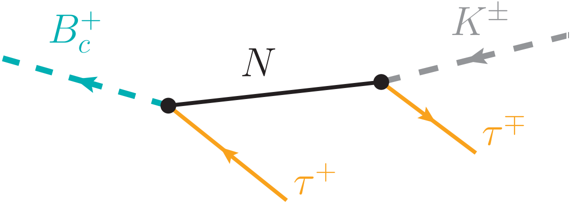
Updated value of R^{CC} is a bit larger than estimates of $R^{CC} \approx 3.54$

$$R^{CC}(m_N, \mu_r) =$$

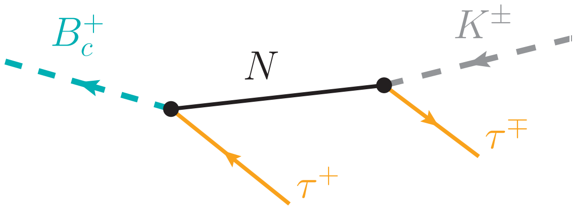




challenges of a low-mass analyses



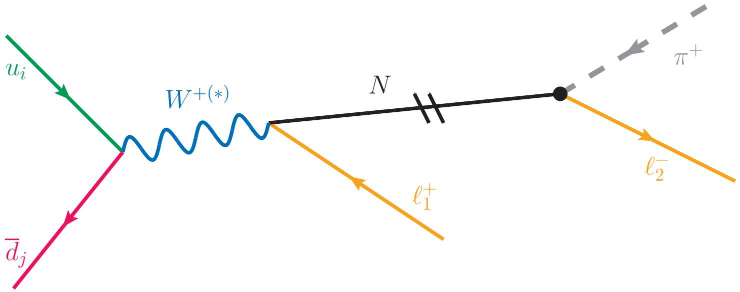
For $m_N \ll M_W$, N can appear in $\mathcal{B}_c^+ \to \tau^+\tau^\mp K^\pm$ decays (or similar)



$\mathcal{B}_c^+$ is low-pT physics

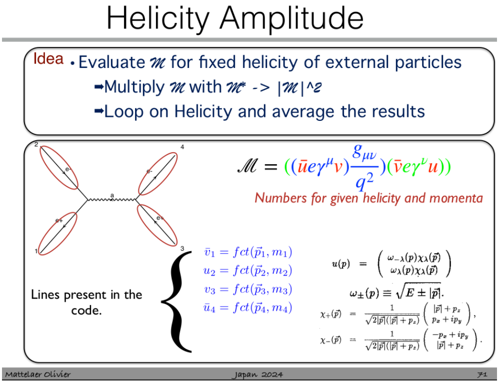
- signal rates are higher, but so are background rates
- lower kinematical scales $\Longrightarrow$ more difficult to trigger/tag
- less certain knowledge of production mode

exclusive decay modes at high p_T



how to do this in a generator?

Event generators build amplitudes algorithmically via Feynman rules



Example (mg5amc):

- for $i \to f$ process, start from f and attach permutations of legs allowed by Feynman rules until i is reached
  - for $e^+e^- \to \mu^+\mu^-$, try $Z/\gamma \to \mu^+\mu^-$ (✓)
  - for $e^+e^- \to \mu^+\mu^-$, try $g \to \mu^+\mu^-$ (✗)
- algorithm will not attach g anywhere since nothing carries color index

Assume some set of Feynman rules containing the following:

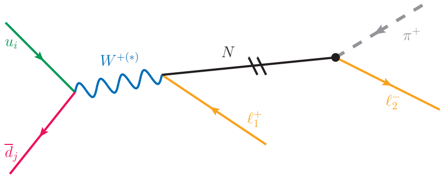
– SM (massless QCD)

– N coupling to W (Pheno. Type I)

Degrand, RR, et al [1602.06957]

– N coupling to M (low-energy EFT)

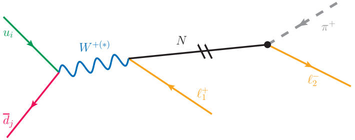
Coloma, Fernandez-Martinez, et al [2007.03701]



Example (mg5amc):

- for $u\overline{d} \to W \to N\ell \to \pi\ell\ell$, attach permutations of legs to $(\pi\ell\ell)$ as allowed by Feynman rules until $u\overline{d}$ is reached
  - try $g \to \pi\ell$ (✗)
  - try $N \to \pi\ell$ (✓)
  - try $u\overline{d} \to \pi$ (✗)
- algorithm will not attach g to π since **no color charge**
- algorithm will not attach $u\overline{d}$ to π since **no Feynman rule**

Light mesons from light N at the LHC



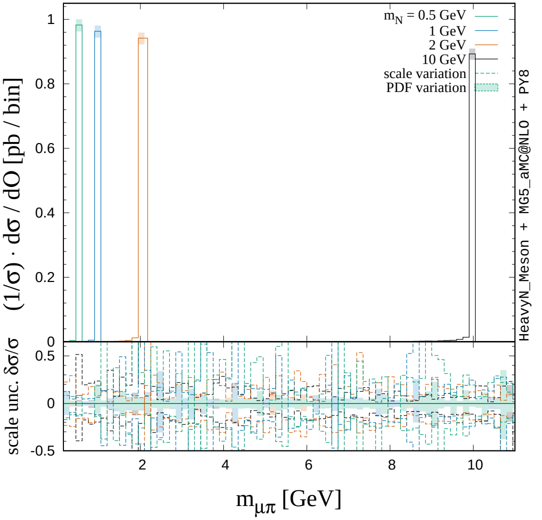
Proof-of-concept:

1. $pp \to W^{(*)} \to Ne^\pm$ at NLO in QCD at $\sqrt{s} = 13$ TeV LHC

2. $N \to \mu^\pm \pi^\mp$ decay with full spin correlation

3. full parton shower (PY8)

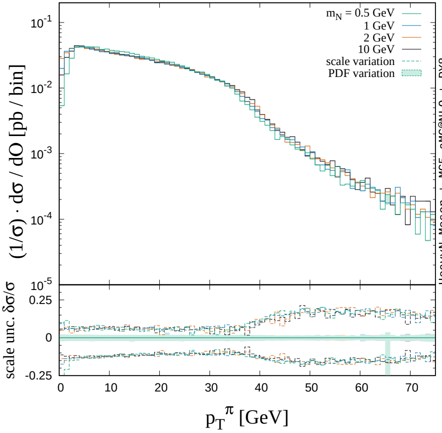
4. basic reconstruction



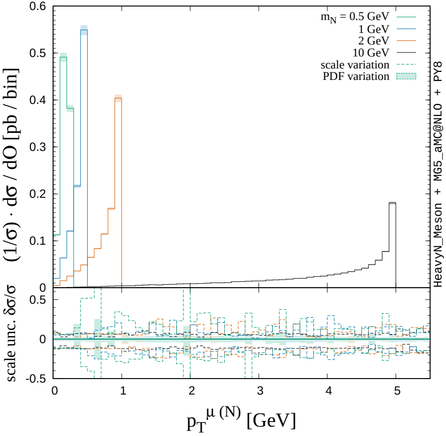
[w/ Jeon, Fernandez-Martinez, et al (*in progress*)]

Light mesons from light *N* at the LHC

lab frame



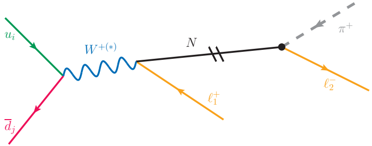
N's frame



Summary and conclusion

ν have mass and discoverying their origin motivates searches at colliders!

for reviews, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]



- (sub-)GeV sterile N is a well-motivated solution (but not only solution!)
- new analytical results for energies and boosts in the lab frame
- new software (NuWidth++) for computing total width of GeV-scale N
- new software (HeavyN_Meson) for simulating $N \to M\ell/\nu$, $M \to N\ell/\nu$, and $\tau \to NM$ at colliders

- final results out summer 2024!

final words

3-year postdoc vacancy [deadline 15 Nov]

Join #TeamSNAIL **(Scattering neutrinos on Atoms In the LHC)** to work on νDIS@LHC

PAGE CONTENTS

Job Information

Organisation/Company	Institute of Nuclear Physics Polish Academy of Sciences
Department	Department of Particle Theory /NZ42/
Research Field	Physics
Researcher Profile	Recognised Researcher (R2)
Country	Poland
Application Deadline	15 Nov 2024 - 23:59 (Europe/Warsaw)
Type of Contract	Temporary
Job Status	Full-time
Hours Per Week	40
Offer Starting Date	1 Oct 2025
Is the job funded through the EU Research Framework Programme?	Not funded by a EU programme
Reference Number	5/Ad/2024
Is the Job related to staff position within a Research Infrastructure?	No

Offer Description

The successful candidate will be expected to carry out theoretical and phenomenological investigations into neutrino-nucleus deep-inelastic scattering for activities at CERN's Forward Physics Facility as part of the "Scattering Neutrinos on Atoms at the LHC (SNAIL) project. Depending on individual talents and interests, projects may involve Standard Model physics and/or physics Beyond the Standard Model, as well as contributing to the development of the MadGraph5aMC@NLO event generator. The candidate will also be expected to participate and coorganize local group activities, e.g. seminars wand workshops.

Application page already up but advertising campaign starts in October [protip: “adjunct/adiunkt” in PL = fixed-term contract]


neutrino
collider
model
production
TeV
LHC
hadron
decay
heavy
jet
mass
processes
standard
channel
veto
mechanism
leading
discovery
data
range
test
Monte
GeV
order
current
Type
seesaw
process
context
VBS
top
NLO
tool
Carlo
quark
NNLO
well
due
QCD
result
probe
available
using
review
impact
system
LRSM
cross
transverse
one
pair
high
rate
100
via
case

Thank you!

backup