Unravelling the richness of dark sector by FASERν

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This work is based on

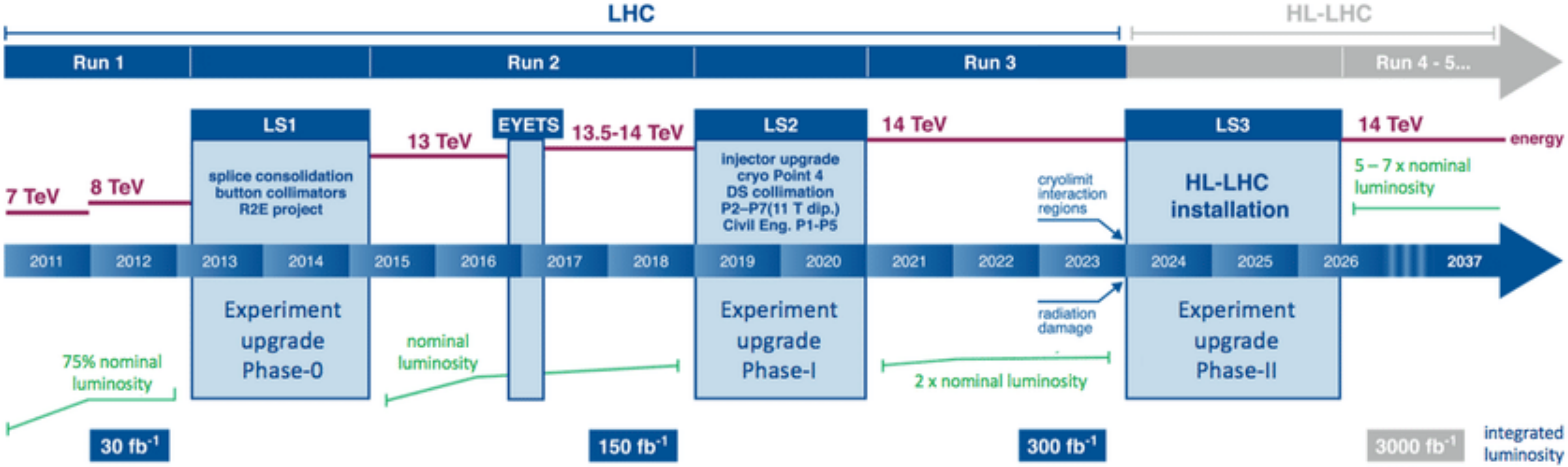
- P. Bakhti, YF, S. Pascoli, "Unravelling the richness of dark sector by FASERν," arXiv: 2006.05437

Work done during my stay at ICTP, Trieste, Italy

elusives
neutrinos, dark matter & dark energy physics

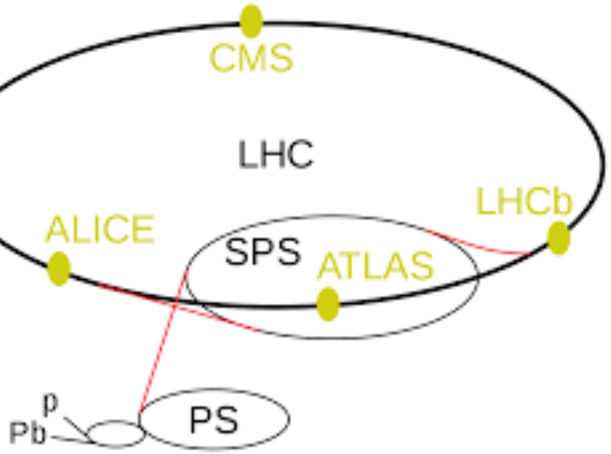
invisiblesPlus
neutrinos, dark matter & dark energy physics

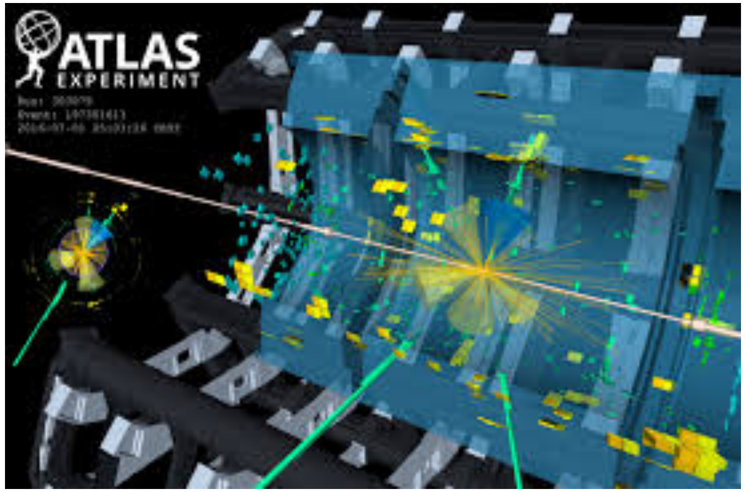
LHC timeline and luminosity



Run III: 14 TeV; 150 fb^{-1}; 2021-2023

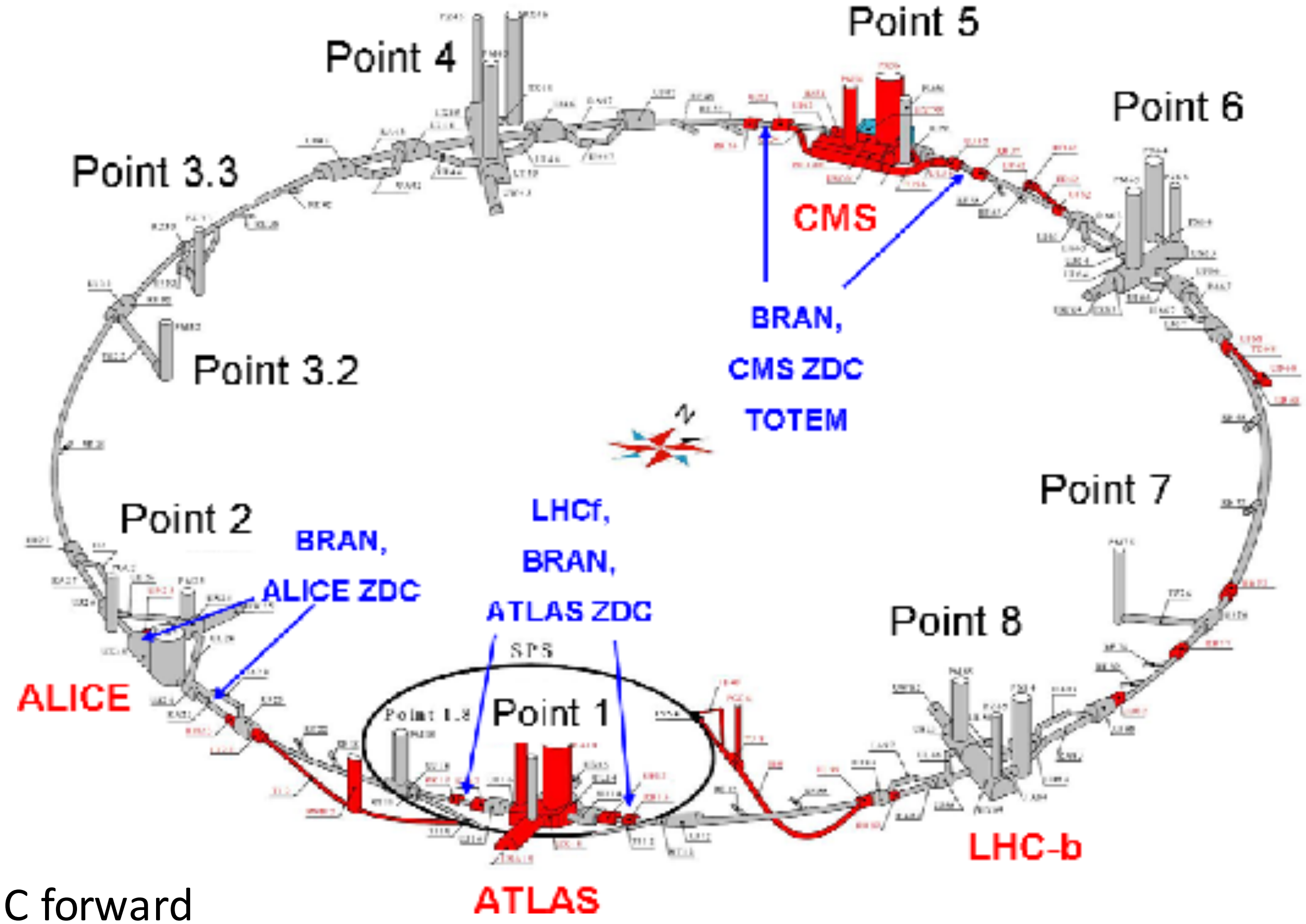
Main detectors of the LHC





Smaller detectors

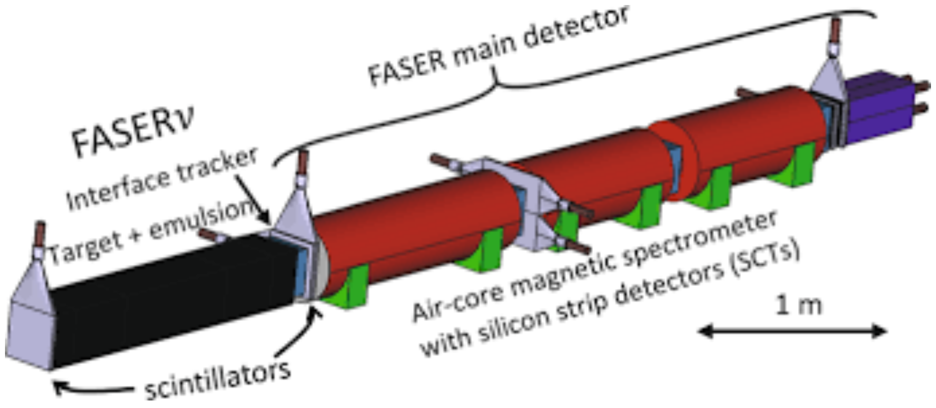
ZDC=Zero Degree Calorimeter



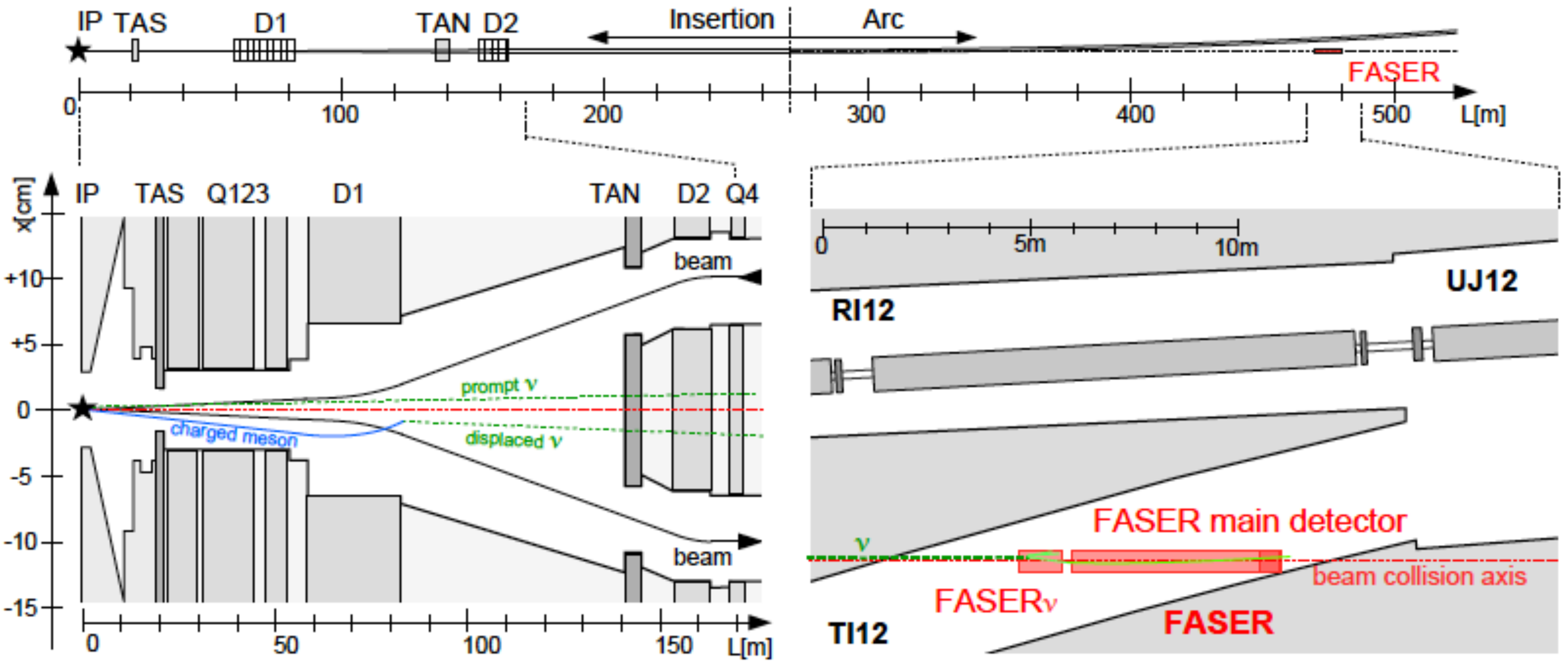
LHCf=LHC forward

FASER

- FASER: ForwArd Search ExpeRiment

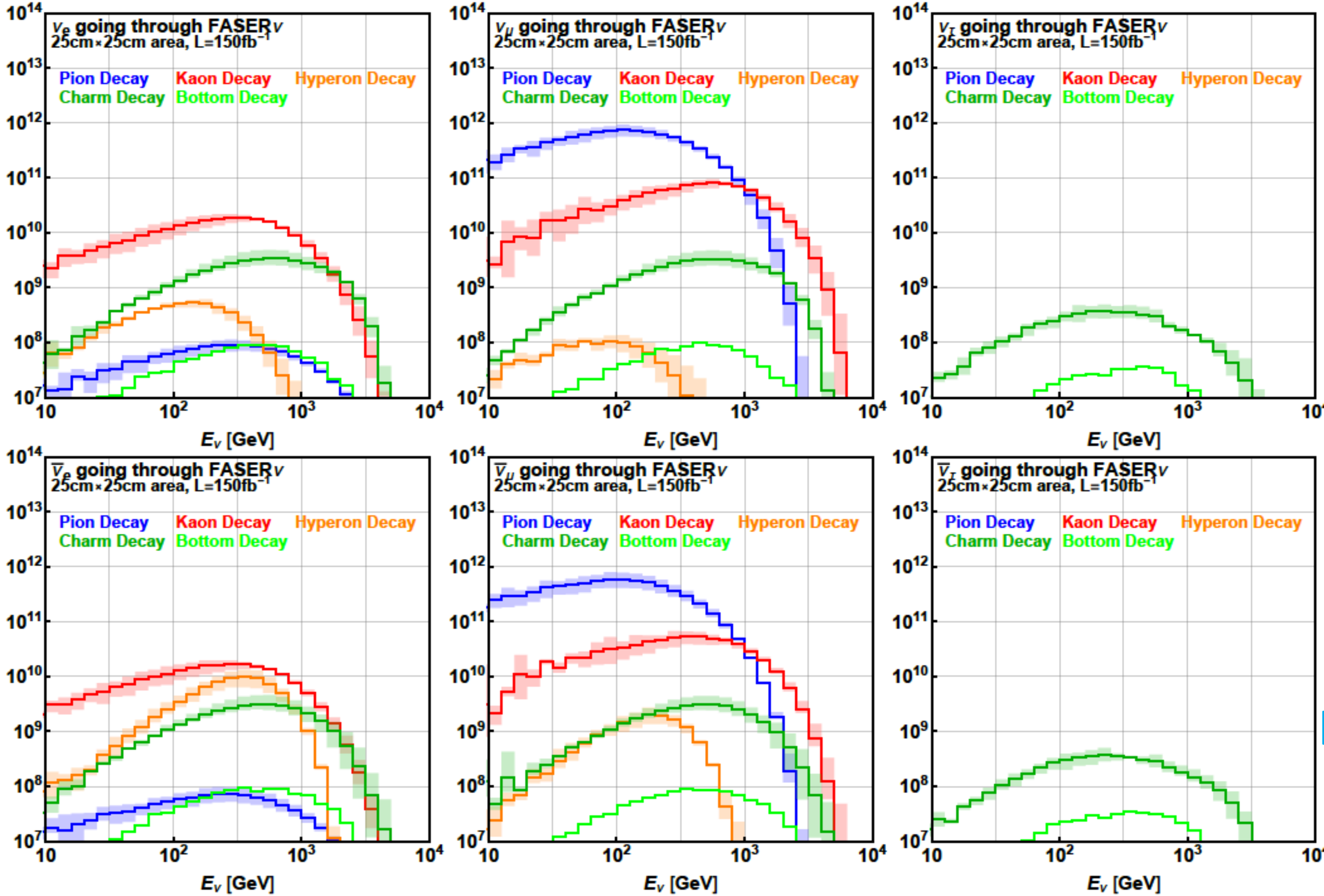


- FASERν Run III: 14 TeV; $150\ fb^{-1}$; 2021-2023



FASER collaboration, arXiv:1908.0231

10 m of concrete and 90 m of rock

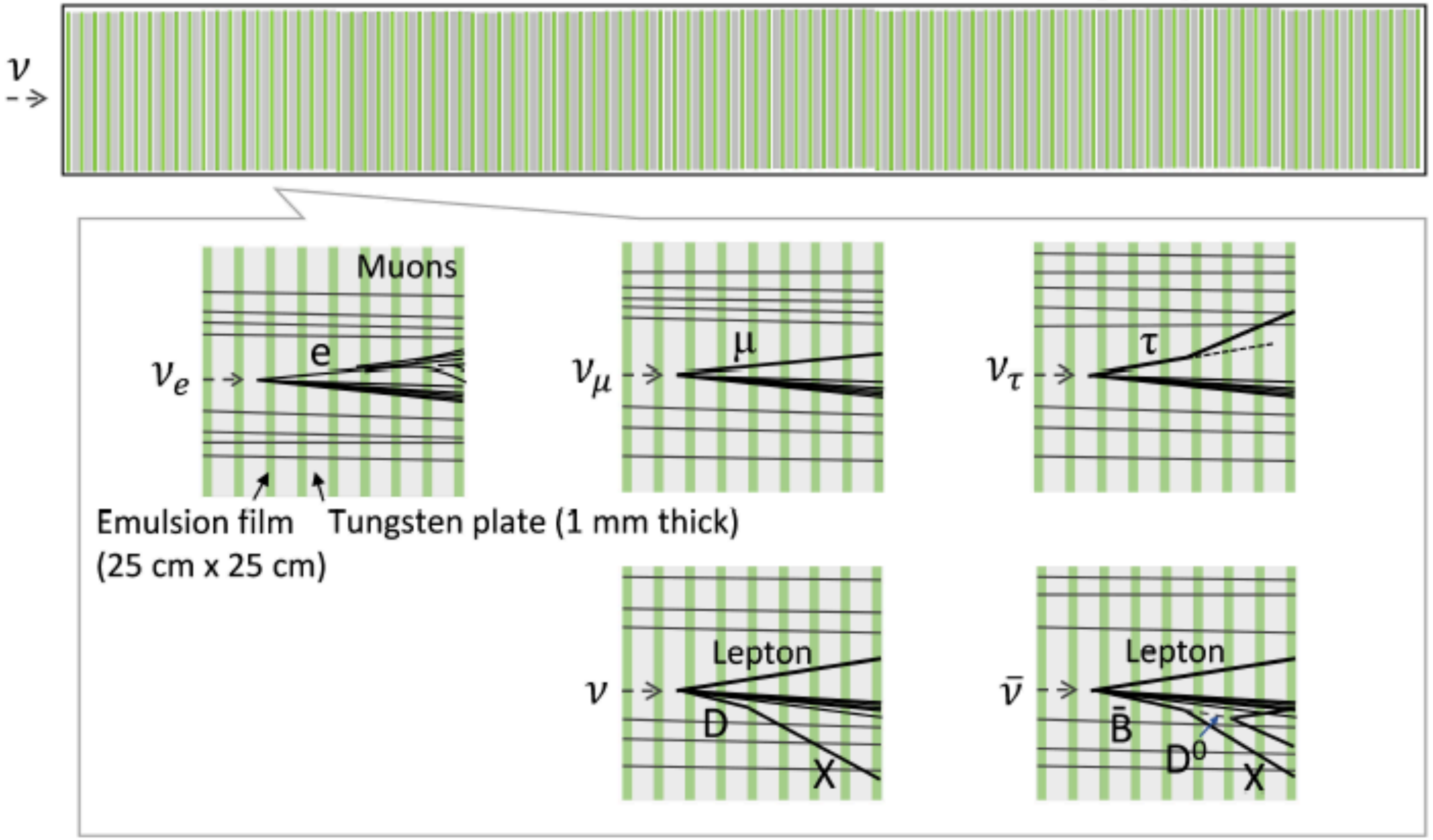


FASER collaboration,
arXiv:1908.0231

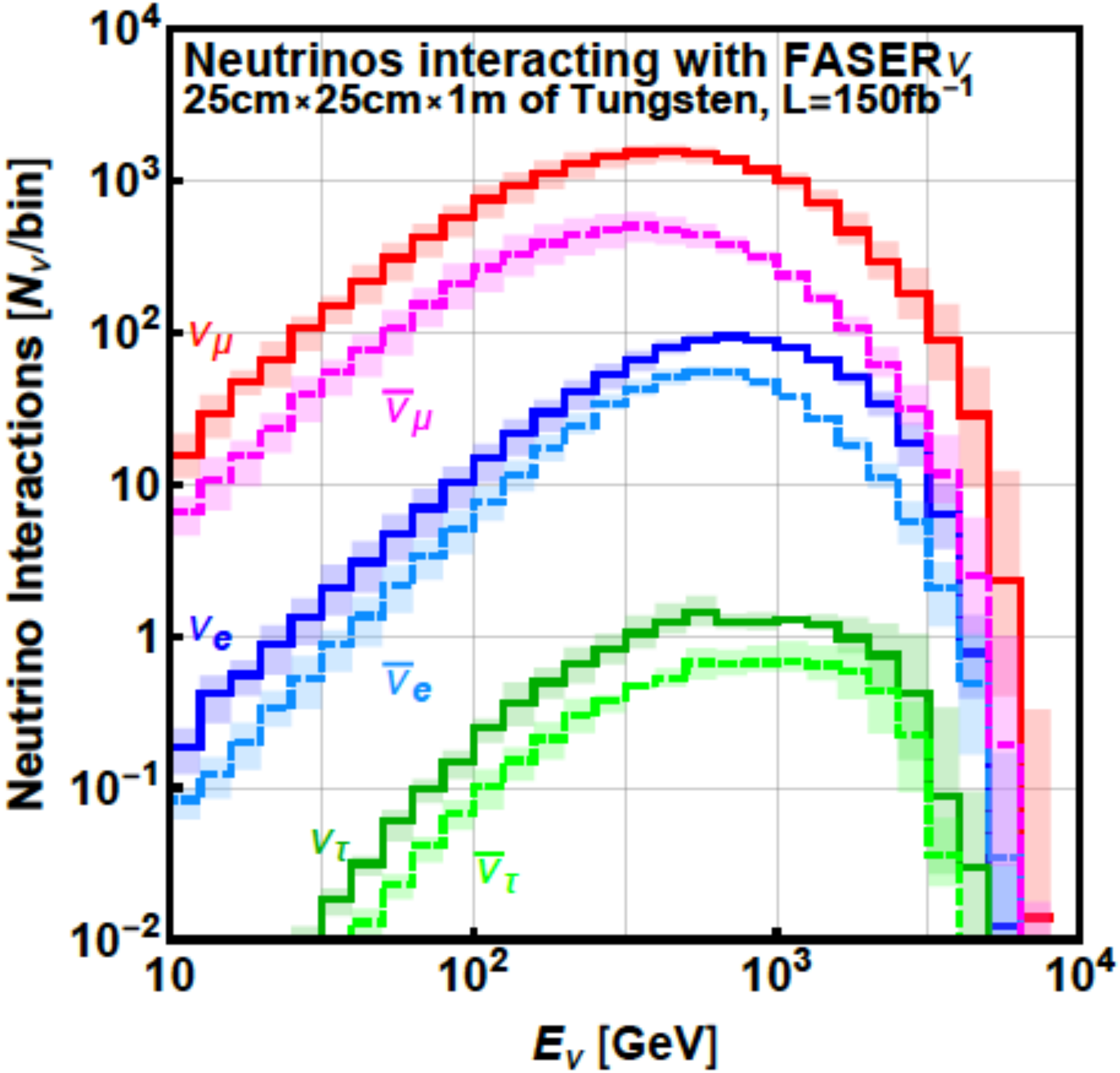
$Br(K^+ \to \mu^+ \nu_\mu) = 63\%$

$Br(K^+ \to \pi^0 e^+ \nu_e) = 5\%$

Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates



FASER collaboration, arXiv:1908.0231



FASER collaboration, arXiv:1908.0231

25 cm × 25 cm × 1.35 m emulsion detector

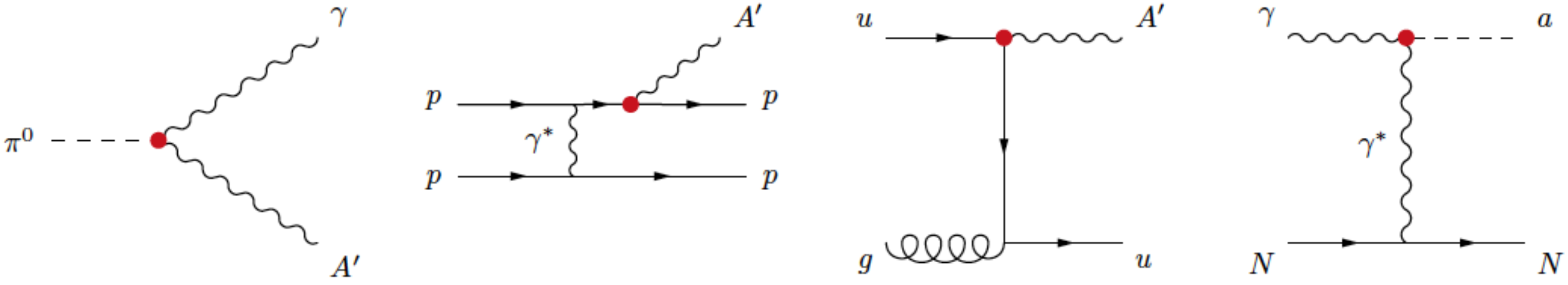
tungsten target mass of 1.2 tons.

1300 ν_e, 20,000 ν_μ, and 20 ν_τ

New physics in FASER

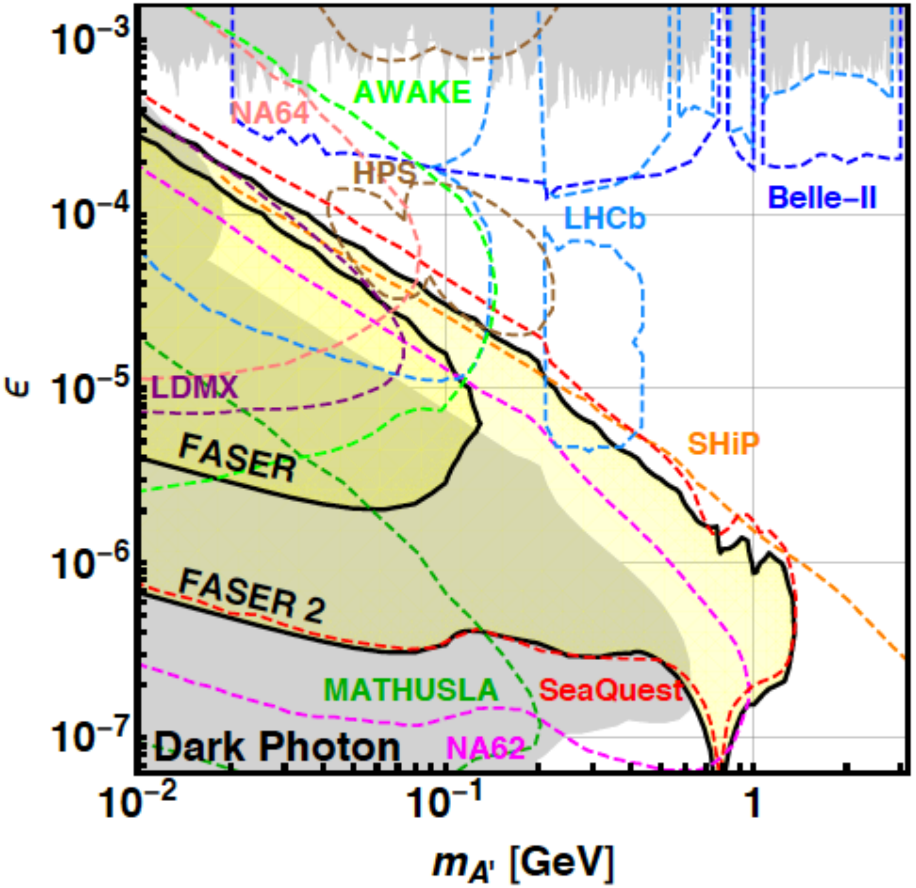
- FASER Collaboration, Phys. Rev. D 99 (2019) no.9, 095011;
- J. Alimena et al., arXiv:1903.04497;
- J. L. Feng et al, Phys. Rev. D 97 (2018) no.5, 055034;
- N. Okada and D. Raut, arXiv:1910.09663;
- I. Boiarska et al, arXiv:1908.04635;
- F. Kling and S. Trojanowski, Phys. Rev. D 97 (2018) no.9, 095016;
- J. C. Helo, M. Hirsch and Z. S. Wang, JHEP 1807 (2018) 056;
- F. Deppisch, S. Kulkarni and W. Liu, Phys. Rev. D 100 (2019) 035005;
- J. L. Feng et al, Phys. Rev. D 98 (2018) no.5, 055021;
- R. N. Mohapatra and N. Okada, arXiv:1908.11325;
- A. Berlin and F. Kling, Phys. Rev. D 99 (2019) no.1, 015021;
- K. Jodowski, F. Kling, L. Roszkowski and S. Trojanowski, arXiv:1911.11346;
- D. Dercks, J. De Vries, H. K. Dreiner and Z. S. Wang, Phys. Rev. D 99 (2019) no.5, 055039.

- FASER Collaboration, “FASER's Physics Reach for Long-Lived Particles, ” Phys. Rev. D 99 (2019) no.9, 095011;



- FASER Collaboration, "FASER's Physics Reach for Long-Lived Particles, " Phys. Rev. D 99 (2019) no.9, 095011;

$$\frac{1}{2}m_X^2 X^\mu X_\mu - g_X j_\mu^X X^\mu - \frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} X^{\mu\nu}$$



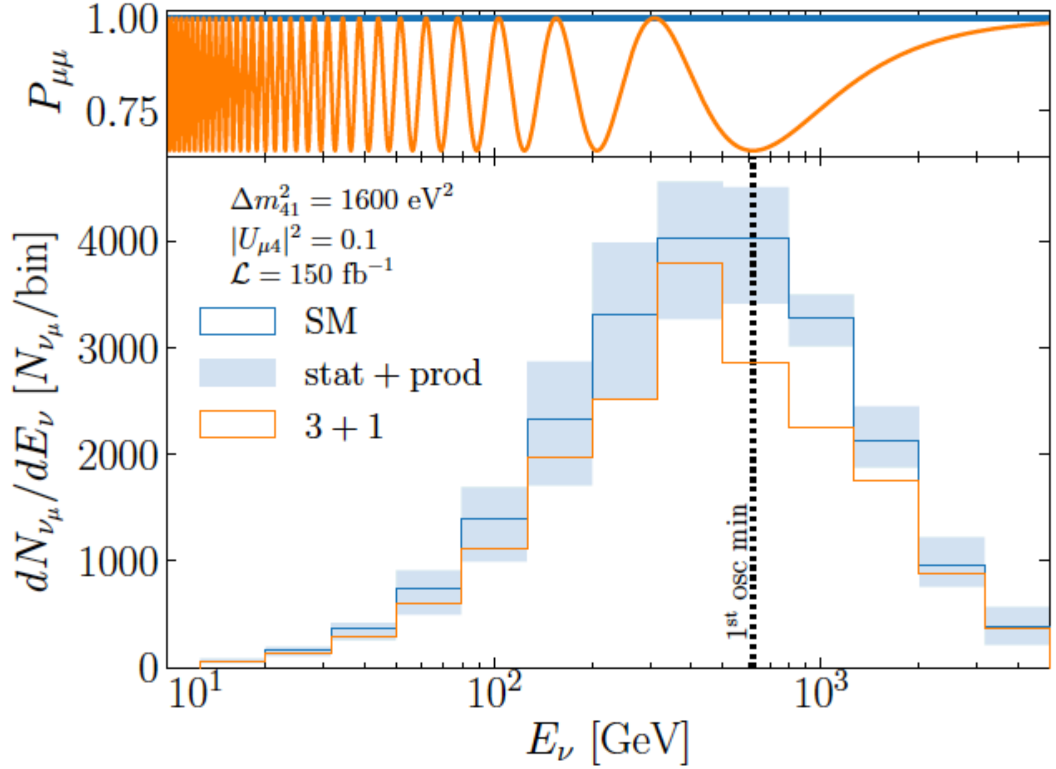
Testing 3+1 model at FASERν

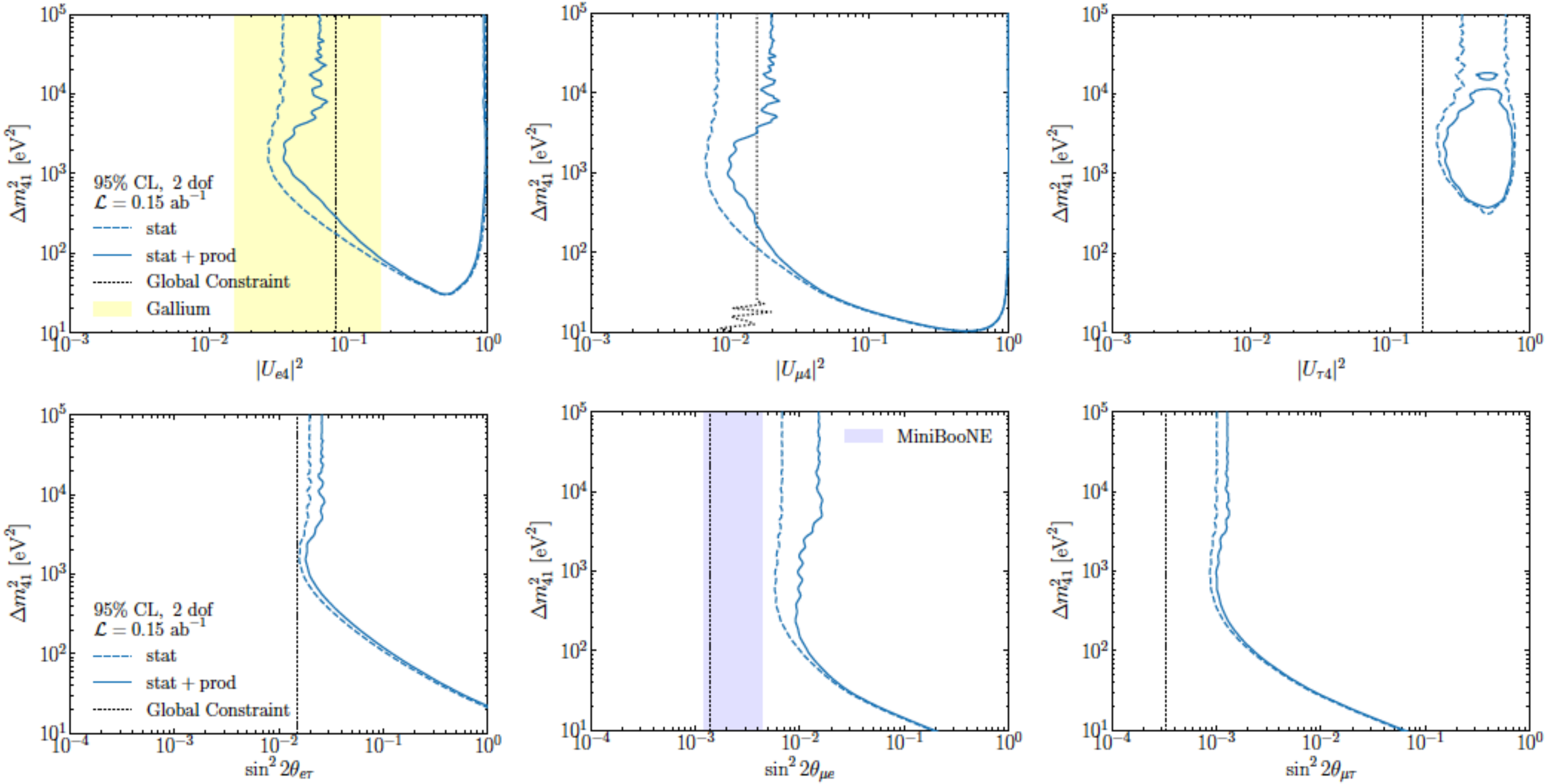
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\frac{\Delta m_{41}^2 L}{4E}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{\alpha\beta}\sin^2\frac{\Delta m_{41}^2 L}{4E}\ .$$

FASER collaboration, arXiv:1908.0231

$$m_{\nu_4} = 40\ eV$$




10^5
10^4
10^3
10^2
10^1
Δm^2_{41} [eV^2]
95% CL, 2 dof
$\mathcal{L} = 0.15$ ab^{-1}
stat
stat + prod
Global Constraint
Gallium
10^{-3}
10^{-2}
10^{-1}
10^0
$|U_{e4}|^2$
$|U_{\mu 4}|^2$
$|U_{\tau 4}|^2$
10^{-4}
$\sin^2 2\theta_{e\tau}$
MiniBooNE
$\sin^2 2\theta_{\mu e}$
$\sin^2 2\theta_{\mu\tau}$

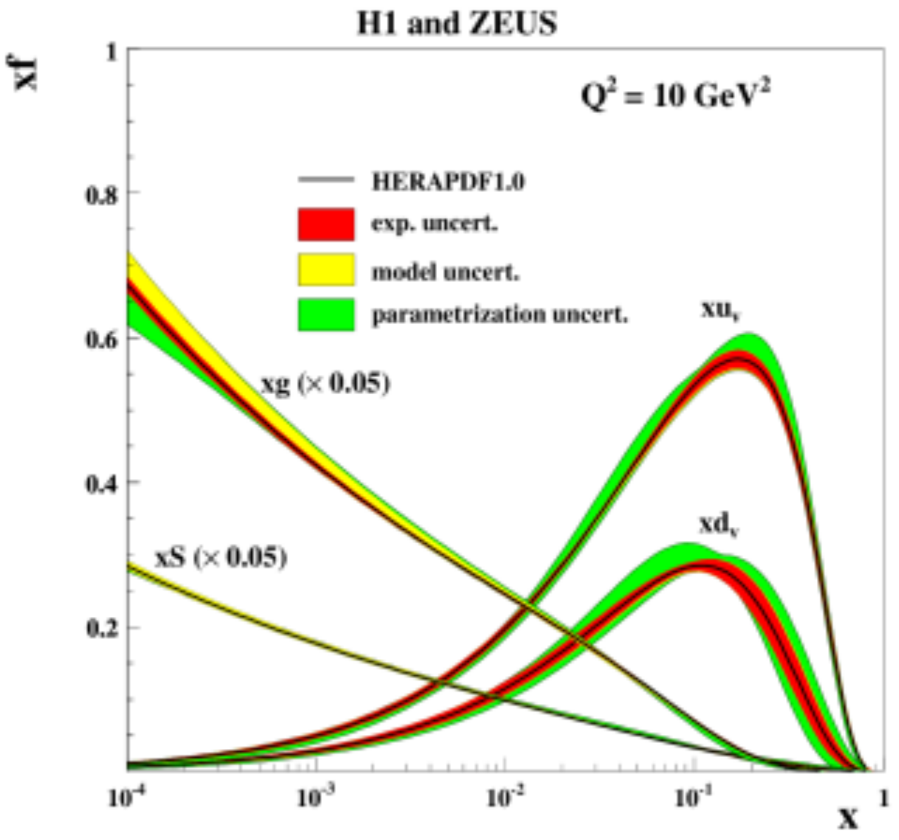
New physics with FASERν

- M. Bahraminasr, P Bakhti and M Rajaee, “Sensitivities to secret neutrino interaction at FASERv,” arXiv:2003.09985;

- Felix Kling, “Probing Light Gauge Bosons in Tau Neutrino Experiments,” arXiv: 2005.03594.

- P. Bakhti, YF, S. Pascoli, “Unravelling the richness of dark sector by FASERν,” arXiv: 2006.05437

Parton Distribution Function (PDF)



Two partons colliding

$$\boxed{p_1 = p(x_1, 0, 0, x_1) \qquad \text{and} \qquad p_2 = p(x_2, 0, 0, -x_2)}$$

$$\boxed{s = 4x_1 x_2 p^2}$$

$$\boxed{p = 7\ \mathrm{TeV}}$$

$$\boxed{x_1 \sim 0.1,\ \ x_2 \sim 10^{-7}} \quad \Longrightarrow \quad \boxed{s \sim \mathrm{GeV}^2}$$

Kinematics tells us that particles lighter than GeV can be produced and emitted in the forward direction.

Need for intermediate particles

- At the Interaction Point (IP)

$$\boxed{\mathrm{Proton} + \mathrm{Proton} \rightarrow X' + \ldots}$$

- X’ should not have too small coupling to SM particles to be abundantly produced at IP.

$$\boxed{X' \rightarrow X\bar{X}}$$

- X should be feebly interacting so that survive up to FASERν .

Signature of X particles at FASERν .

$$X \rightarrow f + \bar{f}$$

Standard model fermions

$$X \rightarrow f + \bar{f} + Y$$

Missing energy-momentum; dark matter?

Decay length 1 mm-10 cm

$$X \rightarrow \eta + \bar{\eta} \quad \eta \rightarrow f\bar{f} \quad \bar{\eta} \rightarrow f\bar{f}$$

$$X \rightarrow \eta + \bar{\eta} + Y \quad \eta \rightarrow f\bar{f} \quad \bar{\eta} \rightarrow f\bar{f}$$

Dark matter

What is dark matter made of?

WIMP paradigm in its heyday

- WIMP=Weakly Interacting Massive Particle

Freeze-out scenario of dark matter

$$\downarrow$$

$$\left.\begin{array}{r} \langle v_{DM}\sigma(DM+DM)\rangle = 1 \text{ pb} \\ \langle v_{DM}\sigma(DM+DM)\rangle \sim \dfrac{g^4}{4\pi M^2} \\ g \sim e\sin\theta_W \end{array}\right\} \Rightarrow \boxed{M \sim \text{few} \times 100 \text{ GeV}}$$

Hopes for WIMP discovery

- LHC: p+p → DM+monophoton or DM+monojet

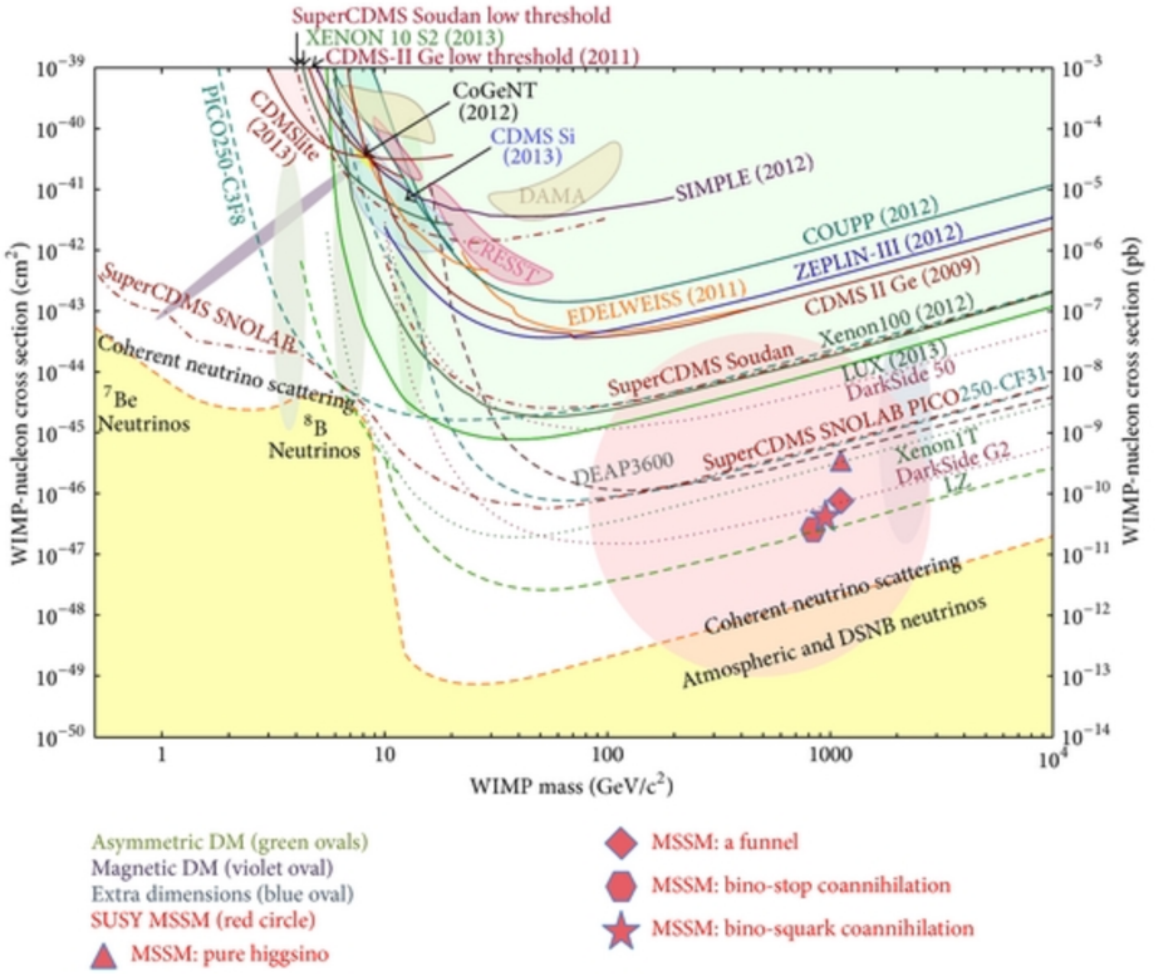
- Direct DM searches: DM+nucleus → DM+ recoiled nucleus

- Indirect DM searches: DM+DM → SM particles

In regions that DM density is higher than the average: Galaxy center, DM halo, Earth or sun center

High hopes for DM detection

Null results so far

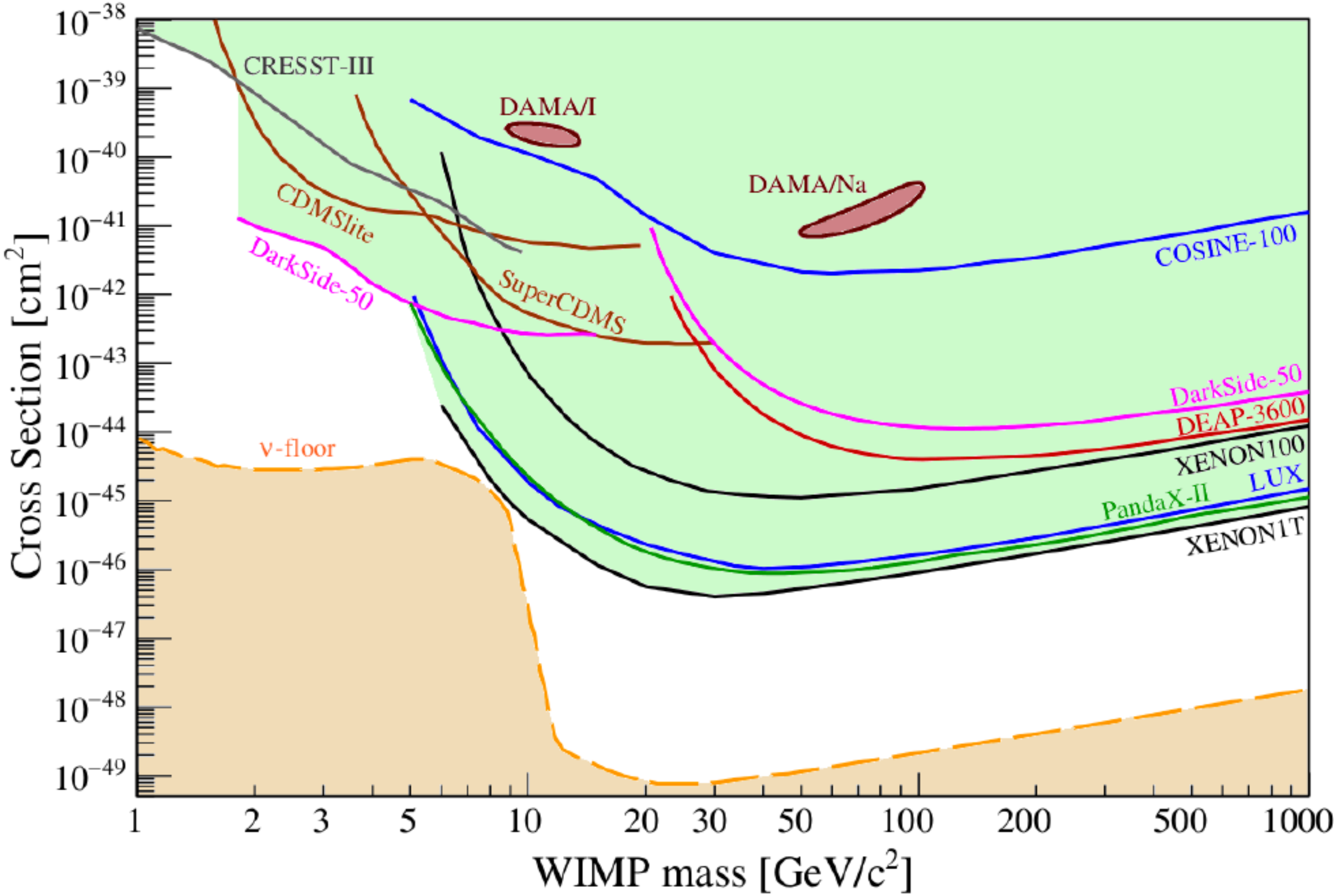


http://newscenter.lbl.gov

In 2013, WIMP was still young.

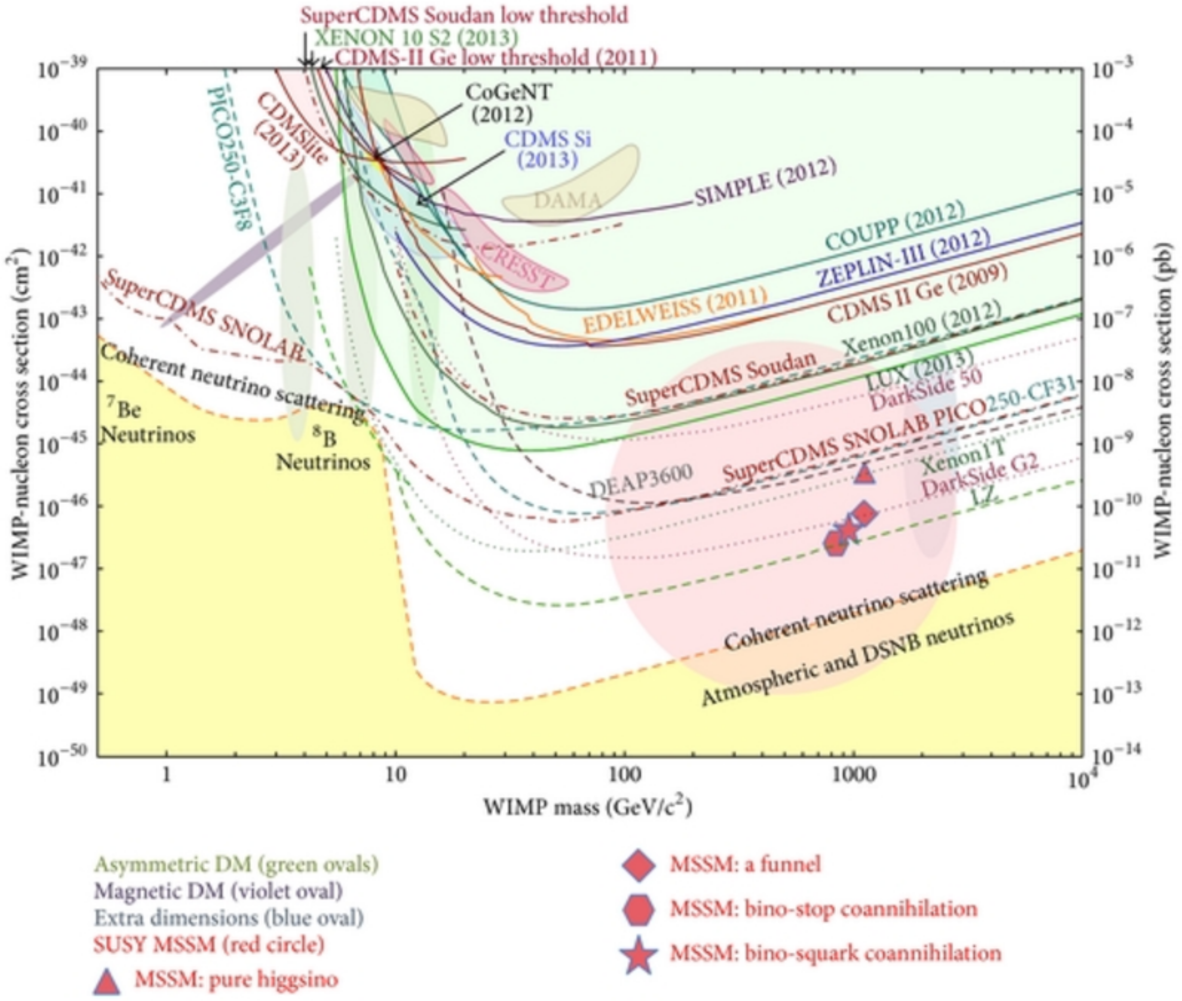
Italian: WIMP era ancora giovane

Iranian: Javan



E. Aprile et al. (XENON1T), Phys. Rev. Lett. 121 (2018) 111302.

Marc Schumann, "Direct Detection of WIMP Dark Matter: Concepts and Status" *J.Phys.G* 46 (2019) 10, 103003



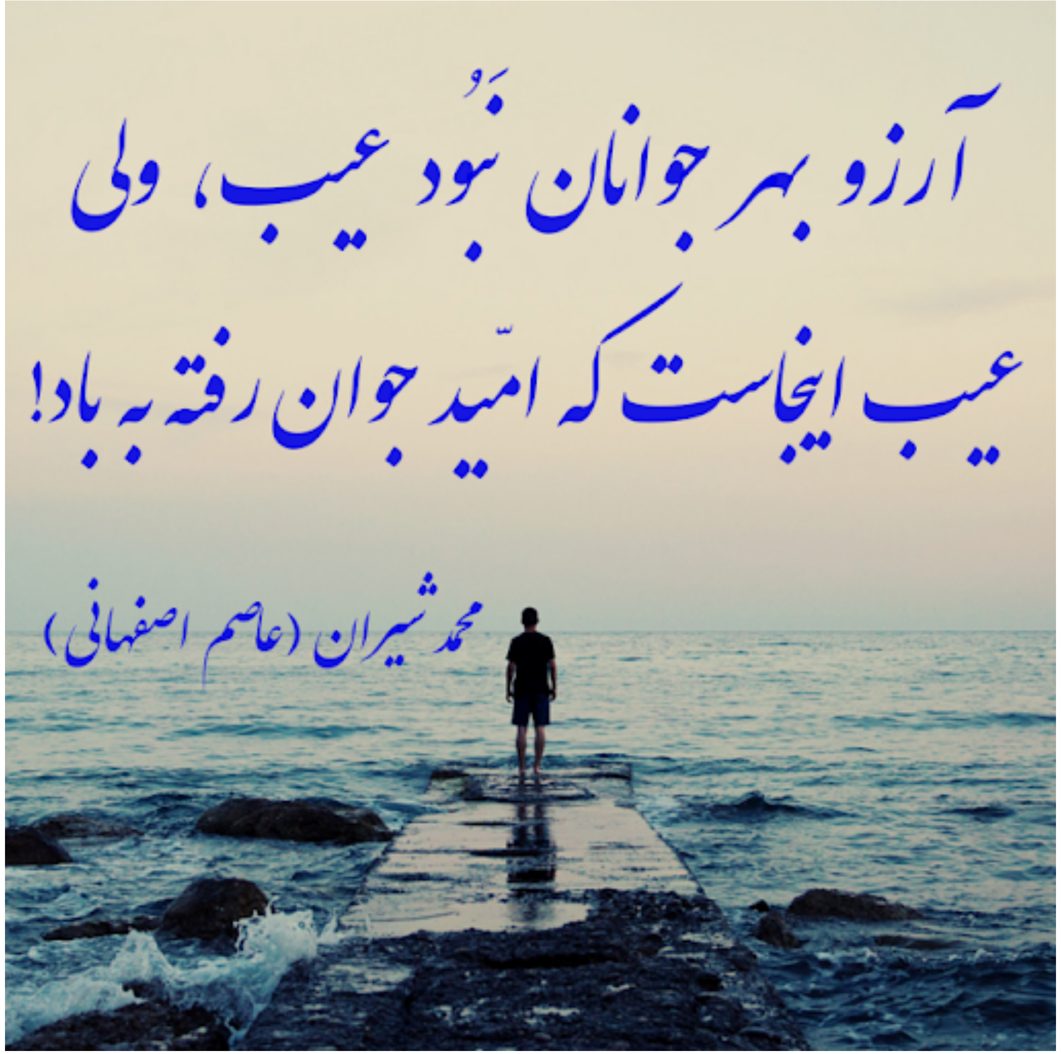
http://newscenter.lbl.gov

In 2013, WIMP was still young.

Italian:WIMP era ancora giovane

Iranian: Javan

Iranian saying



آرزو بهر جوانان نَبُود عیب، ولی
عیب اینجاست که امّید جوان رفته به باد!

محمد شیران (عاصم اصفهانی)

High hopes for DM detection

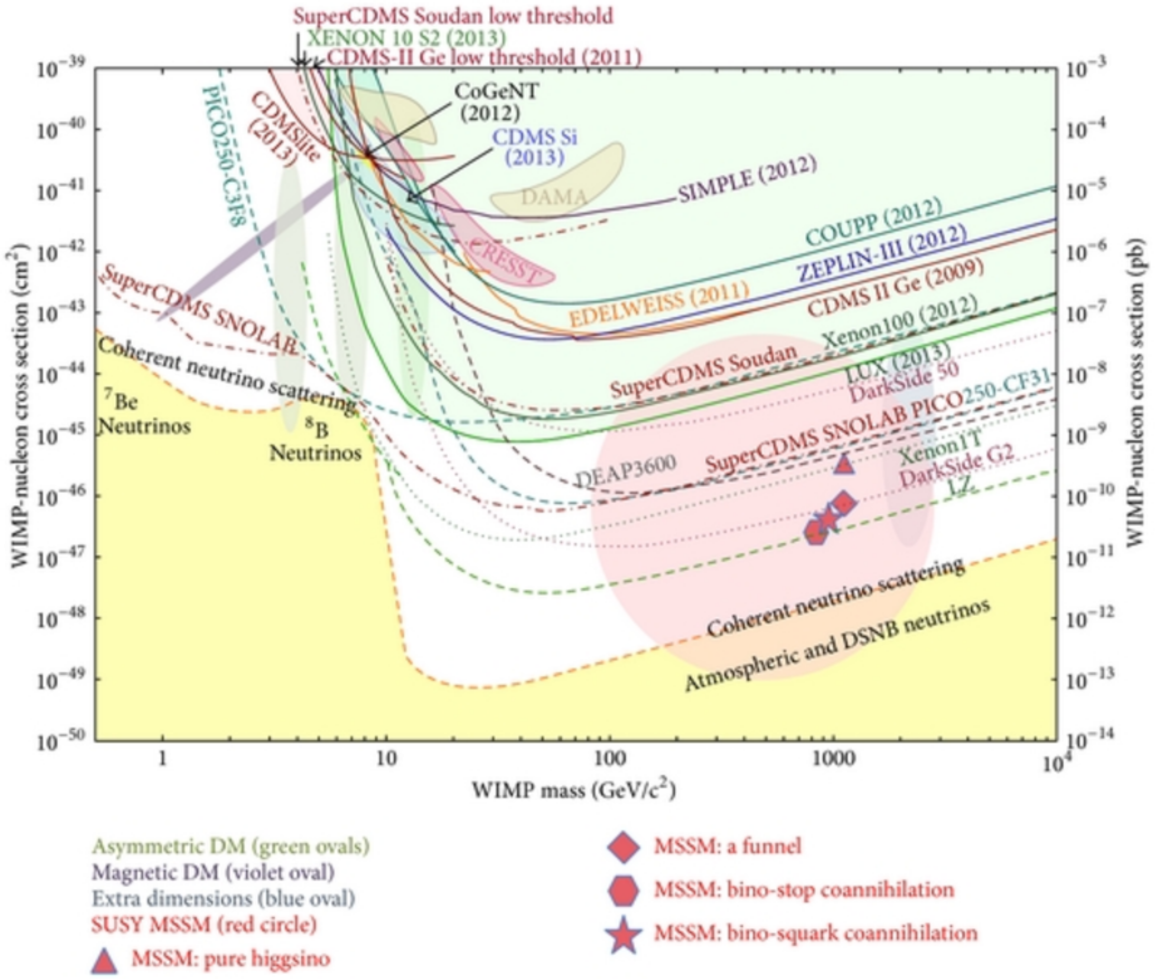
Hope for WIMP is not given up.

But the Hegemony of WIMP as THEE DM candidate is broken

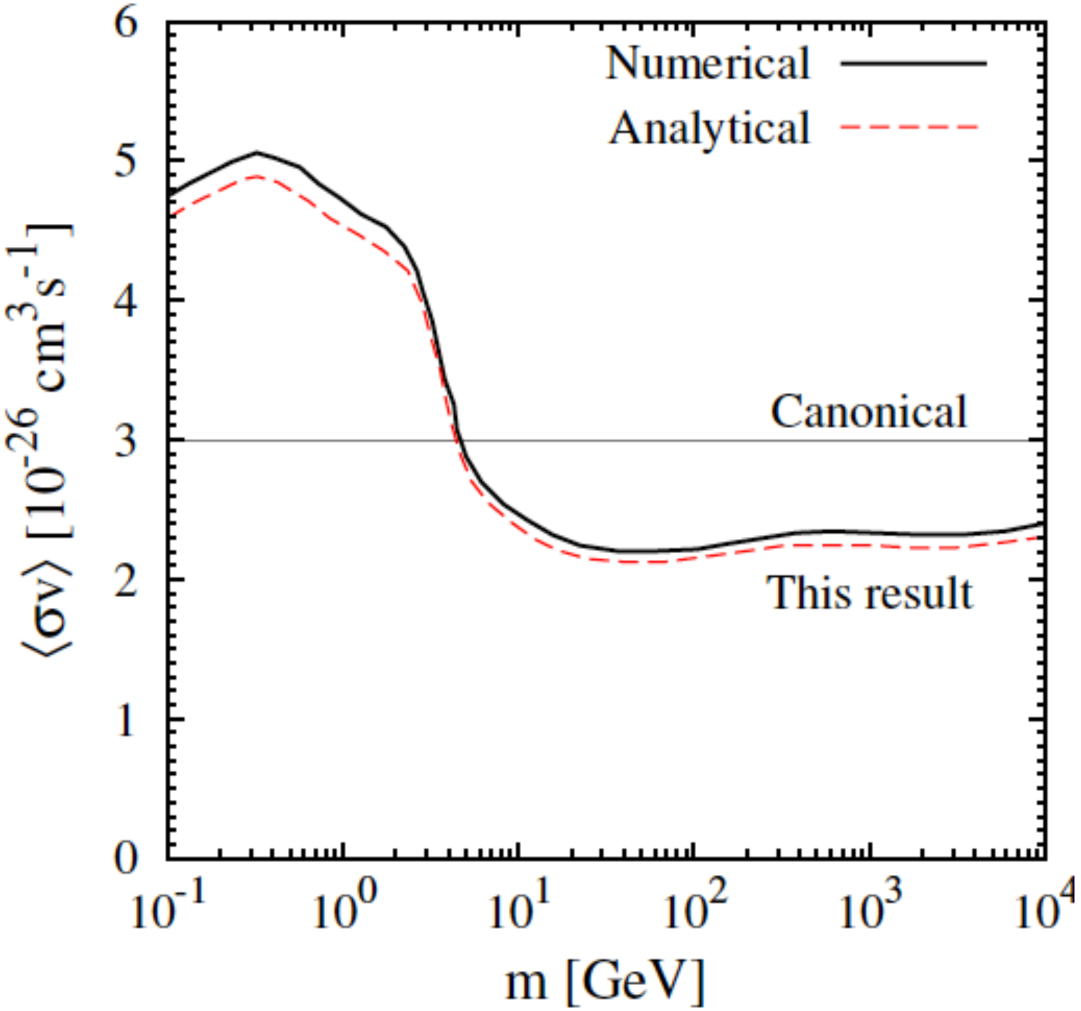
Time to leave the comfort zone

- Comfort zone: 100 GeV-1 TeV
- Whole range: $M > 10^{-21} eV$

GeV scale DM


SuperCDMS Soudan low threshold
XENON 10 S2 (2013)
CDMS-II Ge low threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
SuperCDMS SNOLAB
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
Coherent neutrino scattering
^{7}Be Neutrinos
^{8}B Neutrinos
Coherent neutrino scattering
Atmospheric and DSNB neutrinos
WIMP-nucleon cross section (cm^2)
WIMP-nucleon cross section (pb)
WIMP mass (GeV/c^2)
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
Asymmetric DM (green ovals)
Magnetic DM (violet oval)
Extra dimensions (blue oval)
SUSY MSSM (red circle)
MSSM: pure higgsino
MSSM: a funnel
MSSM: bino-stop coannihilation
MSSM: bino-squark coannihilation

More precise evaluation of annihilation from DM abundance



Freeze-out scenario

$$\boxed{\sigma \sim 1 \; pb}$$

Steigman, Dasgupta and Beacom, *Phys.Rev.D* 86 (2012) 023506

Light dark matter annihilation rate

$$\boxed{\sigma \sim \frac{g^4}{4\pi M^4} m_{DM}^2}$$

M= Mass of the mediator

$$\boxed{m_{DM} \sim \mathrm{GeV}}$$

If annihilation is to SM particles: electron, muon, u, d, s, gluons or photons

$$M/g > \mathrm{TeV} \quad \Longrightarrow \quad \sigma \ll pb$$

B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39 (1977) 165.

One exception: SLIM model

- New fields:
- Majorana Right-handed neutrino
- SLIM=Scalar as LIght as MeV

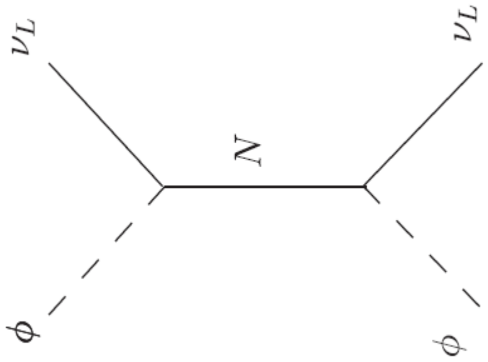
Boehm, Y. F., T. Hambye, S. Palomares-Ruiz and S. Pascoli, PRD 77 (2008) 43516;

- Effective Lagrangian: $\mathcal{L}_I \supset g\phi\bar{N}\nu$

- New parameters:

$$g \quad m_\phi \quad m_N$$

Annihilation cross-section



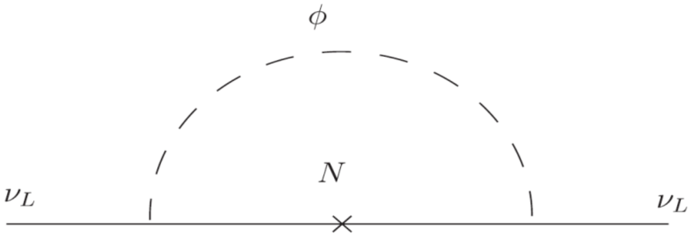
$$\langle\sigma(\phi\phi\rightarrow\nu\nu)\mathrm{v}_r\rangle=\langle\sigma(\phi\phi\rightarrow\bar{\nu}\,\bar{\nu})\mathrm{v}_r\rangle$$

$$\simeq\frac{g^4}{4\pi}\frac{m_N^2}{(m_\phi^2+m_N^2)^2},$$

$$g\simeq10^{-3}\sqrt{\frac{m_N}{10\ \mathrm{MeV}}}\left(\frac{\langle\sigma\nu_r\rangle}{10^{-26}\ \mathrm{cm}^3/\,\mathrm{s}}\right)^{1/4}\left(1+\frac{m_\phi^2}{m_N^2}\right)^{1/2}$$

neutrino masses

- In this scenario, SLIM does not develop any VEV so the tree level neutrino mass is zero.
- Radiative mass in case of real SLIM scalar:



Ultraviolet cutoff Λ

$$m_\nu = \frac{g^2}{16\pi^2} m_N \left[\ln\left(\frac{\Lambda^2}{m_N^2}\right) - \frac{m_\phi^2}{m_N^2 - m_\phi^2} \ln\left(\frac{m_N^2}{m_\phi^2}\right) \right]$$

Bounds on SLIM mass

$$m_\phi < M_N$$

$$O(1)\ \mathrm{MeV} \lesssim m_N \lesssim 10\ \mathrm{MeV}.$$

GeV scale Dark matter

$$DM + DM \to \eta + \bar{\eta}$$

Beyond SM

$$\boxed{\sigma \sim \frac{g^4}{4\pi M^4} m_{DM}^2}$$

$$\boxed{m_{DM} \sim \text{GeV}}$$

$$\boxed{M/g \sim 100 \text{ GeV}}$$

$$\Longrightarrow \quad \boxed{\sigma \sim 1\ pb}$$

GeV scale Dark matter

$$DM + DM \to \eta + \bar{\eta}$$

Beyond SM

$$\boxed{m_{DM} \sim \text{GeV}}$$

$$\boxed{m_\eta < m_{DM}}$$

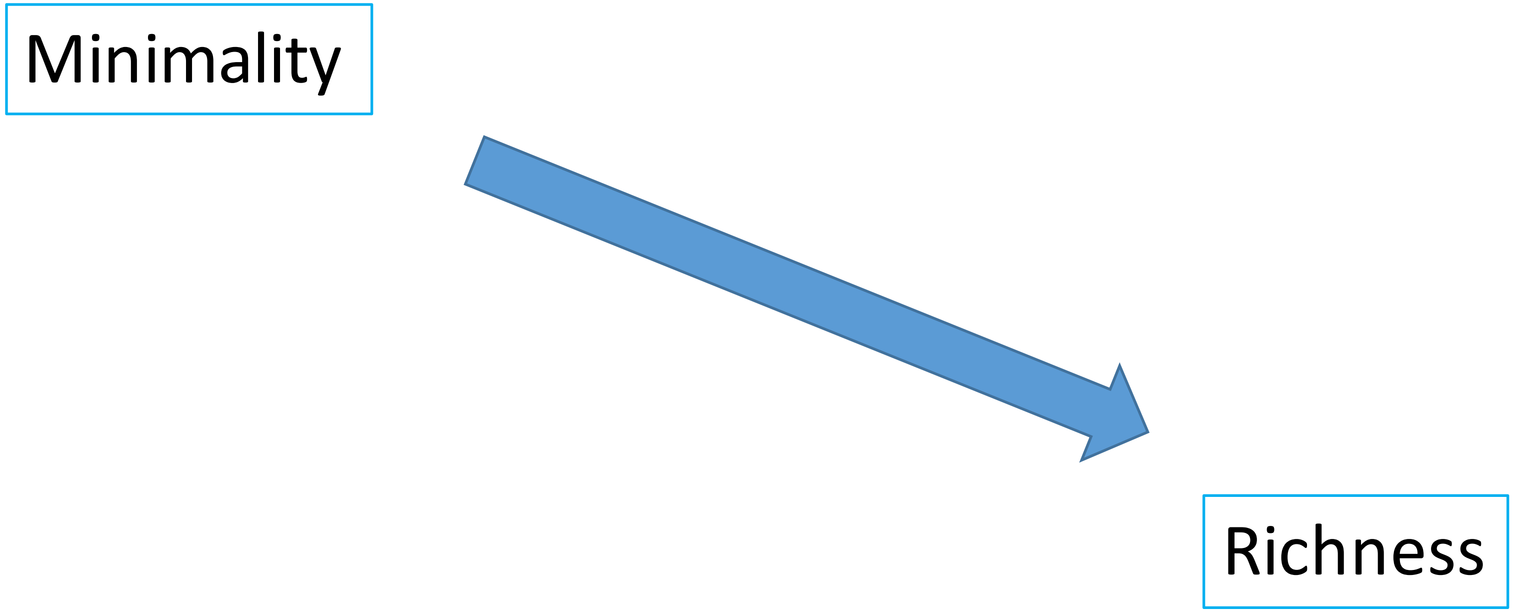
$$\eta \to f\bar{f}$$

SM fermion

$$\left.\begin{array}{l} m_\eta > 10 \text{ MeV} \\ \tau_\eta < 1 \text{ sec} \end{array}\right\} \Rightarrow$$

No trouble for BBN

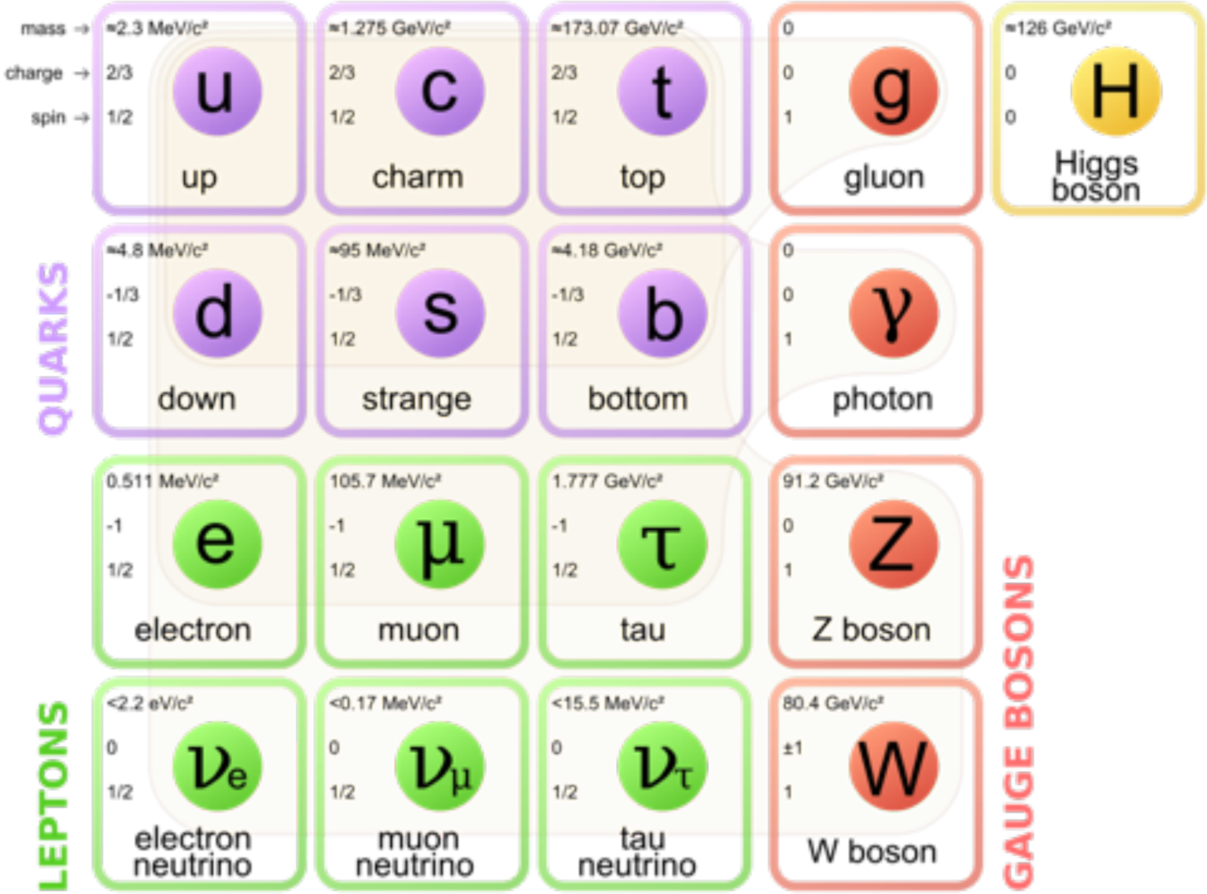
Shift of paradigm in DM model building



Minimality

Richness

Inspired by 5% of matter (ordinary matter)



Richness of SM makes life dazzling

Scenery from Iran

- Why should DM to be minimal?

- It would be boring if it is so.

- More exciting possibilities: Multicomponent DM, SIDM,….

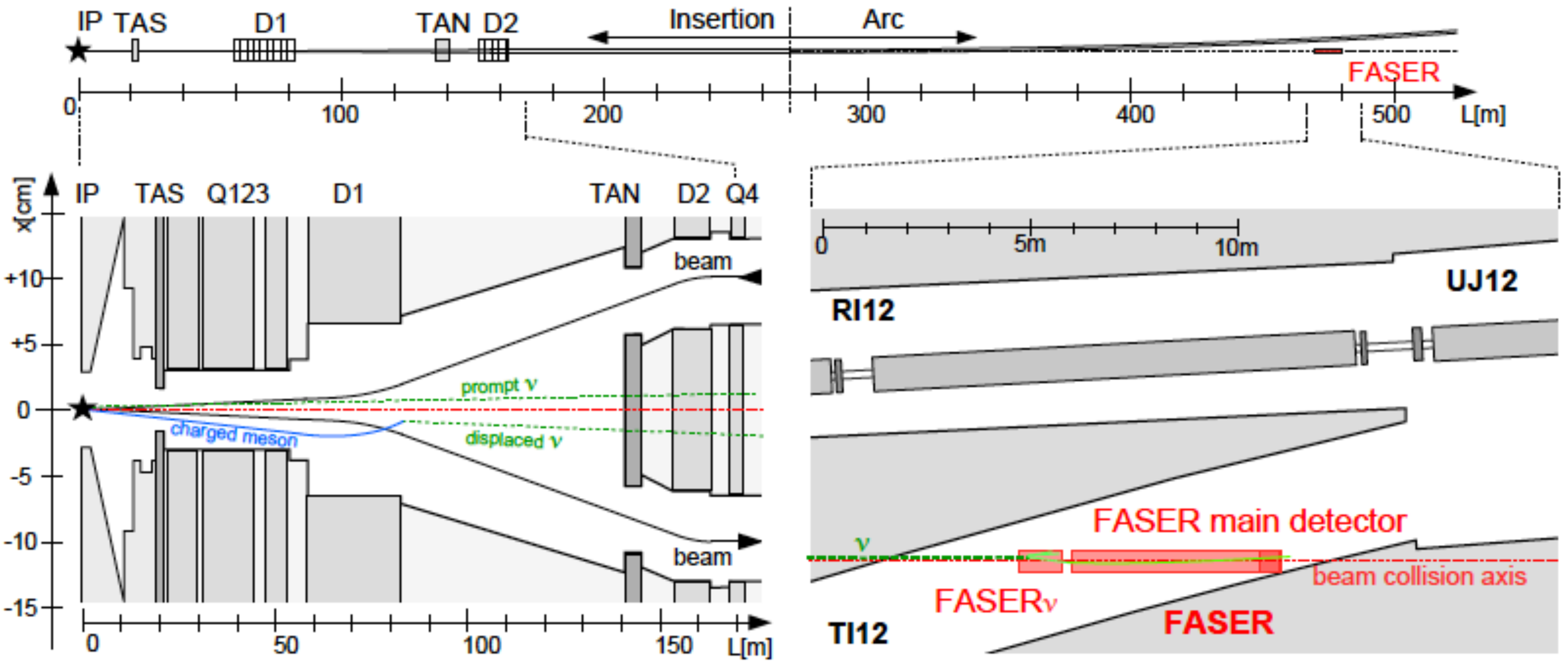
Can we uncover the richness of dark sector?

- We should not overlook any possibility to do so.

- FASERν: Superb position and spatial resolution

Reconstructing invisible tracks of neutral particles decaying to charged leptons

- The point of our paper: FASERν can be a useful tool.



FASER collaboration, arXiv:1908.0231

10 m of concrete and 90 m of rock

Toy model

- Intermediate X’ is produced at IP.
- Before reading detector, $\boxed{X' \rightarrow X\bar{X}}$
- X decays at FASERν to the SM charged leptons:

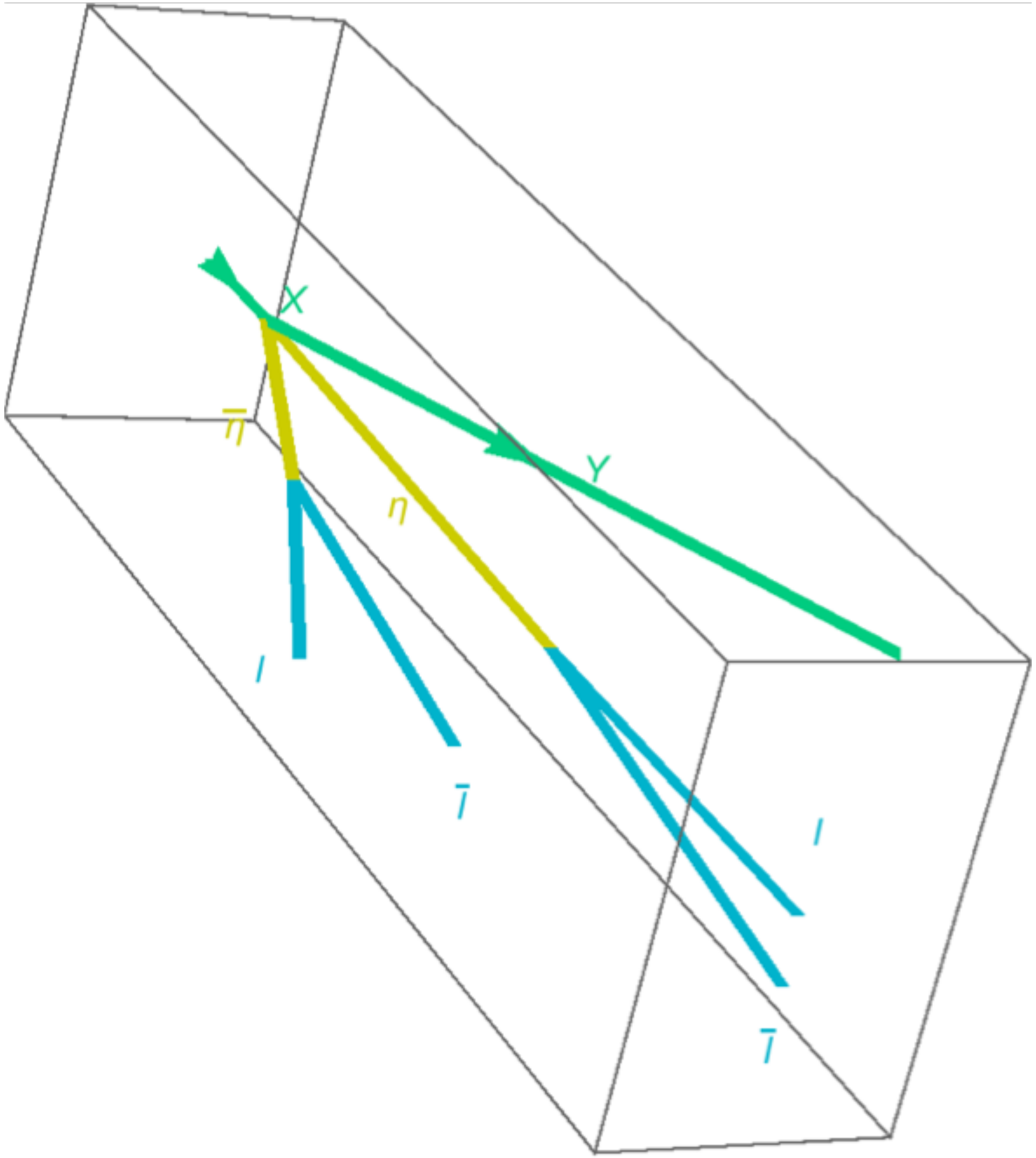
A generic scenario

$$X \rightarrow \eta\bar{\eta}Y$$

Missing energy and momentum

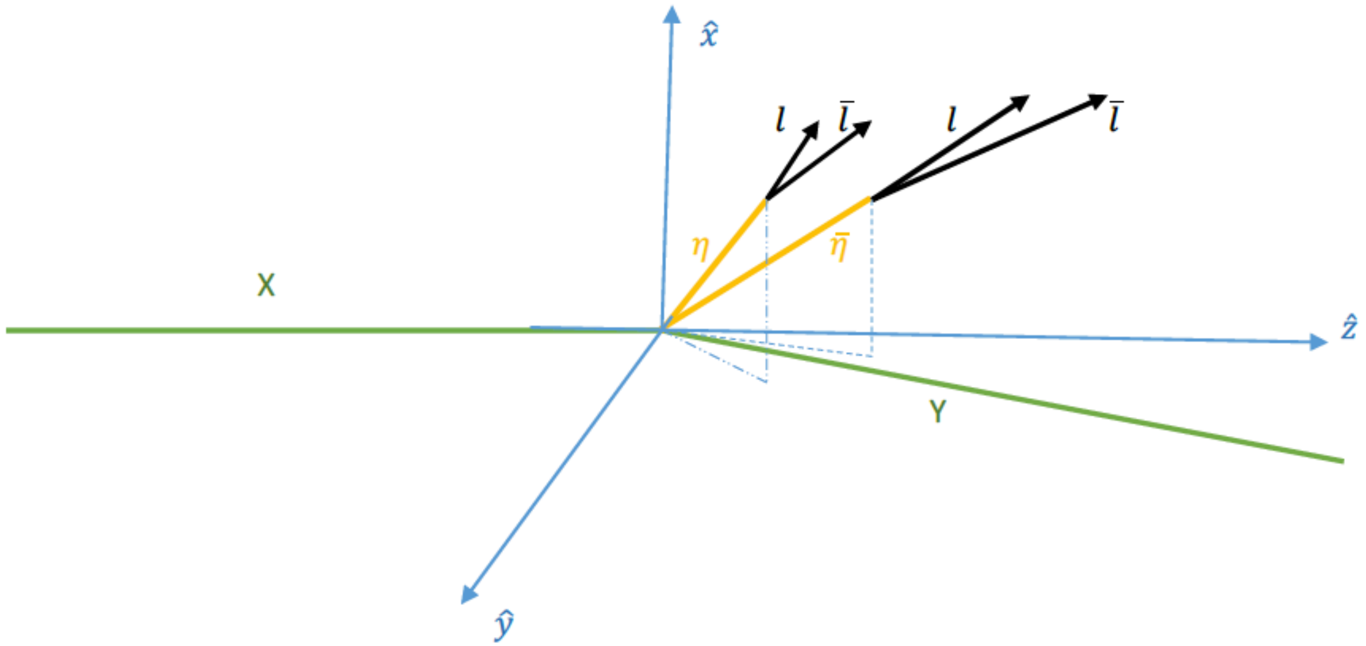
- η and $\bar{\eta}$ decay after 1mm-10cm: $\boxed{\eta \rightarrow l\bar{l}}$ $\boxed{\bar{\eta} \rightarrow l\bar{l}}$

Specific model
Demonstrating ability
Of FASERν


X
η̄
Y
η
l
l̄
l
l̄

Signature at FASERν

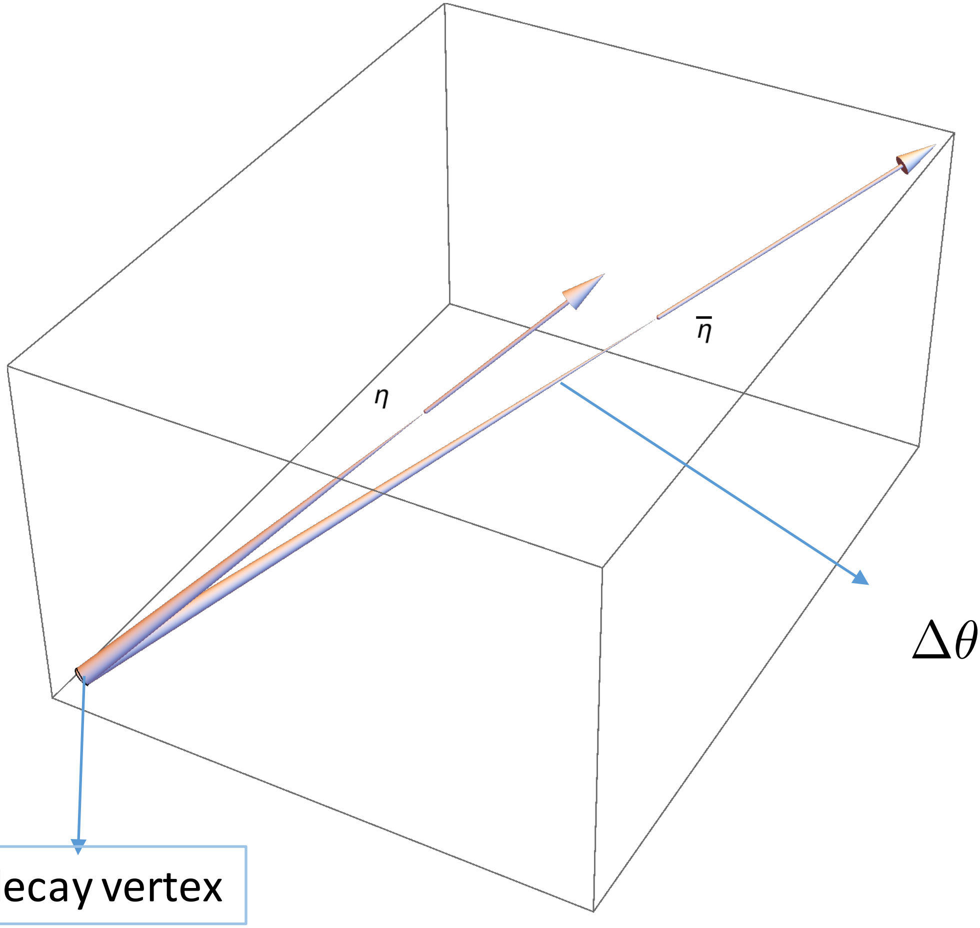
- Two pairs charged leptons plus missing energy



Energy momentum of leptons can be measured

⇓

The energy momentum of $\bar{\eta}$ and η



$\Delta\theta_\eta$

X decay vertex

Need for intermediate particles

- At the Interaction Point (IP)

$$\text{Proton} + \text{Proton} \to X' + ...$$

- X’ should not have too small coupling to SM particles to be abundantly produced at IP.

$$X' \to X\bar{X}$$

Possibilities for X’

1) Z’ boson of $B - a_e L_e - a_\mu L_\mu - a_\tau L_\tau$ (with $a_e + a_\mu + a_\tau = -3$) or kinetically mixed $\epsilon Z'_{\mu\nu} B^{\mu\nu}$
2) Scalar ϕ coupled to quarks: $\phi\bar{u}u,\ \phi\bar{d}d,\ \phi\bar{s}s$

Mixed with SM Higgs or Mixed with new inert Higgs

Small mixing to first generation

Production from Heavy meson decay at IP

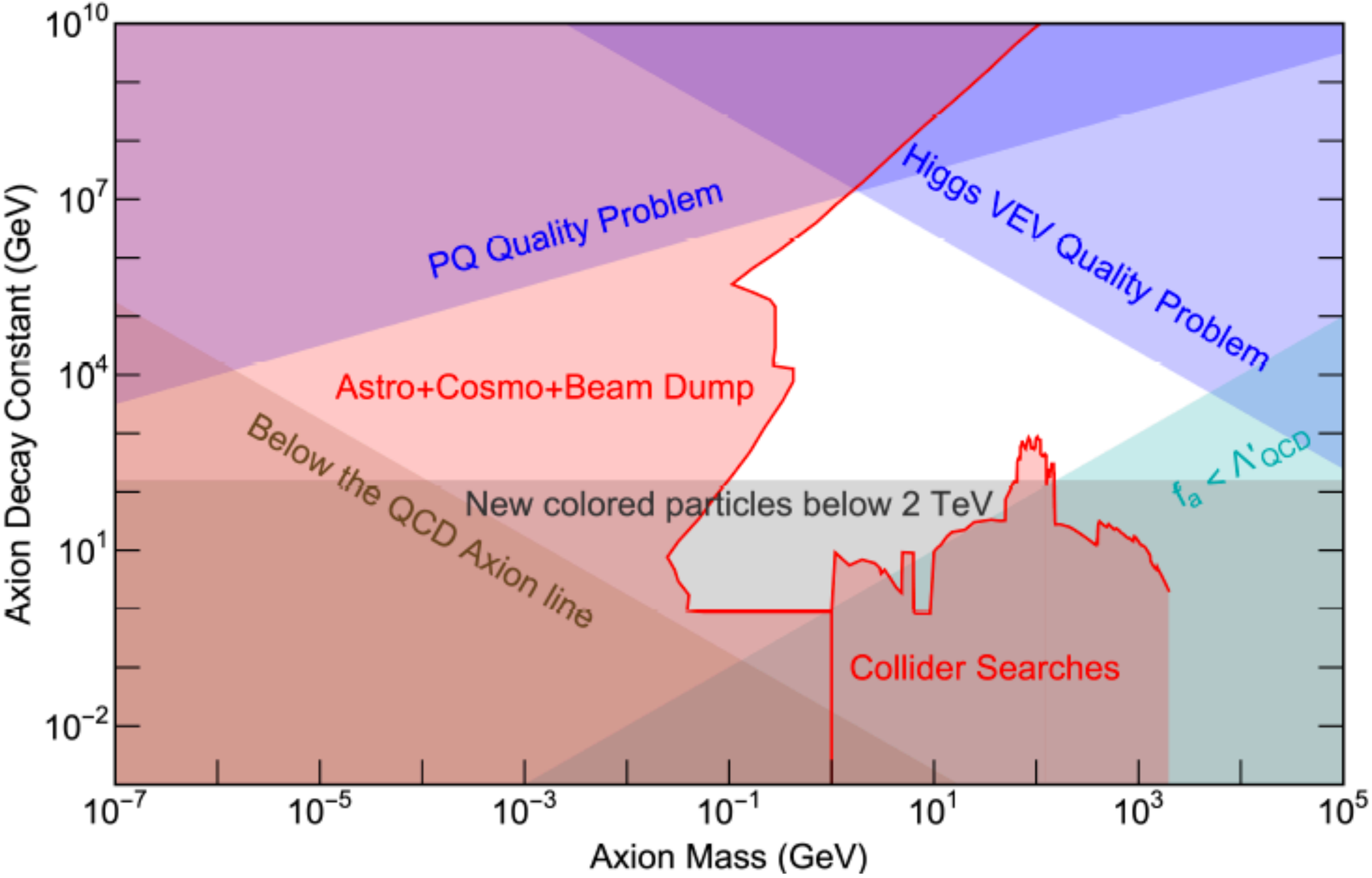
arbitrary coupling to first generation

Direct production from parton interaction at IP

Possibilities for X’

1) Z’ boson of $B - a_e L_e - a_\mu L_\mu - a_\tau L_\tau$ (with $a_e + a_\mu + a_\tau = -3$) or kinetically mixed $\epsilon Z'_{\mu\nu} B^{\mu\nu}$
2) Scalar ϕ coupled to quarks: $\phi \bar{u} u, \ \phi \bar{d} d, \ \phi \bar{s} s$
3) Pseudoscalar axion: $$\frac{X' G^i_{\mu\nu} G^i_{\alpha\beta} \epsilon^{\mu\nu\alpha\beta}}{\Lambda},$$

solving the QCD θ-term.



$$\Lambda = 8\pi f_a/\alpha_{QCD}$$

Hook, Kumar, Liu and Sundrum, “The high quality QCD axion and the LHC,” PRL 124 (2020) 22, 221801

Fast decay of X’

- X’ with a mass larger than 3 pion mass decays fast to gluons
- We want it to decay faster to $X\bar{X}$

Scalar X: $\boxed{\lambda m_{X'} X'\bar{X}X}$

Fermion X: $\boxed{\lambda X'\bar{X}X.}$

$$\lambda > 10^{-6} \quad \Longrightarrow \quad Br(X' \to X\bar{X}) \gg Br(X' \to \text{hadrons})$$

X’ will decay after traveling less than one meter.

Production of X’

Interaction Point (IP): $g(p_1) + g(p_2) \rightarrow X'(p_1 + p_2)$

$$p_1 = p(x_1, 0, 0, x_1) \quad \text{and} \quad p_2 = p(x_2, 0, 0, -x_2)$$

$$m_{X'} = p\sqrt{4x_1x_2} \quad \text{where} \quad \frac{m_{X'}^2}{4p^2} < x_1, x_2 < 1.$$

$$\langle |M^2| \rangle = \frac{2p^4x_1^2x_2^2}{\Lambda^2}.$$

$$\frac{d\sigma_{tot}(E_{X'})}{dE_{X'}} = \frac{\pi}{32\Lambda^2}\frac{m_{X'}^2}{p^2}\frac{1}{P_{X'}}F_g(\frac{E_{X'} + P_{X'}}{2p})F_g(\frac{E_{X'} - P_{X'}}{2p})$$

Production of X’

$$\text{Interaction Point (IP): } g(p_1) + g(p_2) \to X'(p_1 + p_2)$$

$$p_1 = p(x_1, 0, 0, x_1) \quad \text{and} \quad p_2 = p(x_2, 0, 0, -x_2)$$

$$m_{X'} = p\sqrt{4x_1x_2} \quad \text{where} \quad \frac{m_{X'}^2}{4p^2} < x_1, x_2 < 1.$$

$$\frac{d\sigma_{tot}(E_{X'})}{dE_{X'}} = \frac{\pi}{32\Lambda^2}\frac{m_{X'}^2}{p^2}\frac{1}{P_{X'}}F_g(\frac{E_{X'} + P_{X'}}{2p})F_g(\frac{E_{X'} - P_{X'}}{2p})$$

Gluon PDFs at $Q^2 = m_{X'}^2$

Angular distribution of the emitted X’

$$\boxed{\text{Interaction Point (IP): } g(p_1)+g(p_2) \rightarrow X'(p_1+p_2)}$$

Transverse momentum ignored

$$p_t = 200 \text{ MeV}$$

$$\boxed{p_1 = p(x_1, 0, 0, x_1) \quad \text{and} \quad p_2 = p(x_2, 0, 0, -x_2)}$$

$$\boxed{\text{emission of } X' \text{ within a small solid angle of } \pi\theta_t^2 \text{ where } \theta_t = p_t/E_{X'}}$$

Transverse momentum of protons in a bunch<1 MeV<< 200 MeV

Is this the only production mode?

$$g + g \to X' + g \text{ or } g + q \to X' + q.$$

High transverse momentum for X’

Reaching ATLAS (and CMS) but not FASER

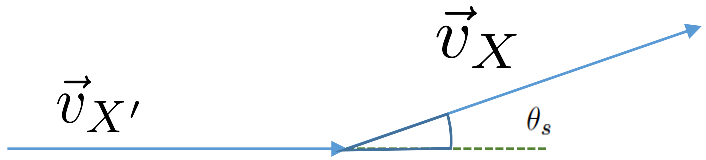
X particles directed towards FASER:

$$dN(E_X)/dE_X|_{2\to 2} < 20\% \text{ of } dN(E_X)/dE_X|_{2\to 1}$$

Angular spread of X

Momentum of X in the rest frame of X': $\boxed{k = (m_{X'}^2/4 - m_X^2)^{1/2}}$

X' velocity in the lab frame: $\boxed{v_{X'} = (1 - m_{X'}^2/E_{X'}^2)^{1/2}}$



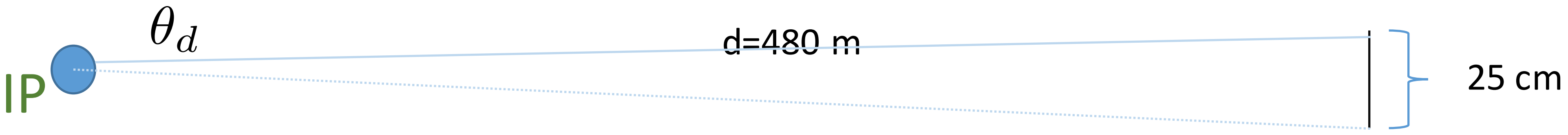
$$\theta_s = \arctan\left(\frac{2k}{E_{X'} v_{X'} \sqrt{1 - 4k^2/(m_{X'}^2 v_{X'}^2)}}\right)$$

For $p_t \ll k \sim m_{X'}/2$, $\Rightarrow$ $\theta_s > \theta_t$

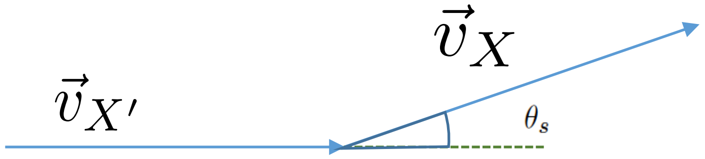
For $m_X \to m_{X'}/2$, $k \ll m_X/2$ $\Rightarrow$ $\theta_s < \theta_t$

Angular spread of X'

fraction of X reaching FASERν



$$\boxed{\theta_d = 5 \times 10^{-4}}$$



$$\theta_s = \arctan\left(\frac{2k}{E_{X'}v_{X'}\sqrt{1-4k^2/(m_{X'}^2 v_{X'}^2)}}\right)$$

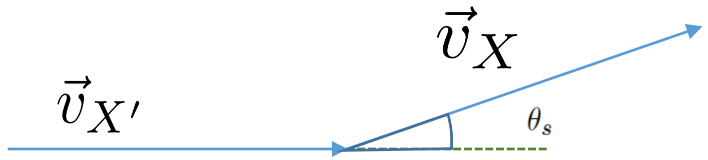
For $p_t \ll k \sim m_{X'}/2,$ ⇒ $\boxed{f = \theta_d^2/(2(1-\cos\theta_s))}$

For $m_X \to m_{X'}/2,\ k \ll m_X/2$ ⇒ $\boxed{f = \theta_d^2/\theta_t^2}$

Spectrum of X from X’ decay at FASER

Momentum of X in the rest frame of X’: $\boxed{k = (m_{X'}^2/4 - m_X^2)^{1/2}}$

X’ velocity in the lab frame: $\boxed{v_{X'} = (1 - m_{X'}^2/E_{X'}^2)^{1/2}}$



$$\theta_s = \arctan\left(\frac{2k}{E_{X'} v_{X'} \sqrt{1 - 4k^2/(m_{X'}^2 v_{X'}^2)}}\right)$$

For $p_t \ll k \sim m_{X'}/2$, $\Longrightarrow$

For $m_X \to m_{X'}/2$, $k \ll m_X/2$ $\Longrightarrow$

$$\boxed{E_X = \frac{E_{X'}}{2}(1 + \frac{2k}{m_{X'}})}$$

Spectrum of X from X’ decay at FASER and FASERν

$$\frac{d\sigma_{tot}(E_{X'})}{dE_{X'}} = \frac{\pi}{32\Lambda^2}\frac{m_{X'}^2}{p^2}\frac{1}{P_{X'}}F_g(\frac{E_{X'}+P_{X'}}{2p})F_g(\frac{E_{X'}-P_{X'}}{2p})$$

$$\frac{dN(E_X)}{dE_X} = Lf\frac{d\sigma_{tot}}{dE_{X'}}|_{E_X}\frac{2}{1+\sqrt{1-4m_X^2/m_{X'}^2}}$$

Luminosity

$$E_X = \frac{E_{X'}}{2}(1+\frac{2k}{m_{X'}})$$

$dE_{X'}/dE_X$

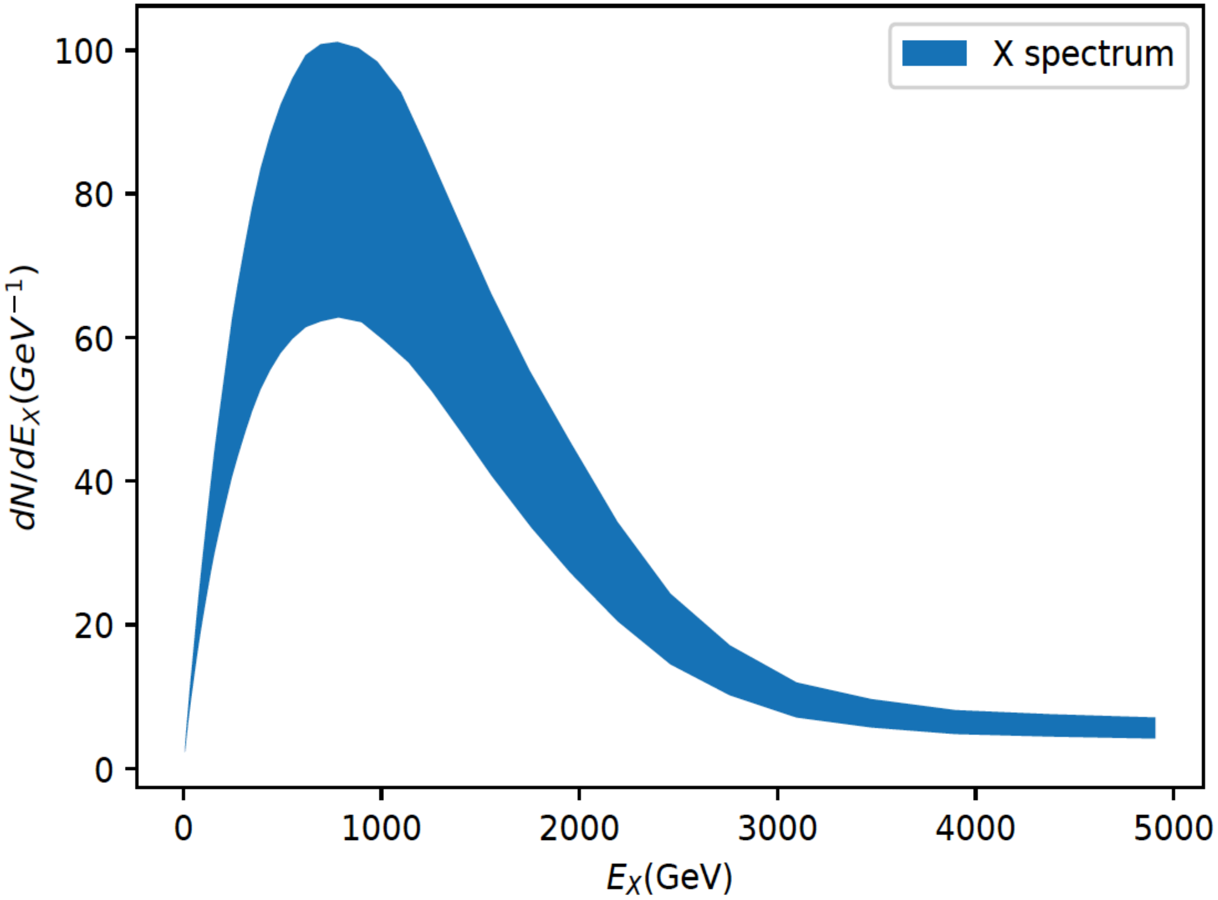
Spectrum of X emitted towards FASER and FASERν

$$\frac{d\sigma_{tot}(E_{X'})}{dE_{X'}} = \frac{\pi}{32\Lambda^2}\frac{m_{X'}^2}{p^2}\frac{1}{P_{X'}}F_g\Big(\frac{E_{X'}+P_{X'}}{2p}\Big)F_g\Big(\frac{E_{X'}-P_{X'}}{2p}\Big)$$

$$\frac{dN(E_X)}{dE_X} = L f \frac{d\sigma_{tot}}{dE_{X'}}\Big|_{E_X}\frac{2}{1+\sqrt{1-4m_X^2/m_{X'}^2}}$$

$$f = \theta_d^2/(2(1-\cos\theta_s)) \propto \text{detector area}$$

Spectrum of X emitted towards FASERν



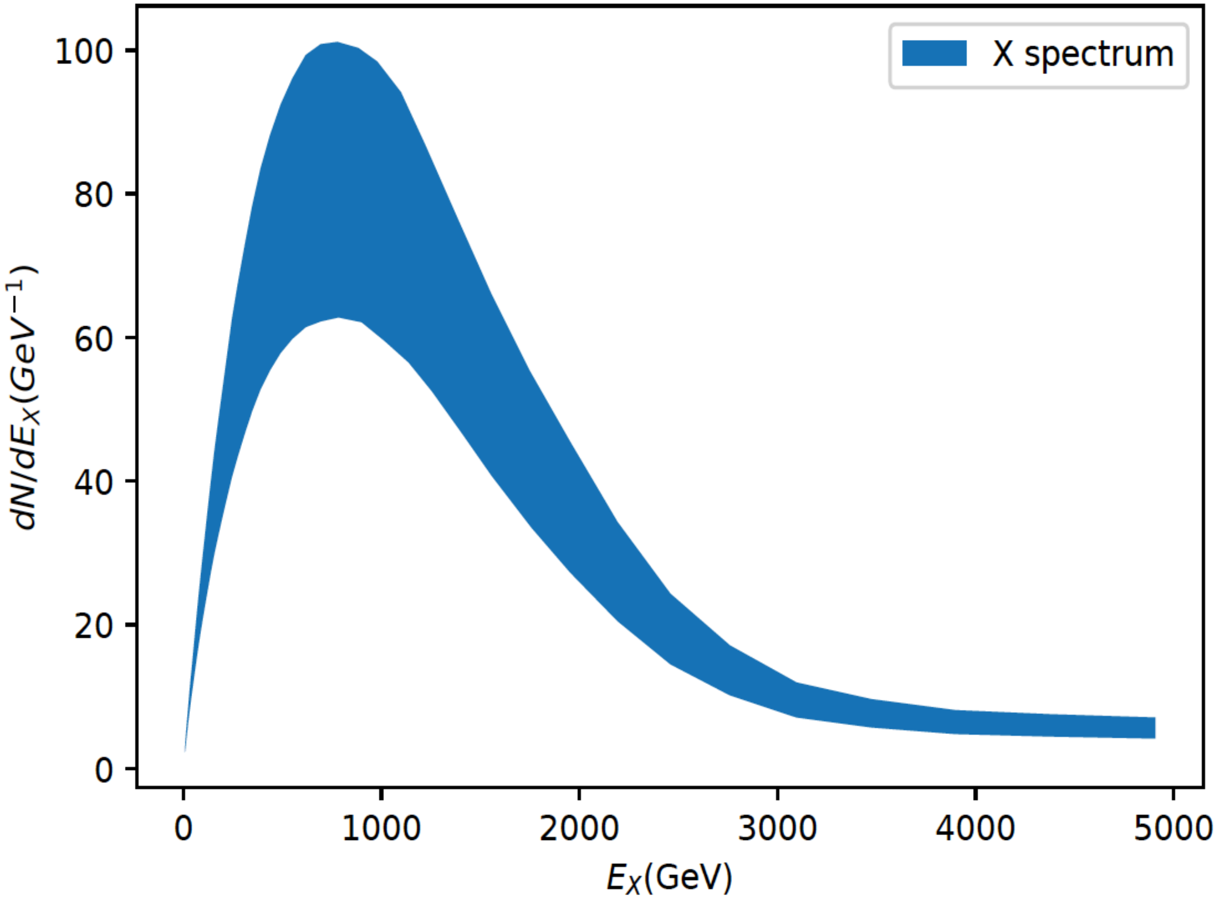
$\boxed{\text{run III of LHC}}$

$\boxed{\sqrt{s} = 14\ \text{TeV}}$ $\boxed{150\ \text{fb}^{-1}}$

$$m_{X'} = 3\,\text{GeV},\, m_X = 1\,\text{GeV}$$

$$\boxed{\Lambda = 2 \times 10^4\ \text{GeV}}$$

Spectrum of X emitted towards FASERν



run III of LHC

$\sqrt{s} = 14$ TeV

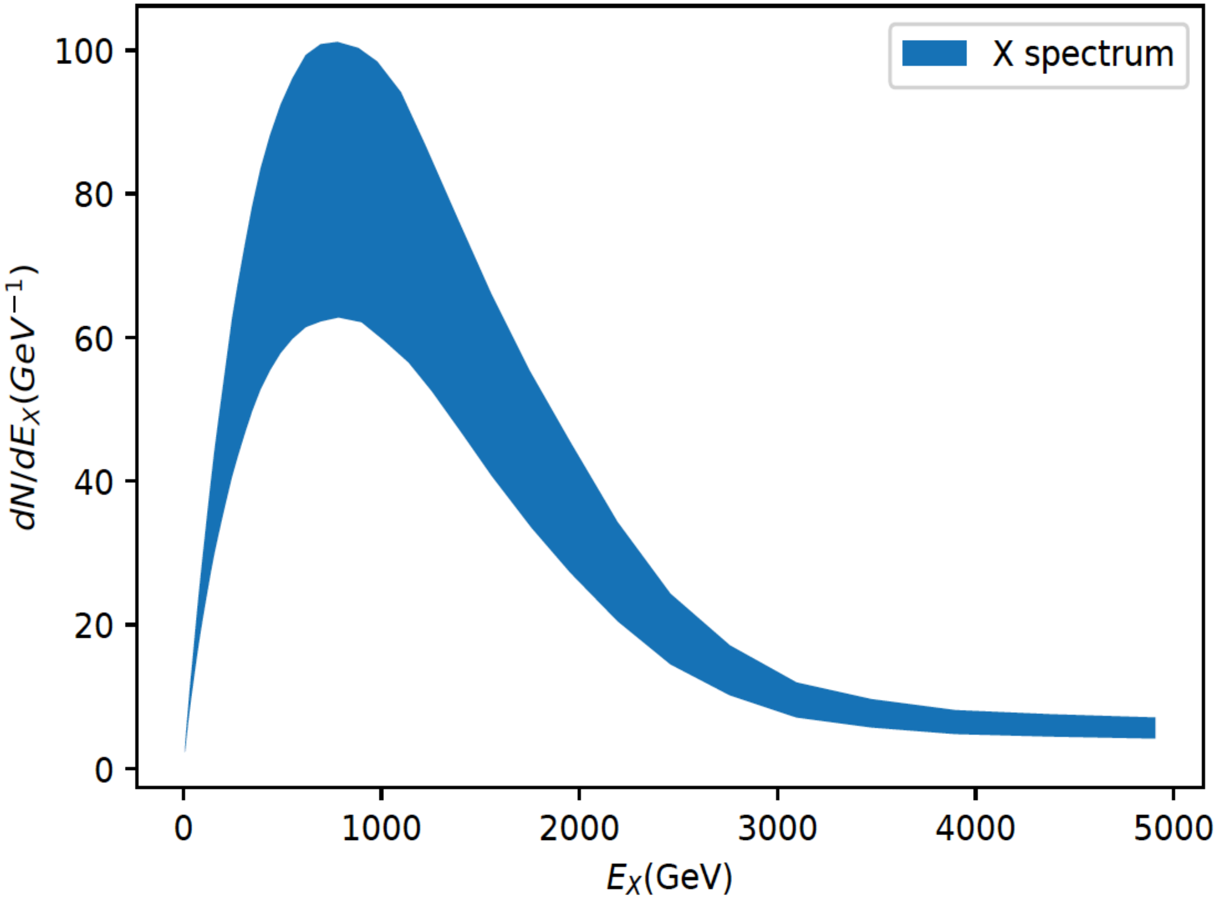
150 fb^{-1}

$m_{X'} = 3$ GeV, $m_X = 1$ GeV

$\Lambda = 2 \times 10^4$ GeV

PDFs: J. Rojo *et al.*, J. Phys. G **42** (2015) 103103

Spectrum of X emitted towards FASERν



Total number = O(100000)

run III of LHC

$\sqrt{s} = 14$ TeV

150 fb^{-1}

$m_{X'} = 3\,\mathrm{GeV}, m_X = 1\,\mathrm{GeV}$

$\Lambda = 2 \times 10^4$ GeV

Number of X decaying at FASERν

$$\boxed{\frac{dN(E_X)}{dE_X} \exp^{-\frac{d}{\tau_X \gamma_X}} \left(\frac{s_z}{\tau_X \gamma_X} \right) dE_X}$$

$\propto$ detector area

Detector length

Proportional to Volume

Number of X decaying at FASERν

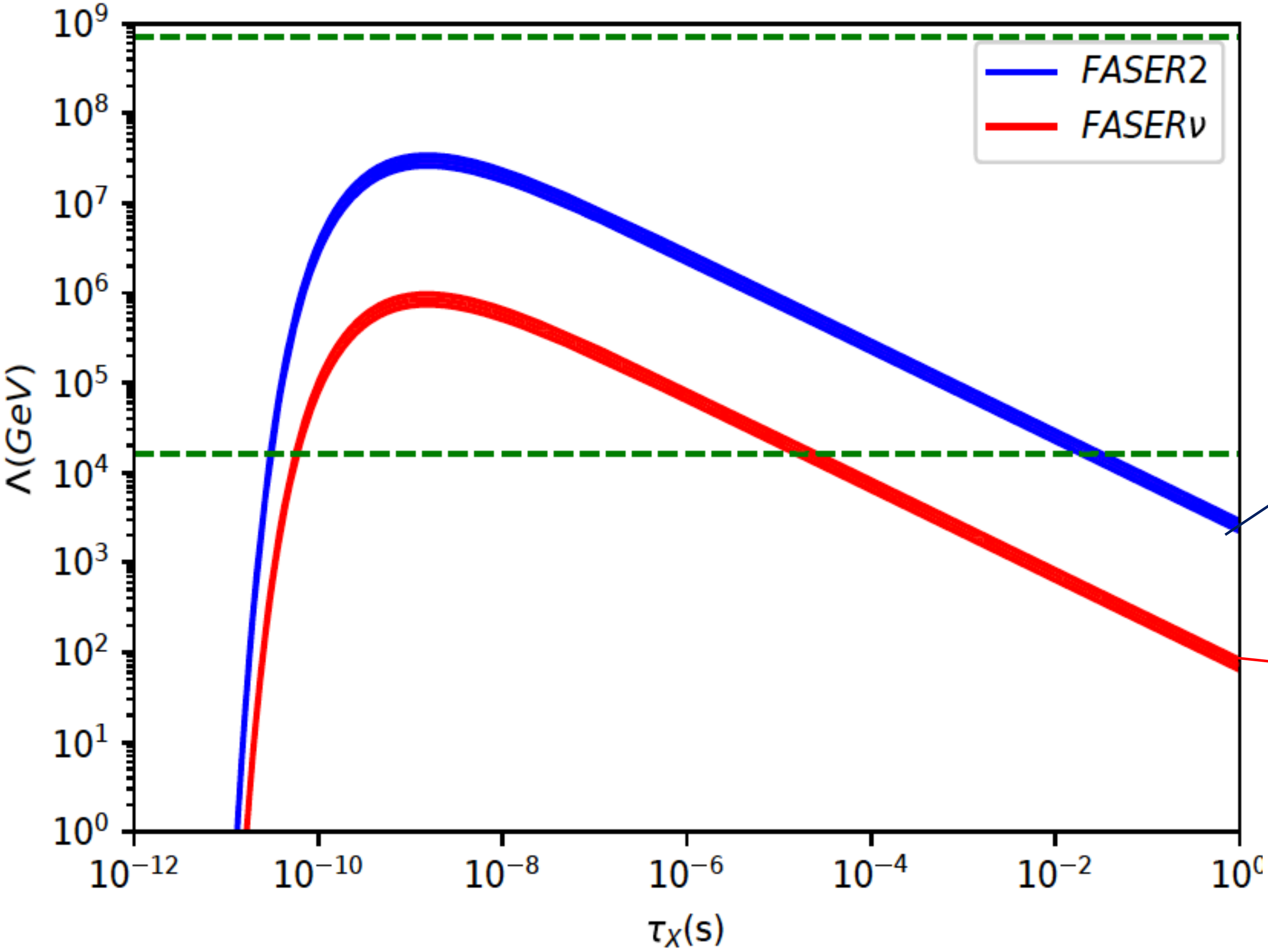
$$\boxed{\frac{dN(E_X)}{dE_X}\exp^{-\frac{d}{\tau_X\gamma_X}}\left(\frac{s_z}{\tau_X\gamma_X}\right)dE_X}$$

$$\gamma_X = m_X/E_X$$

Length of the detector:

- FASERν $\boxed{s_z = 1.3\ \mathrm{m}}$
- FASER2: $(upgrade\ of\ FASER\ for\ HL - LHC)$ $\boxed{s_z = 5\ \mathrm{m}}$

Bound on the coupling



high luminosity run of LHC

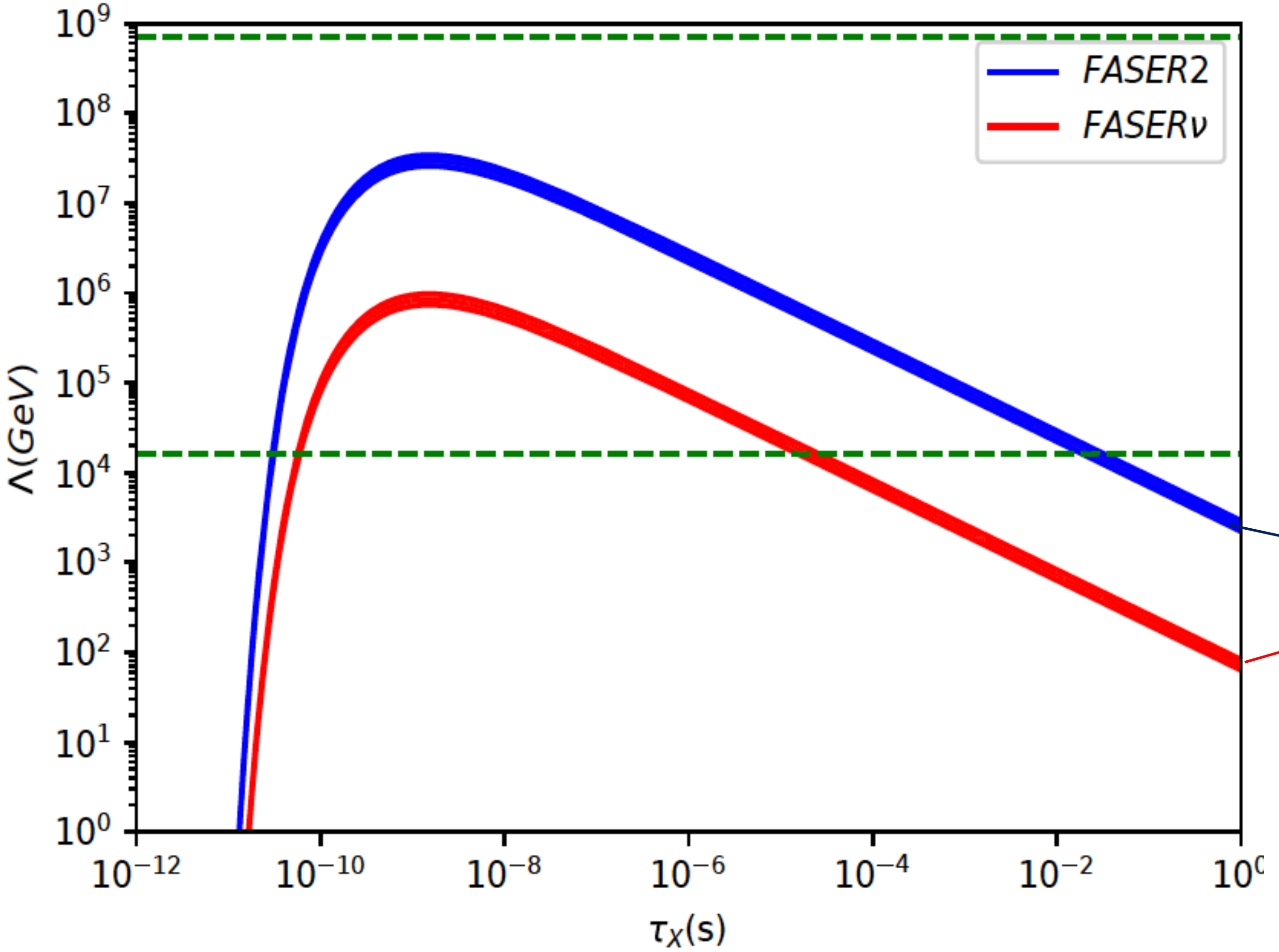
during 2026-2035

the run III of LHC

during 2021-2023

$m_{X'} = 3$ GeV and $m_X = 1$ GeV.

Bound on the coupling

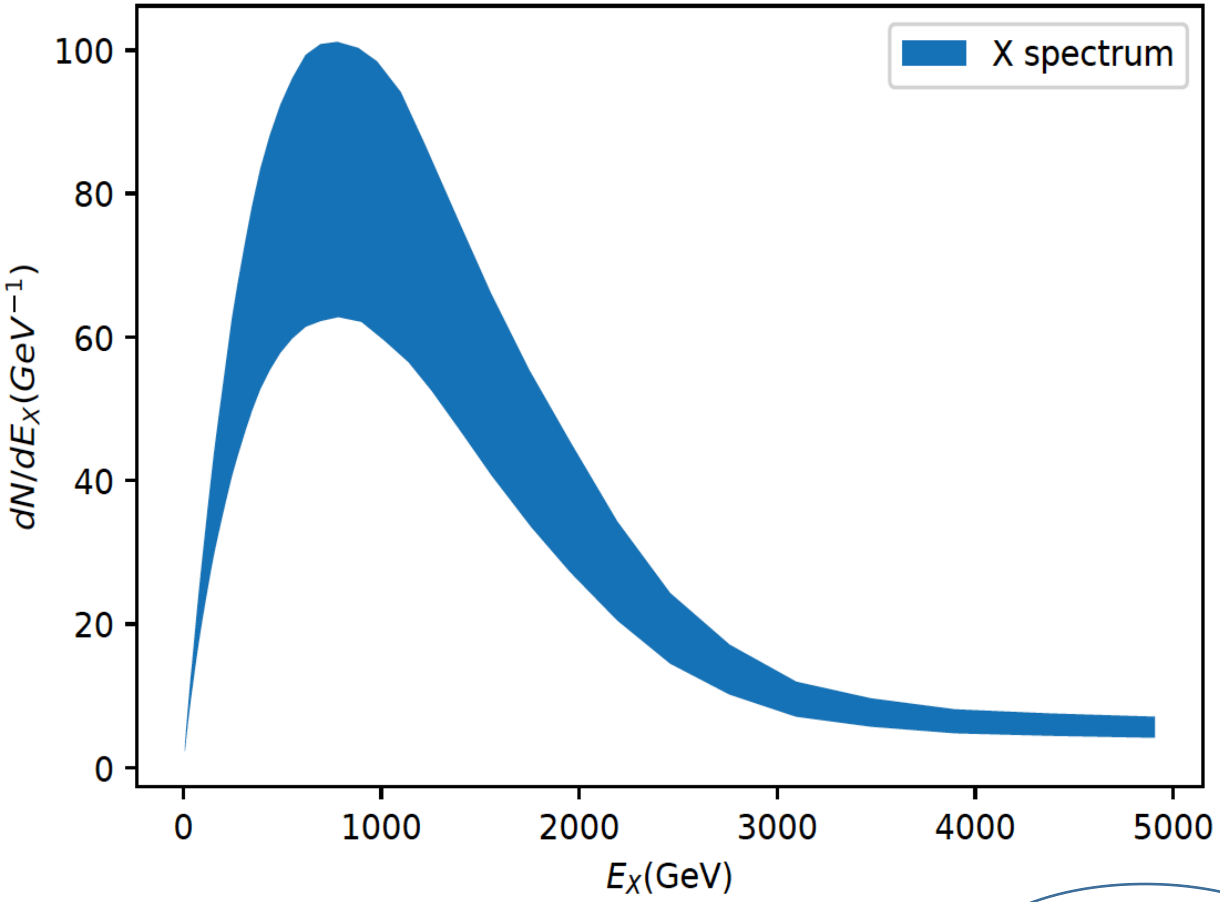


$$\boxed{\frac{dN(E_X)}{dE_X}\exp^{-\frac{d}{\tau_X\gamma_X}}\left(\frac{s_z}{\tau_X\gamma_X}\right)dE_X}$$

$$\boxed{\tau_X\Lambda^2 = cte}$$

$m_{X'} = 3$ GeV and $m_X = 1$ GeV.

Spectrum of X emitted towards FASERν



run III of LHC

$\sqrt{s} = 14$ TeV

150 fb^{-1}

$$m_{X'} = 3\,\mathrm{GeV},\, m_X = 1\,\mathrm{GeV}$$

$$\Lambda = 2 \times 10^4\ \mathrm{GeV}$$

<0.01

Total number = O(100000)

$$\frac{dN(E_X)}{dE_X} \exp^{-\frac{d}{\tau_X \gamma_X}} \left(\frac{s_z}{\tau_X \gamma_X}\right) dE_X$$

Number of events < or = 100

Toy model

- Intermediate X’ is produced at IP.
- Before reaching detector, $\boxed{X' \to X\bar{X}}$
- X decays at FASERν to the SM charged leptons:

A generic scenario

NO BACKGROUND

$X \to \eta\bar{\eta}Y$

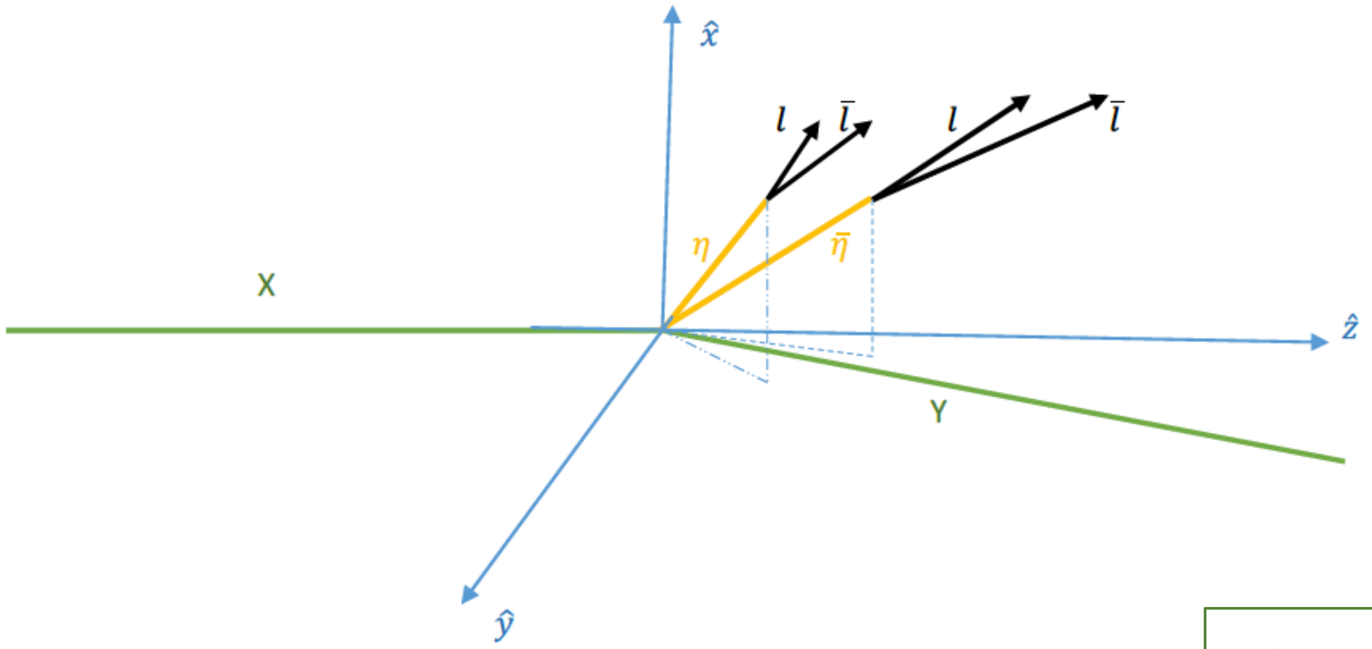
Missing energy and momentum

- η and $\bar{\eta}$ decay after 1mm-10cm: $\boxed{\eta \to l\bar{l}}$ $\boxed{\bar{\eta} \to l\bar{l}}$

Specific model
Demonstrating ability
Of FASERν

Signature at FASERν

- Two pairs charged leptons plus missing energy



$$\sigma_{pos} = 0.4\ \mu\mathrm{m}$$

$$\sigma_{ang} = \sqrt{2}\sigma_{pos}/L_{tr}$$

$$L_{\mathrm{tr}} = 1\ \mathrm{cm}$$

$$\sigma_{\mathrm{angle}} = 0.06\ \mathrm{mrad.}$$

$$\Delta E/E \sim 30\%.$$

$$\theta_\eta = m_X/E_X$$

$$\theta_l \sim \sqrt{m_\eta^2 - 4m_l^2}/E_\eta$$

$$\boxed{\Delta\theta_\eta \sim \sqrt{(\Delta E/E)^2\theta_l^2/2 + 2\sigma_{ang}^2},}$$

$$\boxed{X \to \eta + \bar{\eta} + Y \text{ or } X \to \eta + \bar{\eta}}$$

$$\Delta P_t < |\vec{p}^{\,t}_{\eta} + \vec{p}^{\,t}_{\bar{\eta}}|$$

$$\Delta P_t = \left(2(\frac{\Delta E}{E})^2[(p^t_{\eta})^2 + (p^t_{\bar{\eta}})^2] + (\sum |\vec{p}_l|^2 + \sum |\vec{p}_{\bar{l}}|^2)\sigma^2_{ang} + |\vec{p}_{\eta} + \vec{p}_{\bar{\eta}}|^2(\Delta\hat{z})^2\right)^{1/2}$$

$(\Delta E/E)^2 \sim 0.3^2$

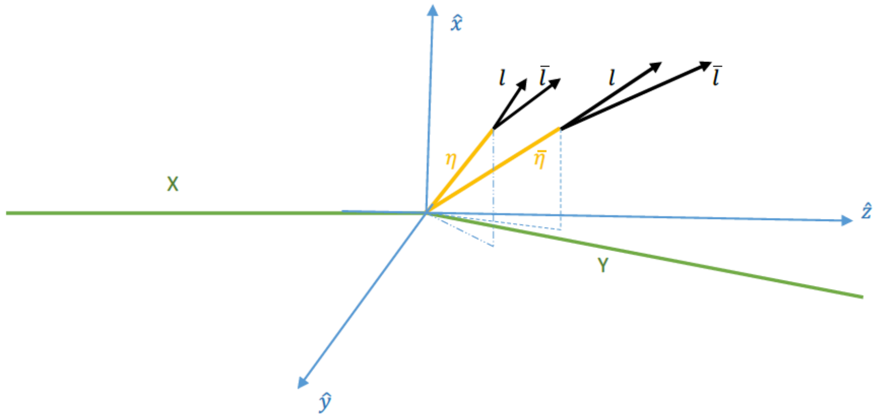
$(\sum |\vec{p}_l|^2 + \sum |\vec{p}_{\bar{l}}|^2) \sim |\vec{p}_{\eta}|^2 \sim |\vec{p}_{\bar{\eta}}|^2$

$\Delta\hat{z} \sim 10^{-3}$

$$X \to \eta + \bar{\eta} + Y \text{ or } X \to \eta + \bar{\eta}$$

$$\Delta P_t < |\vec{p}^{\,t}_{\eta} + \vec{p}^{\,t}_{\bar{\eta}}|$$

$$\Delta P_t = \left(2\left(\frac{\Delta E}{E}\right)^2[(p^t_\eta)^2 + (p^t_{\bar{\eta}})^2] + \left(\sum |\vec{p_l}|^2 + \sum |\vec{p_{\bar{l}}}|^2\right)\sigma^2_{ang} + |\vec{p}_\eta + \vec{p}_{\bar{\eta}}|^2(\Delta \hat{z})^2\right)^{1/2}$$



Angle between projections of momenta to xy plane

$< 90^\circ$	+
$> 90^\circ$	–

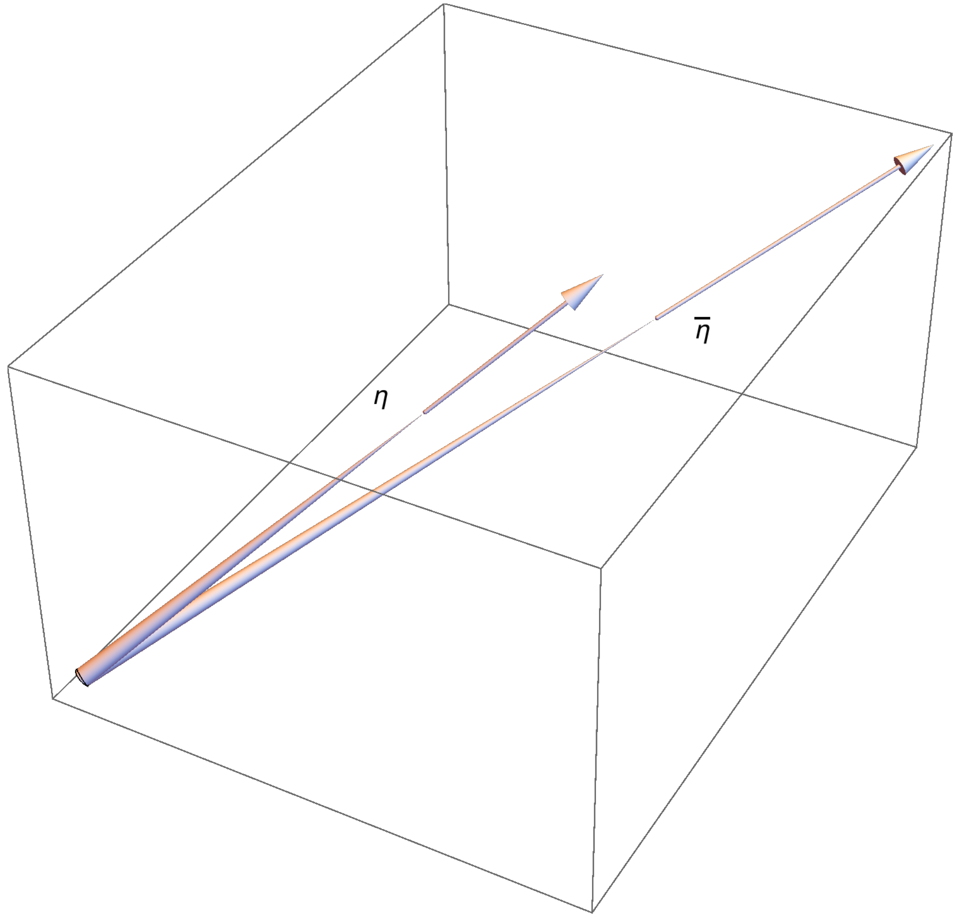
Reconstructing the mass of η

$$m_\eta^2 = (p_l + p_{\bar{l}})^2$$

$$\Delta m^2_{sin}/m^2_\eta \sim [2(\Delta E/E)^2 + 2(\sigma_{ang}/\theta_l)^2]^{1/2}$$ =40 %

N pairs: $\Delta m^2_{sin}/\sqrt{N}$ → 4 %

Decay length of η



$$\delta L_V = [(l_\eta^2 + l_{\bar{\eta}}^2)(\Delta\theta_\eta)^2 + 2\sigma_{pos}^2 E_X^2/m_X^2]^{1/2}$$

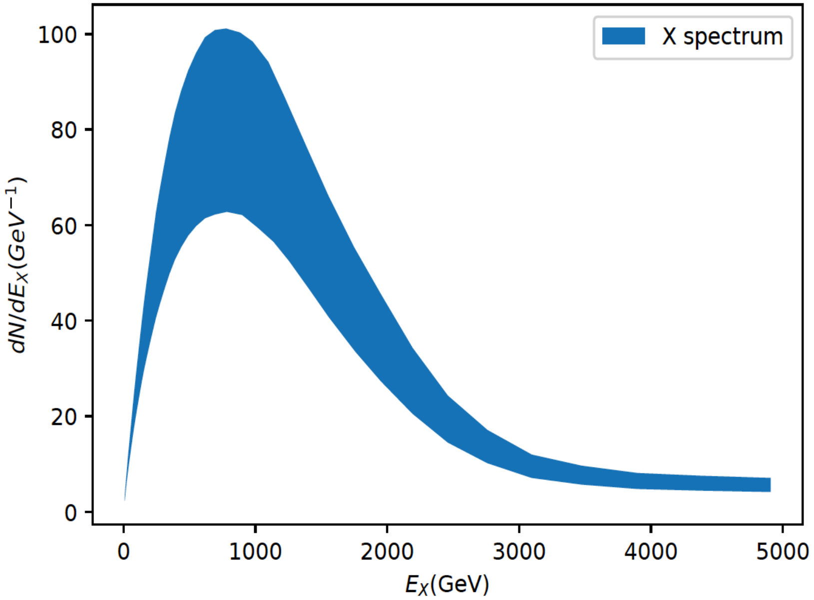
$$\delta L_V \sim (E_X/m_X)\sigma_{pos} \sim 1 \text{ mm} \ll l_\eta, l_{\bar{\eta}}$$

$$\bar{\tau}_\eta = \frac{\sum_{i=1}^N l_\eta^i m_\eta/E_\eta}{N}$$

$$\frac{\delta\tau^{stat}}{\bar{\tau}} = (\frac{2\log 2}{N})^{1/2} \longrightarrow \quad 10\,\%$$

Determining the masses of X and Y

- We do not know the energy of initial X



Any information on the mass of X and Y is limited by both statistics and uncertainties on PDF

Unlike m_η

Connection to dark matter

- X’ can be produced in the early universe by gluon interaction.

$$\text{For } T > m_{X'} \text{ and } \Lambda \lesssim 10^8\,\mathrm{GeV}$$

- X’ decay can produce X and then Y (DM).

Connection to DM

Fermionic X and Y:

$$g_Y \eta \bar{V} Y + g_X \eta \bar{V} X$$

Complex

$$\sigma(Y + \bar{Y} \to \eta + \bar{\eta}) \sim \text{pb}$$

$$\sigma(Y + \bar{Y} \to \eta + \bar{\eta}) = \frac{g_Y^4}{m_V^4} \frac{m_Y^2}{4\pi} \quad \Longrightarrow \quad \frac{m_V}{g_Y} \sim 10 \text{ GeV} \left(\frac{m_Y}{0.1 \text{ GeV}} \right)^{1/2}$$

For real case, cancelation between u and t channels

$$m_V > m_X \quad \Longrightarrow \quad \cancel{X \to V \bar{\eta}}$$

$$\Gamma(X \to Y \eta \bar{\eta}) \sim \frac{g_Y^2 g_X^2}{100\pi^3} \frac{m_X^5}{m_V^4}$$

$$\Gamma(X \to Y \eta \bar{\eta})(m_X/E_X) \sim (480 \text{ m})^{-1} \quad \Longrightarrow \quad g_X \sim 10^{-5} \left(\frac{\text{GeV}}{m_X} \right)^2 \left(\frac{m_V}{m_X} \right) \left(\frac{E_X}{500 \text{ GeV}} \right)$$

Connection to DM

Fermionic X and Y:

$$g_Y \eta \bar{V} Y + g_X \eta \bar{V} X$$

Complex

$\sigma(Y + \bar{Y} \to \eta + \bar{\eta}) \sim \mathrm{pb}$

$$\sigma(Y + \bar{Y} \to \eta + \bar{\eta}) = \frac{g_Y^4}{m_V^4} \frac{m_Y^2}{4\pi} \Longrightarrow \frac{m_V}{g_Y} \sim 10 \text{ GeV} \left(\frac{m_Y}{0.1 \text{ GeV}}\right)^{1/2}$$

For real case, cancelation between u and t channels

$$m_V > m_X \Longrightarrow \cancel{X \to V\bar{\eta}}$$

$$Z_2 \times Z_2$$

Exact

η and Y odd

X and Y odd

$$\cancel{\eta \bar{X} Y}$$

$$\cancel{X \to Y\eta}$$

$$g_X \ll g_Y$$

Connection to DM

$\boxed{Scalar\ X\ \ and\ Y:}$

$$\lambda_1 \bar{Y} X \bar{\eta}\eta + \lambda_2 \bar{X} X \bar{\eta}\eta + \lambda_3 \bar{Y} Y \bar{\eta}\eta.$$

Real or complex

$$\begin{tikzcd} Z_2 \arrow[d] & \times & Z_2 \arrow[d] & \times & Z_2 \arrow[d] \arrow[r, Rightarrow, "\lambda_1"] & Z_2 \times Z_2 & \lambda_1 \ll \lambda_3 \\ \eta & & X & & Y & & \end{tikzcd}$$

$$\cancel{\eta \bar{X} Y} \longrightarrow X \cancel{\rightarrow} Y\eta$$

Connection to DM

$\boxed{Scalar\ X\ \ and\ Y:}$

$$\lambda_1 \bar{Y} X \bar{\eta}\eta + \lambda_2 \bar{X} X \bar{\eta}\eta + \lambda_3 \bar{Y} Y \bar{\eta}\eta.$$

$$\Gamma(X \to Y \bar{\eta}\eta) \sim \frac{\lambda_1^2 m_X}{100\pi^3}$$

$$\Gamma(X \to Y \bar{\eta}\eta)(m_X/E_X) \sim 1/(480\ m),$$

$$\boxed{\lambda_1 = 8 \times 10^{-7}(\mathrm{GeV}/m_X)(E_X/500\ \mathrm{GeV})^{1/2}}$$

Connection to DM

$\boxed{Scalar\ X\ \ and\ Y:}$

$$\lambda_1 \bar{Y} X \bar{\eta}\eta + \lambda_2 \bar{X} X \bar{\eta}\eta + \lambda_3 \bar{Y} Y \bar{\eta}\eta.$$

$$\boxed{\lambda_1 = 8 \times 10^{-7} (\mathrm{GeV}/m_X)(E_X/500\ \mathrm{GeV})^{1/2}}$$

$$\boxed{\sigma(Y\bar{Y} \to \eta\bar{\eta}) \sim \lambda_3^2/(4\pi m_Y^2) \simeq 1\ pb,}$$

$$\Downarrow$$

$$\boxed{\lambda_3 \sim 10^{-4}\sqrt{m_Y/\mathrm{GeV}}}$$

$$\lambda_1 \ll \lambda_3$$

Conclusion

- FASERν , with its superb abilities to reconstruct tracks, is ideal to study new long-lived GeV-scale feebly interacting particles that go through chain decays.

- Intriguing possibility for exploring GeV scale dark matter

Eta decay

$$\lambda_\eta \eta \bar{l} l. \quad \Longrightarrow \quad \eta \to l \bar{l}.$$

$$\tau_\eta = 4\pi/(m_\eta \lambda_\eta^2)$$

$$\lambda_\eta > 10^{-7},\ \tau_\eta E_\eta/m_\eta < 1\ \mathrm{m}$$

$$\eta H^\dagger \Phi + \eta^\dagger \Phi^\dagger H$$