Observation of collider neutrinos
Dark Matter Search

Differential ttW measurement

NExT Meeting
26/4/2023

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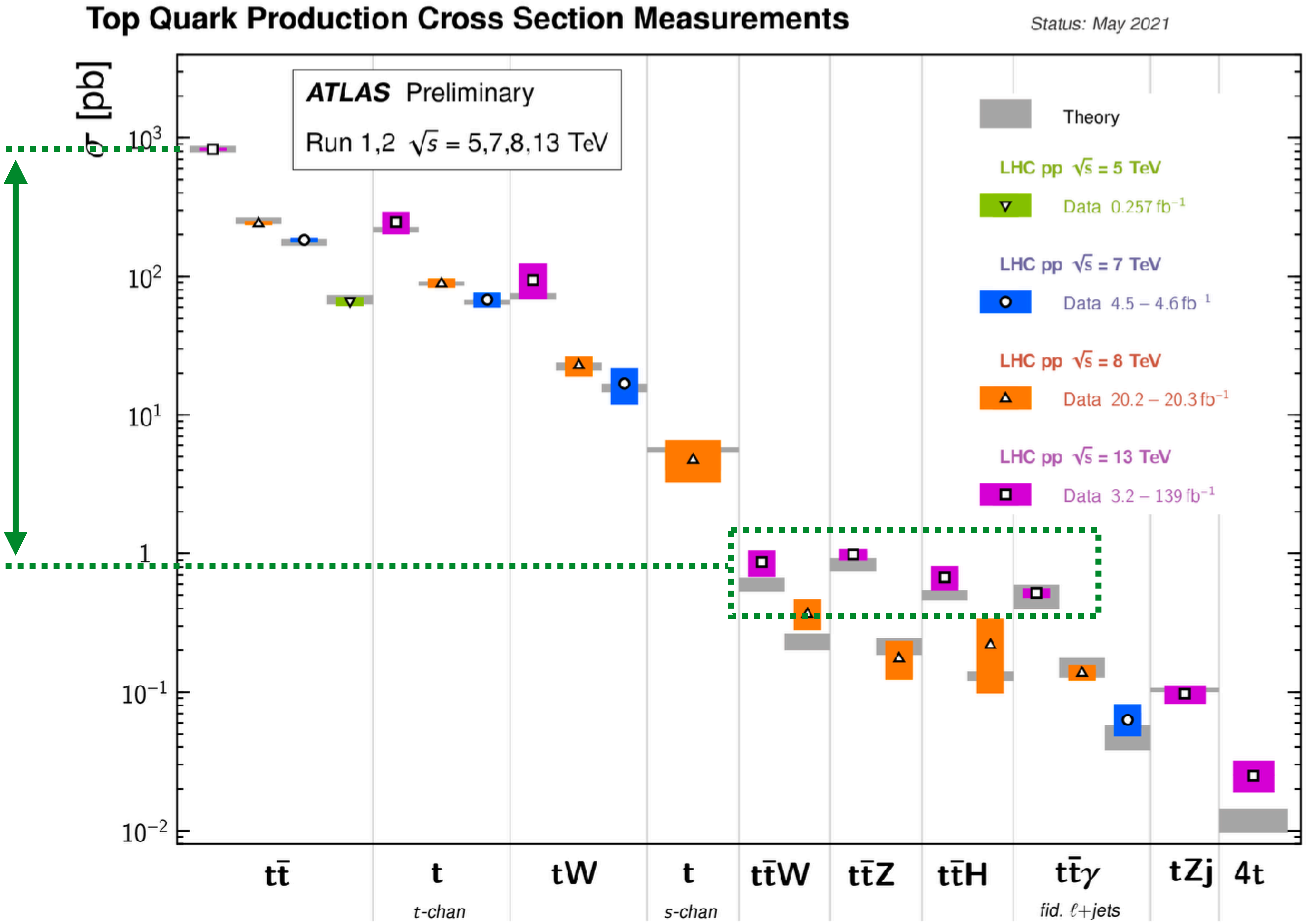
Top+X

3 orders of magnitude below the inclusive tt cross section

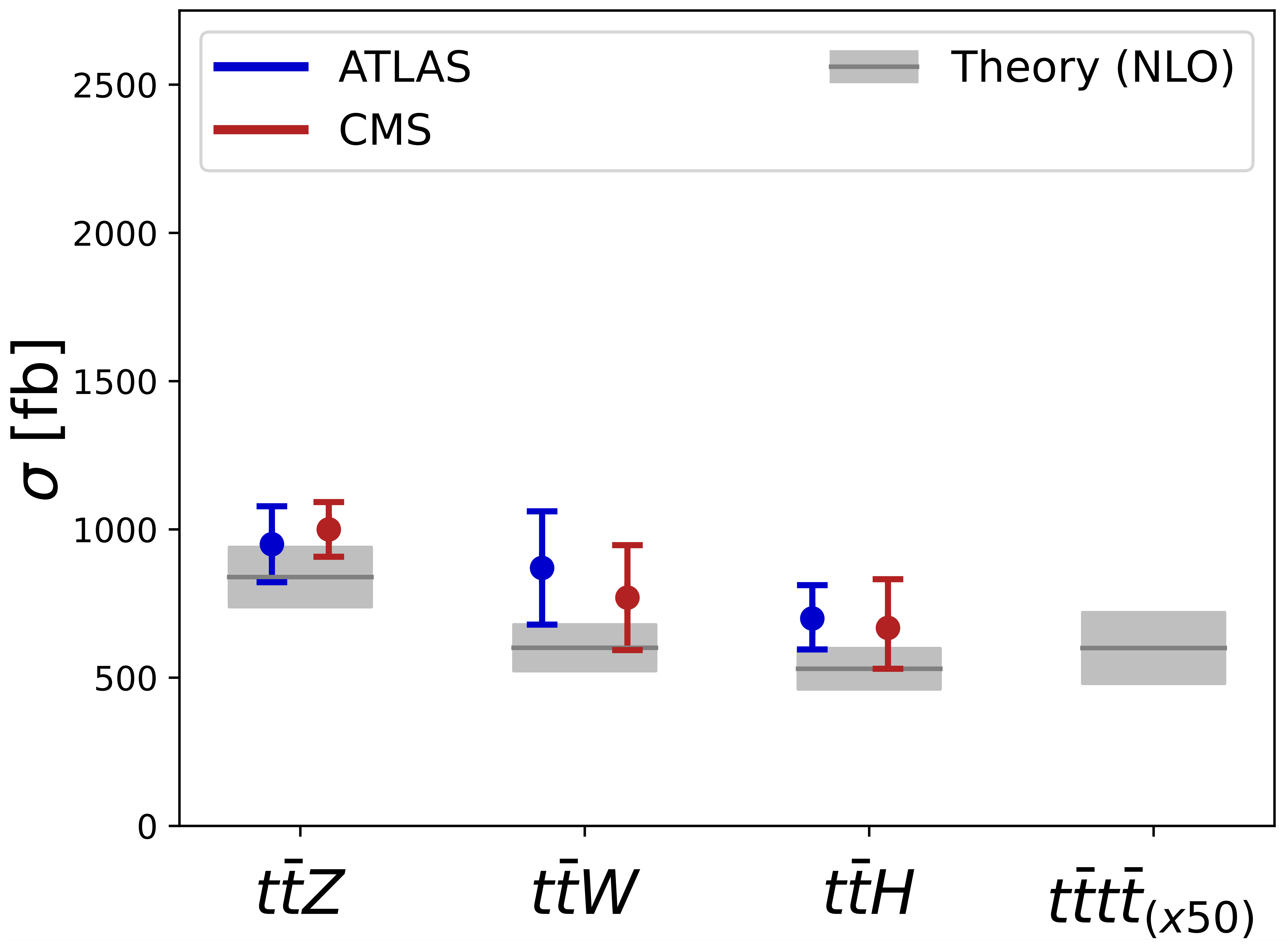


Rare top quark associated production

- Rare Standard Model processes accessible only at the LHC.
  - Just reaching sufficient sensitivity for differential measurements
  - Measurement sensitivity just starting to exceed that of theoretical predictions
- Important backgrounds to new physics searches
  - ttZ in top+MET SUSY searches
  - ttW is major background in any same-sign di-lepton final state
- Rich phenomenology
  - Many final states, EFT interpretations
- ttW deviation from SM…?

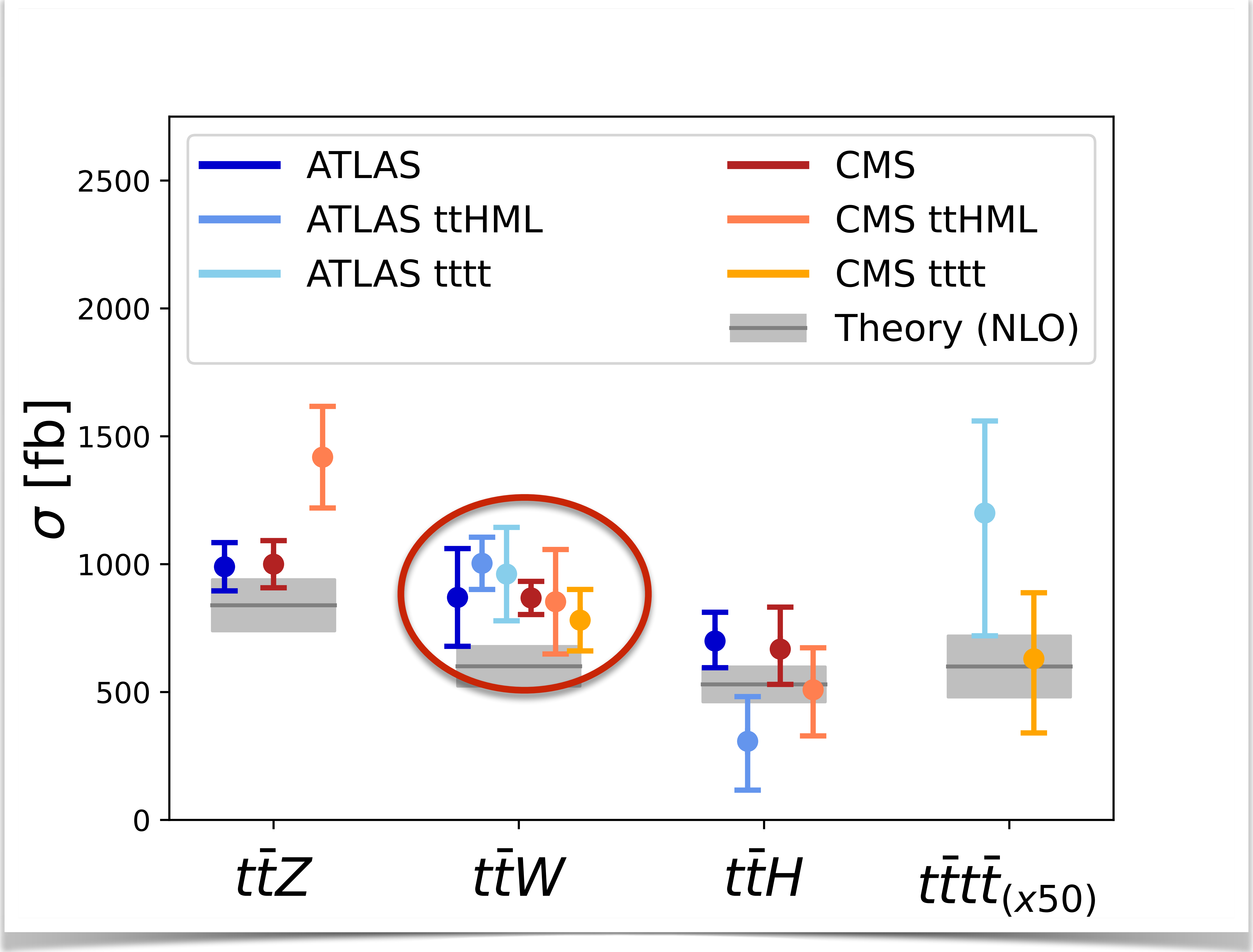
Why ttW?

- Started off as barely a hint of deviation from the SM



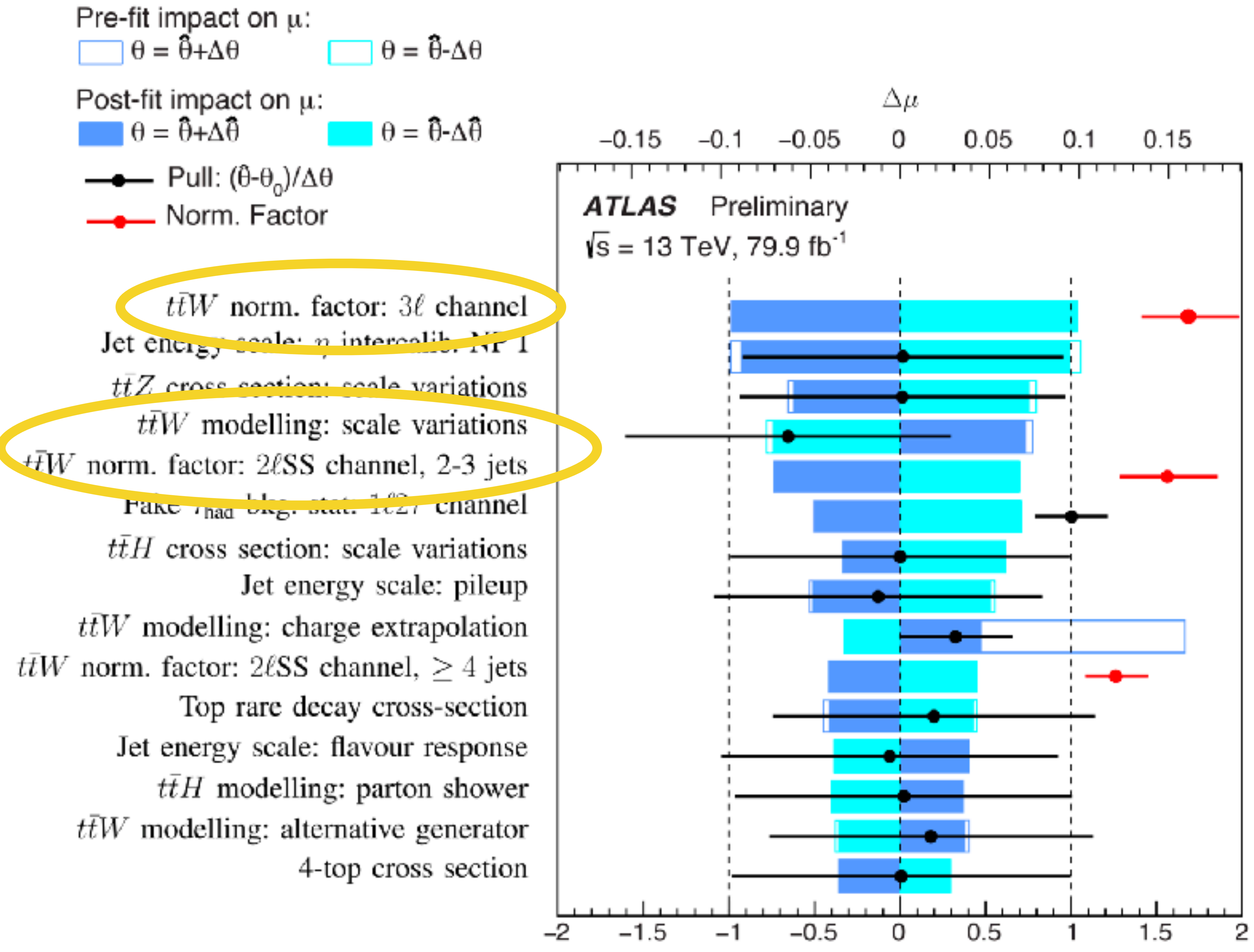
Why ttW?

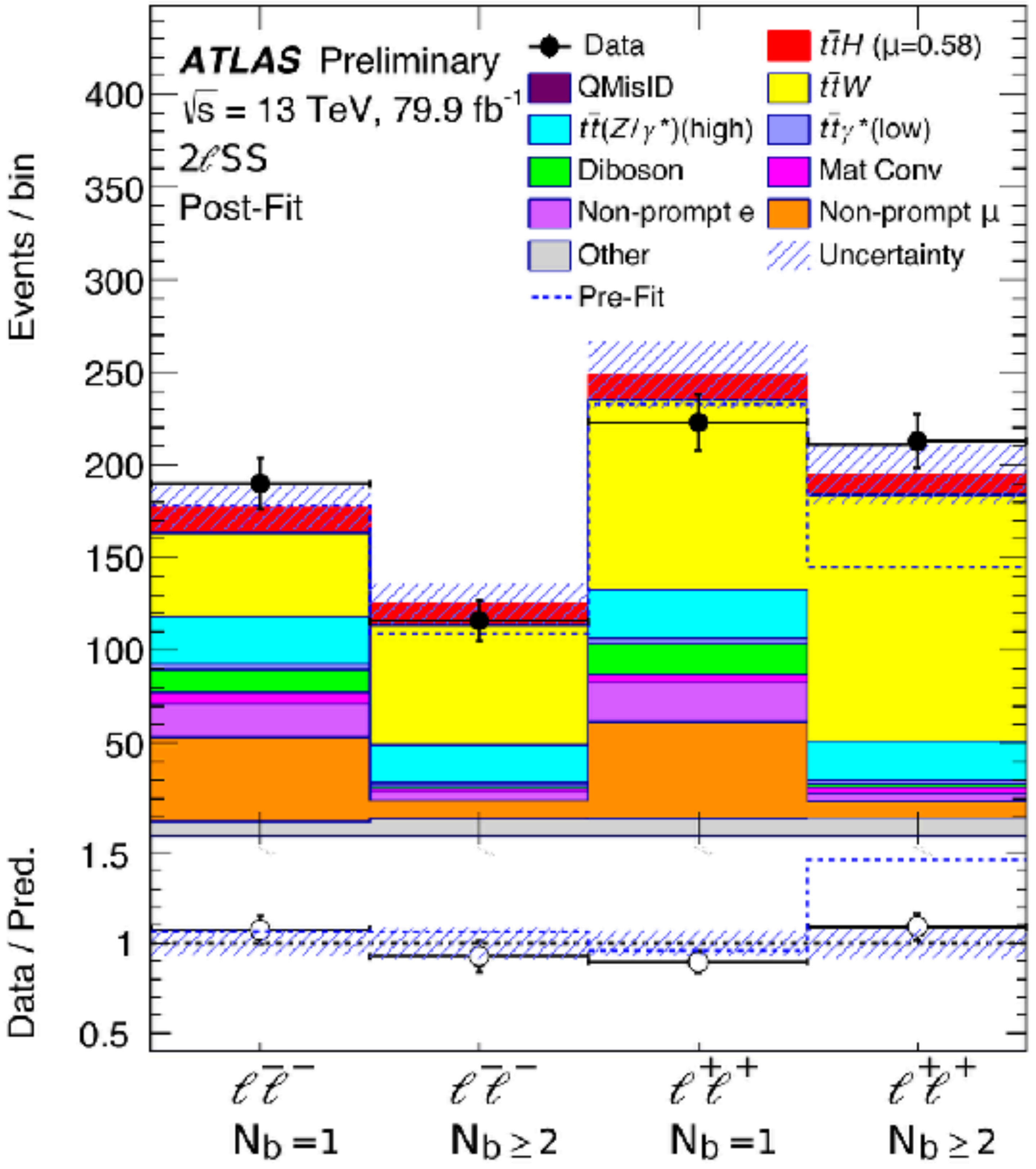
- Started off as barely a hint of deviation from the SM
- Then mounting evidence that something is going on with ttW (or ttW-like final states)

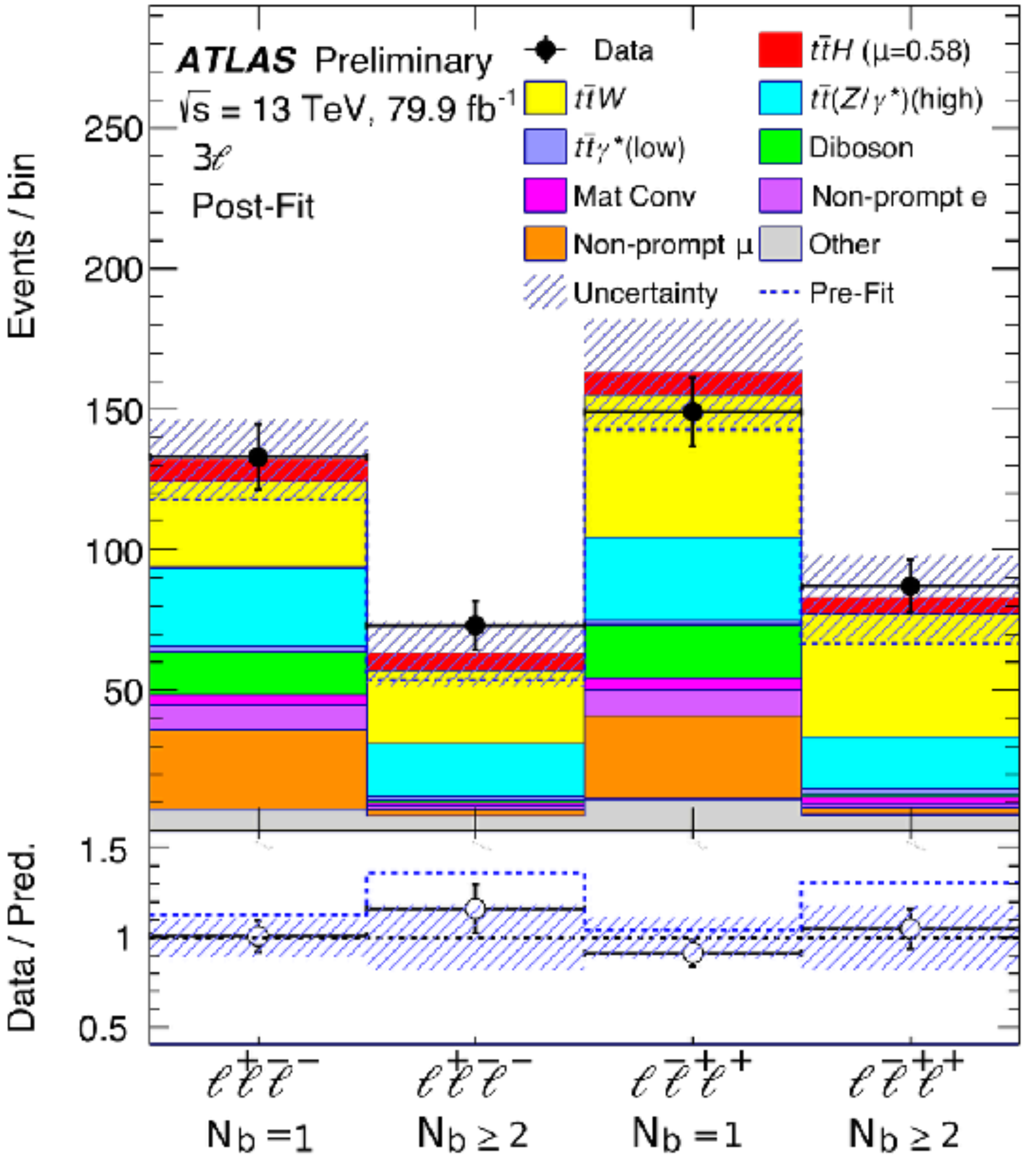


ttW as background to ttH

- In ttH→WW/ZZ/ττ→multi-leptons measurements ttW is a dominant irreducible background
  - Also a dominant uncertainty:



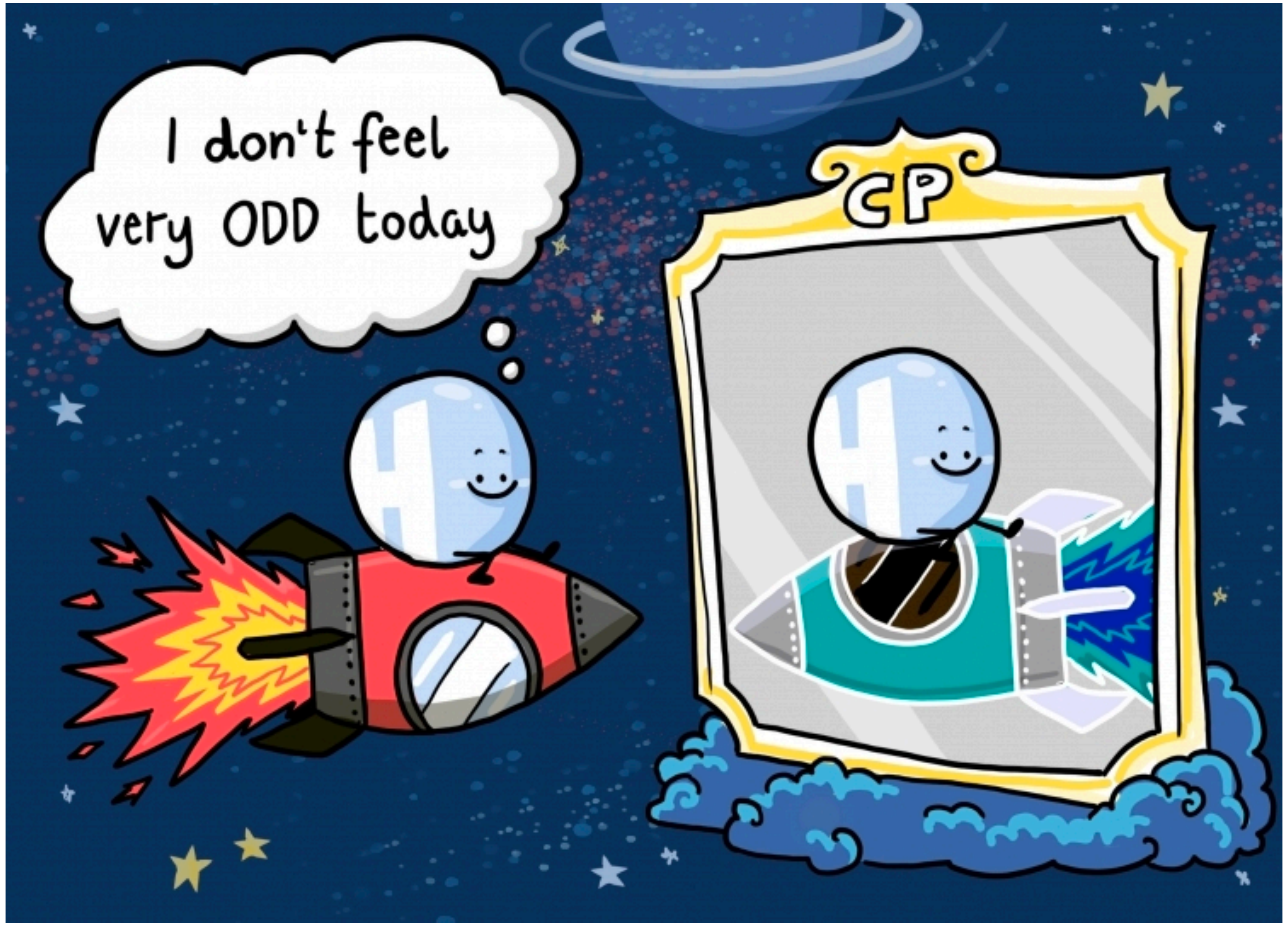




- Normalisation measured to be ~40% higher than best SM prediction at the time.

Why ttH?

- Window into top-Higgs coupling
  - Very important test of EW symmetry breaking
- Higgs CP properties
- Higgs self-coupling



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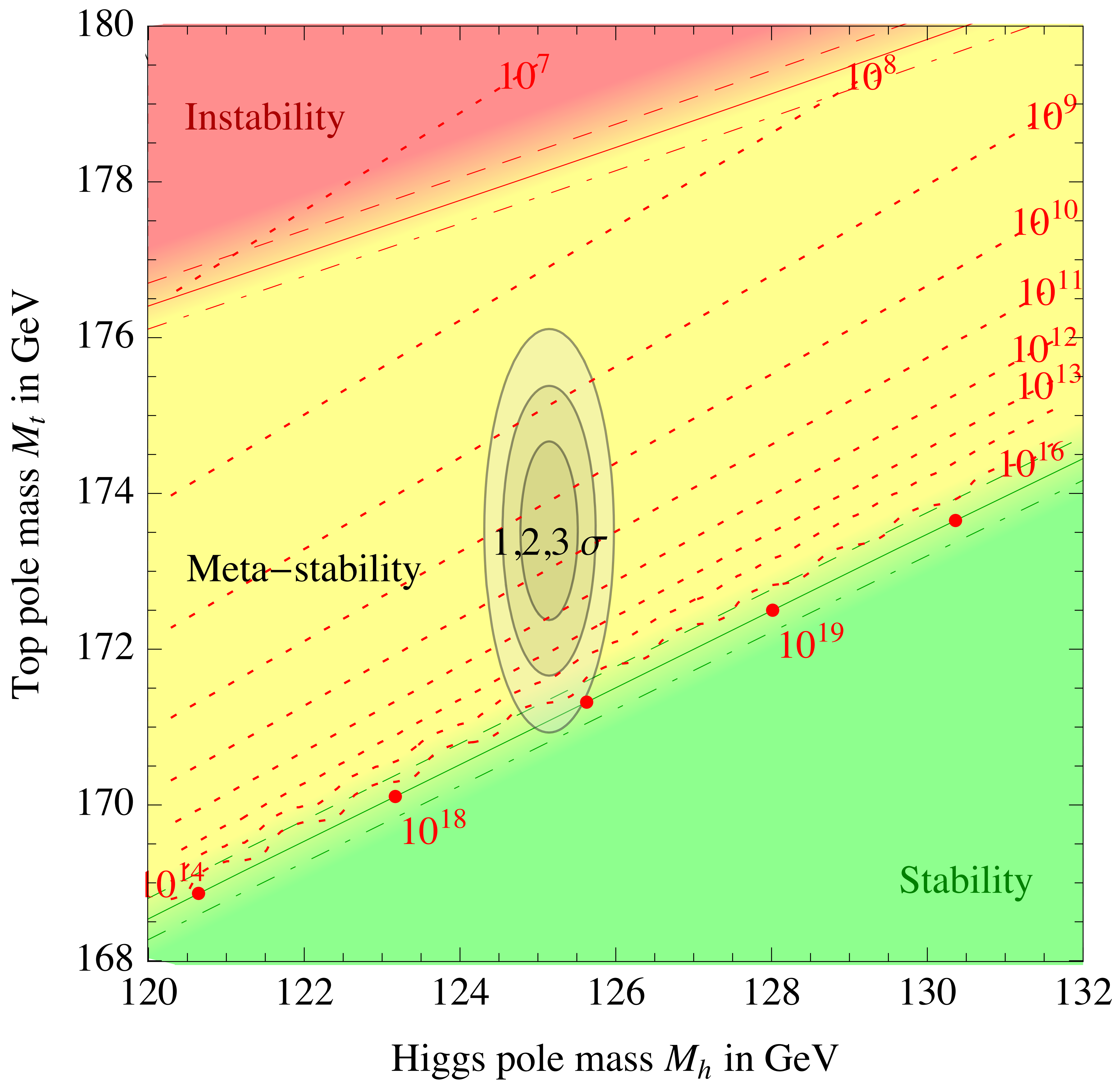
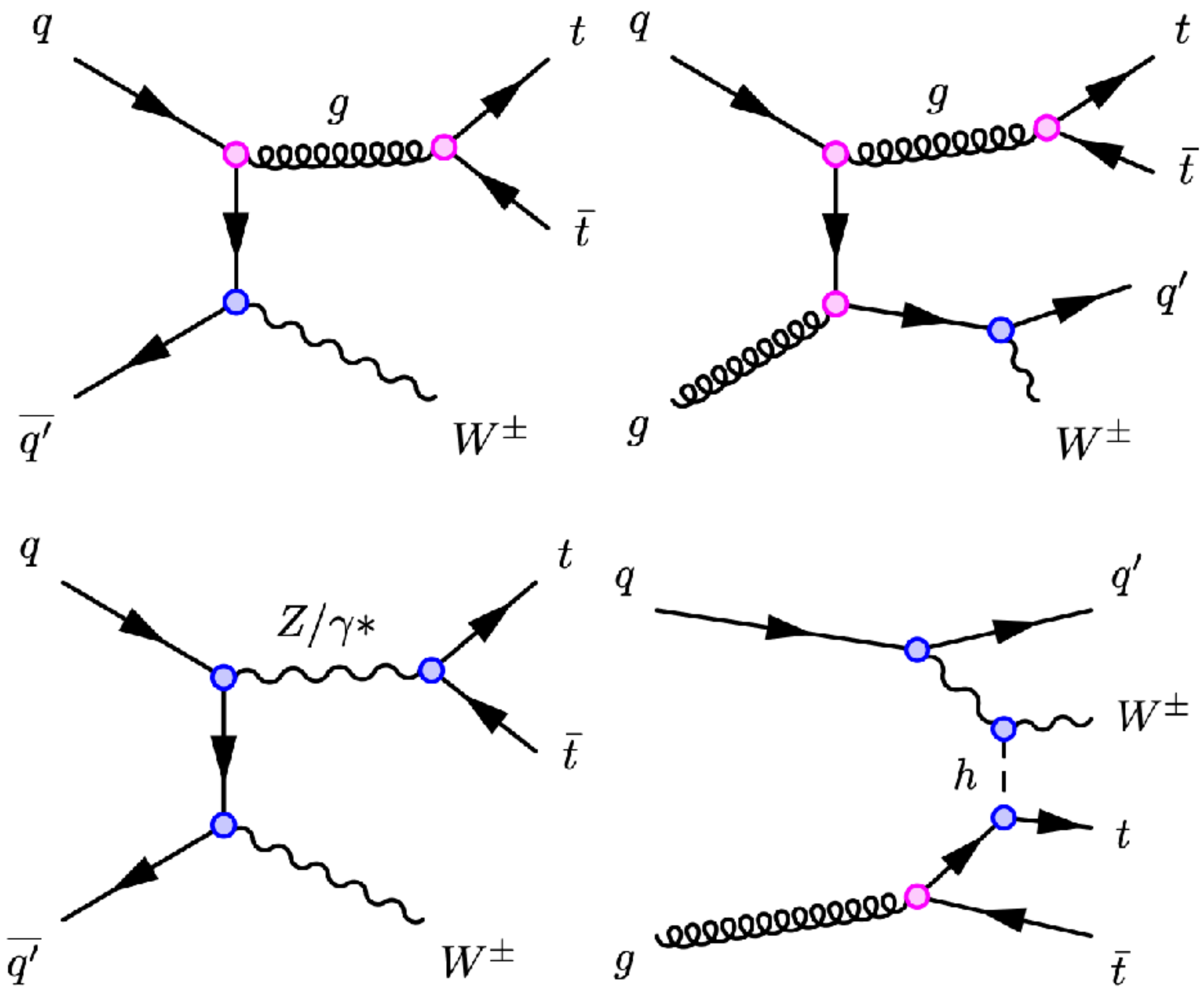


ttW theory basics

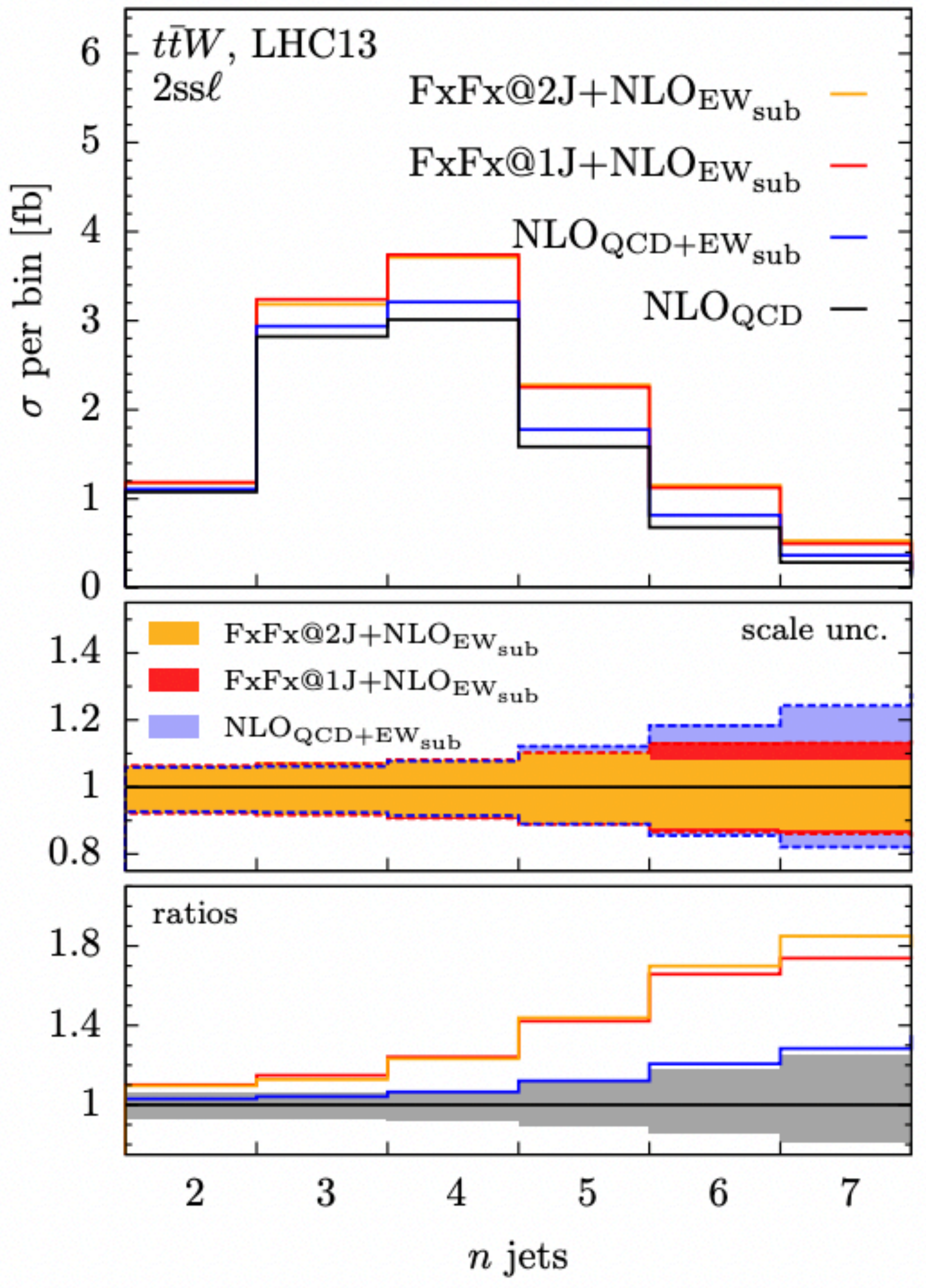
- qq-initiated process
- Large NLO QCD corrections
  - NLO multi-leg merging is important
- Large NLO EWK corrections
- Effects of resummation are small
- No NNLO calculations!



Theory predictions

- NLO + EW corrections from Powheg, MG5_aMC & Sherpa [2101.11808]
- Multi-leg merged 0-2j@NLO + EW corrections from Frederix et al. [2108.07826]

Order (default scale)	$\sigma \pm$ scale $\pm$ PDF [fb]
FxFx@2J	$691.1(8)^{+65.7(+9.5\%)}_{-74.1(-10.7\%)}$ $^{+7.3(+1.1\%)}_{-7.3(-1.1\%)}$
FxFx@2J+NLO$^{\text{sub}}_{\text{EW}}$	$738.8(8)^{+75.0(+10.1\%)}_{-81.3(-11.0\%)}$ $^{+7.5(+1.0\%)}_{-7.5(-1.0\%)}$
FxFx@2J+NLO$^{\text{lead}}_{\text{EW}}$+NLO$^{\text{sub}}_{\text{EW}}$	$722.4(8)^{+70.2(+9.7\%)}_{-77.7(-10.8\%)}$ $^{+7.2(+1.0\%)}_{-7.2(-1.0\%)}$

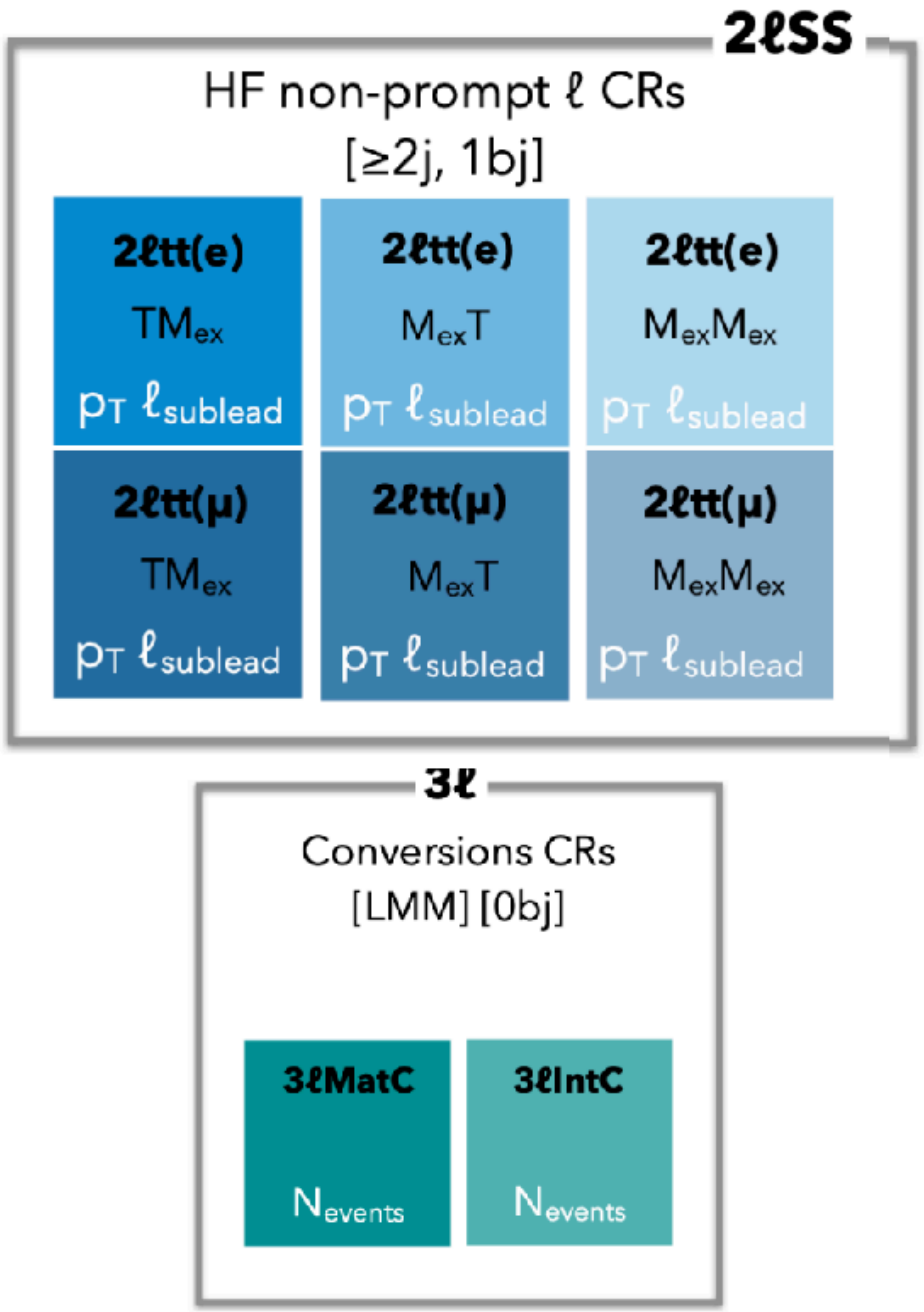


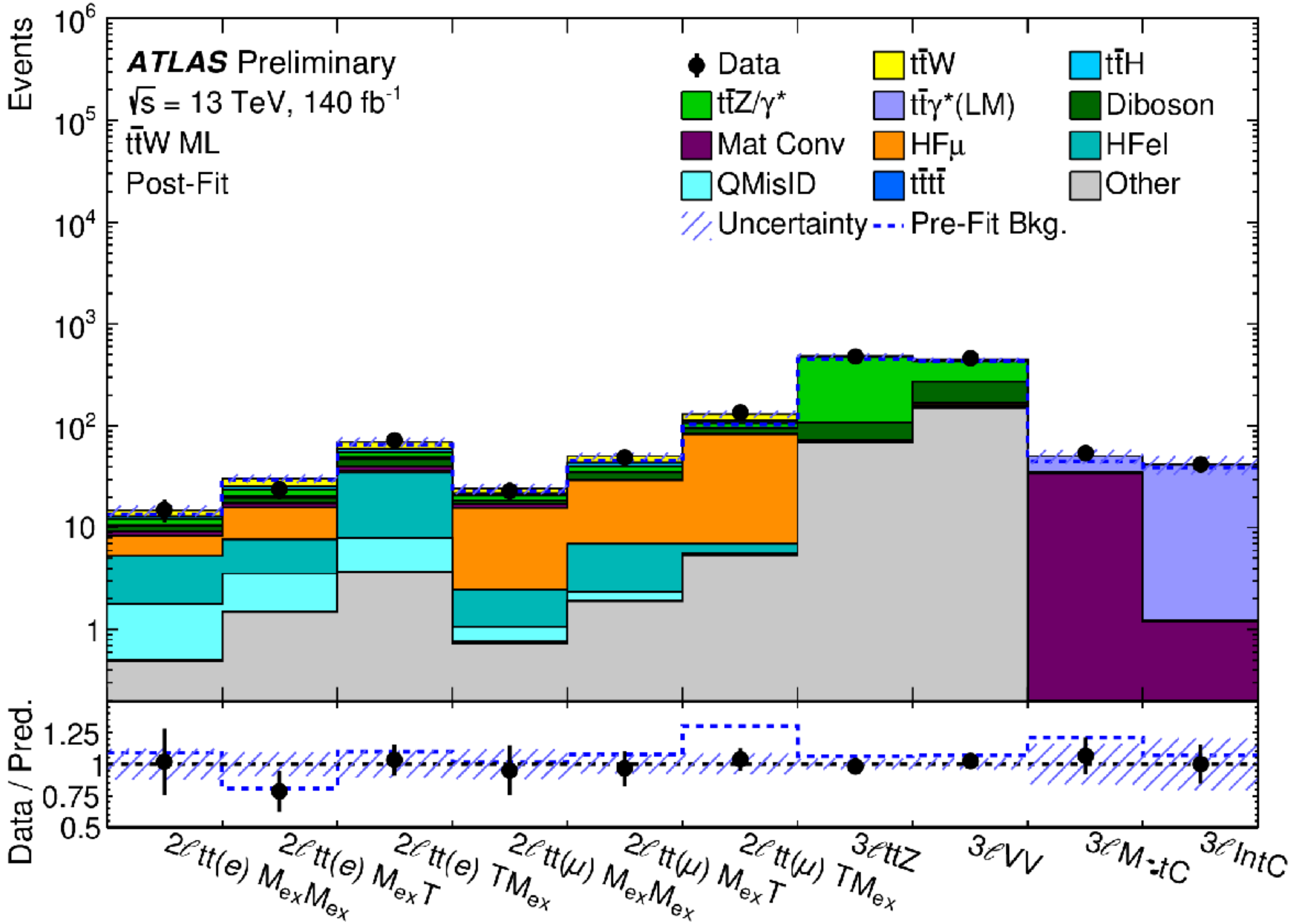
Analysis

- Presentation of recent ATLAS ttW measurement:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-019/
- Trying to understand issues observed in previous measurements (ttW, ttH, 4-tops).
- First ever differential measurement of ttW!
  - Using relatively new profile likelihood unfolding technique
  - Testing state-of-the-art theoretical predictions

Analysis

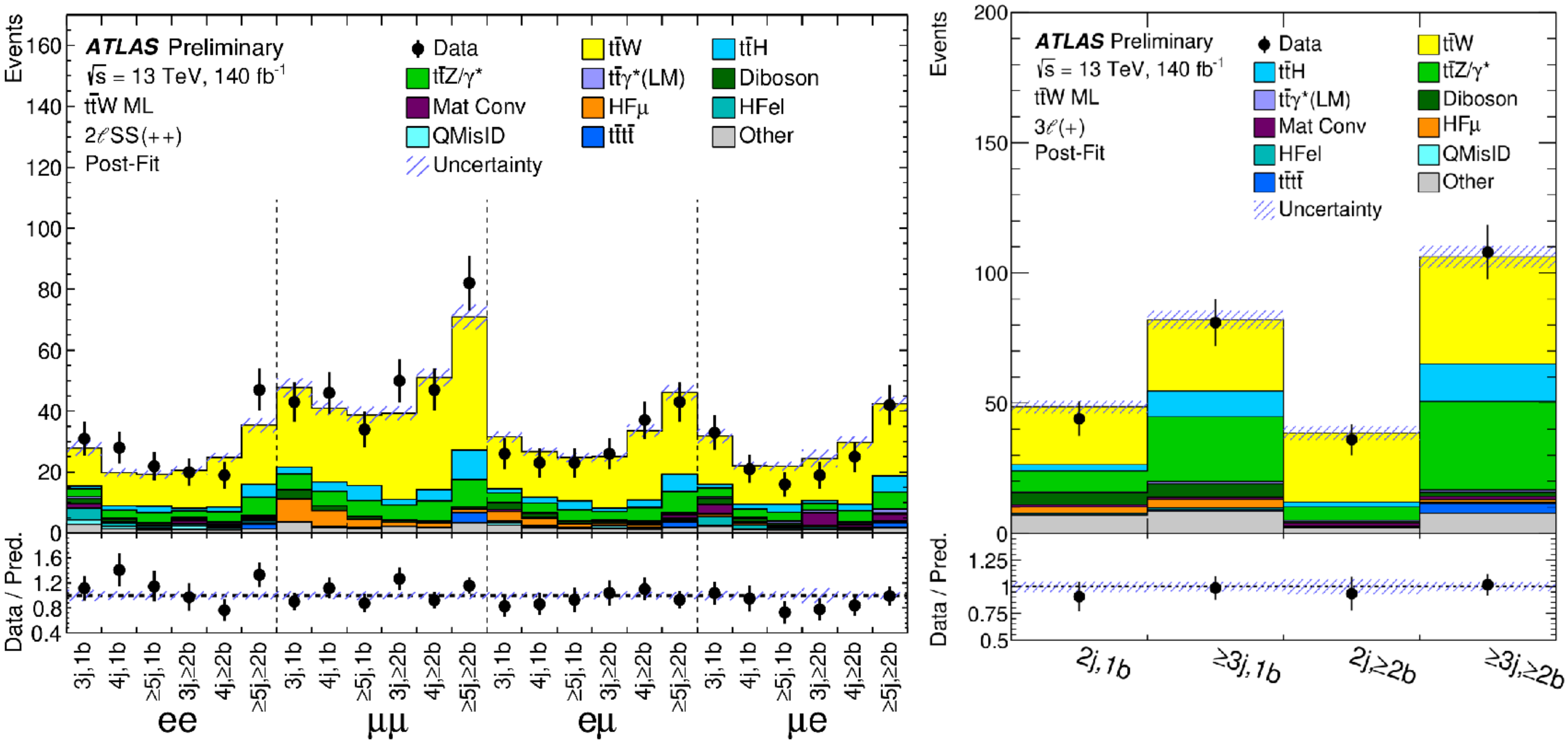
- Background estimate through "Template fit"





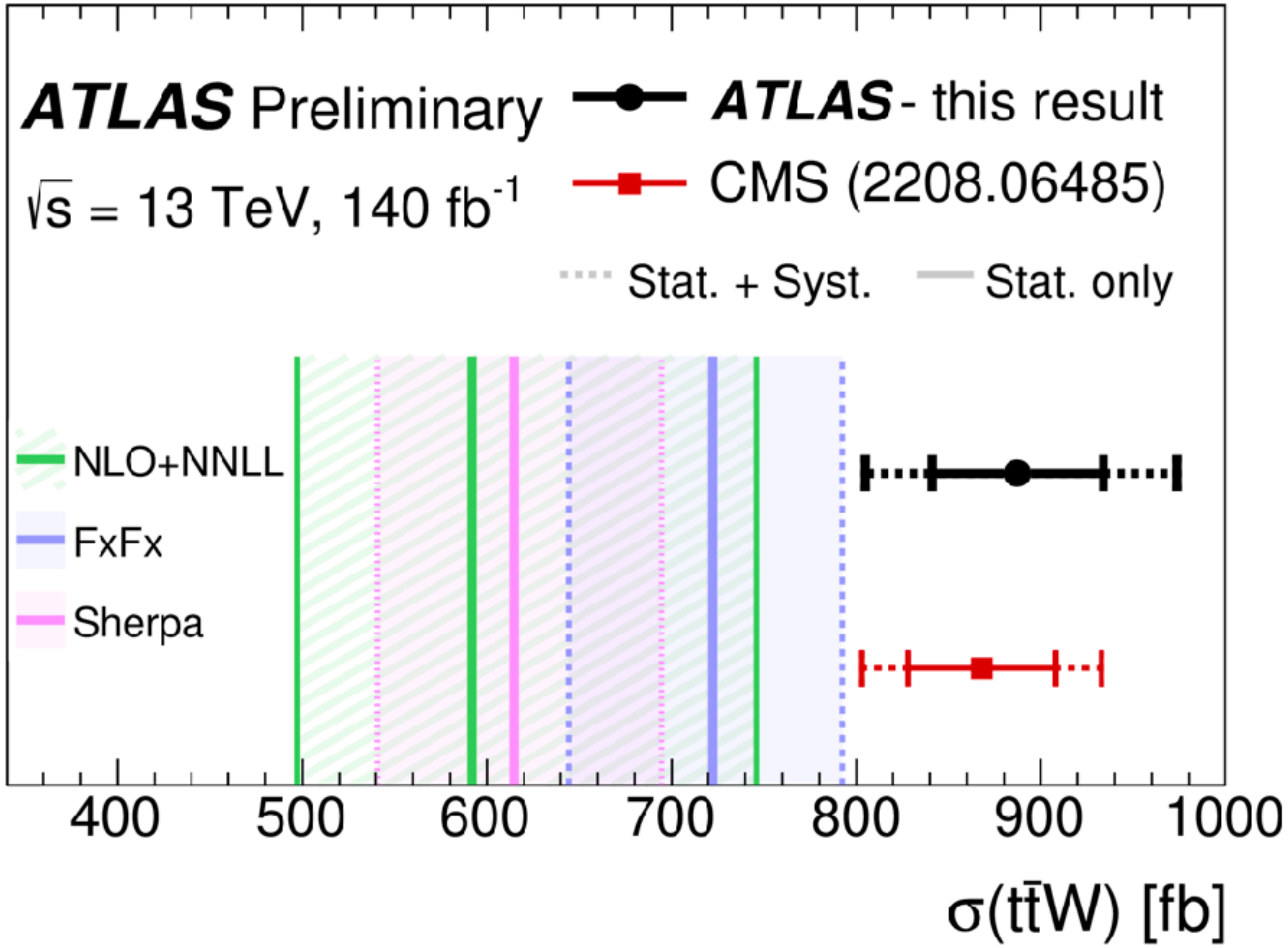
Inclusive fit

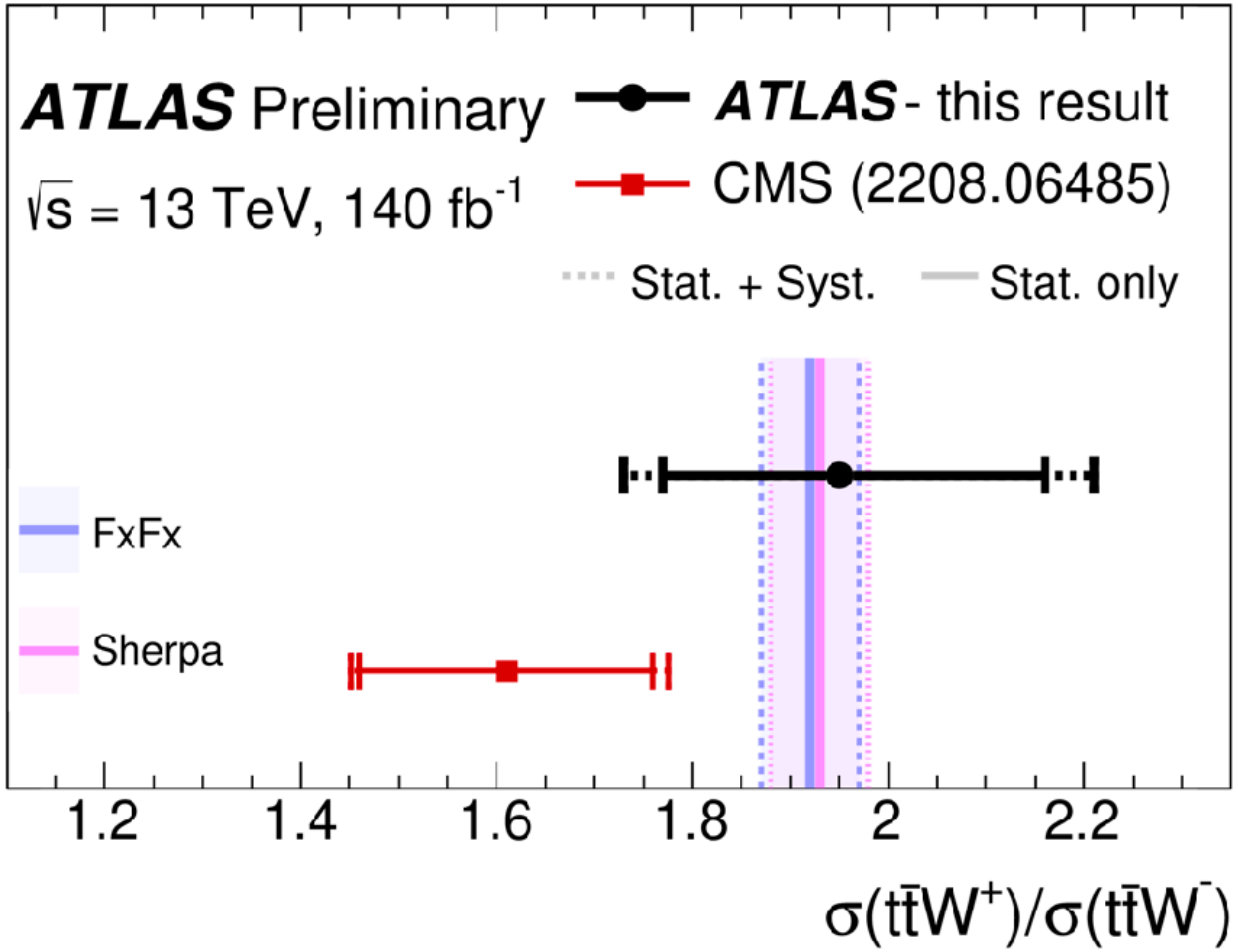
- Split by Njets, Nb and lepton charge and lepton flavour = 48 SS + 8 3L SRs



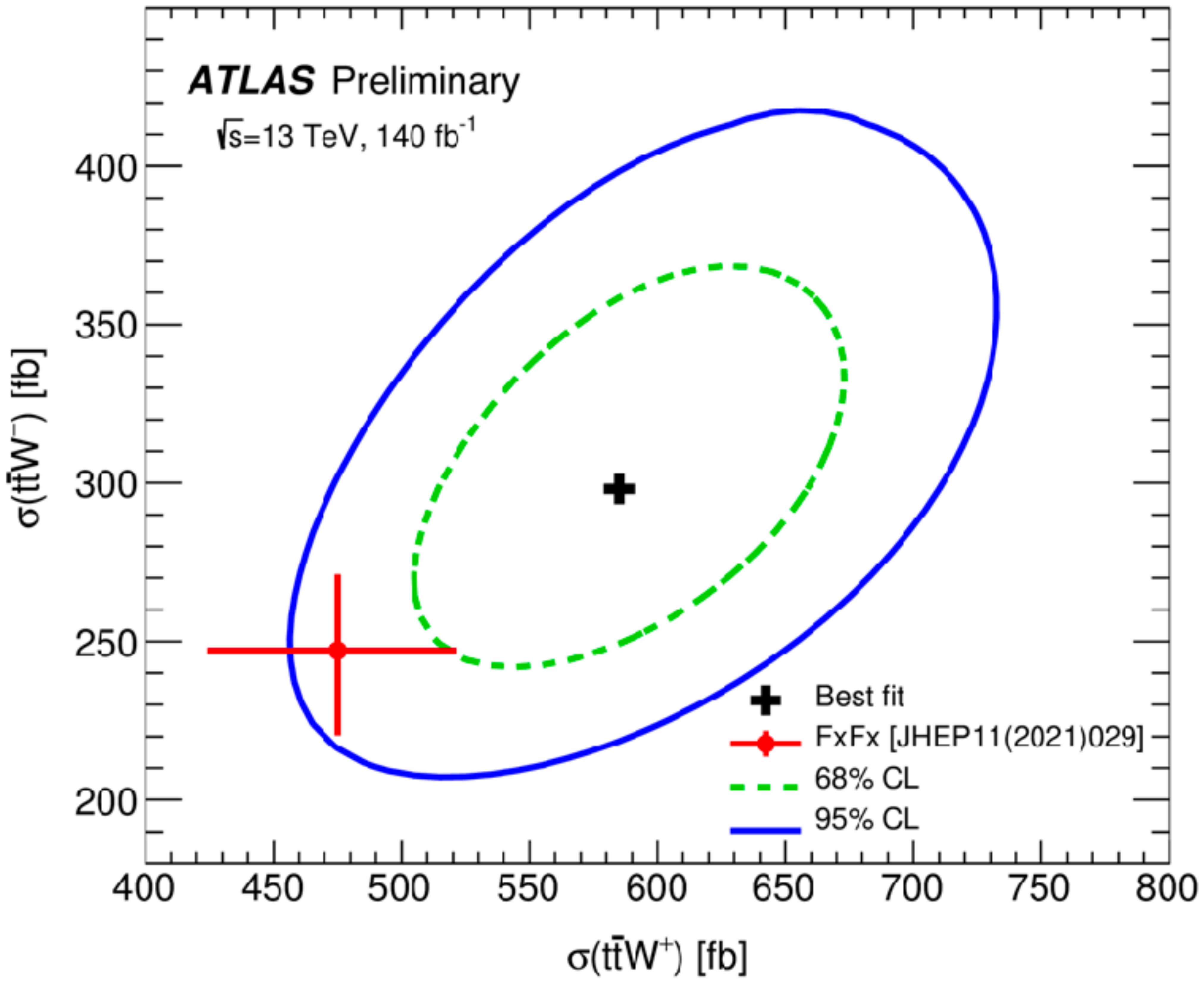
Inclusive results | XS and charge ratio

- σ(ttW) = 890 ± 50 (stat) ± 70 (syst) fb (9% relative uncertainty)
  - Consistent at 1.5σ with FxFx calculation: σ(ttW) = 722+70-78 (scale) ± 7 (PDF) fb
- σ(ttW+)/σ(ttW-) = 1.95 ± 0.21 (stat) ± 0.16 (syst) → consistent with SM





Inclusive results | 2D result and uncertainties



	$\frac{\Delta\sigma(t\bar{t}W)}{\sigma(t\bar{t}W)}$ [%]	$\frac{\Delta\sigma_{\text{fid}}(t\bar{t}W)}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta R(t\bar{t}W)}{R(t\bar{t}W)}$ [%]	$\frac{\Delta A_C^{\text{rel}}}{A_C^{\text{rel}}}$ [%]
$t\bar{t}W$ ME and PS modelling	6.0	7.0	6.0	8.0
Prompt lepton bkg. norm.	2.6	2.5	1.6	2.2
Lepton isolation BDT	2.3	2.3	1.0	1.2
Fakes/VV/$t\bar{t}Z$ norm. (free-floated)	2.3	2.7	1.8	2.5
Non-prompt lepton bkg. modelling	1.9	1.7	2.3	3.1
Trigger	1.9	1.8	0.5	0.7
MC statistics	1.5	1.6	1.9	2.5
$t\bar{t}W$ PDF	1.5	1.4	2.1	2.8
Jet energy scale	1.4	1.9	0.8	1.1
Prompt lepton bkg. modelling	1.3	1.3	1.3	1.9
Luminosity	1.0	1.0	0.08	0.13
Charge Mis-ID	0.7	0.7	0.4	0.5
Jet energy resolution	0.5	0.6	0.7	0.31
Flavour tagging	0.28	0.33	0.5	1.0
$t\bar{t}W$ Scale	0.21	0.9	1.4	1.9
Electron/photon reco.	0.15	0.2	0.12	0.3
MET	<0.10	<0.10	0.17	0.4
Muon	<0.10	<0.10	<0.10	0.4
Pile-up	<0.10	0.25	<0.10	0.3
Total syst.	8	10	8	10
Data statistics	5	5	10	16
Total	9	11	13	19

Differential results | nJets

- Unfold 9 observables. Showing here nJets:

Differential results | Uncertainties

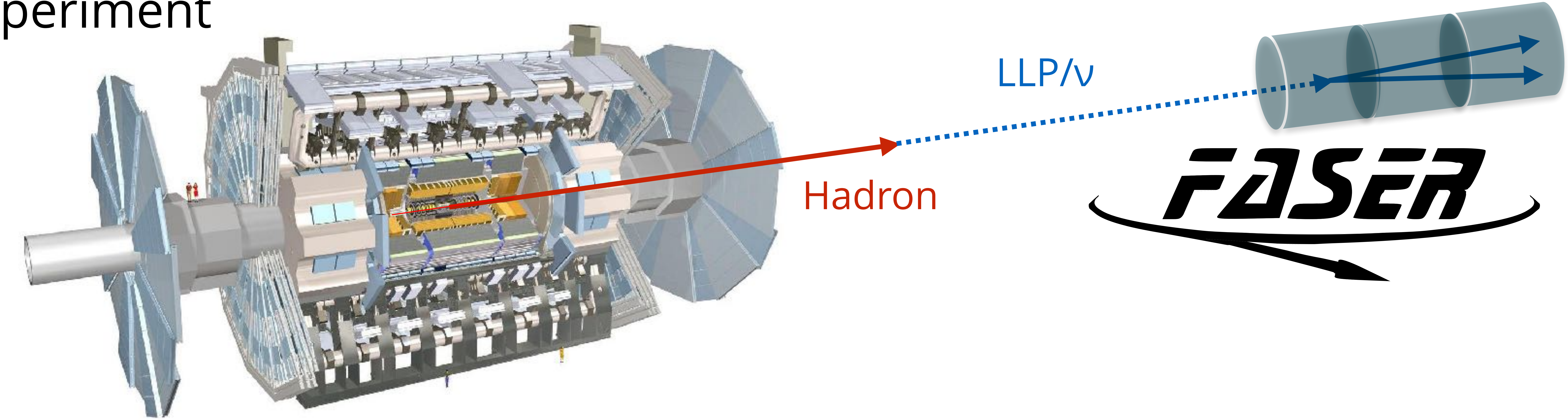
Differential results

- Off-shell theory predictions provided for 3L channel

First FASER Results

Overview

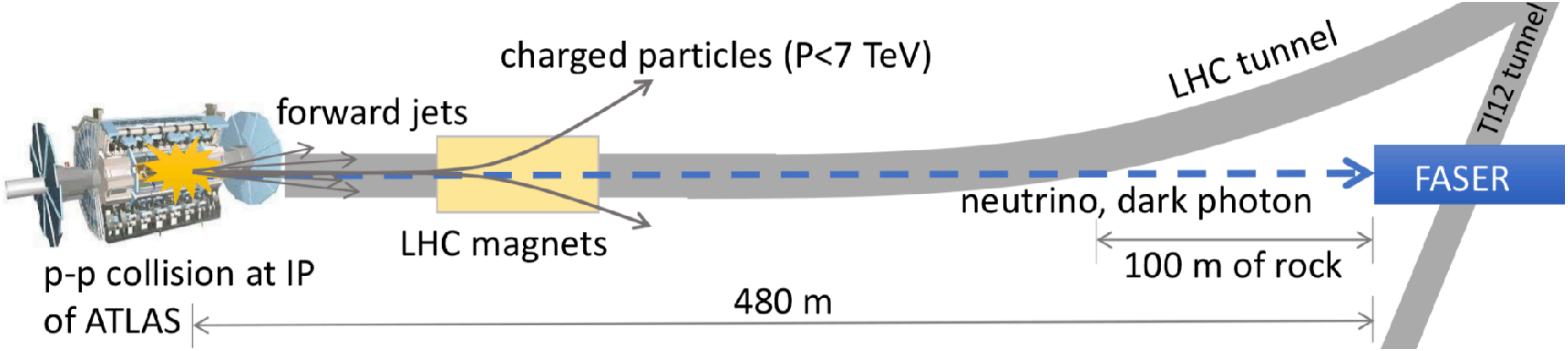
- A new experiment at CERN!



- Detector is 480m from ATLAS IP1
  - In line with beam collision axis. Transverse size of 10cm → mrad regime (η>9.1)
- Inelastic pp cross section is huge → 10^{16} collisions in Run 3 → 10^{17} π, 10^{13} B
  - From only 10^{-8} of solid angle 1% of π_0s are in acceptance.
- **Neutrinos produced copiously in decays of forward hadrons**
- **Very weakly interacting LLPs could be produced in significant numbers**

Location

- The TI12 service tunnel happens to be in just the right place for FASER:



- Old SPS → LEP tunnel
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds
    - Charged particles bent by LHC magnets

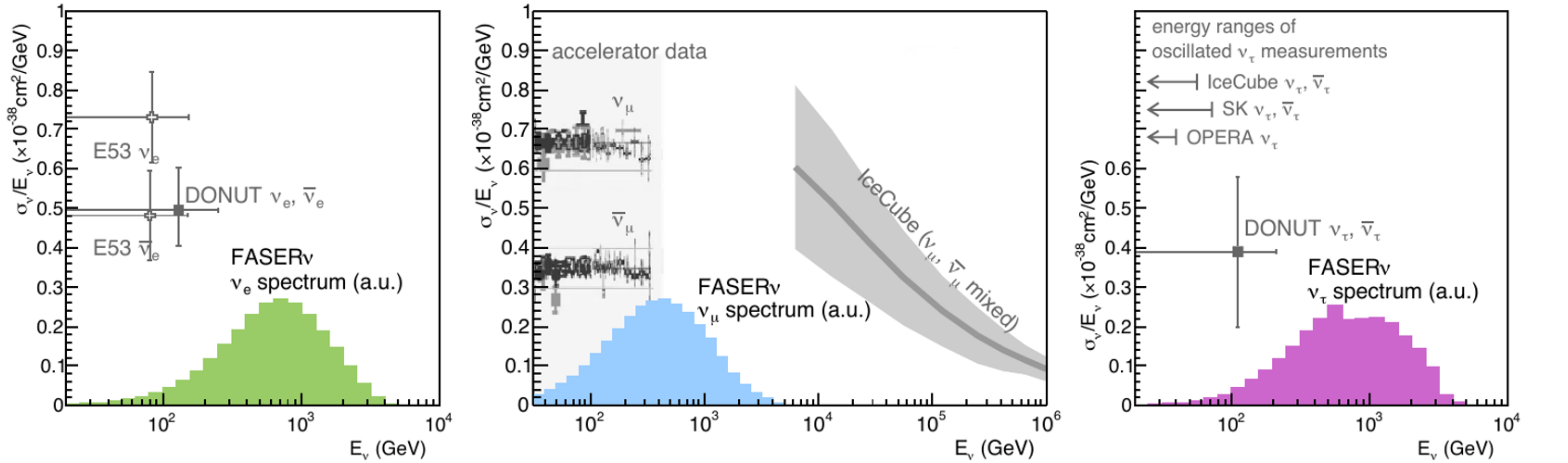
Detector design

- Small inexpensive design [2207.11427]

Installation

Neutrino analysis

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → high interaction cross section
- Extends FASER physics program into SM measurements
  - Targets measurement of highest energy man-made neutrinos
  - Energy range complementary to existing neutrino experiments



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For 35 fb^{-1}	ν_e	ν_μ	ν_τ
Main source	**Kaons**	**Pions**	**Charm**
# traversing FASERν	$\sim 10^{10}$	$\sim 10^{11}$	$\sim 10^{8}$
# interacting in FASERν	≈200	≈1200	≈4

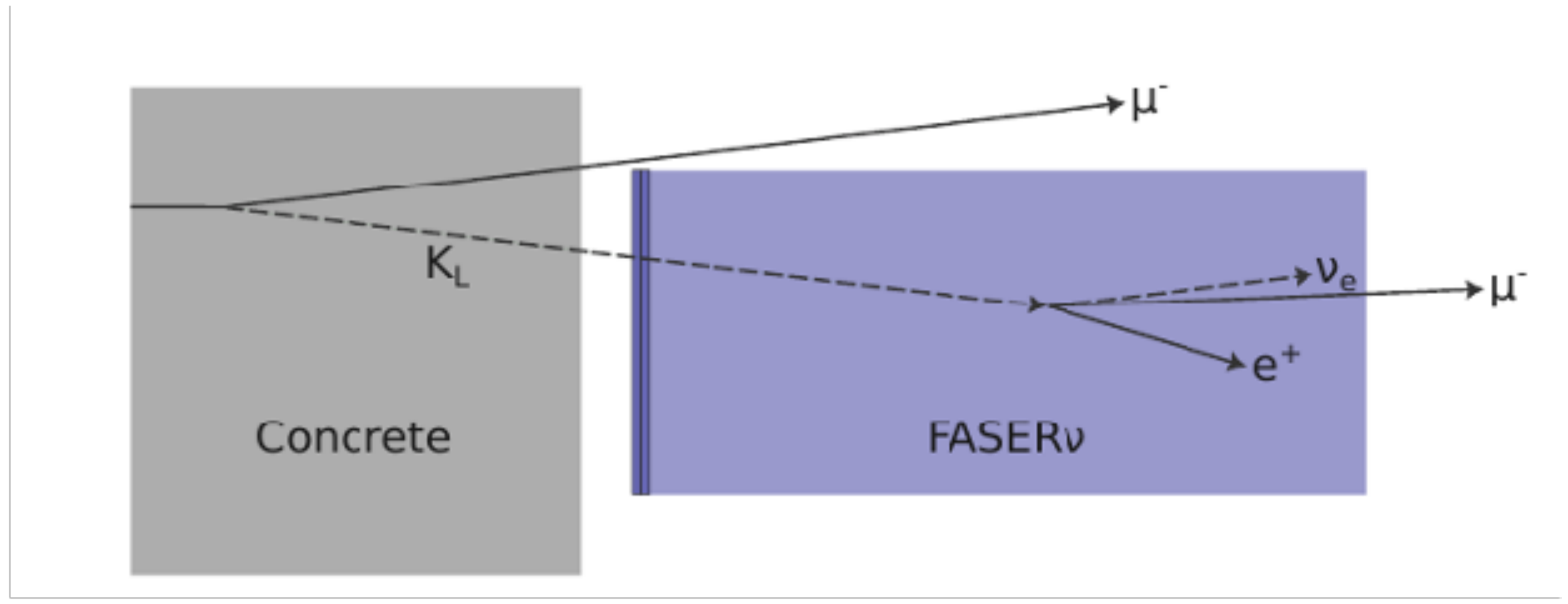
[PRD 104, 113008]

- Study at colliders originally proposed by Rújula and Rückl in 1984!

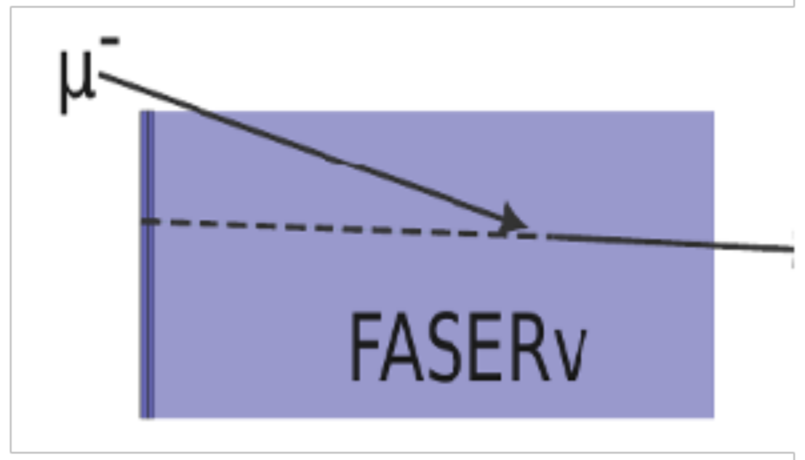
[2303.14185]

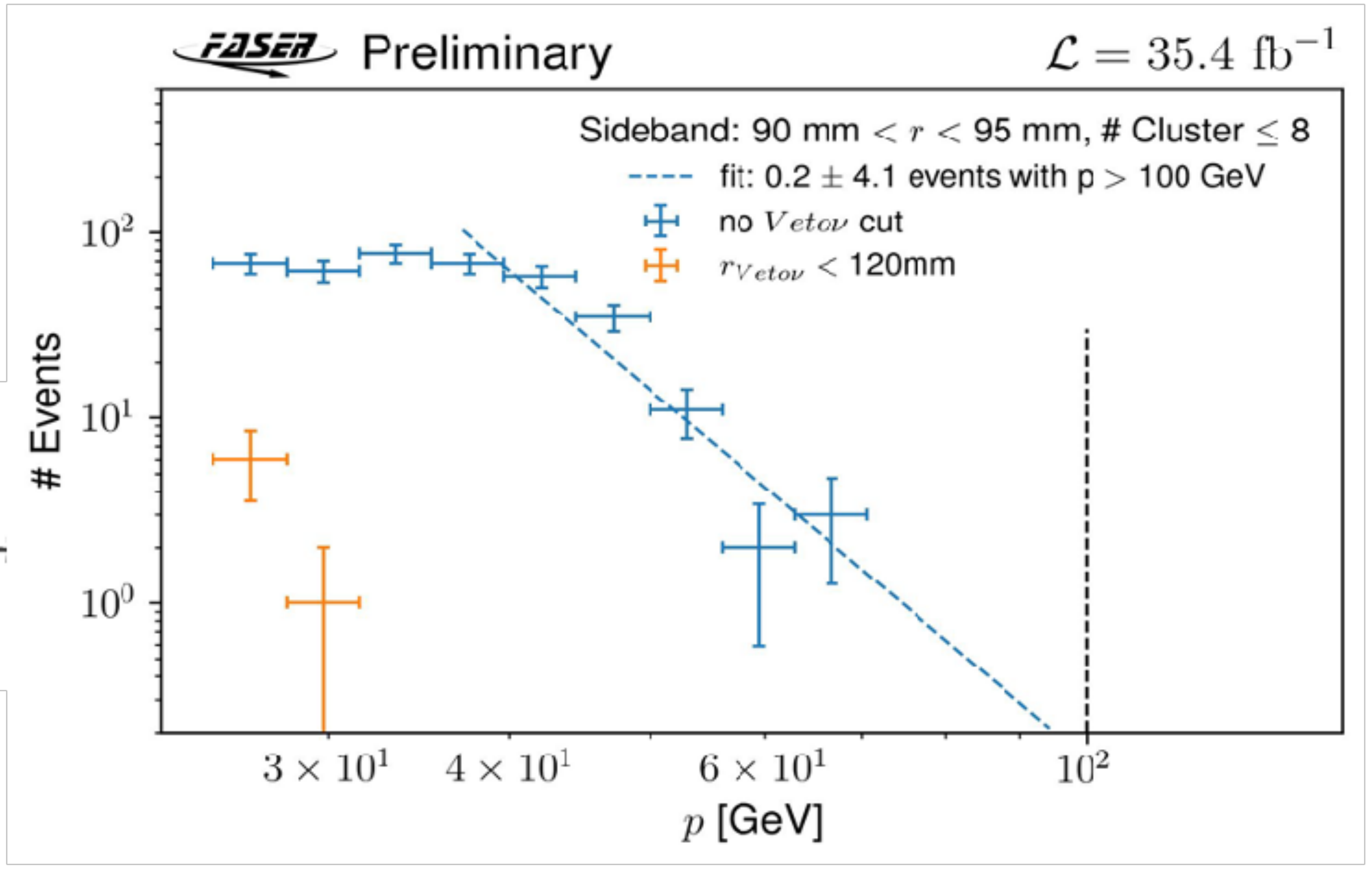
UNIVERSITY OF SUSSEX

- Neutral hadrons estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
  - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
  - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events



- Scattered muons estimated from data SB
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
  - Uncertainty from varying selection





- Veto inefficiency estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Final negligible background due to very high veto efficiency

Neutrino analysis | Selection

[2303.14185]

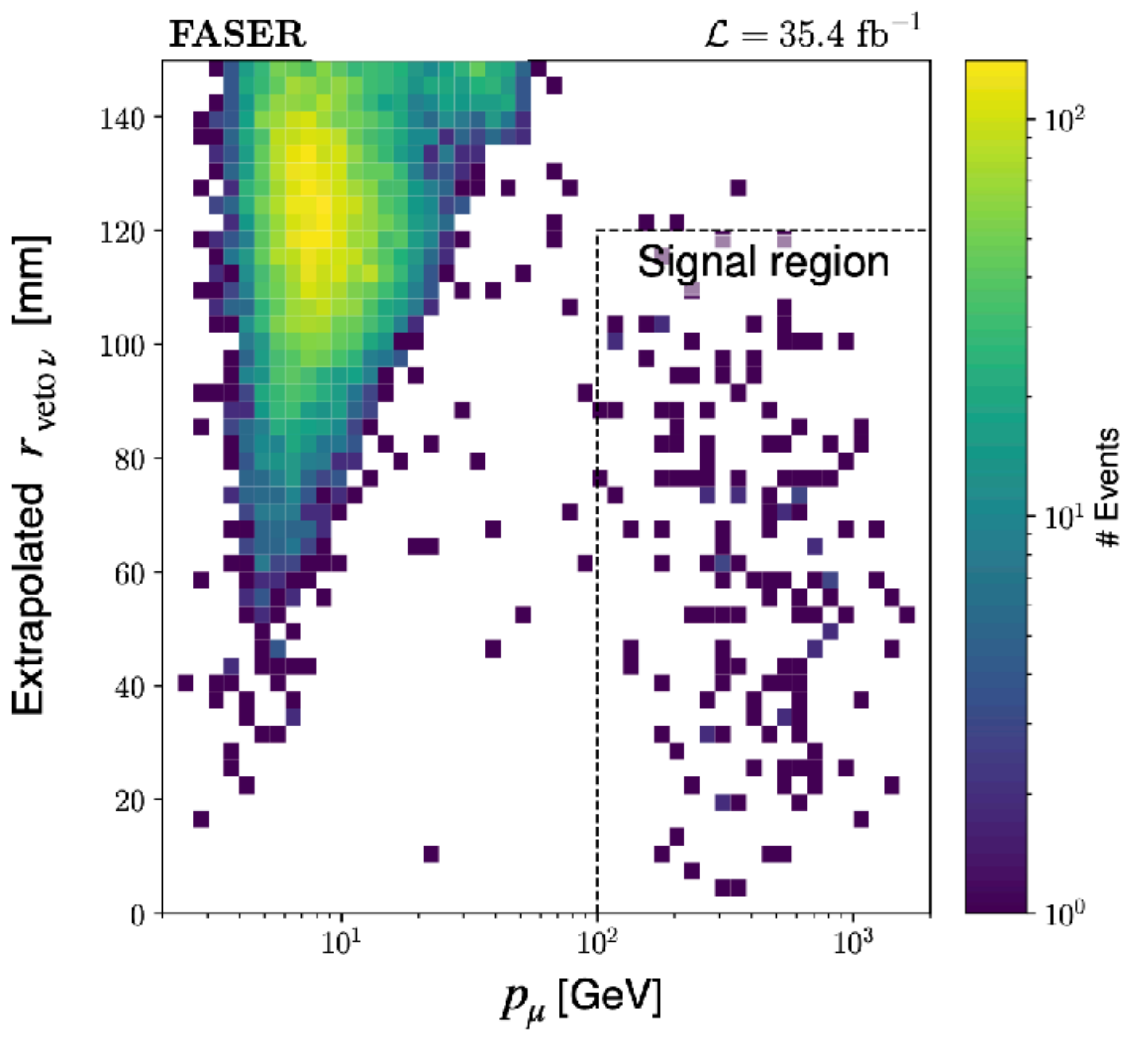
- 1. Collision event with good data quality
- 2. No signal (<40 pc) in 2 front vetos
- 3. Signal (>40 pC) in other 3 vetos
- 4. Timing and preshower consistent with ≥1 MIP
- 5. Exactly 1 good fiducial (r < 95 mm) track
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto

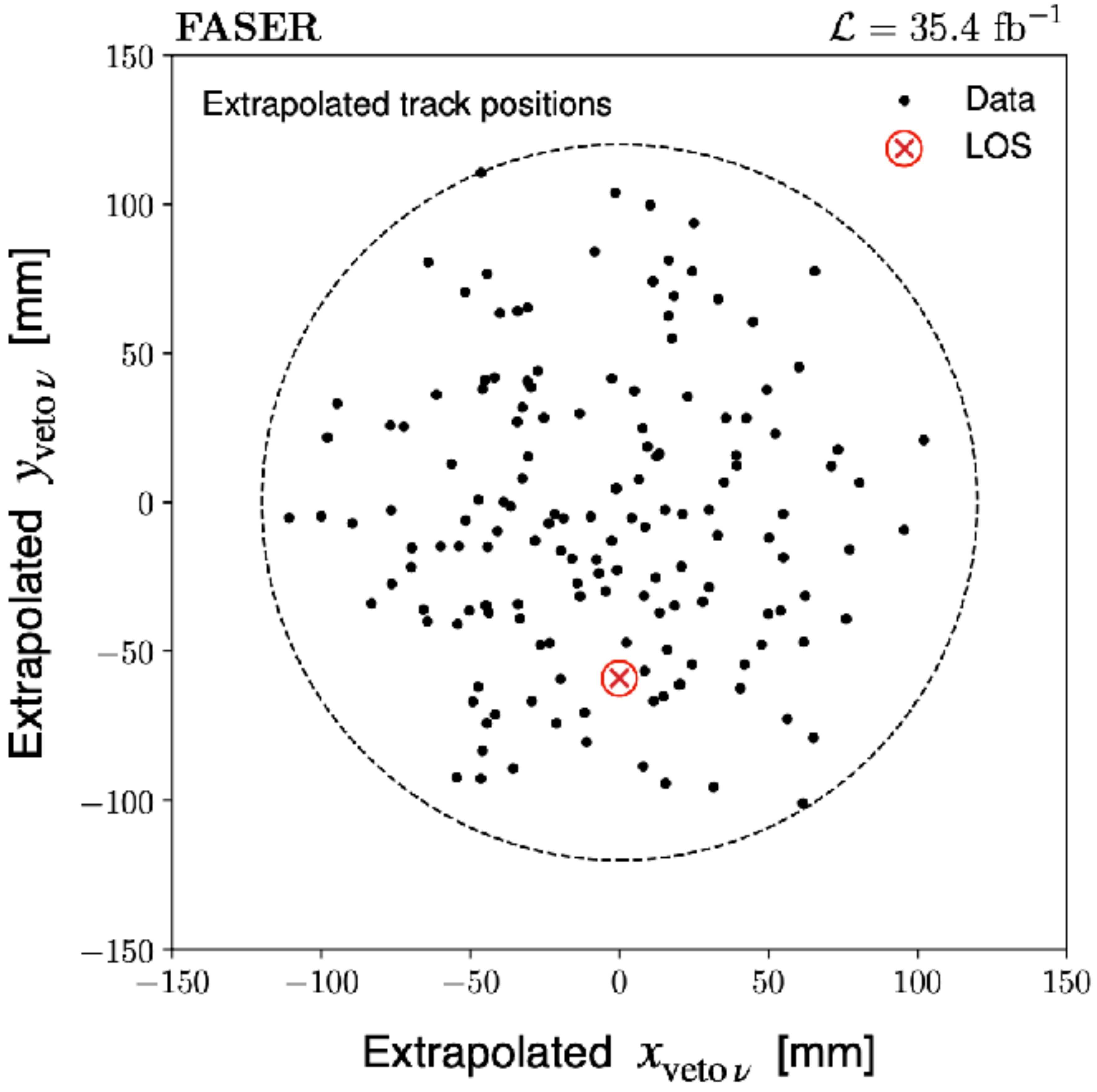
Neutrino analysis | Results

[2303.14185]

Candidate	Events
n_0	153
n_{10}	4
n_{01}	6
n_2	64014695

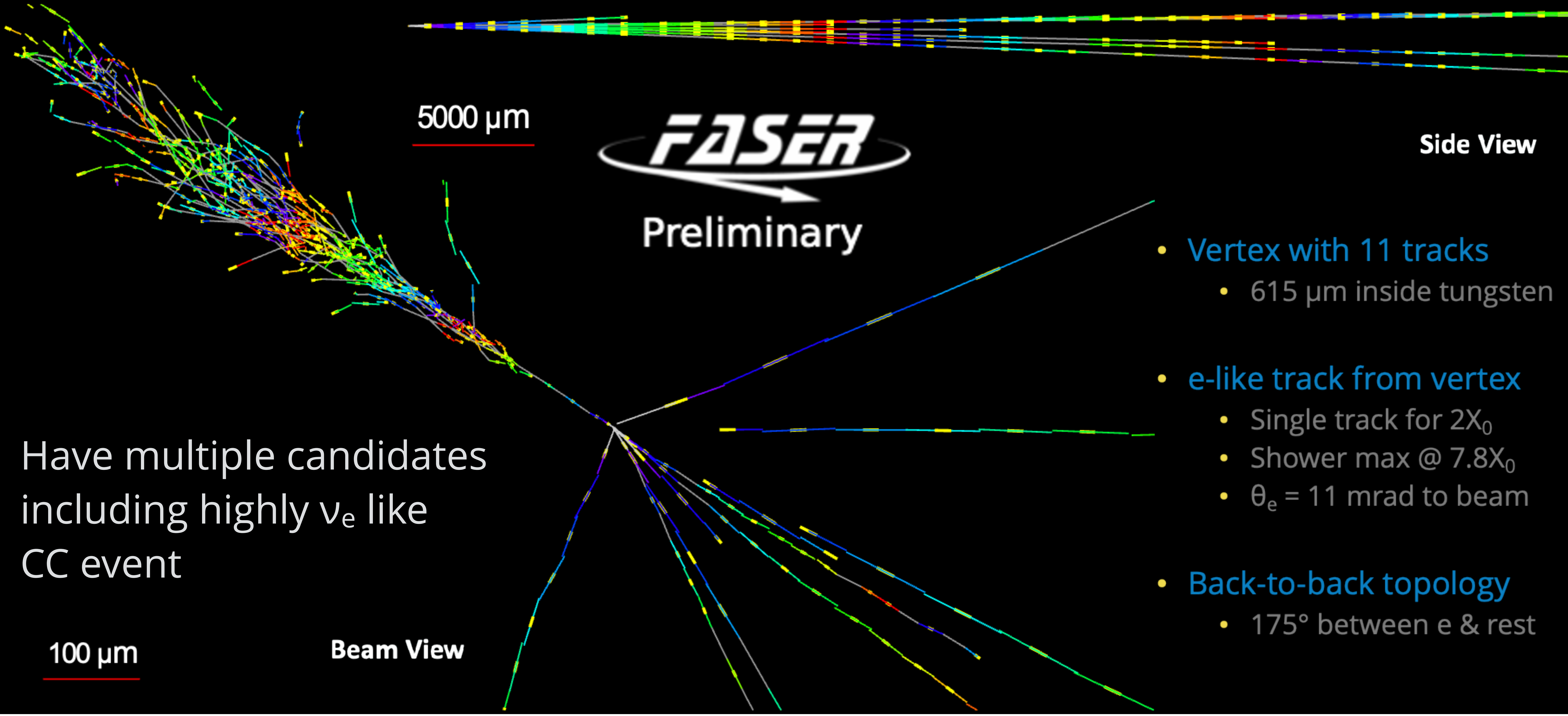
- Unblinded to find 153 events with no veto signal
  - Just 10 events with one veto signal
- **First direct detection of collider neutrinos!**
  - With signal significance of 16σ
  - Expected 151 ± 41 events from GENIE simulation





FASERν | Emulsion candidate

- Analysis of FASERν emulsion detector underway

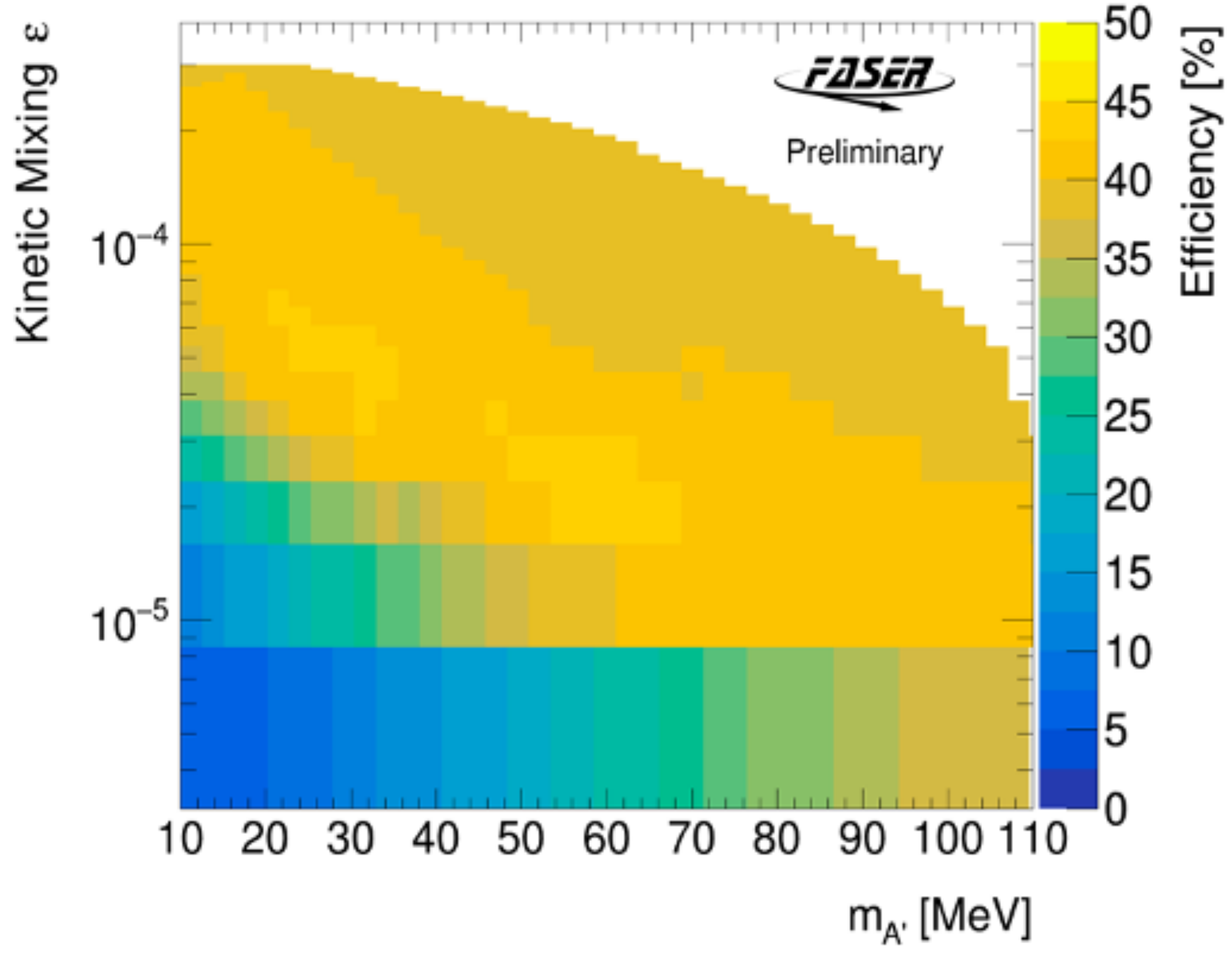


- Have multiple candidates including highly ν_e like CC event

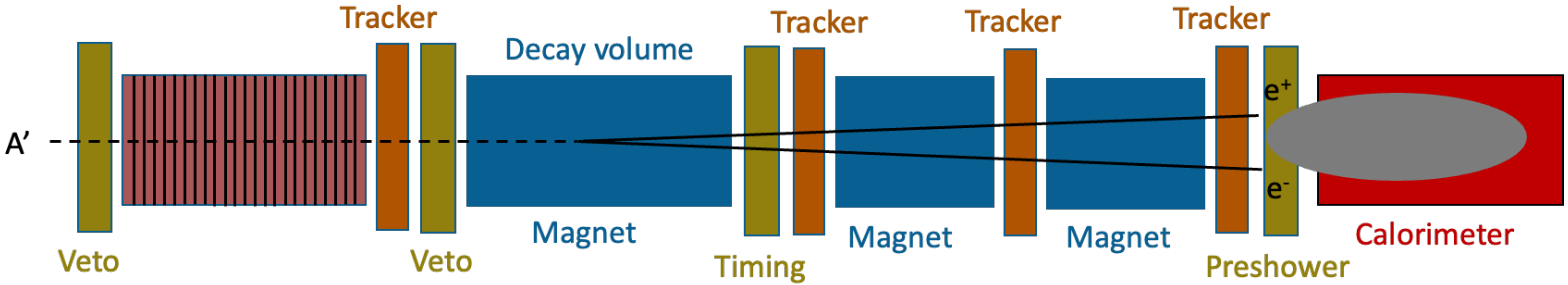
- Vertex with 11 tracks
  - 615 μm inside tungsten
- e-like track from vertex
  - Single track for $2X_0$
  - Shower max @ $7.8X_0$
  - θ_e = 11 mrad to beam
- Back-to-back topology
  - 175° between e & rest

Dark Photon Search | Selection

- Simple and robust A'→e^+e^- selection
  - Blind events with no veto signal and E(calo) > 100 GeV
- Selection
  - 1. Collision event with good data quality
  - 2. No signal (< 40 pc) in any veto scintillator
  - 3. Timing and preshower consistent with ≥2 MIPs
  - 4. Exactly 2 good fiducial tracks
    - p > 20 GeV and r < 95 mm && Extrapolating to r < 95 mm at vetos
  - 5. Calo E > 500 GeV



- Efficiency of ~40% across sensitive region



[CERN-FASER-CONF-2023-001]

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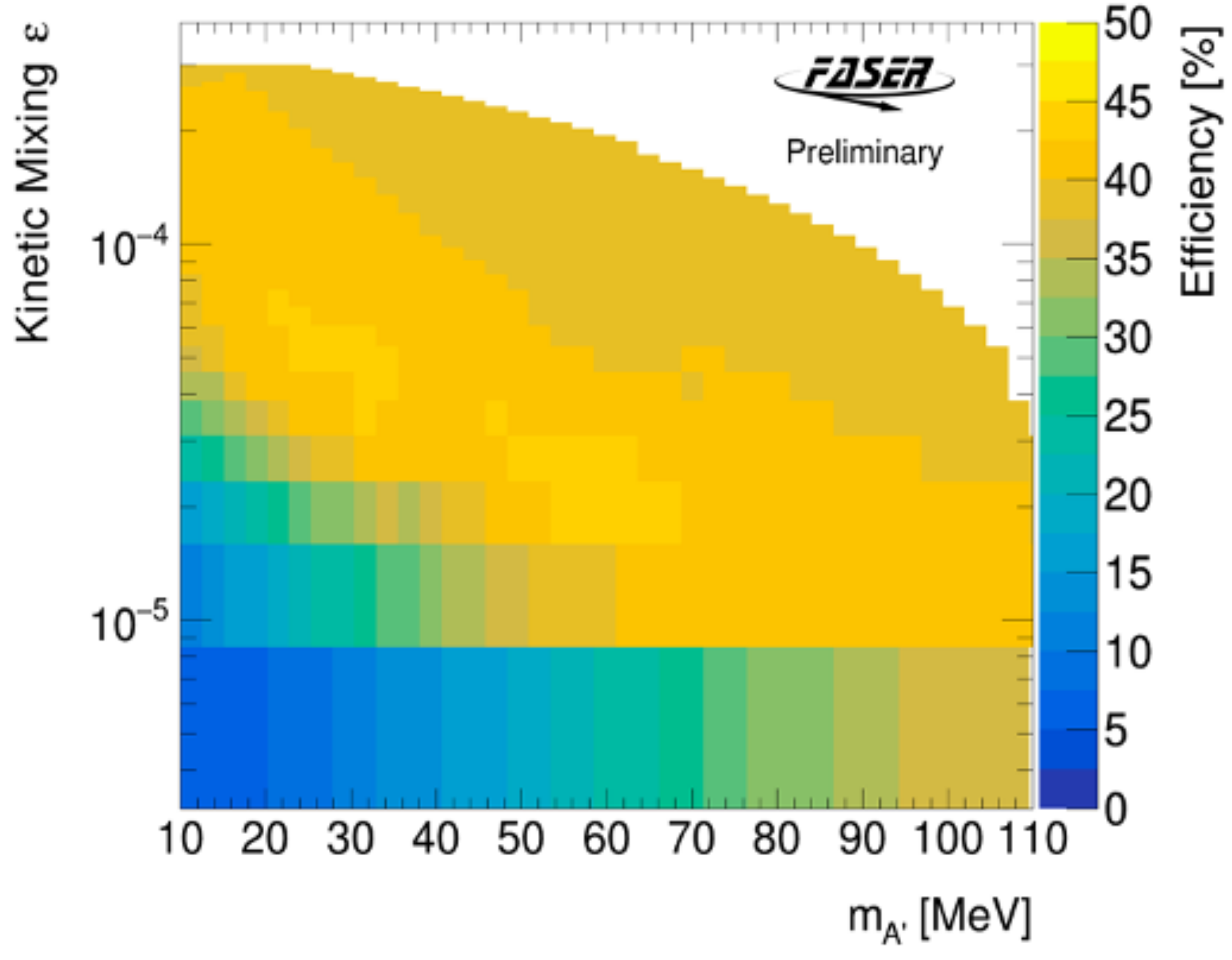

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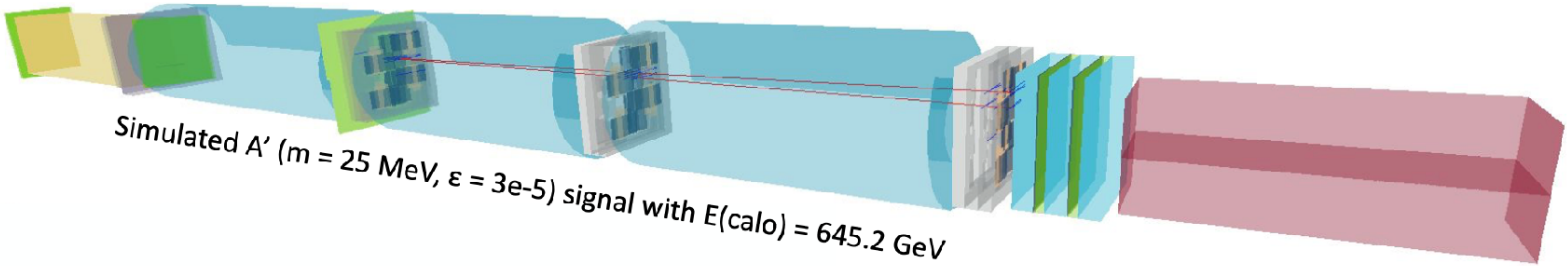
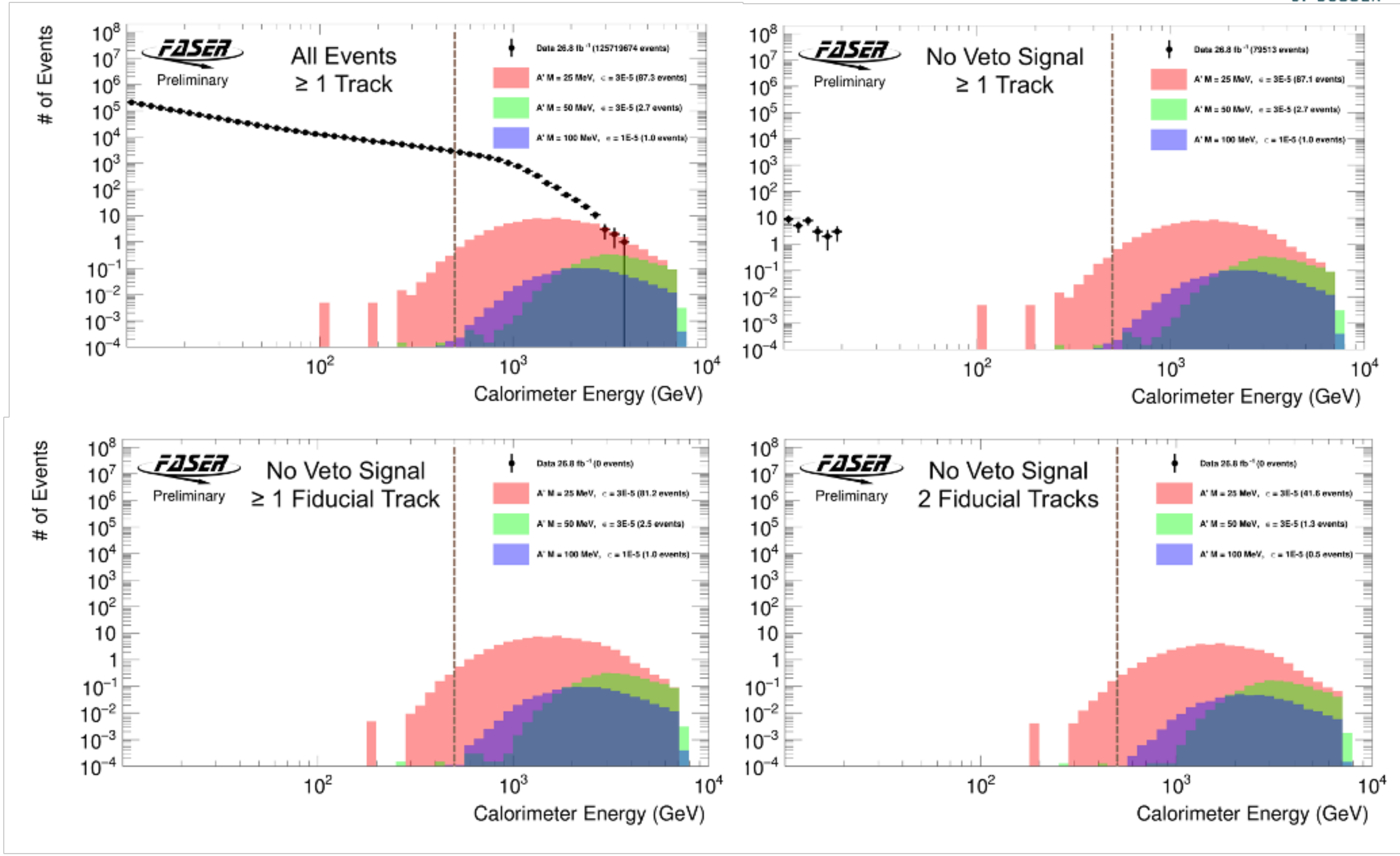


[CERN-FASER-CONF-2023-001]

Dark Photon Search | Results

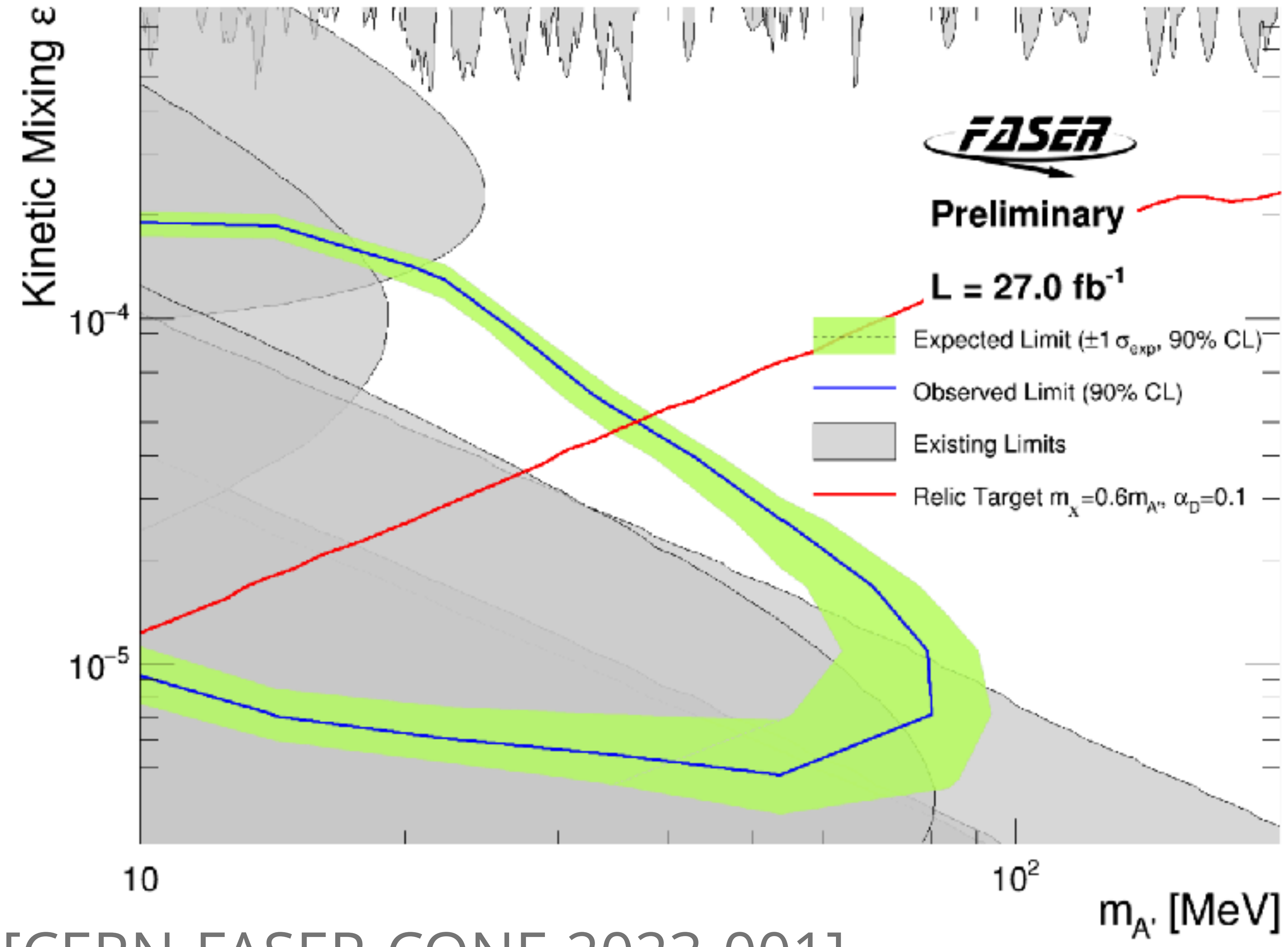
- No events in unblinded signal region
  - Not even any with ≥1 fiducial track

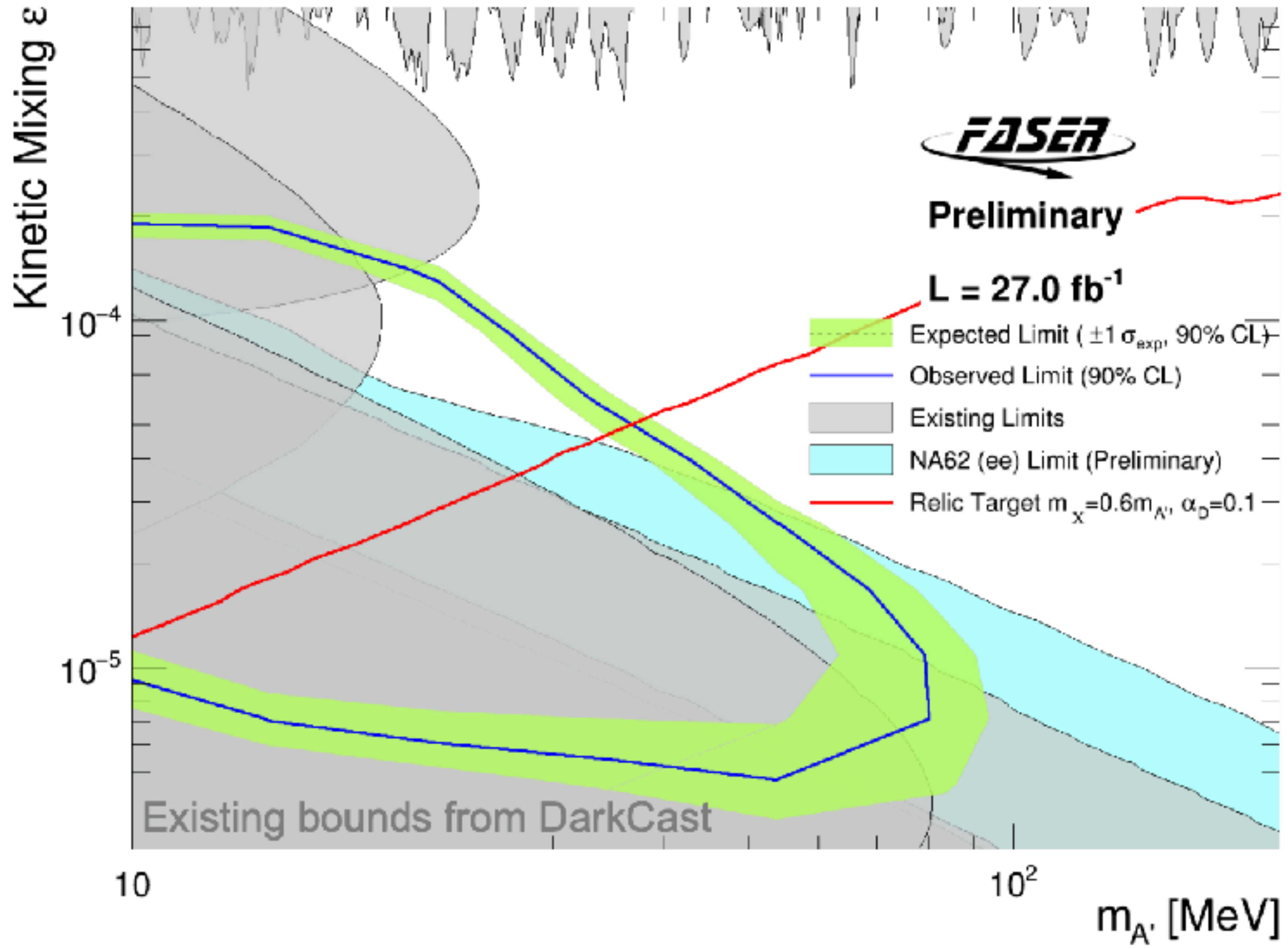


[CERN-FASER-CONF-2023-001]

Dark Photon Search | Limits

- After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.
- First incursion (with NA62) into thermal relic region from low ε since 1990’s.
- Background-free analysis bodes well for future sensitivity.
  - Expect factor of ~10 more luminosity in Run 3 from 2022-25.

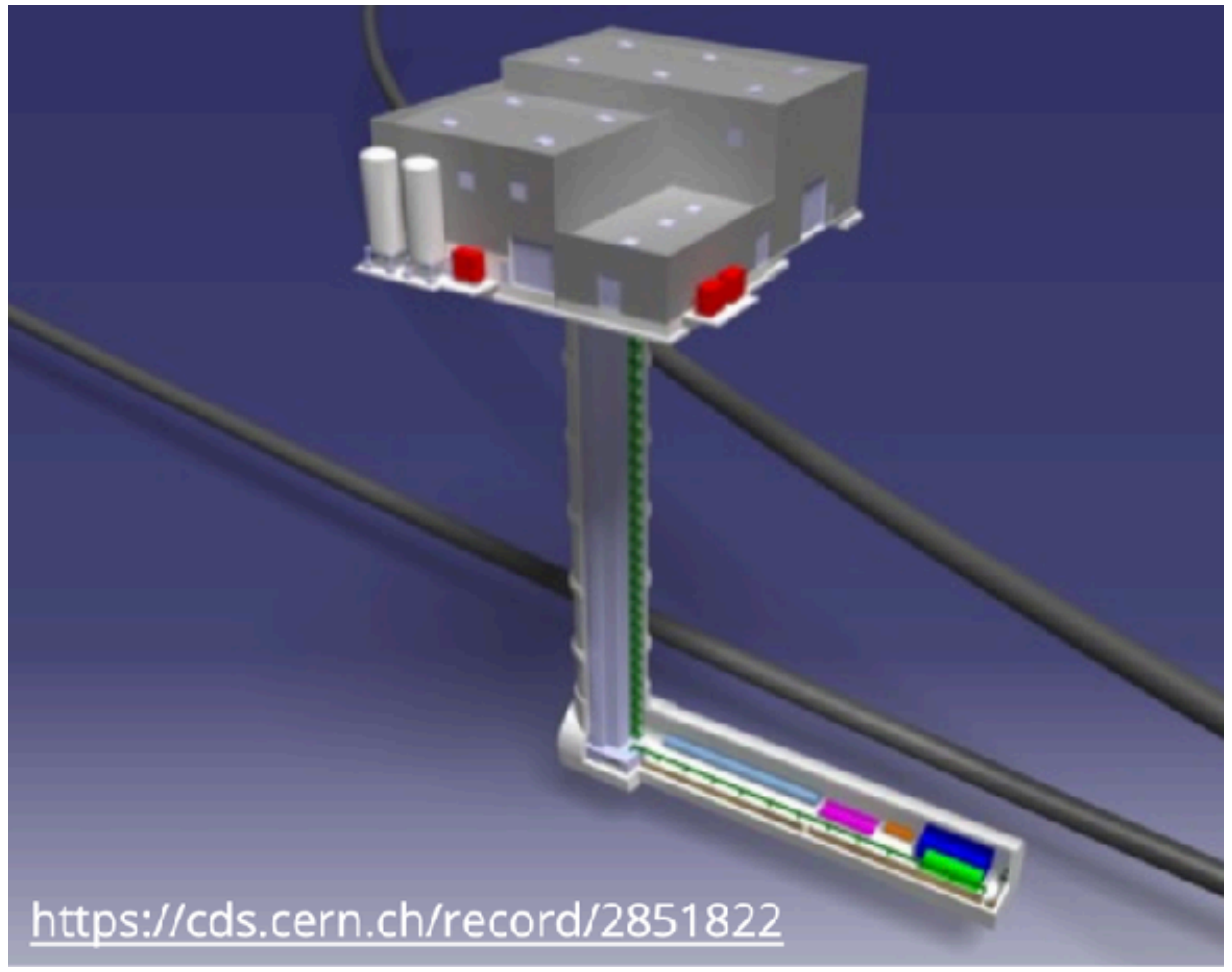


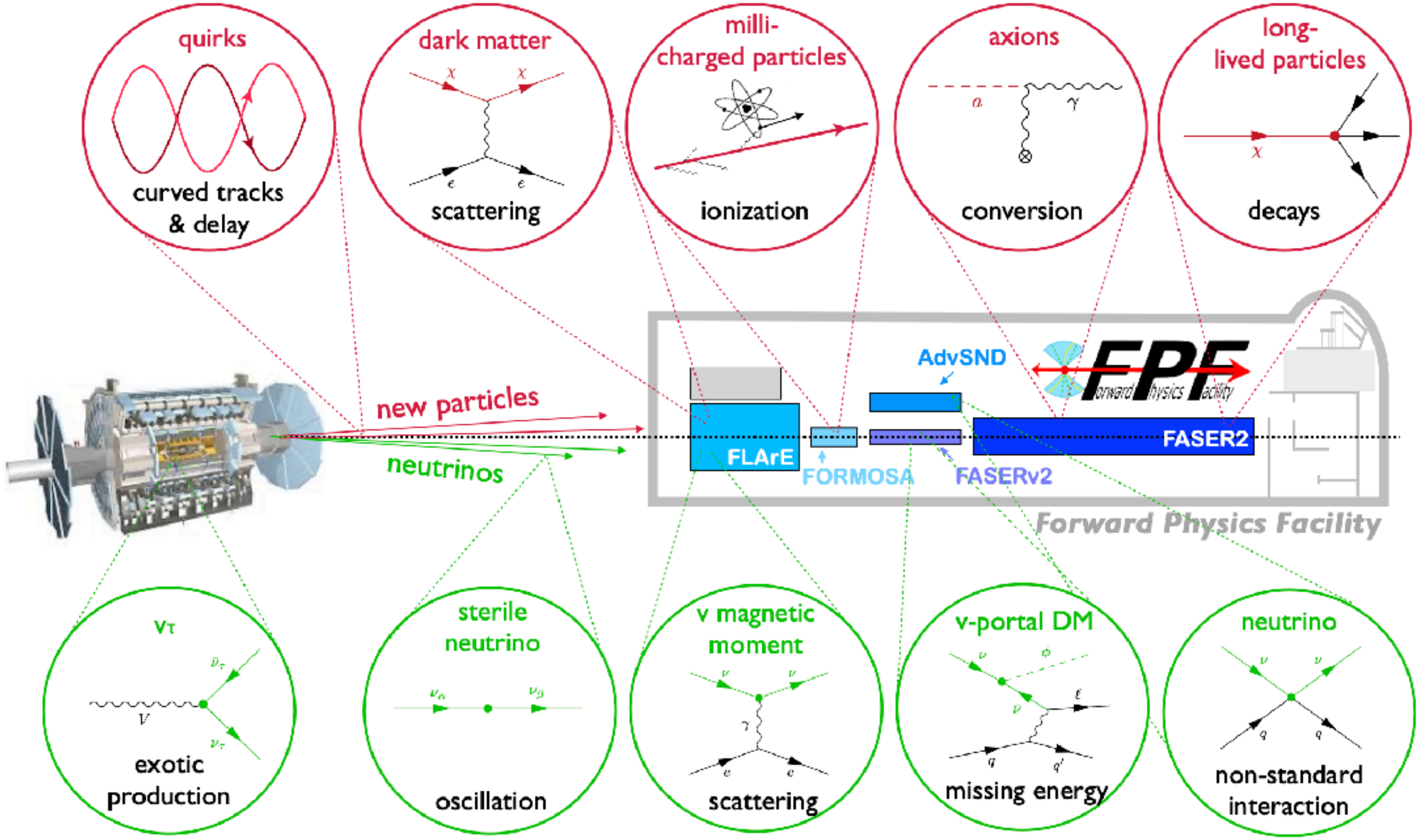


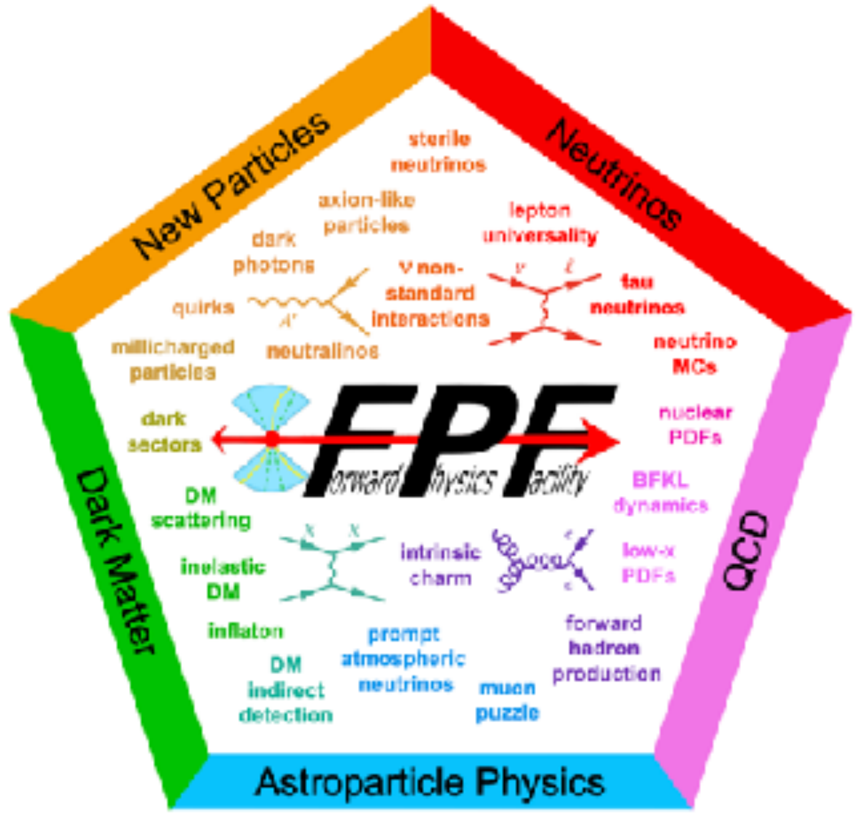
[CERN-FASER-CONF-2023-001]

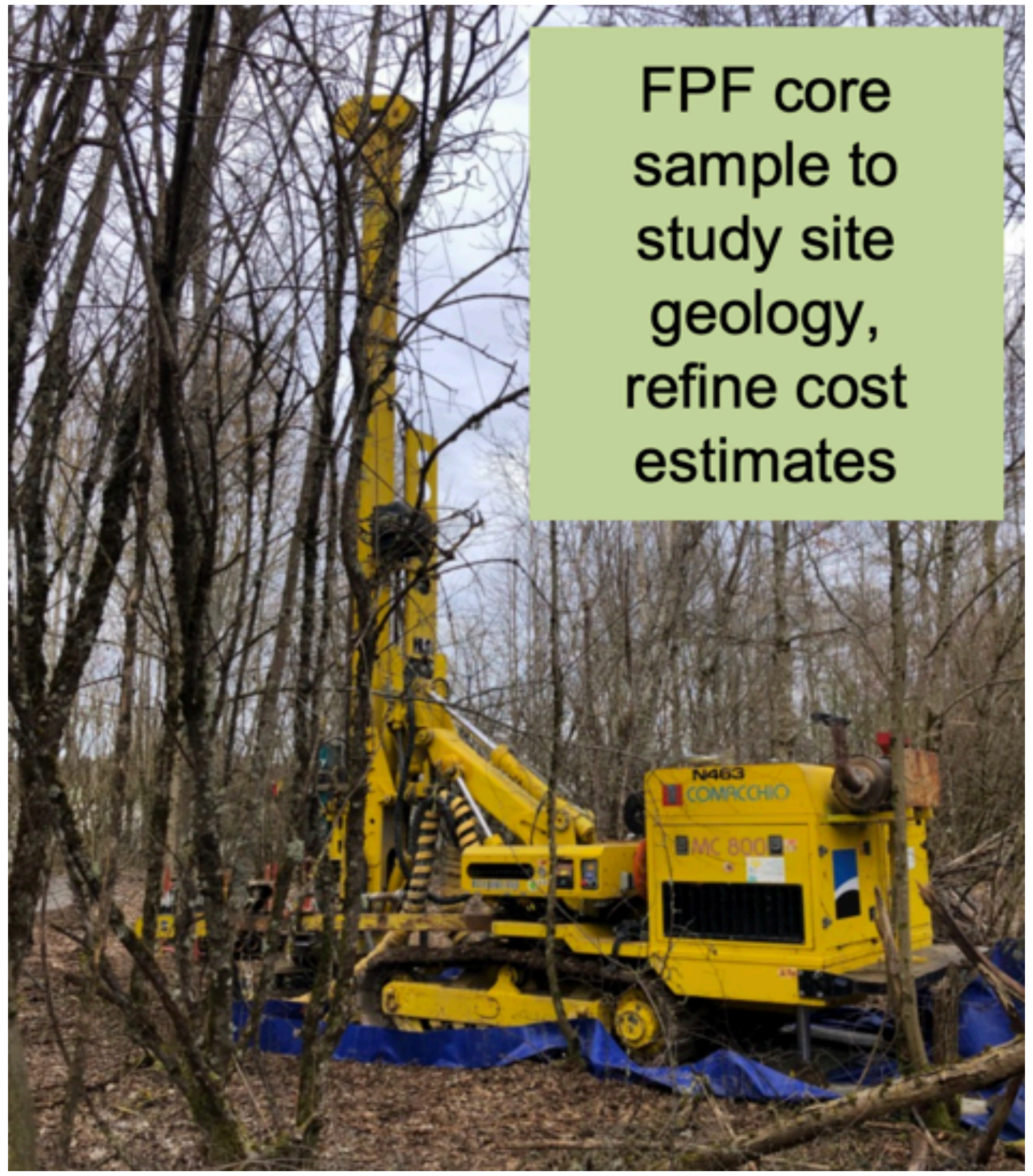
Forward Physics Facility

- FPF Papers:
  - FPF "Short" Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)



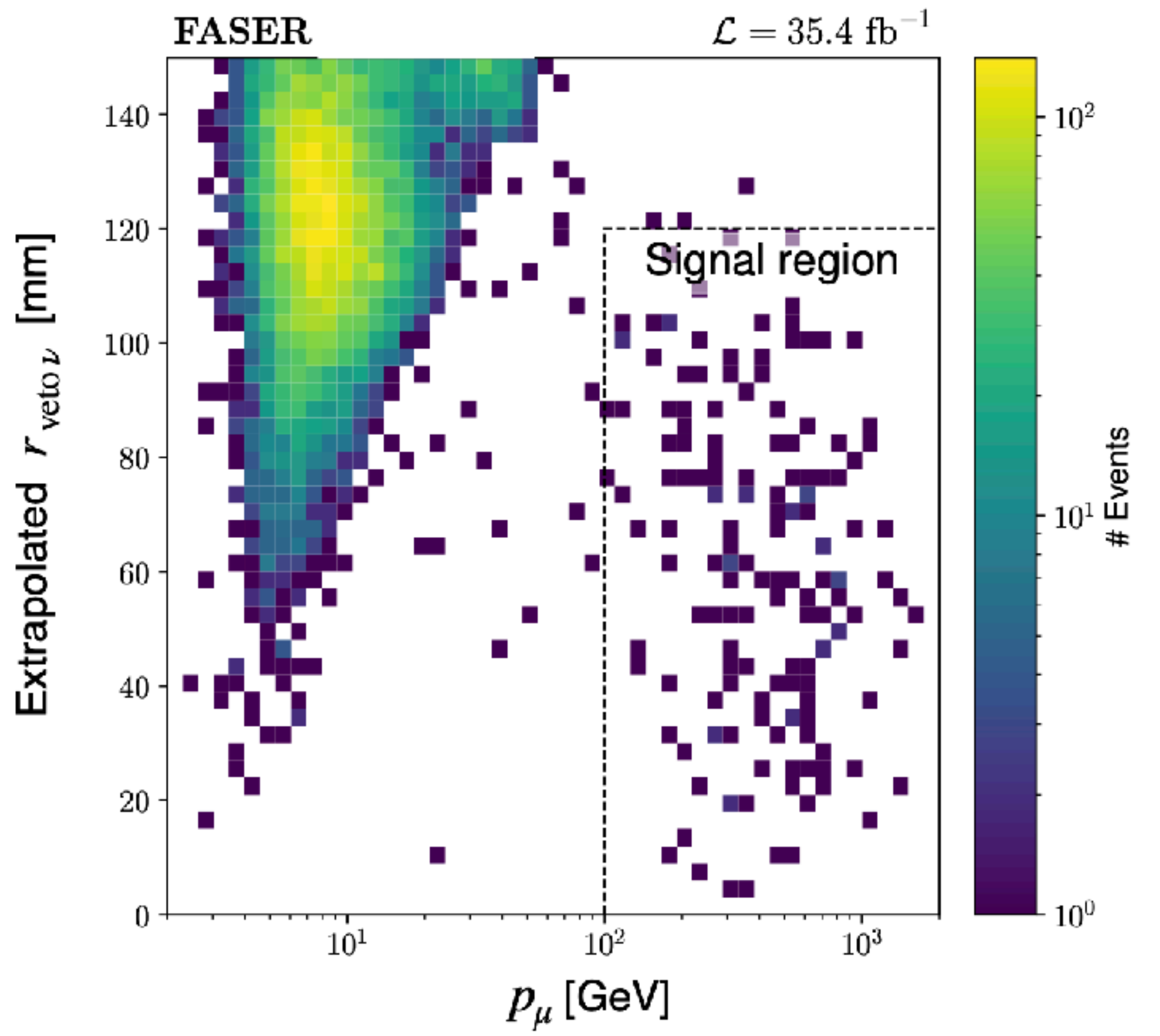


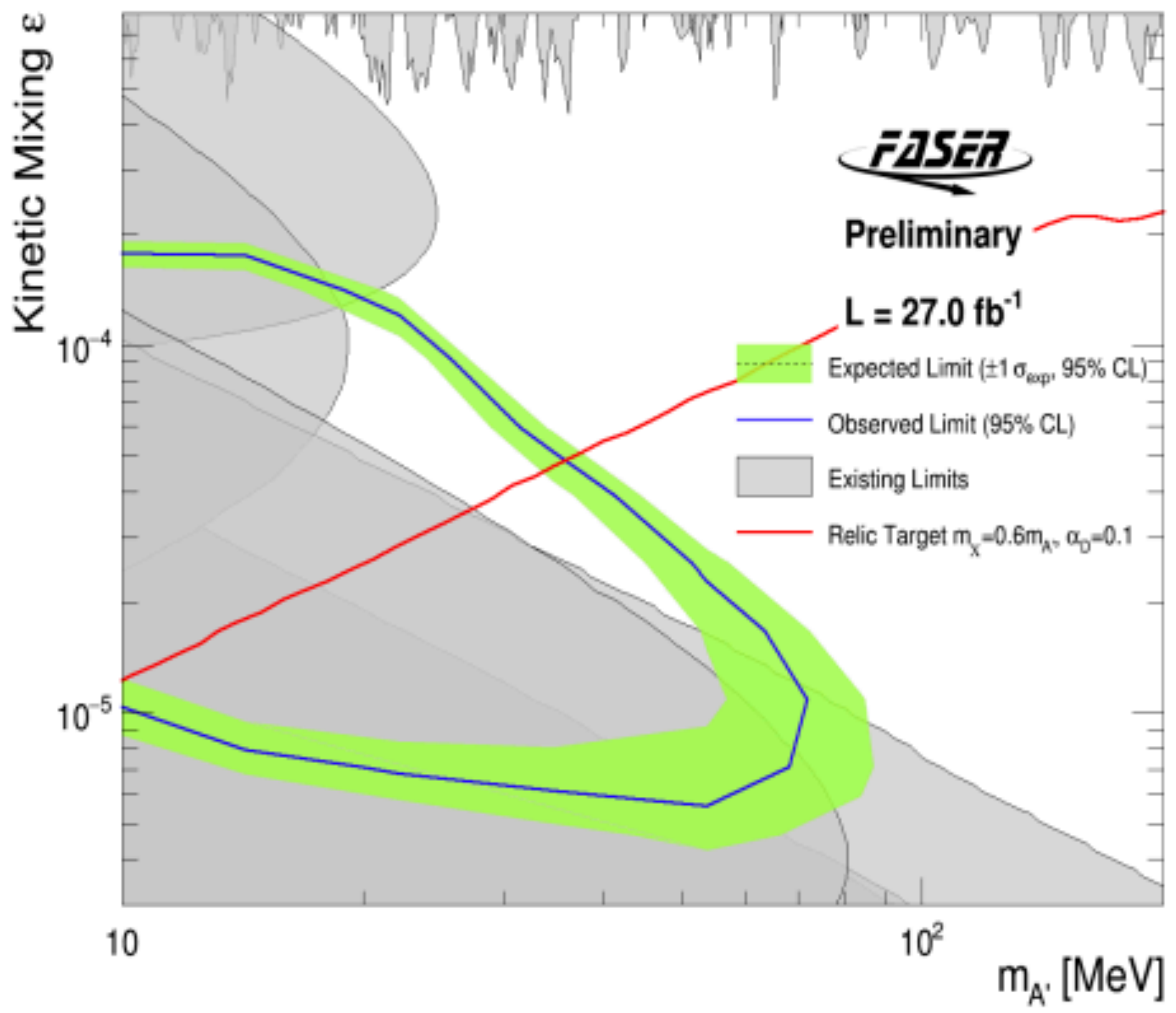




Summary

- FASER successfully took data in 1st year of Run 3
  - Running with fully functional detector and very good efficiency
- First direct observation of collider neutrinos
  - Opens a new field: neutrino physics at the LHC
  - Submitted to PRL [2303.14185]
- Excluded A' in region of 10-100 MeV mass & very small ε
  - First limit in thermal relic region from low coupling for 30 yrs
  - [CERN-FASER-CONF-2023-001]
- More neutrino studies and BSM searches to come
  - Including first results from emulsion detector
  - Searches for ALPs, light gauge bosons, …
- Strongly motivates FPF for the HL-LHC era





Acknowledgements

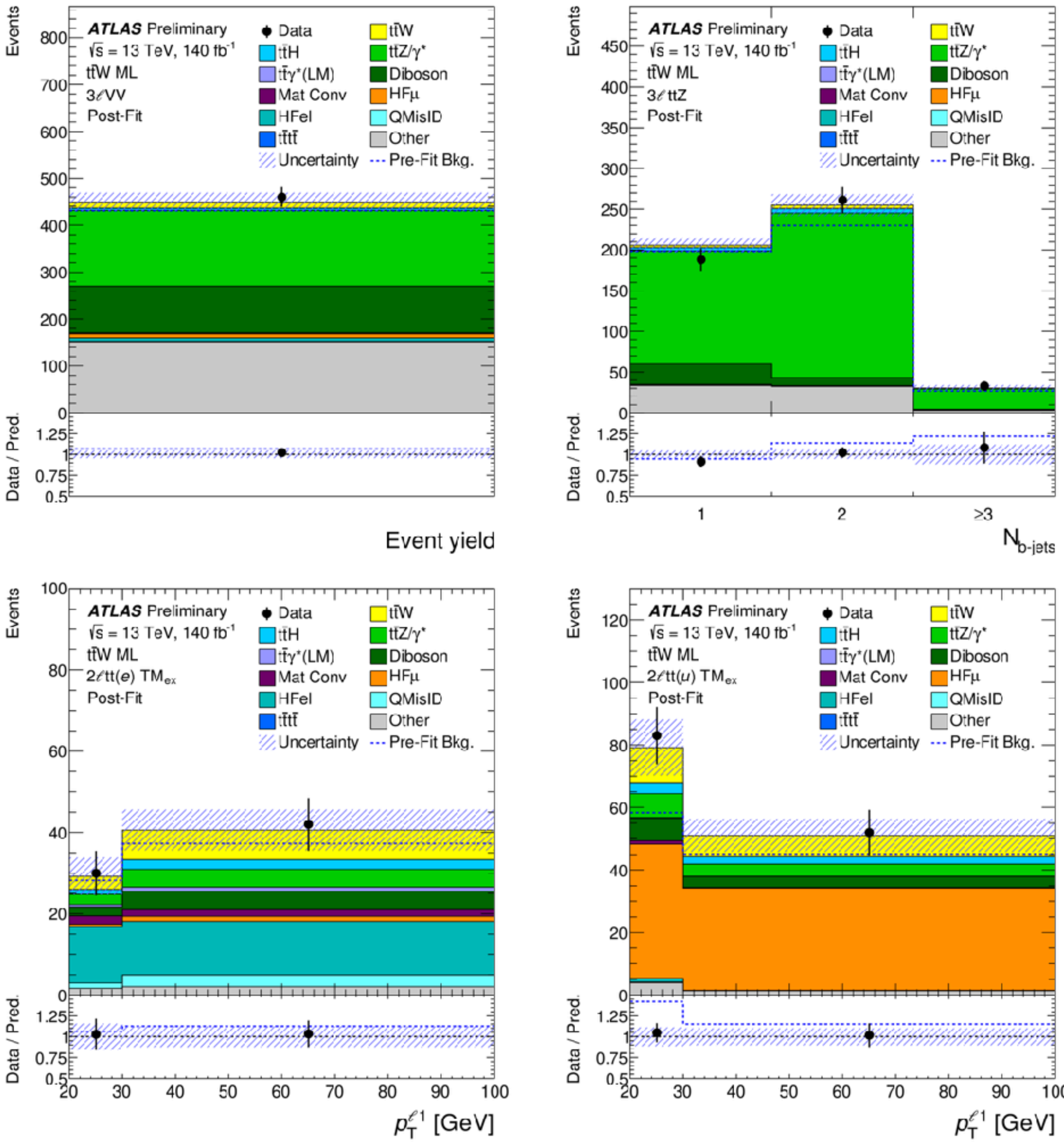
- FASER is supported by:

SIMONS FOUNDATION · HEISING-SIMONS FOUNDATION · NSF · CERN · Swiss National Science Foundation · erc · 科研費 KAKENHI · 国家自然科学基金委员会 National Natural Science Foundation of China

- And would additionally like to thank
  - LHC for the excellent performance in 2022
  - ATLAS for providing luminosity information
  - ATLAS for use of ATHENA s/w framework
  - ATLAS SCT for spare tracker modules
  - LHCb for spare ECAL modules
  - CERN FLUKA team for background sim
  - CERN PBC and technical infrastructure groups for excellent support during design construction and installation

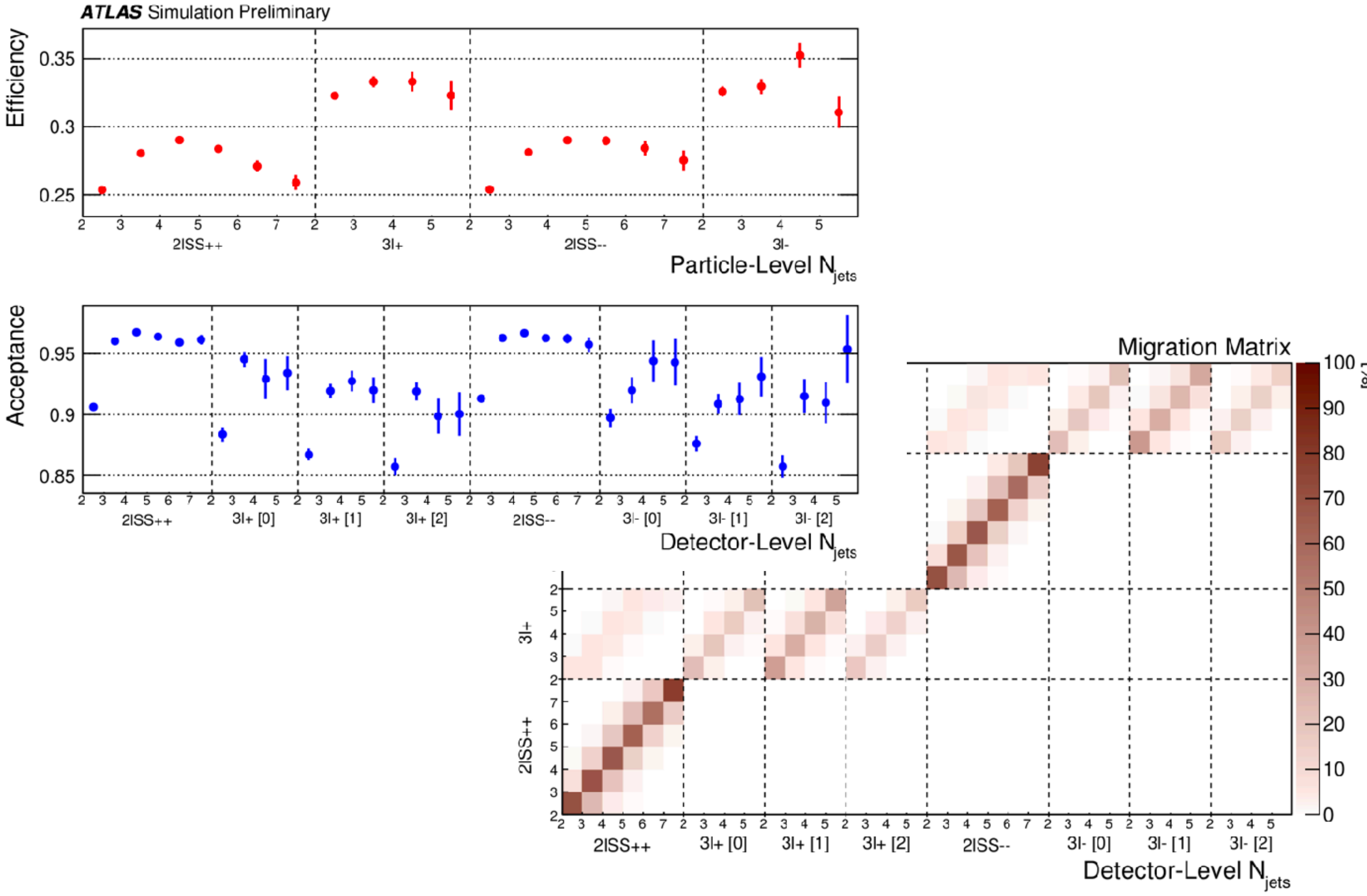
ttW back-ups

Backgrounds



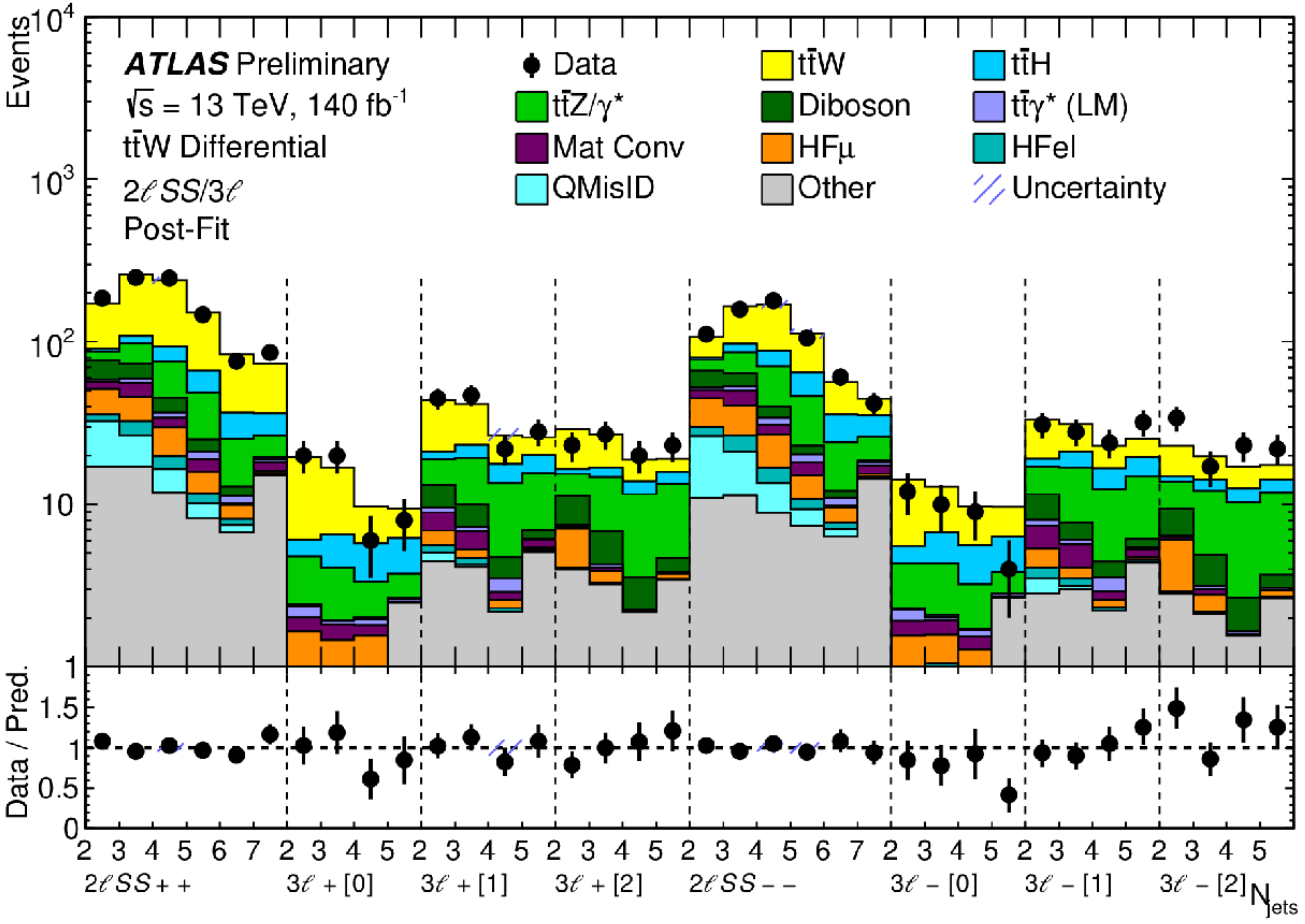
Differential results | Unfolding

- Profile likelihood unfolding technique used.



Differential results

- Background estimate identical
- SR split by observable



Quick Theory Review

Contribution	Orders	% change	Cross section [fb]	Reference
LO QCD	$\alpha\alpha_s^2$	–	$363^{+24\%}_{-18\%}$	[30]
+NLO QCD	$+\alpha\alpha_s^3$	+50.0%	$544^{+11\%}_{-11\%}$	[30]
+ "leading" NLO EW	$+\alpha^2\alpha_s^2$	-4.2%	–	[30]
+ "subleading" NLO EW	$+\alpha^3\alpha_s$	+12.2%	–	[30]
+ "all" NLO EW	$+\alpha^3+\alpha^4$	1.1%+1.3%	$577^{+11\%}_{-11\%}$	[30]
$t\bar{t}W+0,1,2j$ FxFx	$\alpha\alpha_s^2+$(at 1-loop)$\alpha\alpha_s^3+\alpha\alpha_s^4$	–	$691.1^{+9.5\%}_{-10.7\%}$	[28]
+ "subleading" NLO EW	$+\alpha^3\alpha_s^2$	+6.9%	$738.8^{+10.1\%}_{-11.0\%}$	[28]
+ "leading" NLO EW	$+\alpha^2\alpha_s^2$	-2.4%	$722.4^{+9.7\%}_{-10.8\%}$	[28]
NLO+NNLL QCD	–	–	$571.43^{+8.6\%}_{-5.7\%}$	[33]
NLO+NNLL QCD+EW	–	–	$606.13^{+8.9\%}_{-5.8\%}$	[33]
Offshell LO QCD (σ(fiducial$3\ell2b$))	$\alpha^6\alpha_s^2$	–	$0.2218^{+25.3\%}_{-18.8\%}$	[38]
+NLO QCD	$+\alpha^6\alpha_s^3$	+6.6%	–	[38]
+ "leading" NLO EW	$+\alpha^7\alpha_s^2$	-5.5%	–	[38]
+ "subleading" NLO EW	$+\alpha^8\alpha_s$	+13.1%	–	[38]
+ "other" NLO EW	$+\alpha^8$	+1.0%	$0.2554^{+4.0\%}_{-6.5\%}$	[38]

Table 1: Overview of theoretical predictions and their impact on the inclusive $t\bar{t}W$ cross section.

[28] R. Frederix and I. Tsinikos, *On improving NLO merging for* $t\bar{t}W$ *production*, JHEP **11** (2021) 029, arXiv: 2108.07826 [hep-ph] (cit. on p. 5).

[30] R. Frederix, D. Pagani and M. Zaro, *Large NLO corrections in* $t\bar{t}W^{\pm}$ *and* $t\bar{t}t\bar{t}$ *hadroproduction from supposedly subleading EW contributions*, JHEP **02** (2018) 031, arXiv: 1711.02116 [hep-ph]

[33] A. Broggio et al., *Top-quark pair hadroproduction in association with a heavy boson at NLO+NNLL including EW corrections*, JHEP **08** (2019) 039, arXiv: 1907.04343 [hep-ph]

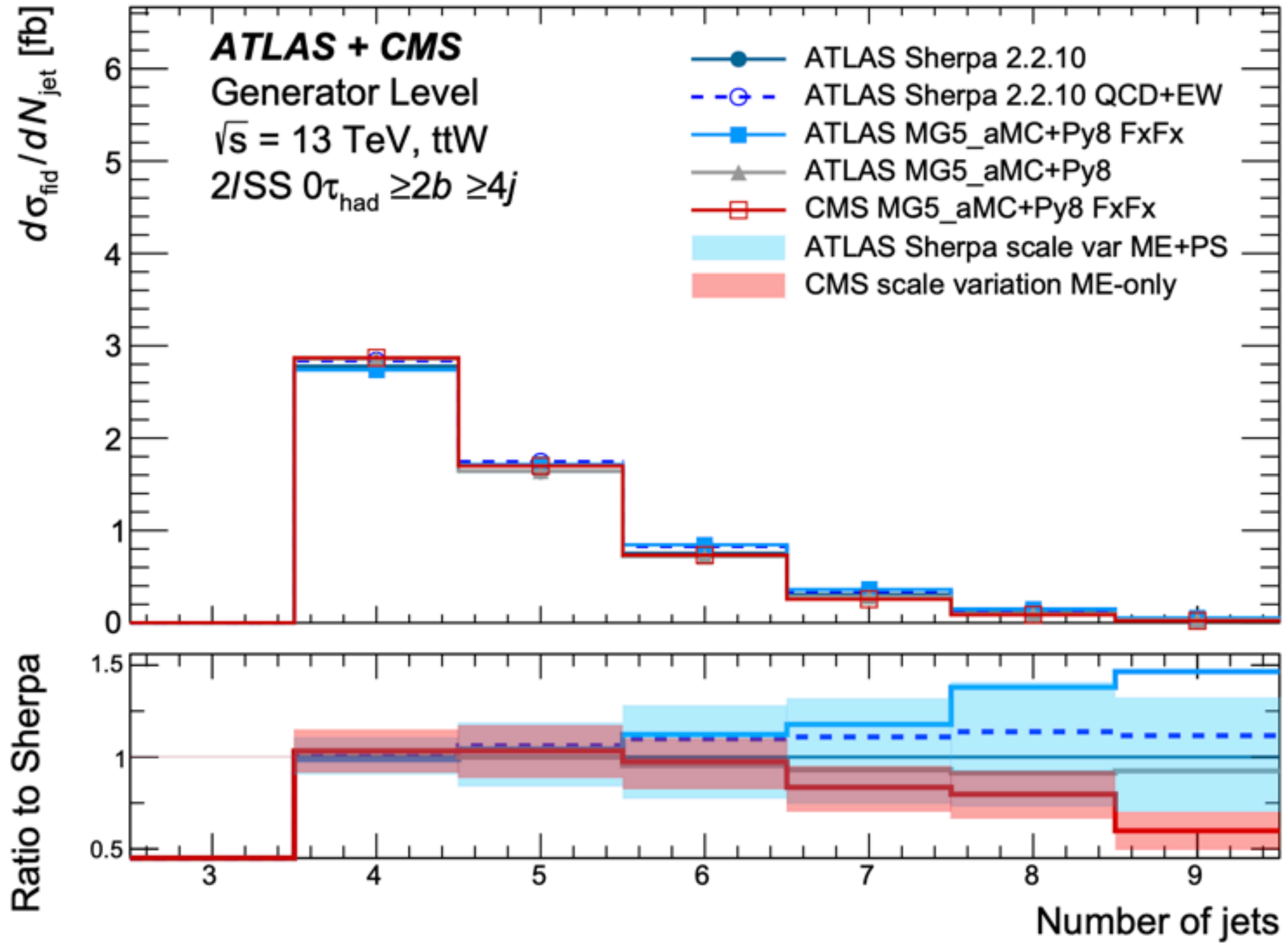
[38] A. Denner and G. Pelliccioli, *Combined NLO EW and QCD corrections to off-shell* $t\bar{t}W$ *production at the LHC*, Eur. Phys. J. C **81** (2021) 354, arXiv: 2102.03246 [hep-ph] (cit. on p. 5).

Path to reference cross section

- From LHC Top WG discussion last summer came proposal to Frederix et al. [2108.07826]

- This is the largest of all ttW prediction cross sections at 722 fb
  - Does not agree well with ~equivalent Sherpa prediction of 616 fb
    - 15% difference is larger than scale uncertainties

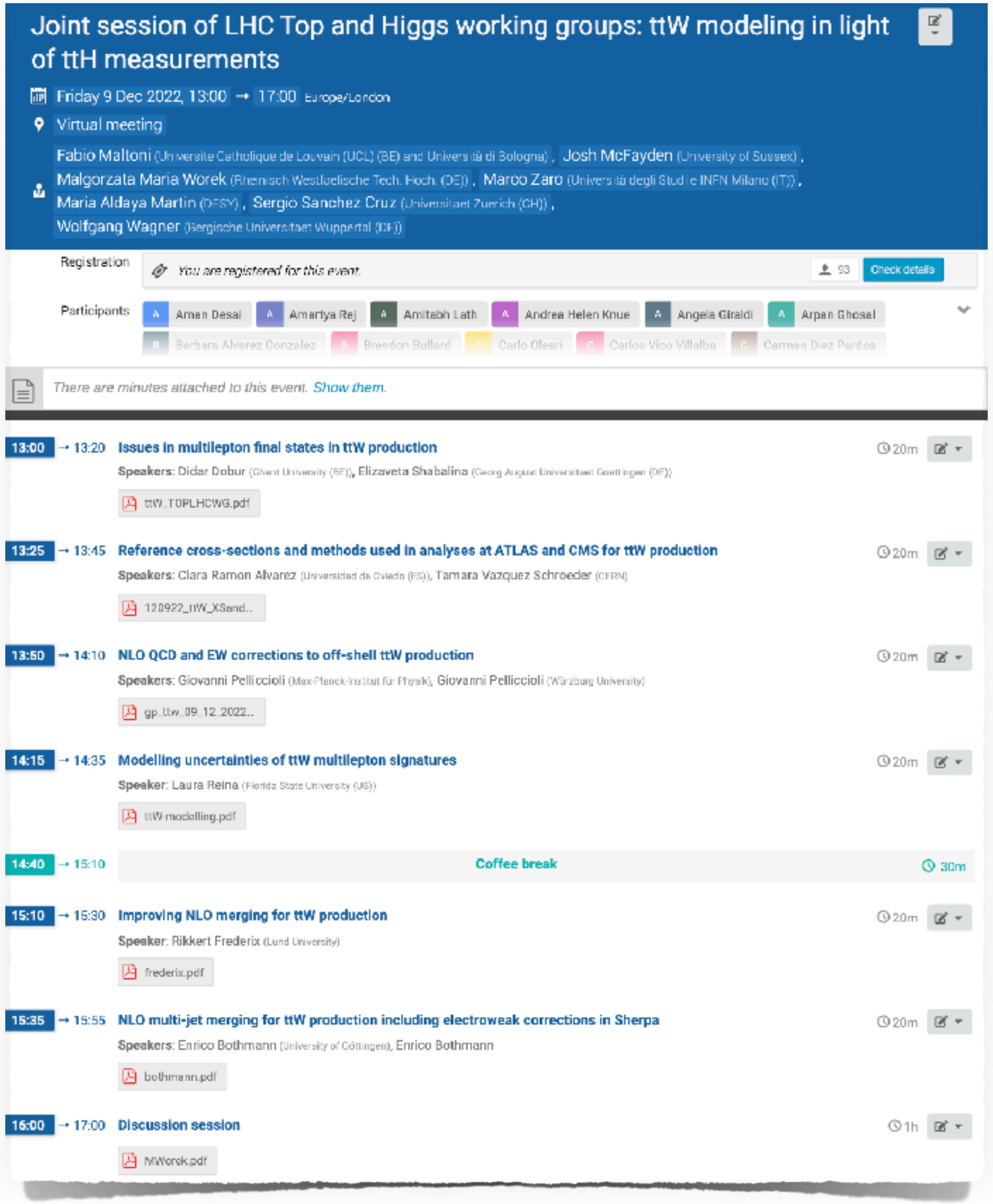
- LHC Higgs WG ttH/tH subgroup note with generator comparisons
  - Comparison between ATLAS & CMS setups
  - Comparison between generators i.e. systematics



Path to reference cross section?

- Discussion in Joint LHC Top — LHC Higgs WGs meeting in December (agenda)
  - Summary from experimental side
  - Summary from theory side
    - Including direct input from MG5_aMC & Sherpa authors

- Stopped short of being able to define a WG-level ***recommendation***
- Did get ***agreement*** between ATLAS and CMS to use Frederix et al. as reference cross-section
  - But did not discuss if/how to normalise QCD & EW parts separately

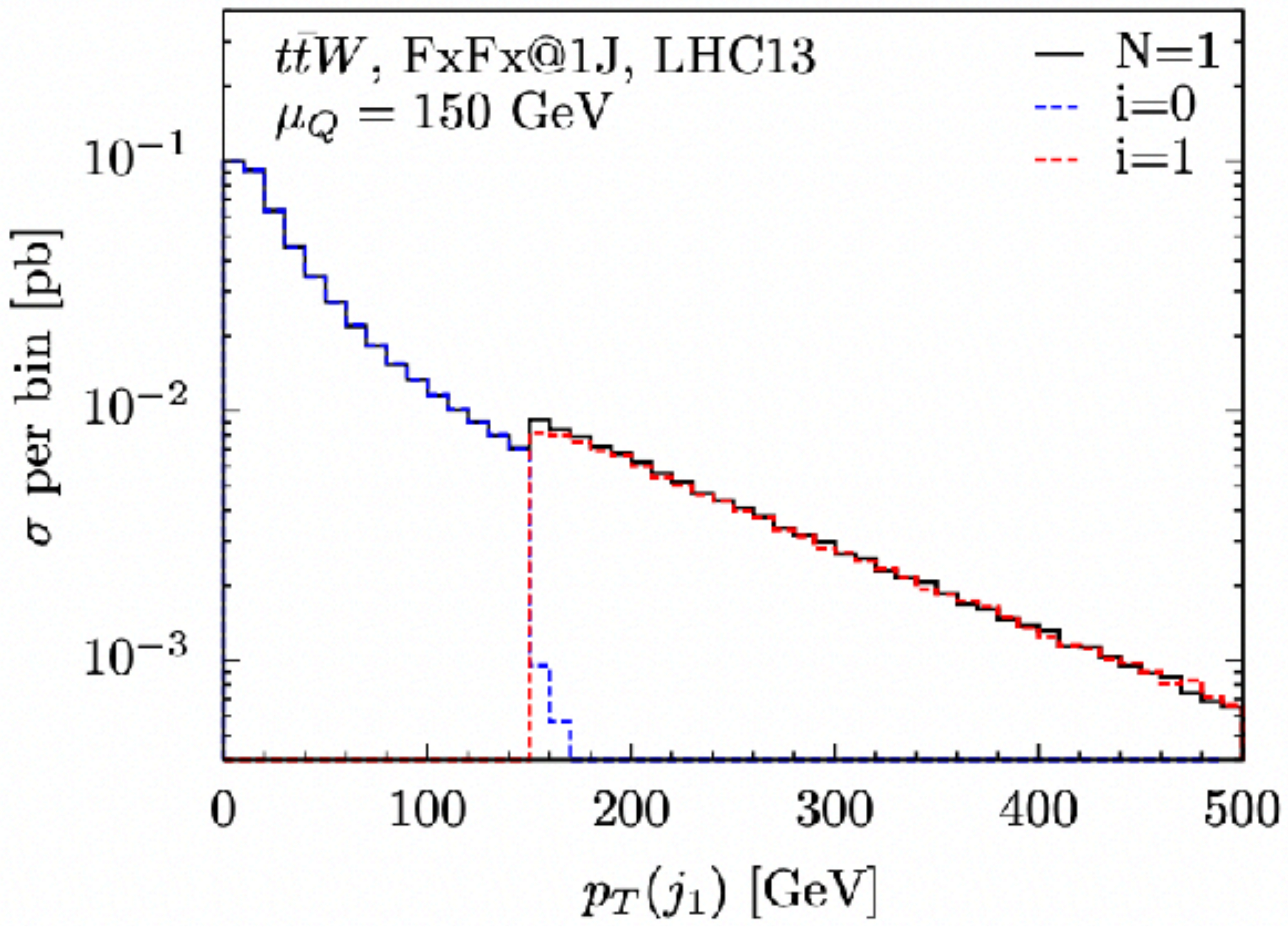


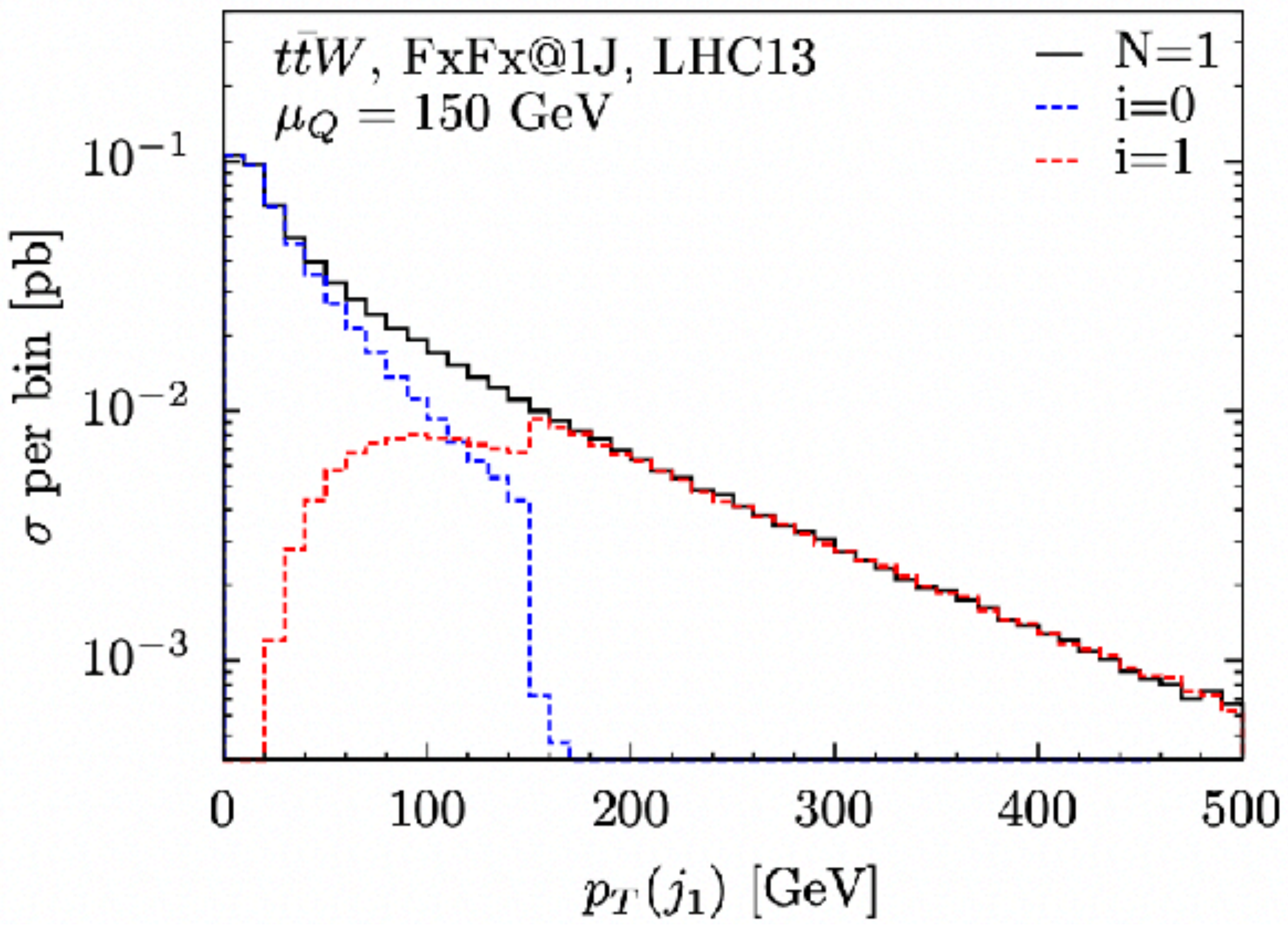
Frederix et al. | NLO merging

- NLO QCD corrections to qg-initiated ttWj contributions shown to be large [1405.0301]
- ttWjj contribution also potentially large [2009.00032]
  - **NLO merging very important (especially in the absence of NNLO predictions)**
- NLO-merged calculation available with MG5_aMC+Py8 FxFx and Sherpa
  - **ttW+0j@NLO**

    → ttW+0,1j@NLO

    "k-factor" = 1.11
  - But easy to get wrong…
    - Care needed with "weak jet" merging [2108.07826]



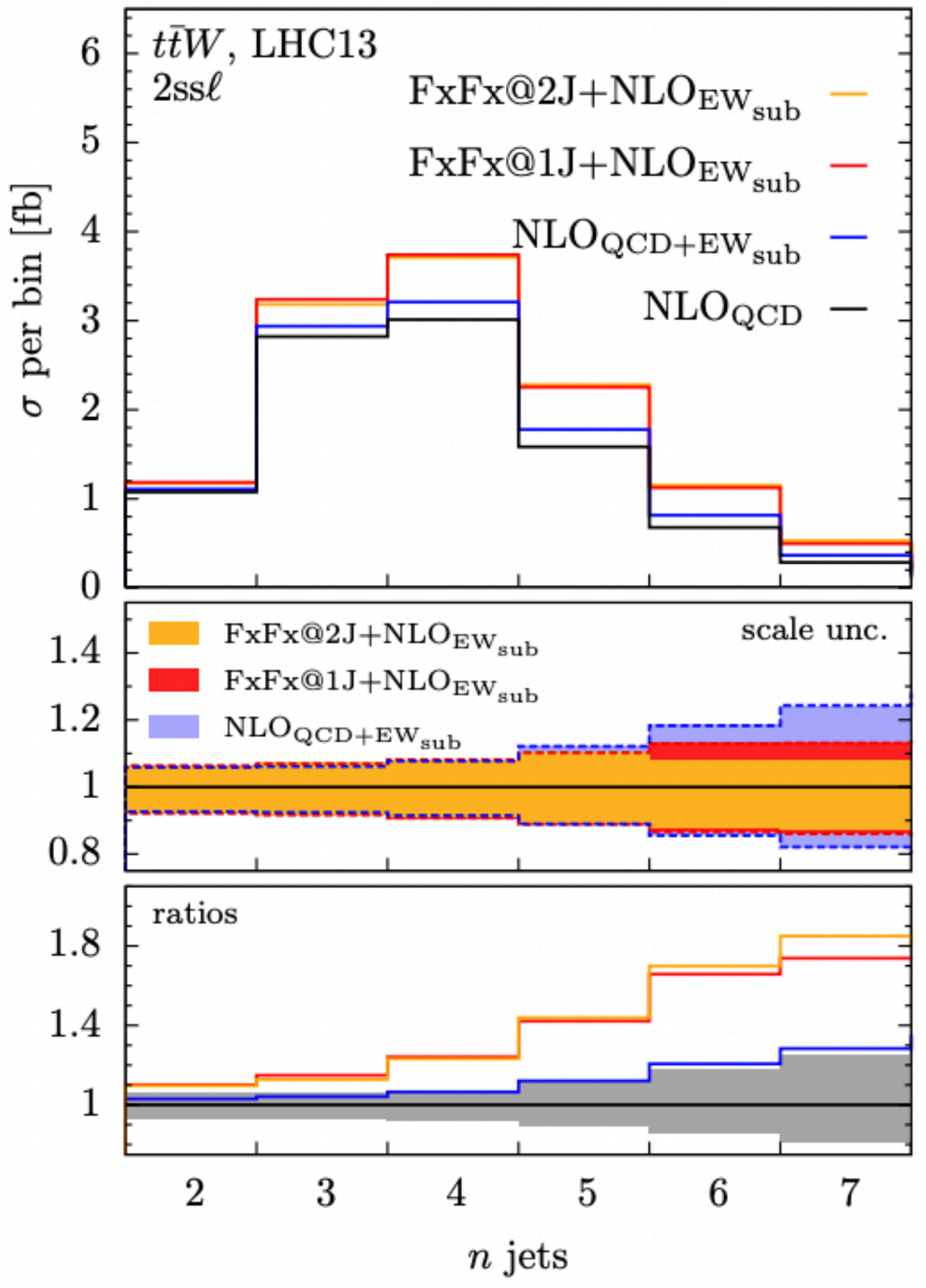


Frederix et al. | EW corrections

- NLO + EW corrections from Powheg, MG5_aMC & Sherpa [2101.11808]

- Multi-leg merged 0-2j@NLO + EW corrections from Frederix et al. [2108.07826]

Order (default scale)	$\sigma \pm$ scale $\pm$ PDF [fb]
FxFx@2J	$691.1(8)^{+65.7(+9.5\%)}_{-74.1(-10.7\%)}$ $^{+7.3(+1.1\%)}_{-7.3(-1.1\%)}$
FxFx@2J+NLO$_{\mathrm{EW}}^{\mathrm{sub}}$	$738.8(8)^{+75.0(+10.1\%)}_{-81.3(-11.0\%)}$ $^{+7.5(+1.0\%)}_{-7.5(-1.0\%)}$
FxFx@2J+NLO$_{\mathrm{EW}}^{\mathrm{lead}}$+NLO$_{\mathrm{EW}}^{\mathrm{sub}}$	$722.4(8)^{+70.2(+9.7\%)}_{-77.7(-10.8\%)}$ $^{+7.2(+1.0\%)}_{-7.2(-1.0\%)}$



Summary

- New ttW reference cross-section now agreed between ATLAS and CMS (from Joint LHC Higgs—LHC Top WGs meeting)
  - Frederix et al. prediction of 722 fb (2jNLO+EW-lead+EW-sub)

- No agreement in how to treat EW and QCD components individually
  - Proposal today on how to deal with this for Sherpa and MG5_aMC+Py8
  - If we agree this should be adopted across Top WG and ATLAS
    - Can propagate k-factors to AMI/TopDataPrep

- The interplay between samples that have their own EWK corrections (Sherpa and Powheg) and those that don’t is rather complicated
  - For ATLAS-wide recommendations we should perhaps try to be really specific about this on TopProcesses page?

- Thoughts?!

LHC Top-Higgs WG meeting | Action Items

- Agree to adopt the total cross-section predicted by MadGraph5_aMC@NLO_FxFx_improved as a reference cross-section:
  sigma = 722 +70 / -78 (scale) +- 7 (PDF) fb. Reference: JHEP 11 (2021) 29.
- Rikkert will work on quantifying the effect of the electroweak-jet treatment (improvement to FxFx)
- Enrico will work towards including the quark-gluon diagrams in Sherpa.
- Timescale for both theory items is the beginning of March 2023. We plan to have a next joint meeting to discuss these results and comparisons between improved FxFx and Sherpa.
- Experimentalists from ATLAS and CMS will provide a Rivet routine defining a common fiducial phase. Time line: before Christmas 2022.
- Plan to use joint-session format to continue work on ttW modeling and modeling uncertainties.
- Plan to establish smaller task force groups to deal with various aspects of the ttW modeling and modeling uncertainties (to be discussed during the meeting in March 2023 or offline).
- We think that regular communication and cooperation which facilitates a close working relationship between theoretical physicists and experimental physicists working for the LHC Top and Higgs working groups is essential if we want to profit from the current state-of-the-art theoretical predictions and theoretical advances in general for ttW.
- Setups for the particular ttW measurements should be communicated to the theory groups at the early stage of measurements. The latter included: SM input parameters, scale settings, PDFs, cuts in the fiducial phase space regions, choice of the observables, binning, details of the MC simulations used for unfolding and comparisons to the LHC data etc.

LHC Higgs WG ttH/tH | ttbb+ttW note

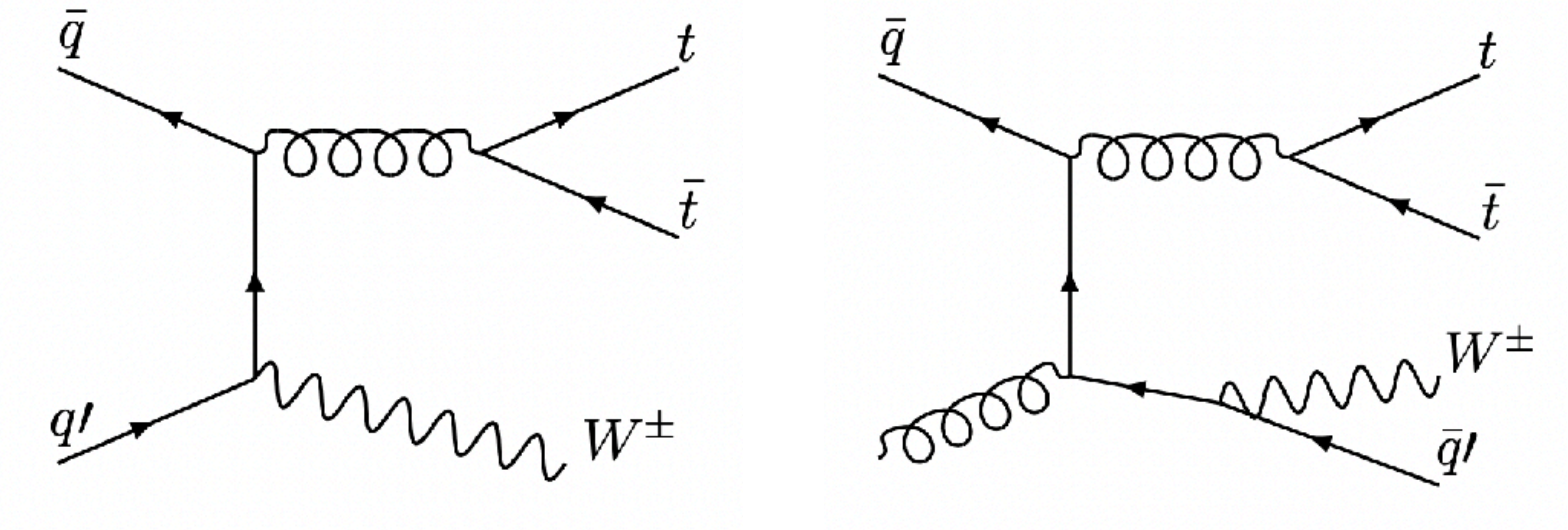
Label	ATLAS Sherpa 2.2.10	ATLAS Sherpa 2.2.10 QCD+EW	ATLAS MG5_aMC+Py8 FxFx	ATLAS MG5_aMC+Py8	CMS MG5_aMC+Py8 FxFx
Process	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}\ell\nu$ ($t\bar{t}W$ inclusive)
Generator	SHERPA 2.2.10 [27]	SHERPA 2.2.10 [27]	MG5_AMC@NLO 2.9.3 [69]	MG5_AMC@NLO 2.3.3 [70]	MG5_AMC@NLO 2.4.2
order of QCD ME	0,1 j@NLO[a]	0,1 j@NLO[a]	0,1 j@NLO	NLO	0,1 j@NLO
ME or core scale	$\mu_R = \mu_F = H_T/2$	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 67, 68]	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 67, 68]
order of EW corr.	-	α^3, $\alpha^2\alpha_s^2$, $\alpha^3\alpha_s$	-	-	-
Parton Shower	SHERPA 2.2.10	SHERPA 2.2.10	PYTHIA 8.245 [8]	PYTHIA 8.210 [8]	PYTHIA 8.226
Merging Scheme	MEPs@NLO [62]	MEPs@NLO [62]	FxFx [24]	-	FxFx
Merging Scale	30 GeV	30 GeV	30 GeV	-	42 GeV
PDF	NNPDF3.0 NNLO [71]	NNPDF3.0 NNLO	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.1 NLO [72]
Tune	SHERPA default	SHERPA default	A14 [33]	A14	CP5 [34]
Cross section[b]	597 fb	615 fb	613 fb	548 fb	220 fb (666 fb[c])

[a] In addition to the implicit 2j@LO contribution from the real emission part of the 1j@NLO calculation, Sherpa adds the 2j@LO as an explicit separate process within the merging such that the ME is supplemented with higher-order improvements such as the CKKW scale choice and Sudakov factors."

[b] σ_{tot}=600.8 fb from YR4 is used for all samples in the generator comparisons in section 3.3.2 except for SHERPA QCD+EW

[c] calculated from $t\bar{t}\ell\nu$ as 0.2198 x (1/ (3 x 0.11))

Theory basics



- qq-initiated process
- Spin correlations are very important as W emission polarises incoming quark [1406.3262].
- First NLO calculation shows large ~30-50% k-factor [1204.5678]
  - Large fraction coming from opening qg-initiated ttWj production mode

First recommendation…

- NLO+PS predictions become available [1208.2665,1507.05640]
- Augmented with "leading" NLO EW corrections ($\alpha^3 + \alpha_S^2\alpha^2$) [1504.03446]
- Led to best "**agreed upon**" calculation:
  Yellow Report 4 [1610.07922]
  - Has been the recommended value for a number of years
- **But misses some crucial inputs now available…**
  - NLO QCD merging
  - "Subleading" NLO EW corrections
  - NNLL resummation
  - Off-shell effects

NLO merging

- NLO QCD corrections to qg-initiated ttWj contributions shown to be large [1405.0301]
- ttWjj contribution also potentially large [2009.00032]
  - **NLO merging very important (especially in the absence of NNLO predictions)**

- NLO-merged calculation available with MG5_aMC+Py8 FxFx and Sherpa
  - **ttW+0j@NLO**

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    "k-factor" = 1.11
  - But easy to get wrong…
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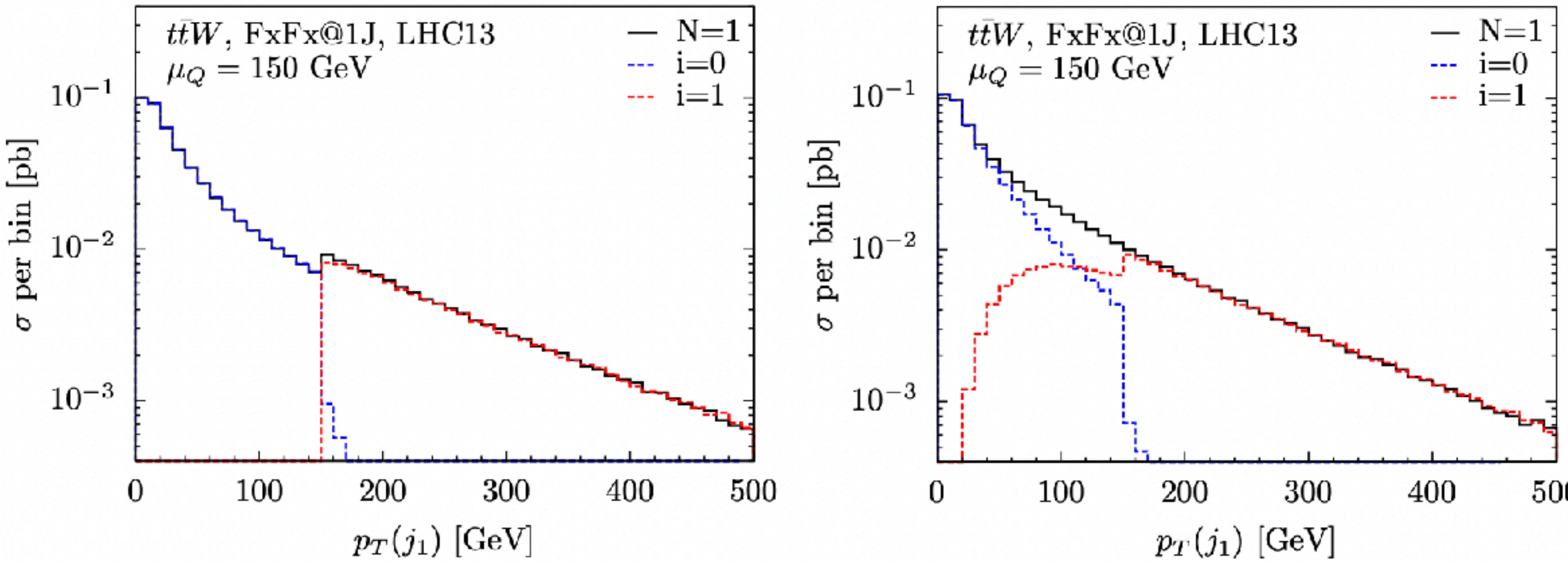
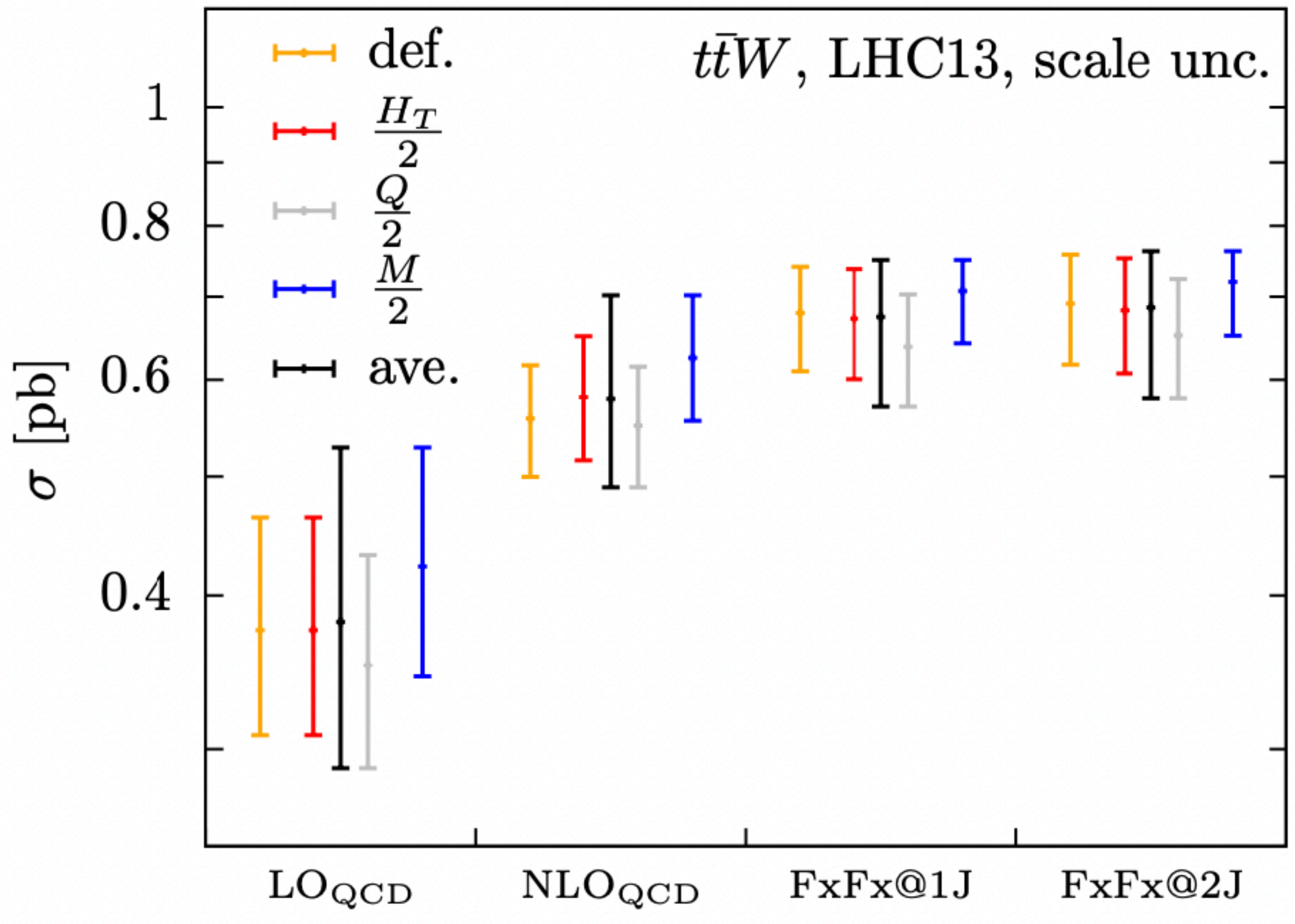
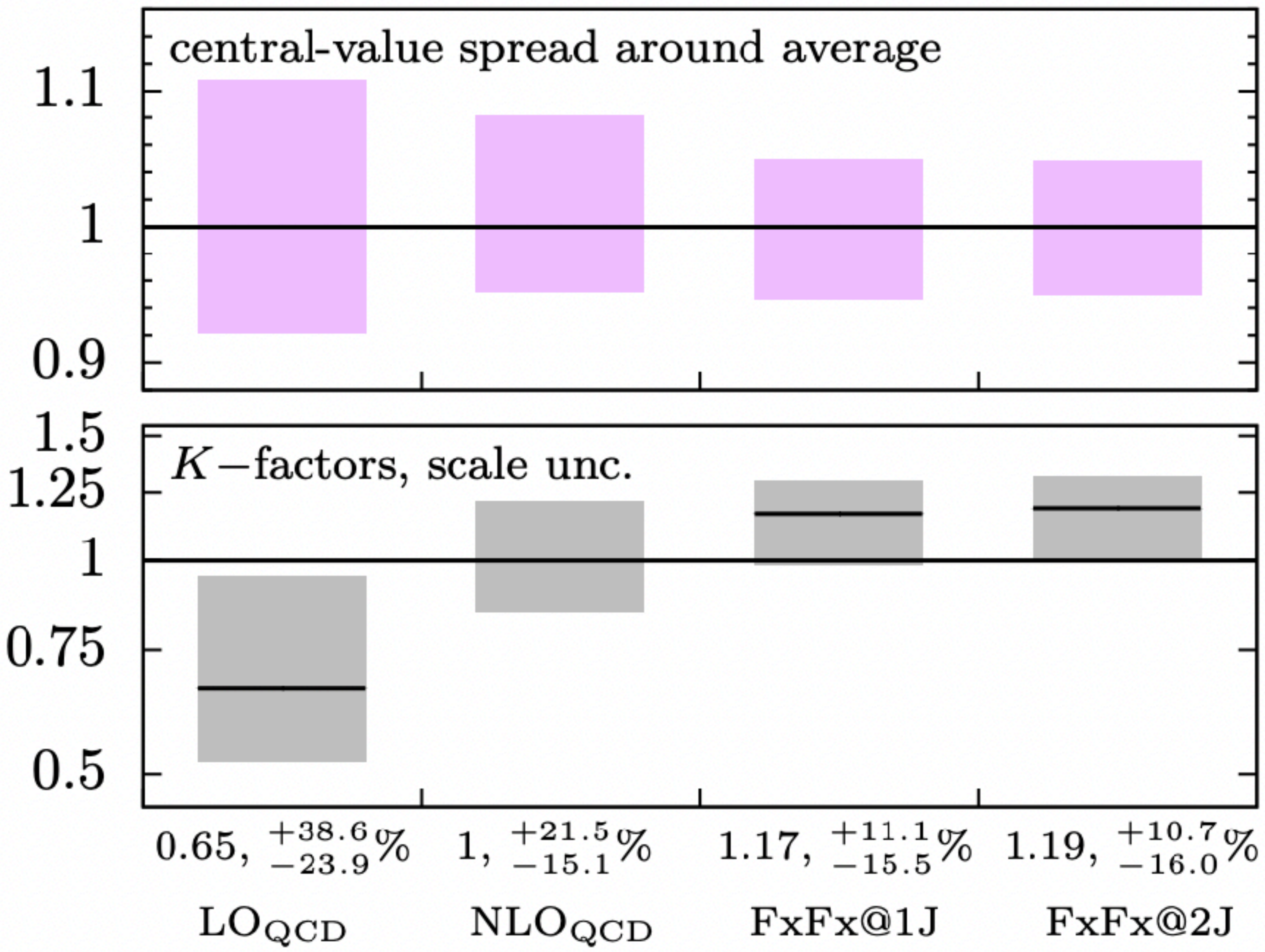


NLO merging

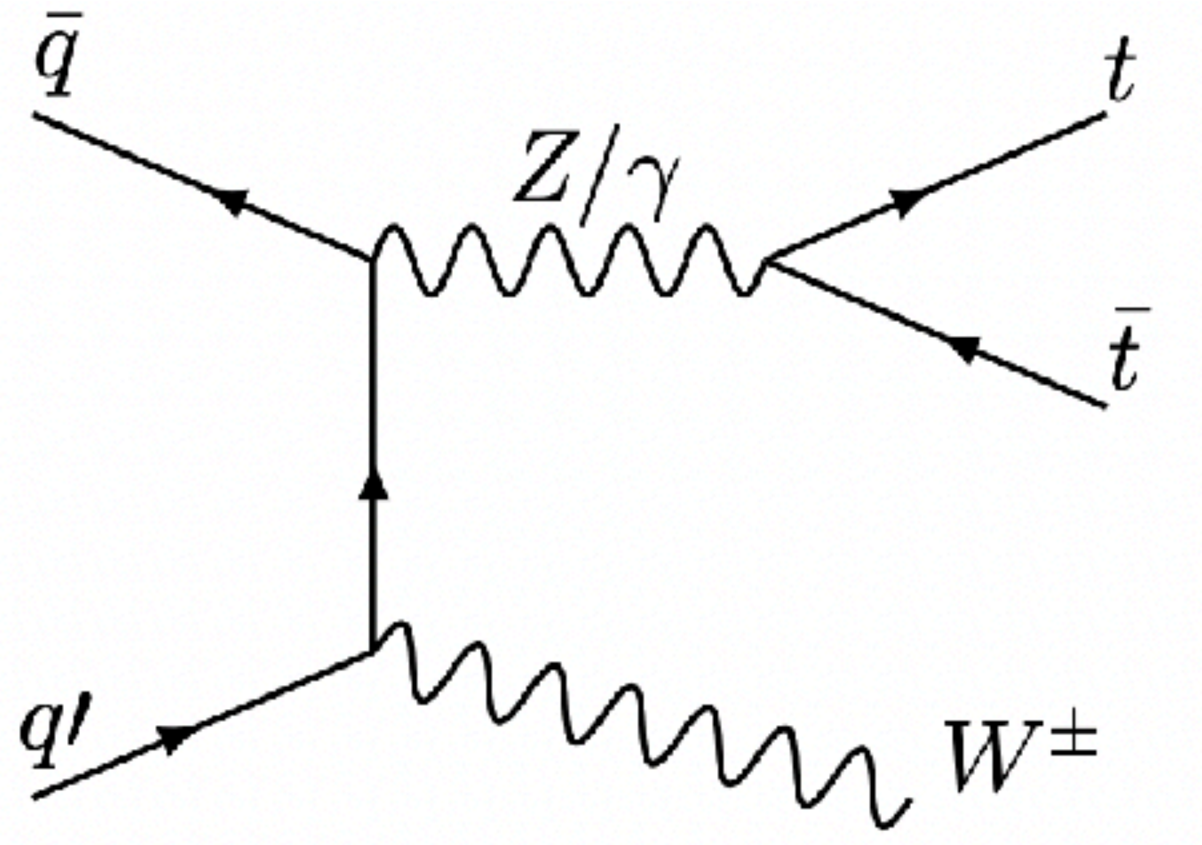
- Multi-leg merged ttW+0-2j@NLO from Frederix et al. [2108.07826]





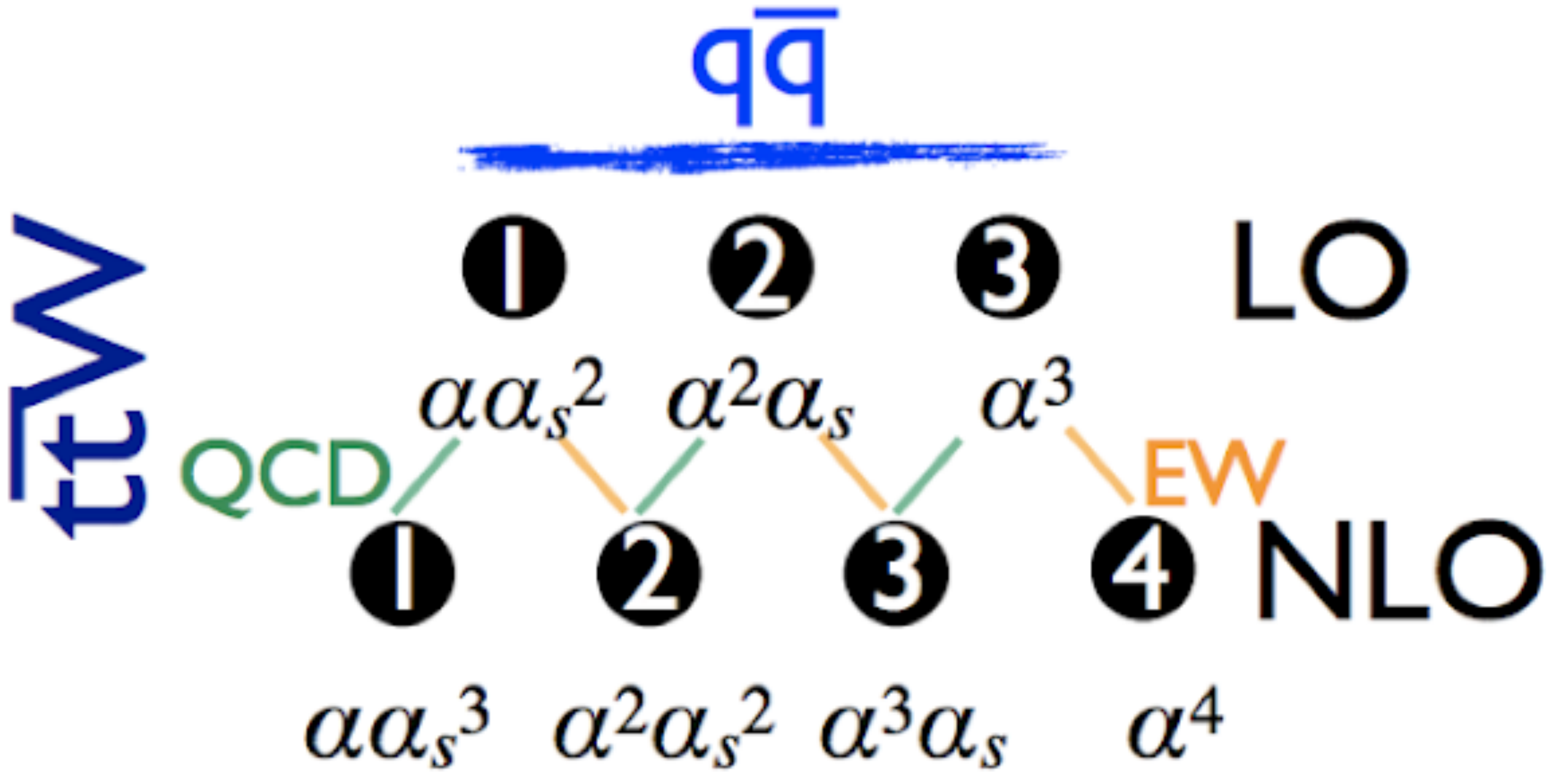
EWK corrections

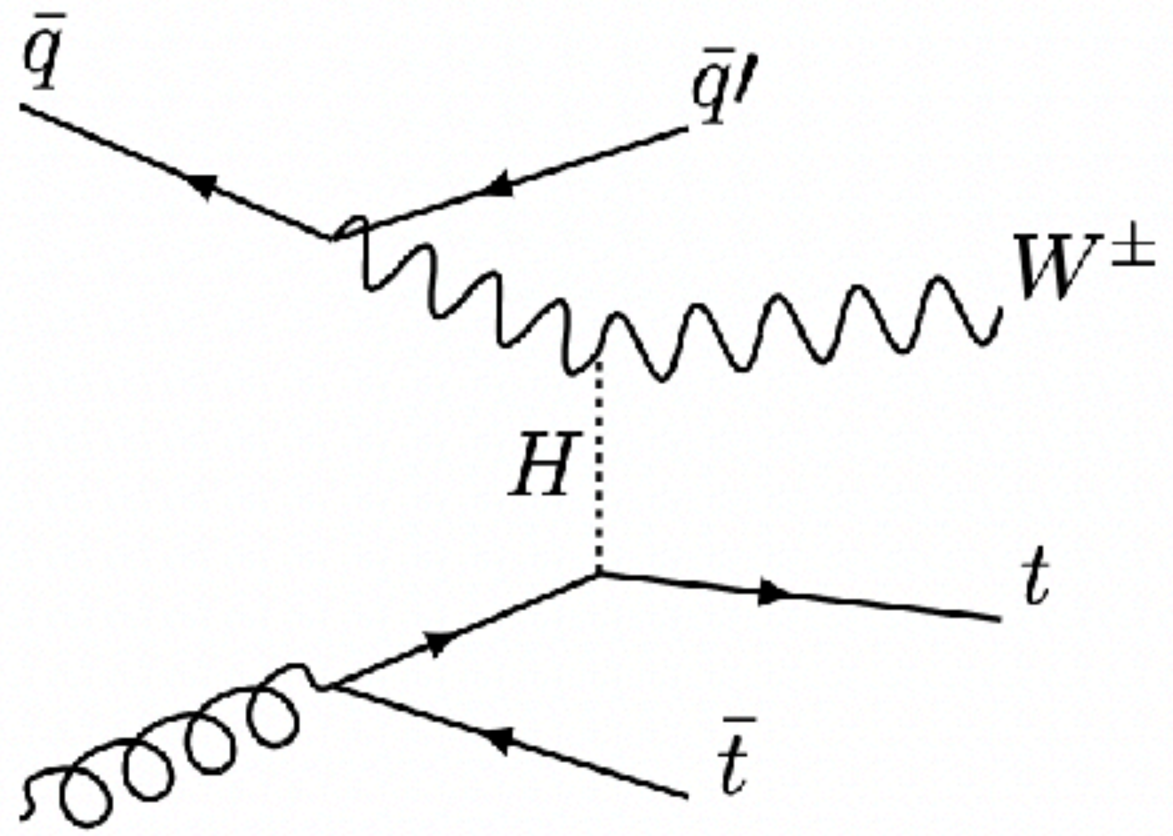
- YR4: *"Subleading NLO terms of O($\alpha_s\alpha^3$) … are not included as they are expected to be strongly suppressed."*
- [1711.02116] shows that these "subleading" NLO EWK corrections are larger than "leading" corrections!
- Resulting inclusive correction is 1.09



13 TeV

δ[%]	$\mu = H_T/2$
LO$_2$	-
LO$_3$	0.9
NLO$_1$	50.0 (25.7)
NLO$_2$	−4.2 (−4.6)
NLO$_3$	12.2 (9.1)
NLO$_4$	0.04 (−0.02)





EWK corrections

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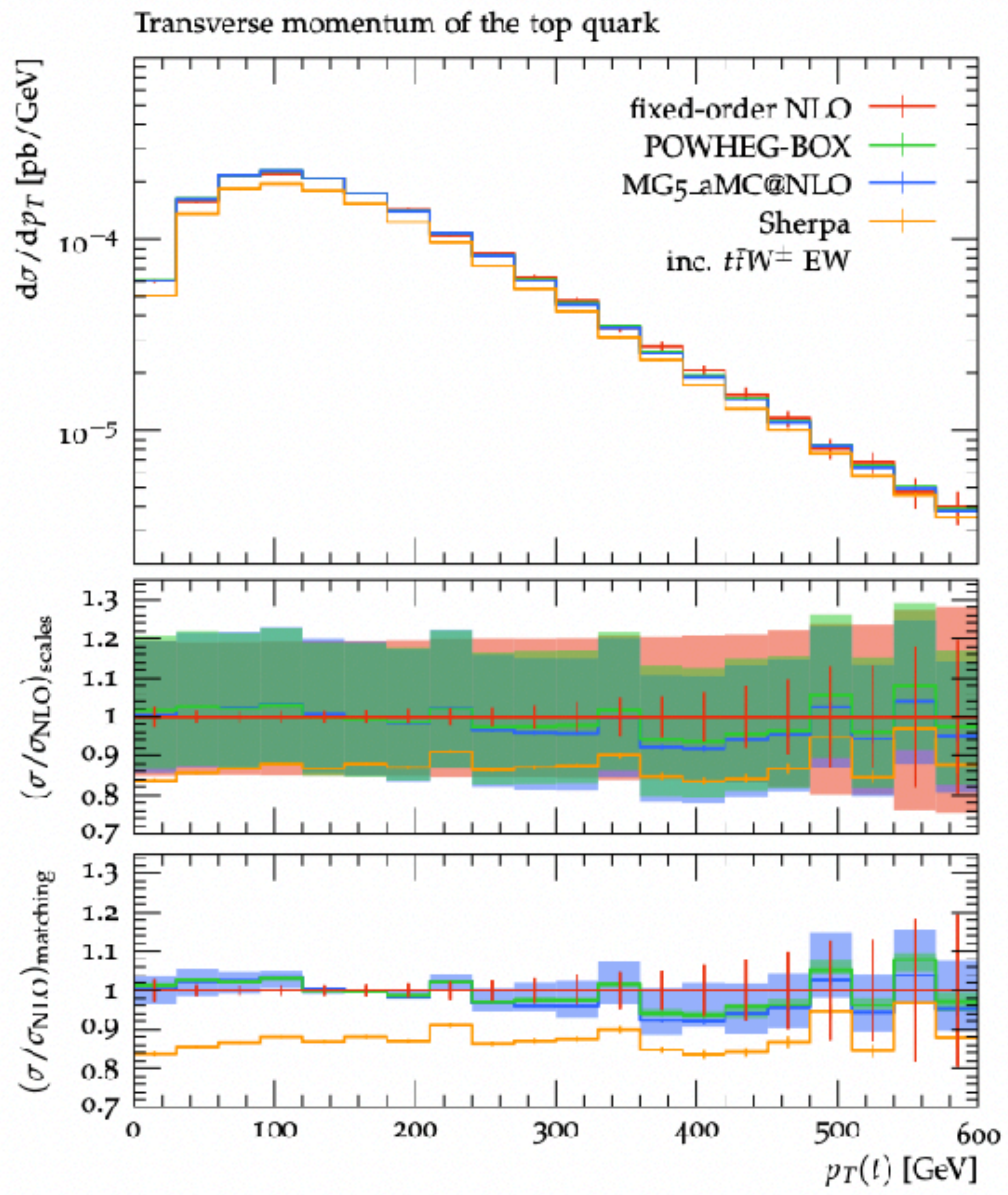
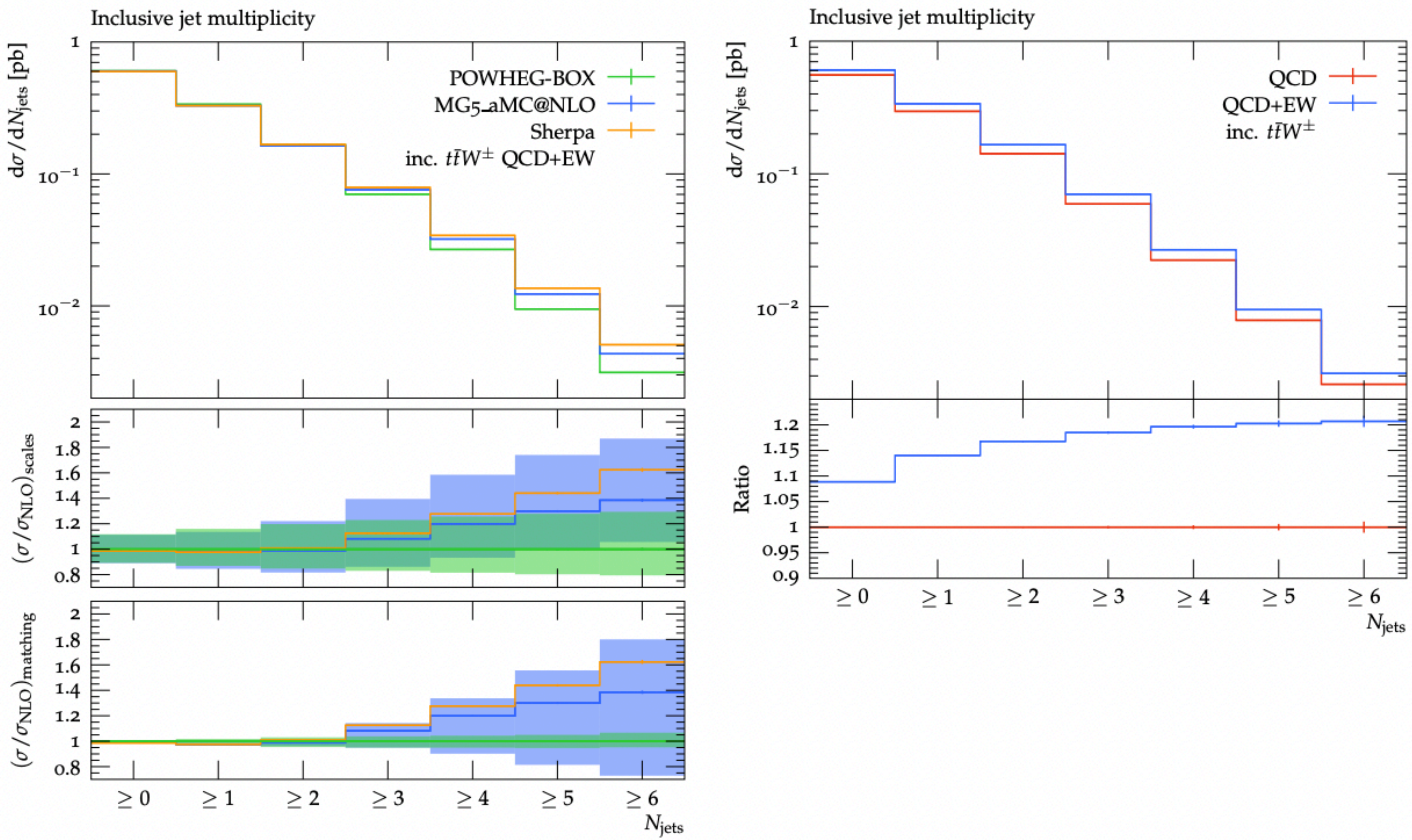
- [1711.02116] shows that these "subleading" NLO EWK corrections are larger than "leading" corrections!
- Resulting inclusive correction is 1.09
- In practise not trivial to produce
  - Sherpa event weights vs dedicated LO sample differ (~2x)
  - Sherpa and MG LO sample cross sections differ by ~25%.
  - Powheg similar to MG [2101.11808]
- Includes very phenomenologically interesting tW-scattering vertex!



Putting it together

- NLO + EW corrections from Powheg, MG5_aMC & Sherpa [2101.11808]



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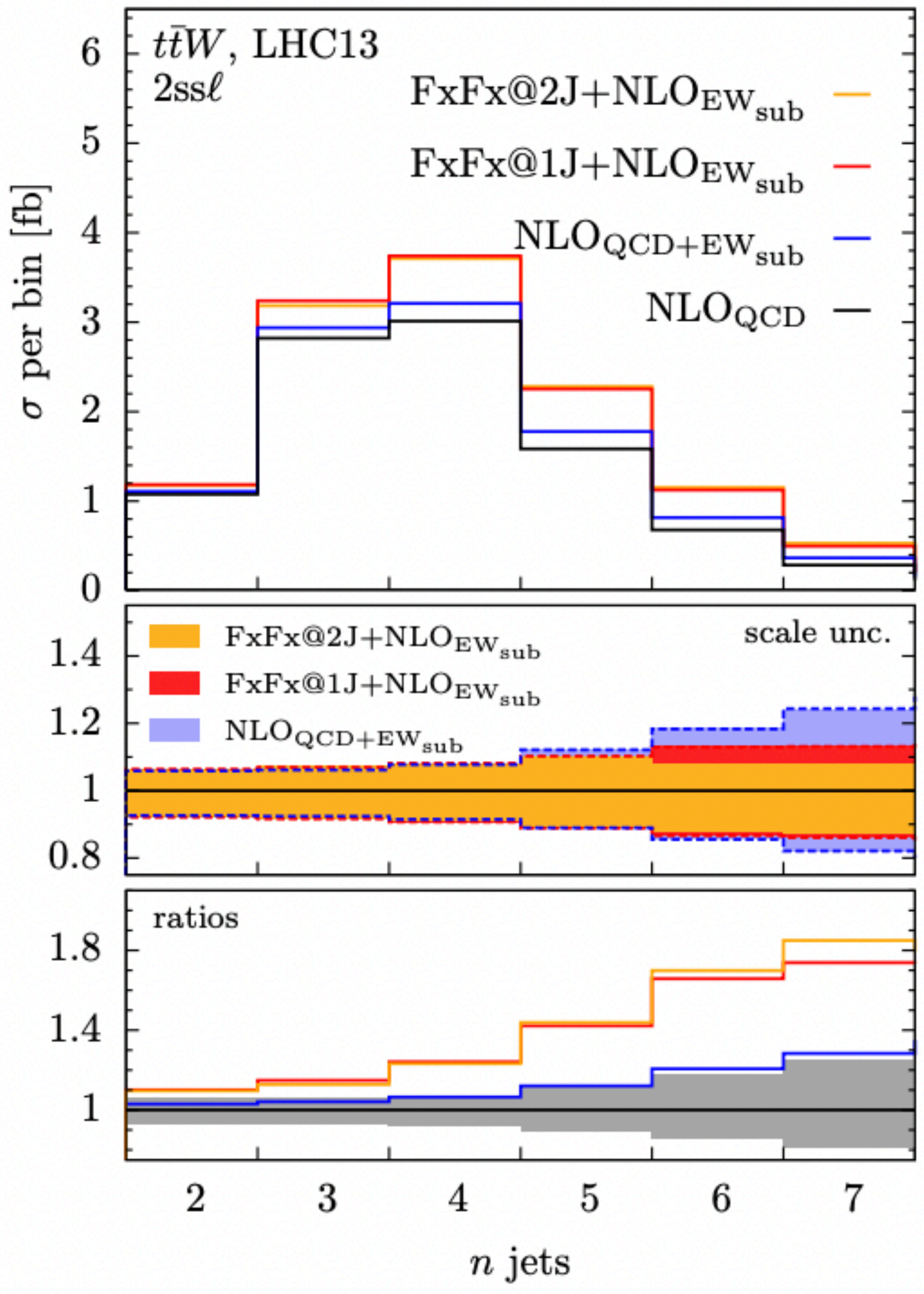
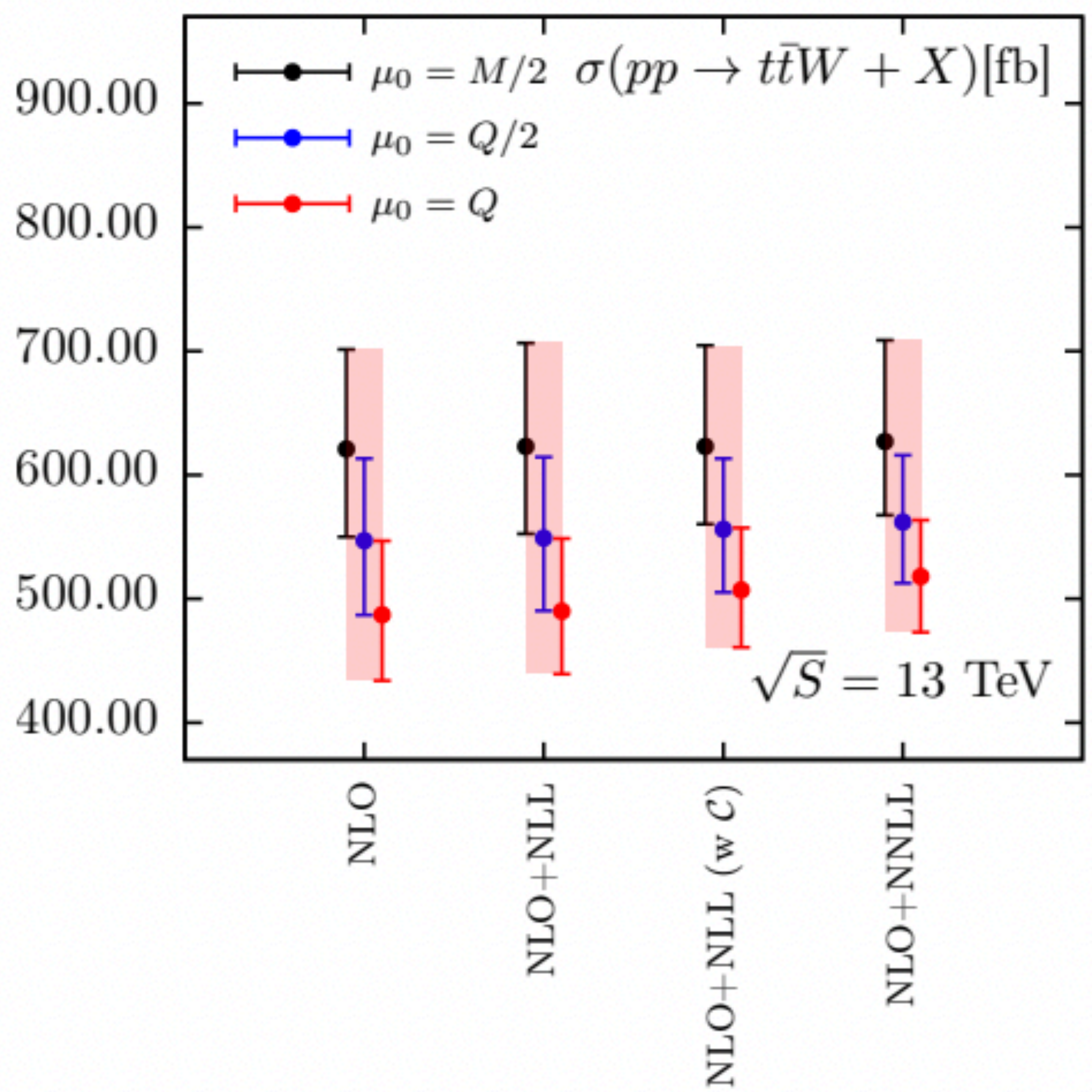
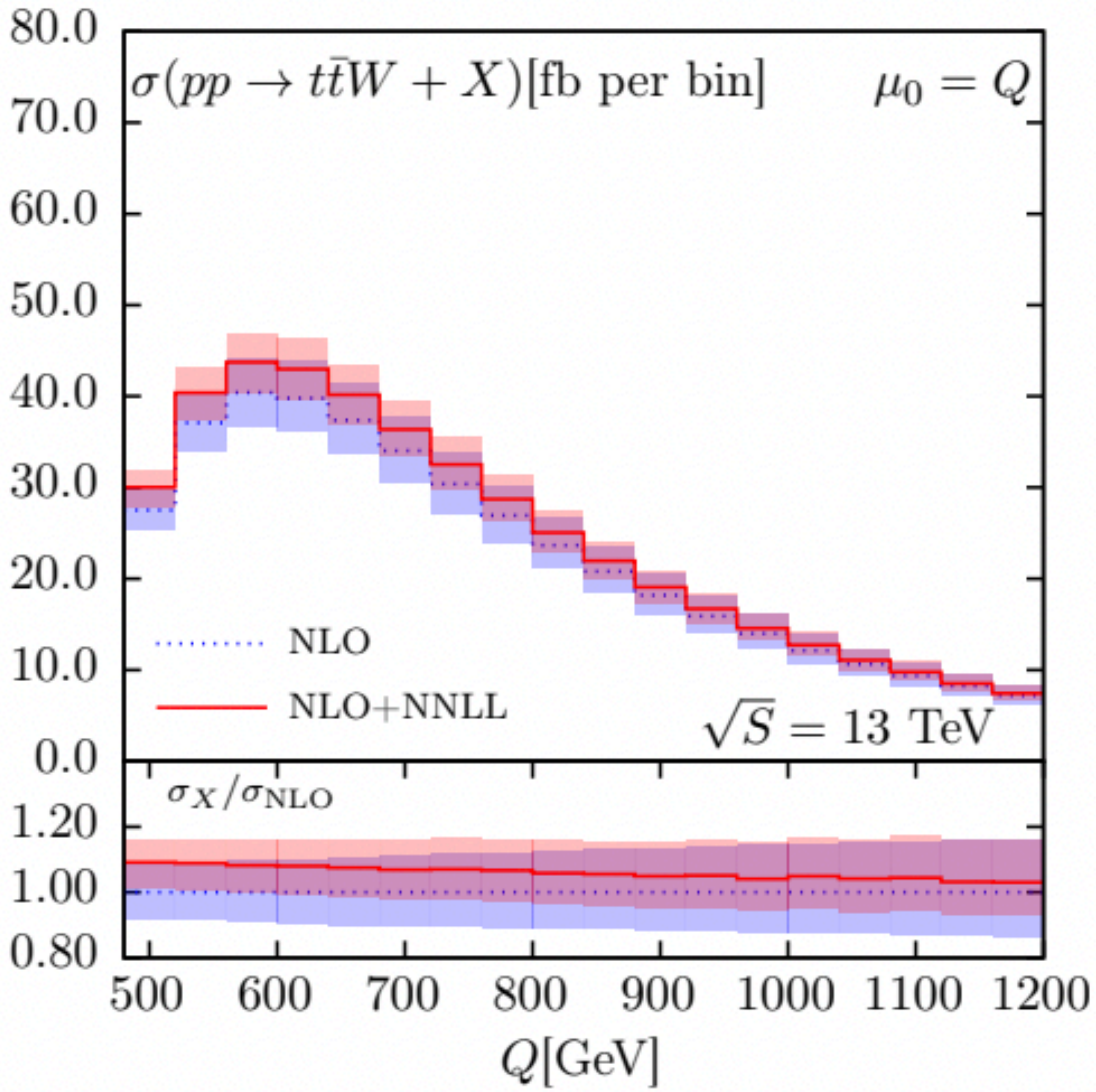


NLO+NNLL

- First calculations at NLO+NNLL become available [1812.08622]

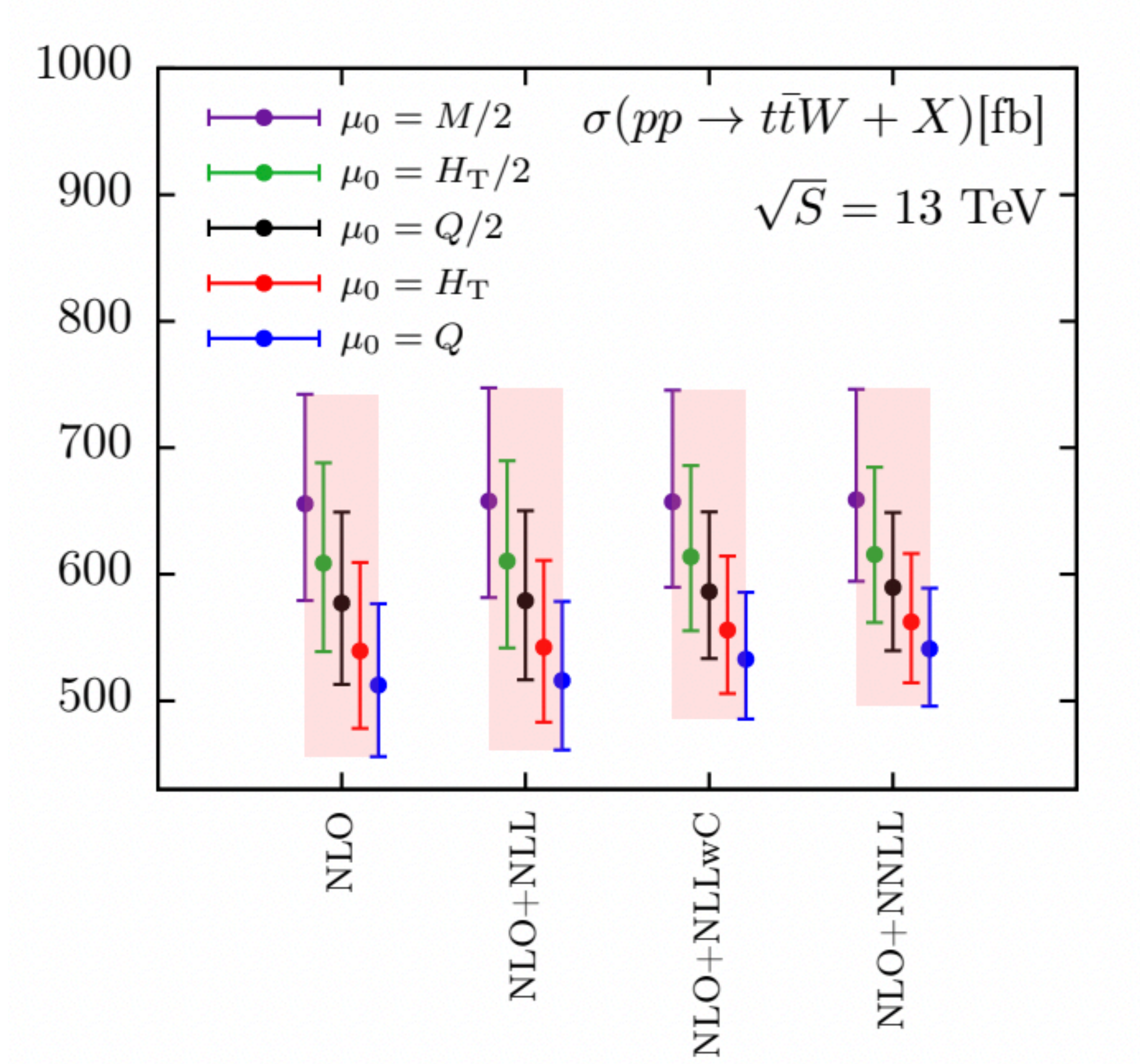


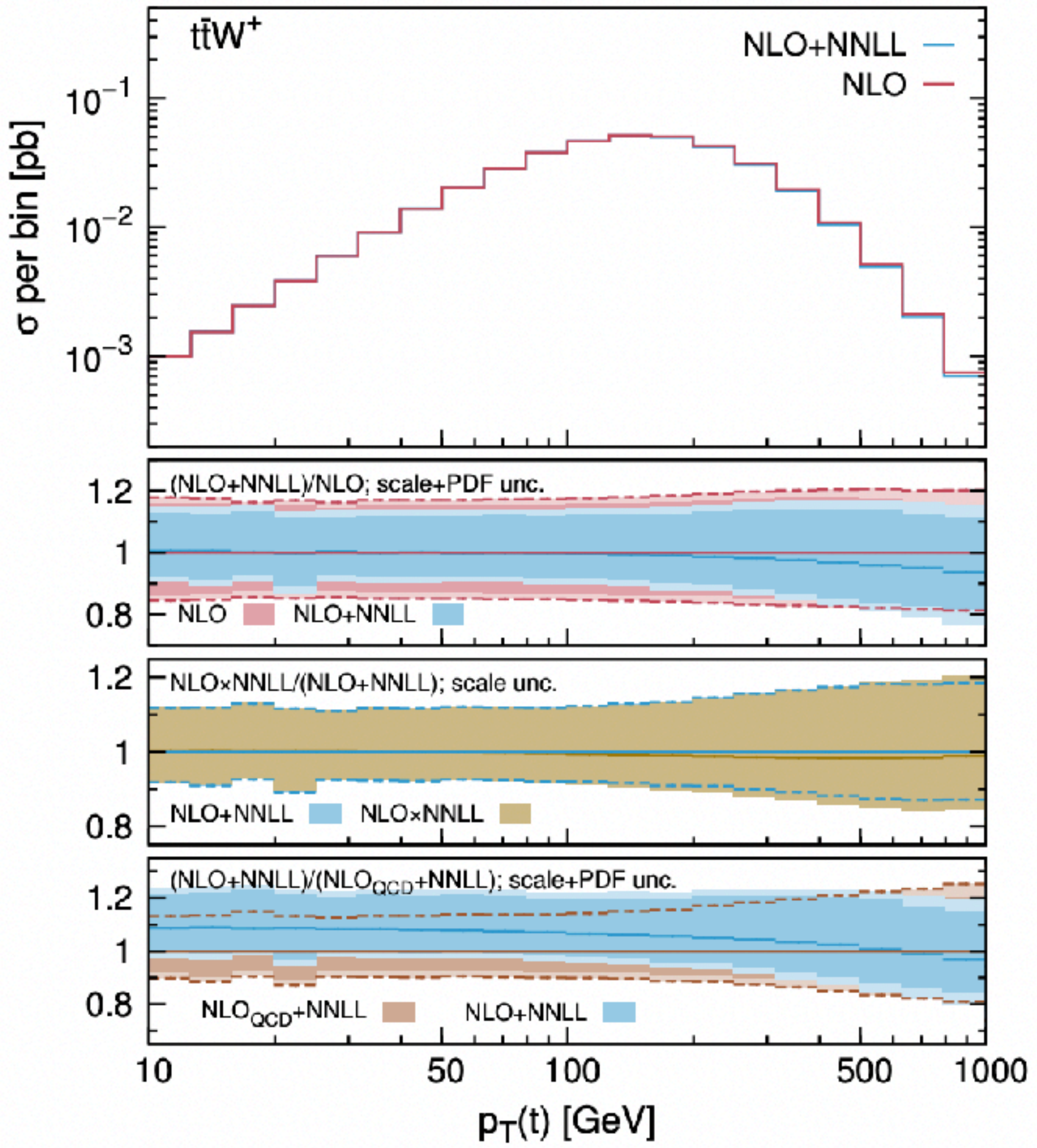


NLO+NNLL

- First calculations at NLO+NNLL become available [1812.08622]

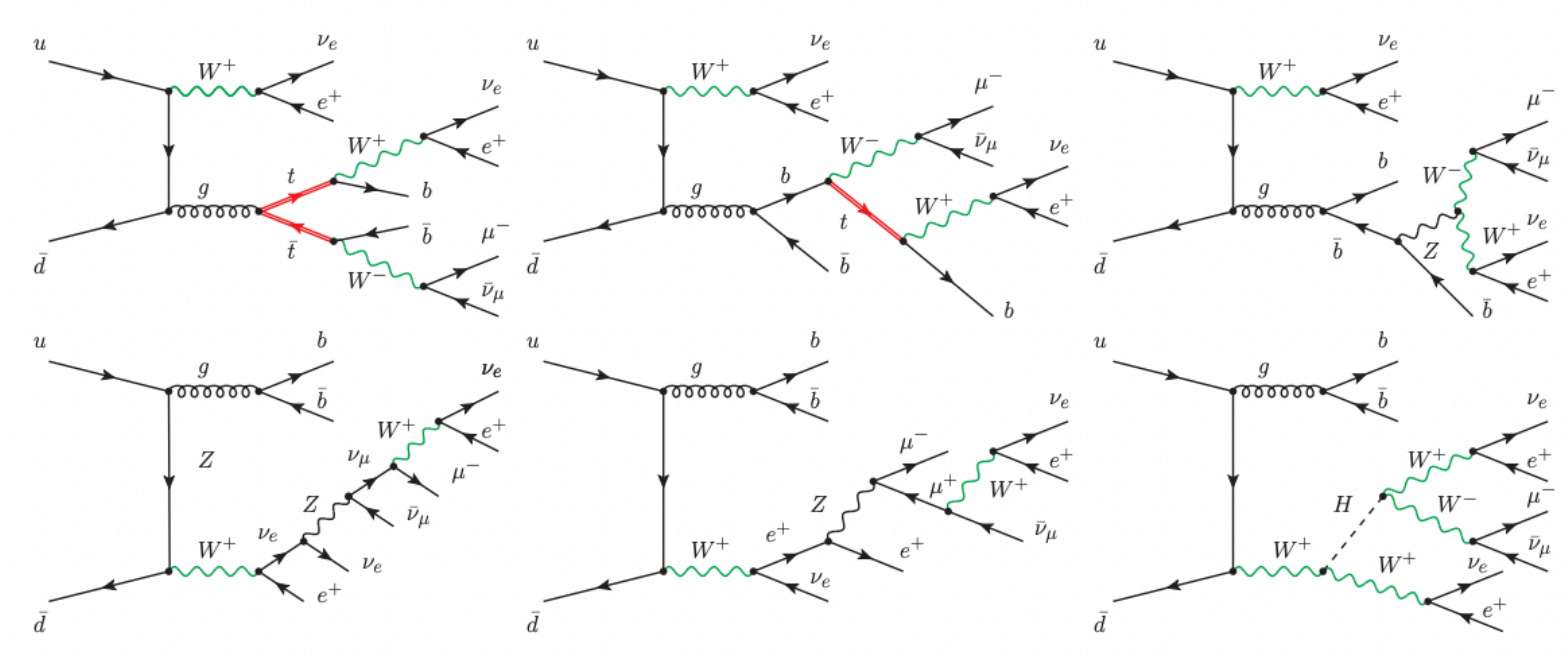
- NLO EW corrections are added on top [1907.04343, 2001.03031]





Off-shell

- NLO off-shell calculations also become available [2005.09427,2007.12089,2012.01363]



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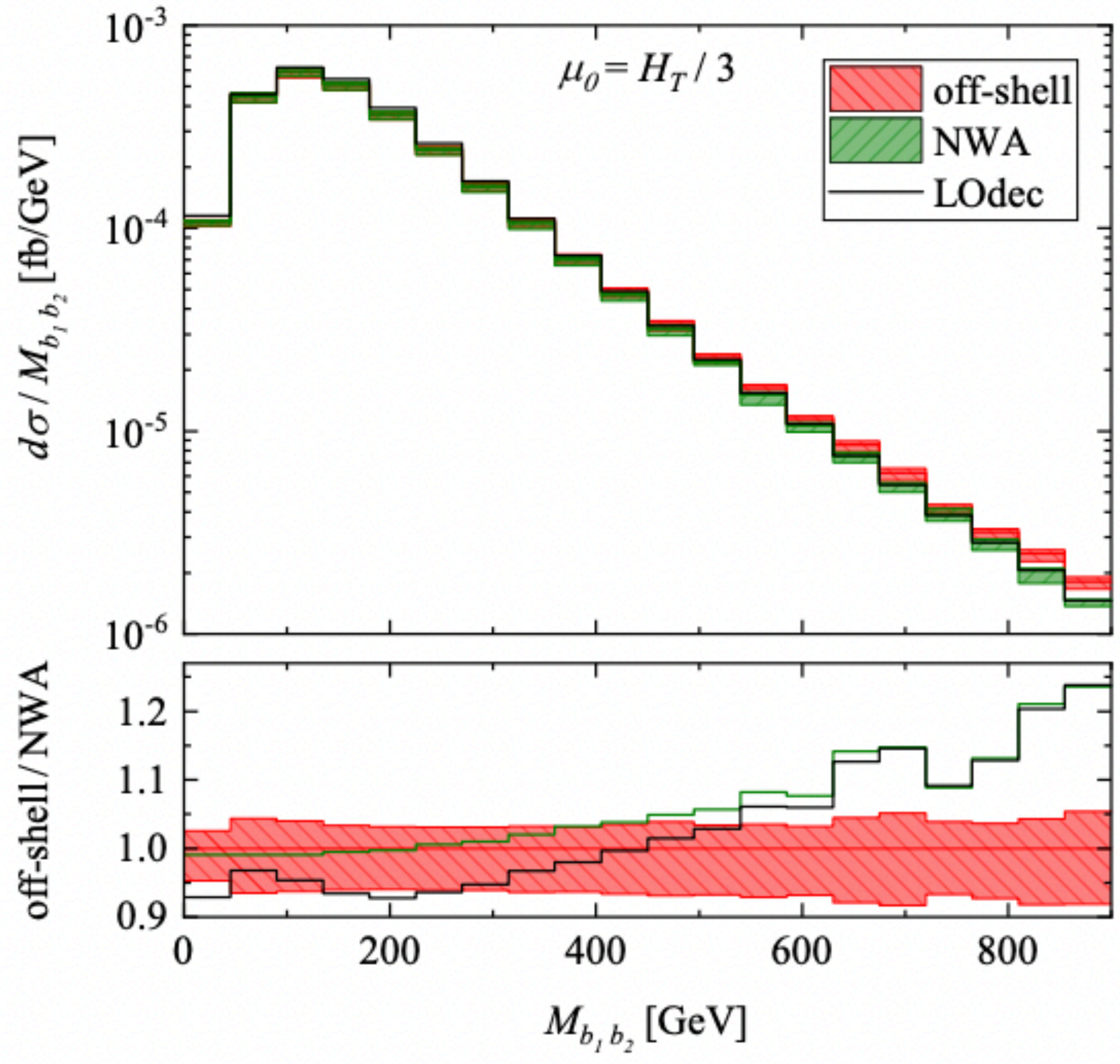
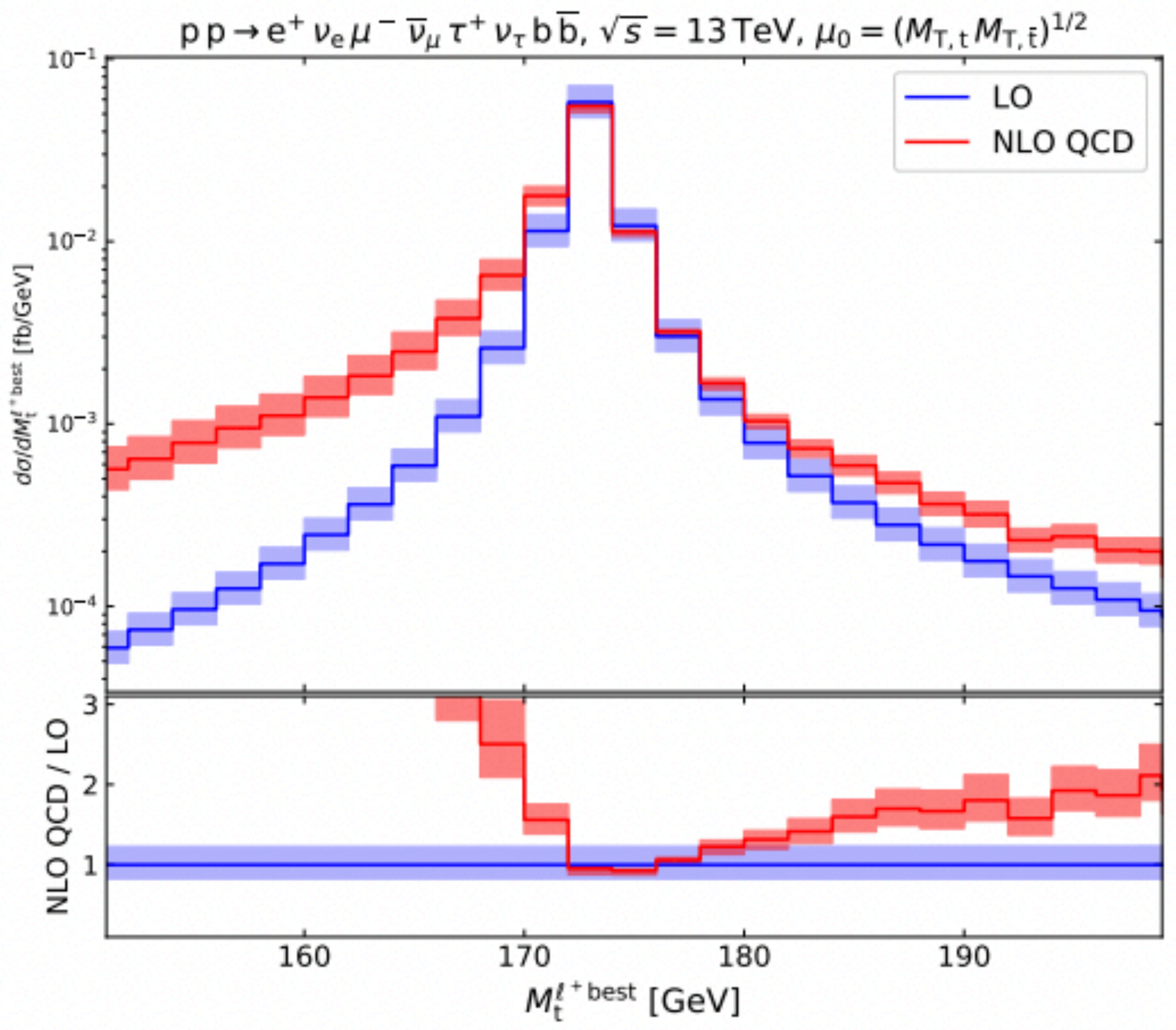
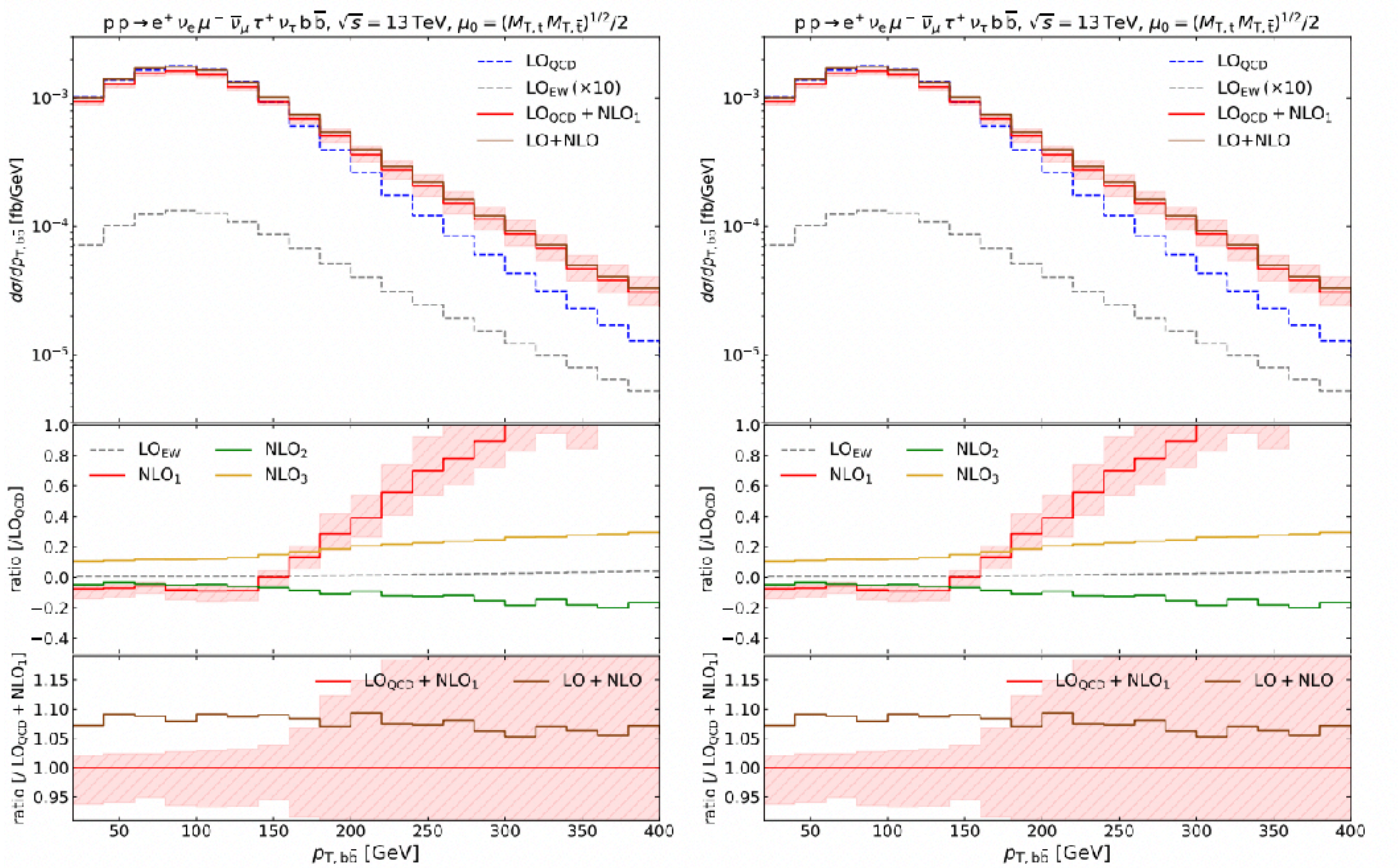
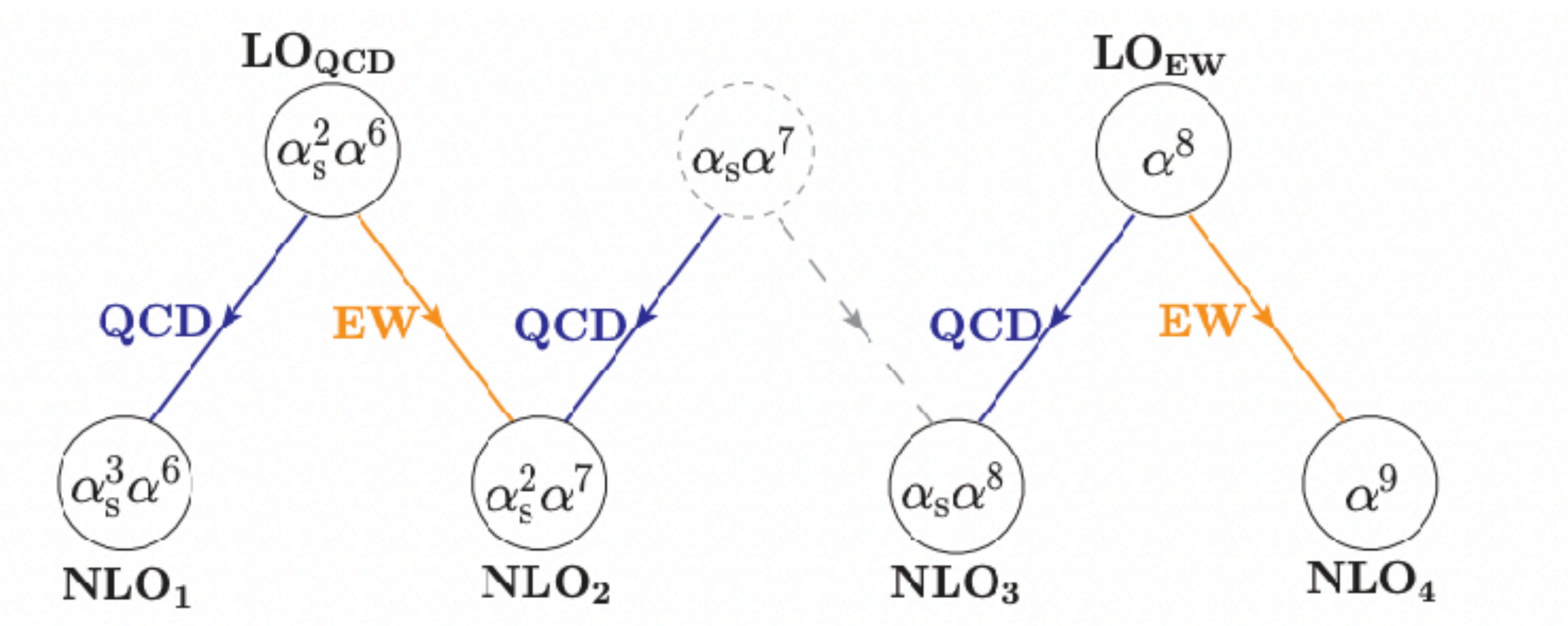




Off-shell

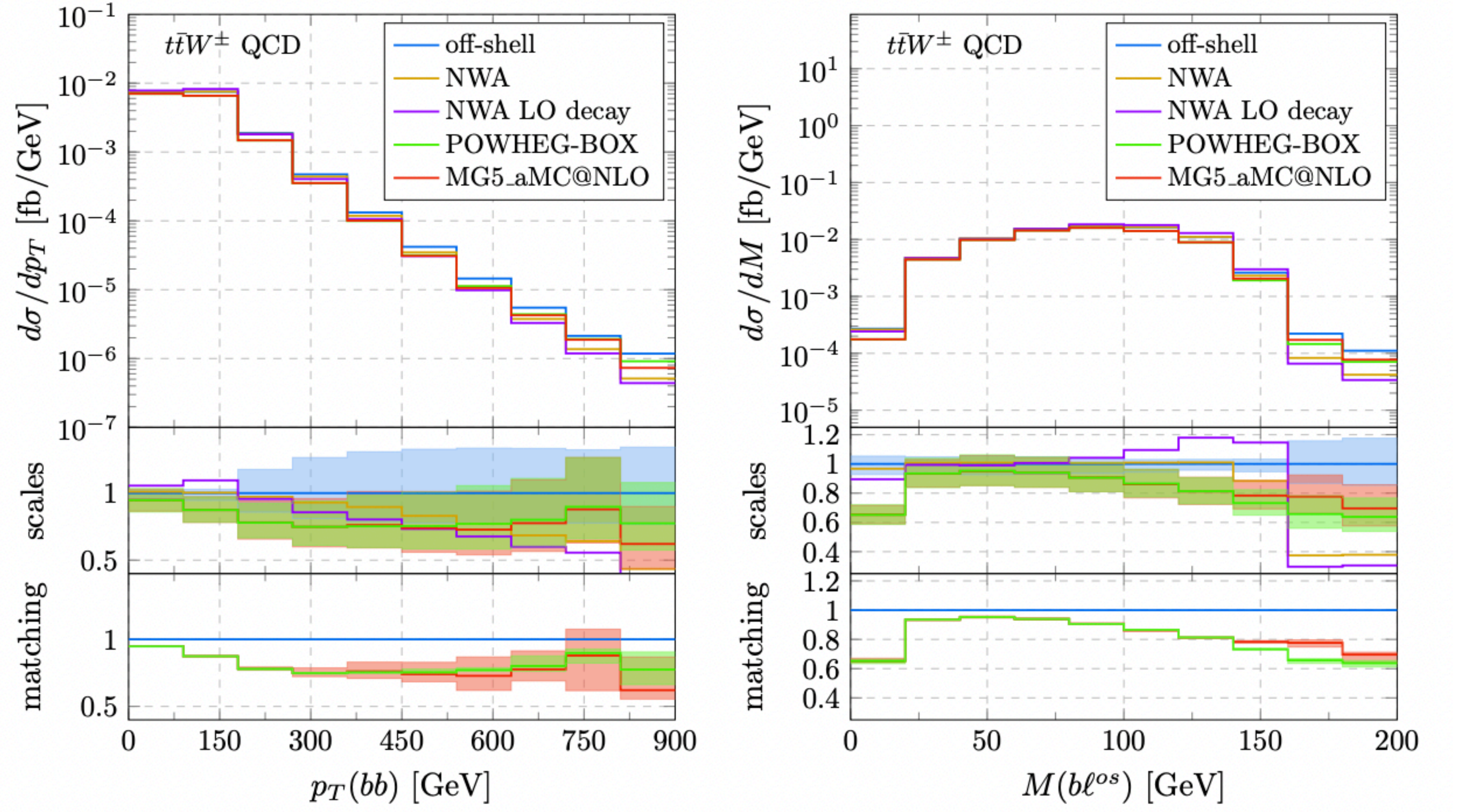
- NLO off-shell calculations also become available [2005.09427,2007.12089,2012.01363]
- NLO EW corrections are added to the off-shell predictions [2102.03246]





Off-shell vs NWA vs LO decay

- Systematic look at modelling uncertainties [2109.15181]



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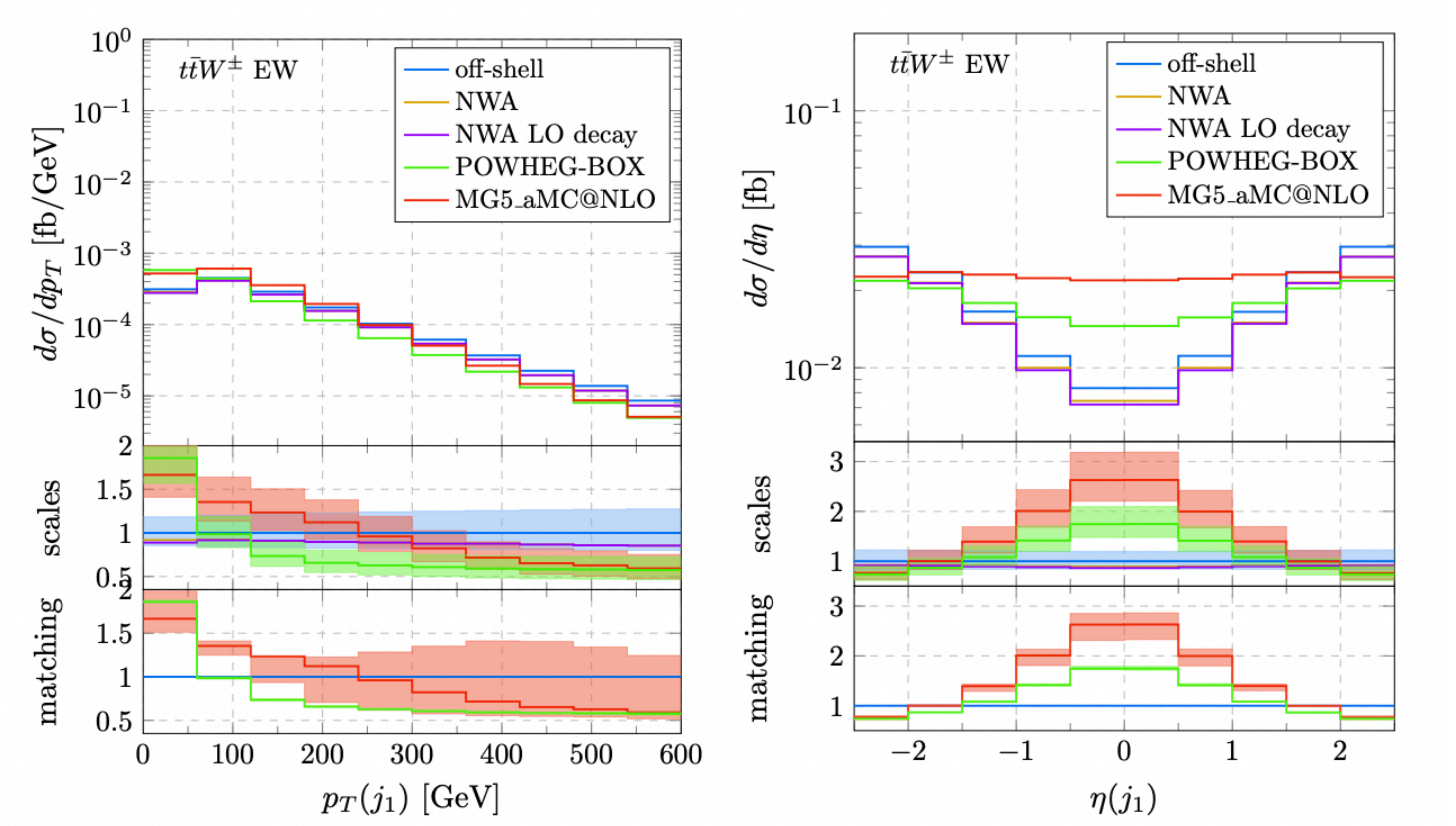
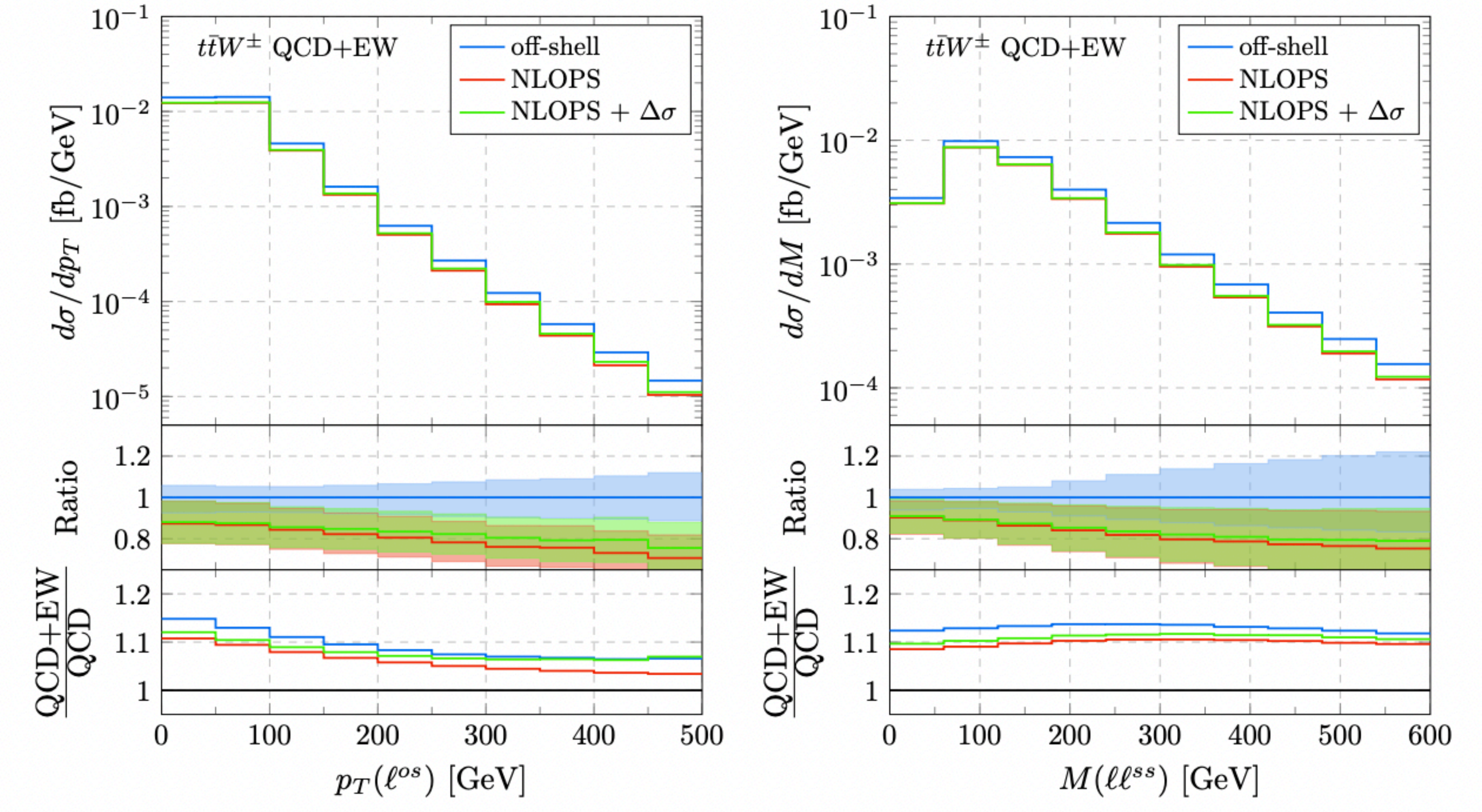


Off-shell vs NWA vs LO decay

- Systematic look at modelling uncertainties [2109.15181]
  - Including method to add off-shell effects to NLOPS sample:



Summary of TH progress

- So far doesn't seem that any of these improvements in calculations are able to resolve tensions between predictions and measurements

- General consensus that NLO+NNLL predictions are not as important at NLO-merged predictions
  - *"a large component of NLO_1 corrections, and therefore the associated scale uncertainties, originates from hard radiation in the gq → ttWq' channel. Therefore, the threshold resummation in the qq→ ttW channels is not expected to drastically reduce the total scale uncertainty."* - [1907.04343]
  - Uncertainty is still smaller, but misses crucial ttWj@NLO and ttWjj@LO contributions

- NLO off-shell calculations show important contributions in certain regions of phase space, but affect on inclusive cross section is small (~5%)

Off-shell effects inclusively

- https://arxiv.org/pdf/2005.09427.pdf

Modelling Approach	σ^{LO} [ab]	σ^{NLO} [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
NWA ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

Back-ups

Collaboration

- 87 members
- 24 institutions
- 10 countries

International laboratory covered by a cooperation agreement with CERN

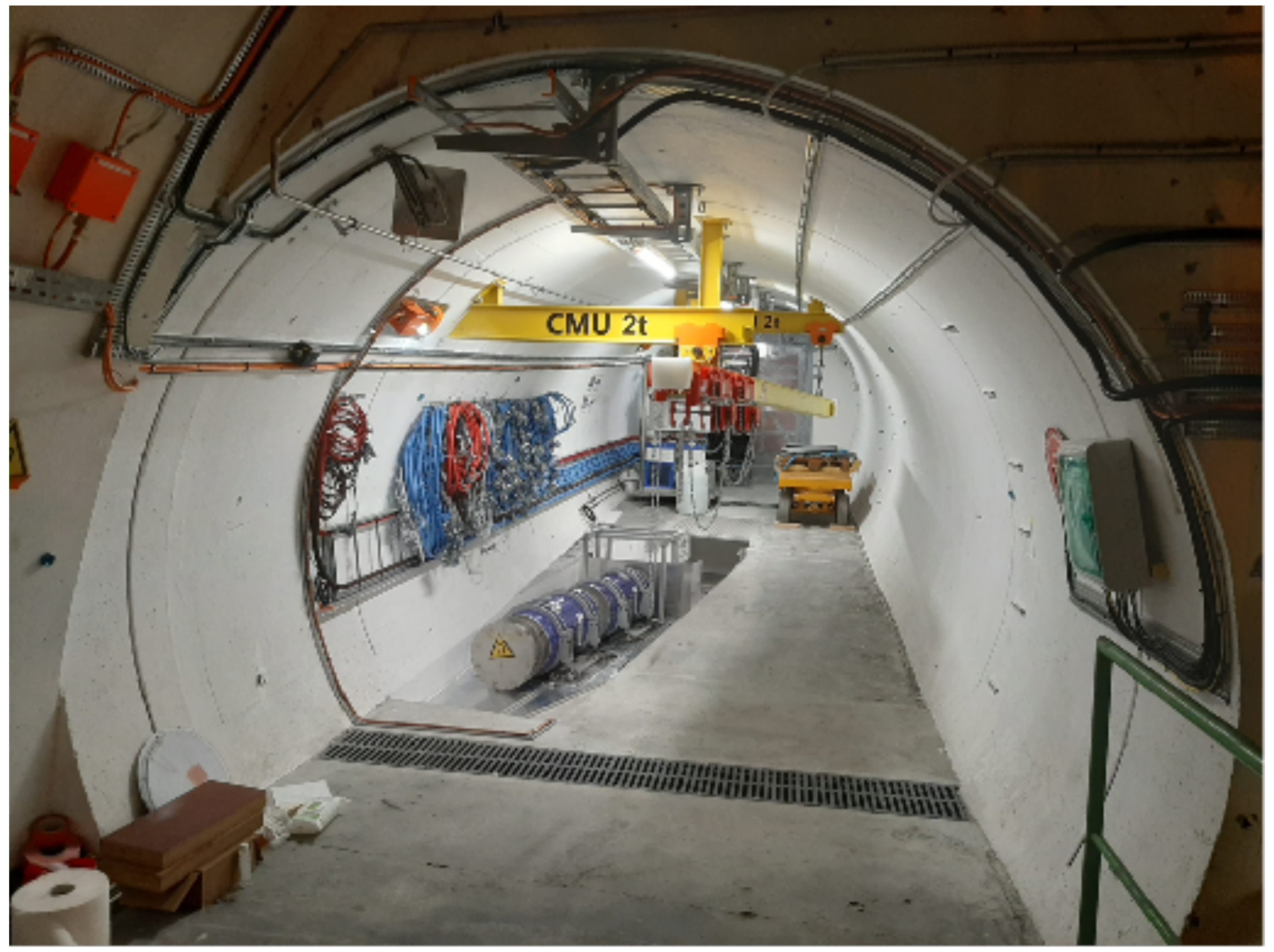
Installation

UNIVERSITY OF SUSSEX

8/18

8/19

4/20

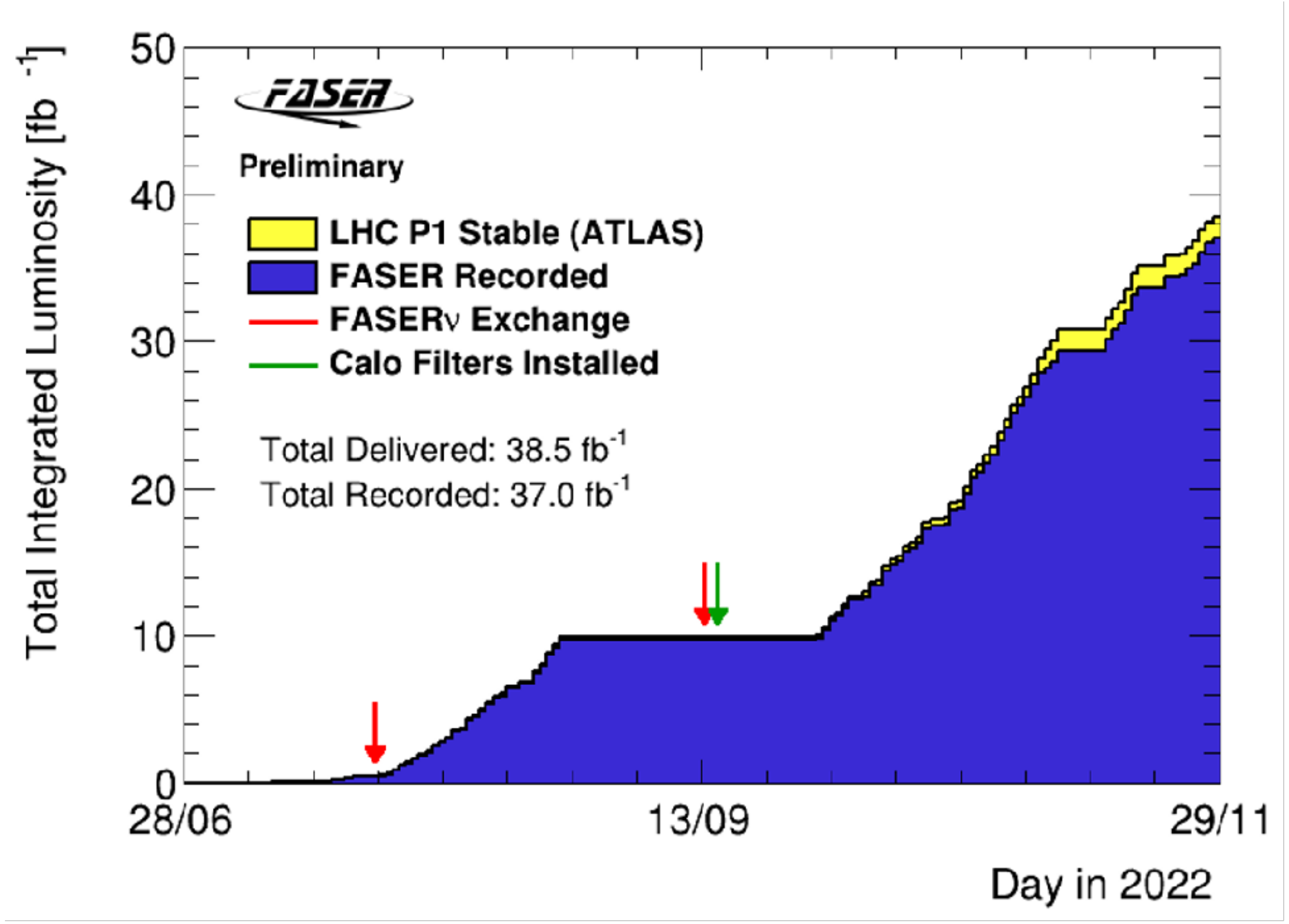


11/20

3/21

Operations

- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered lumi.
  - DAQ dead-time of 1.3%
  - couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after this exchange



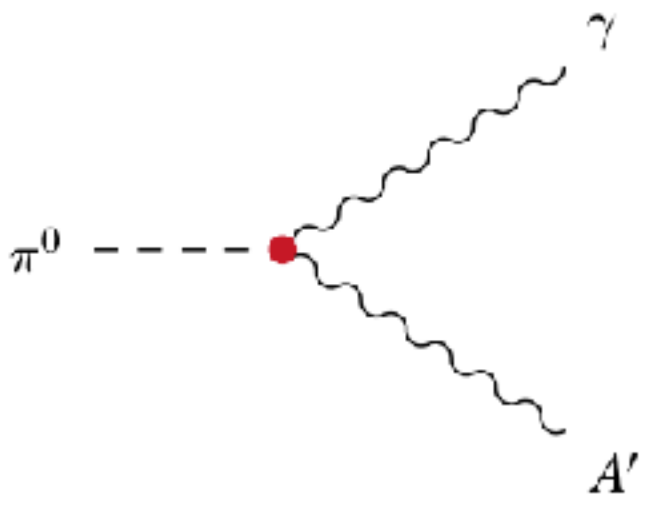
Analyses presented use 27.0 fb^{-1} or 35.4 fb^{-1}

Dark Photon (A') Search

- Dark photon is a common feature of hidden sector models
  - Weakly coupling to SM via kinetic mixing (ε) with SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} \not{A}' f$$

- MeV A's produced mainly in meson decays at LHC

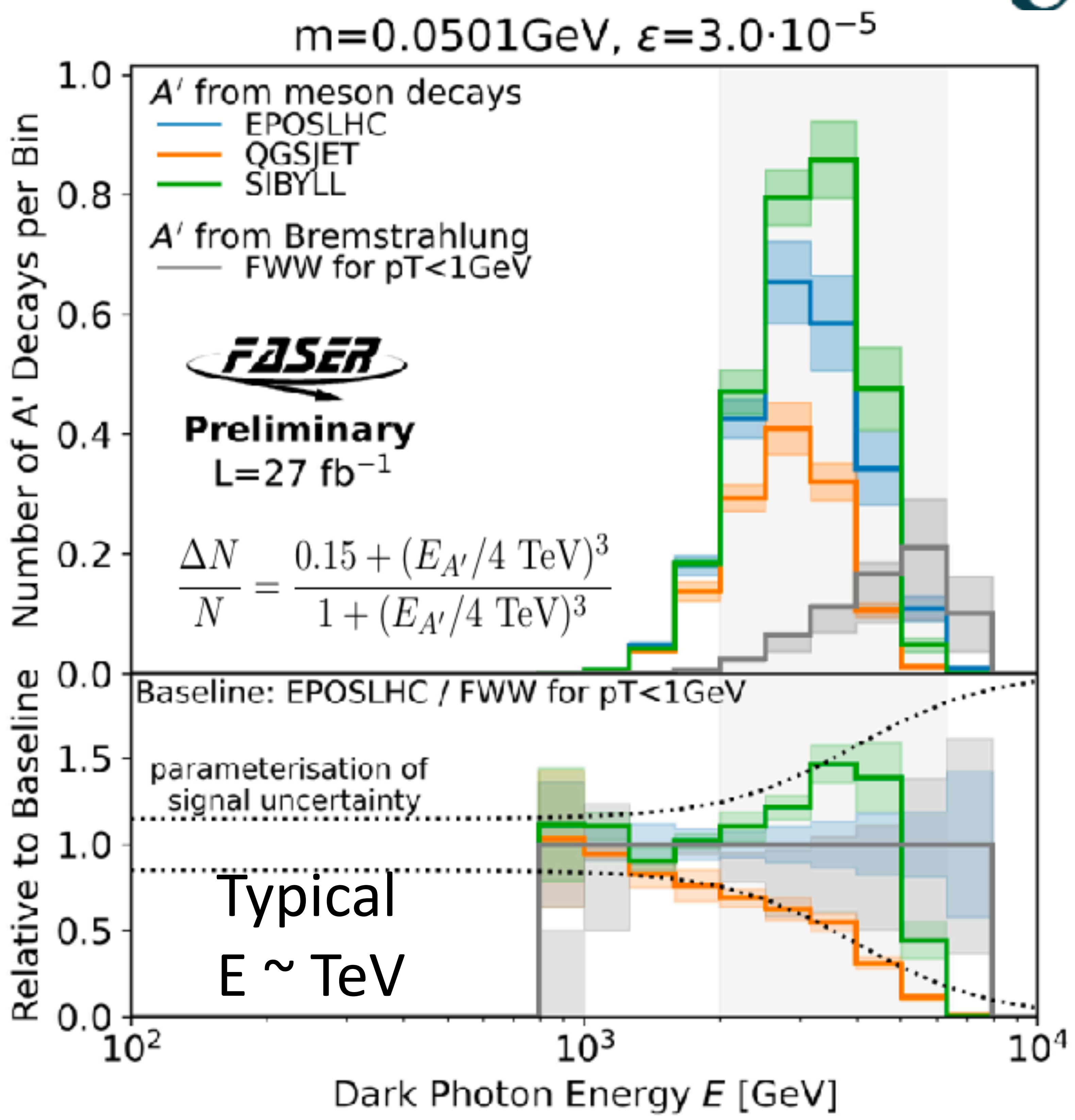


$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- FASER targets small ε, where A' has long decay length

$$L = c\beta\tau\gamma \approx (80 \text{ m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100 \text{ MeV}}{m_{A'}}\right]^2$$

  - Below $2m_\mu$, A' has 100% decay to e^+e^- pair



- A' → e+e- simulated with FORESEE*
  - π0 and η via EPOS-LHC generator
  - Subdominant dark brem. via FWW
- Generator uncertainty dominates
  - Difference to QGSJET/SIBYLL
  - Parameterised based on A' energy

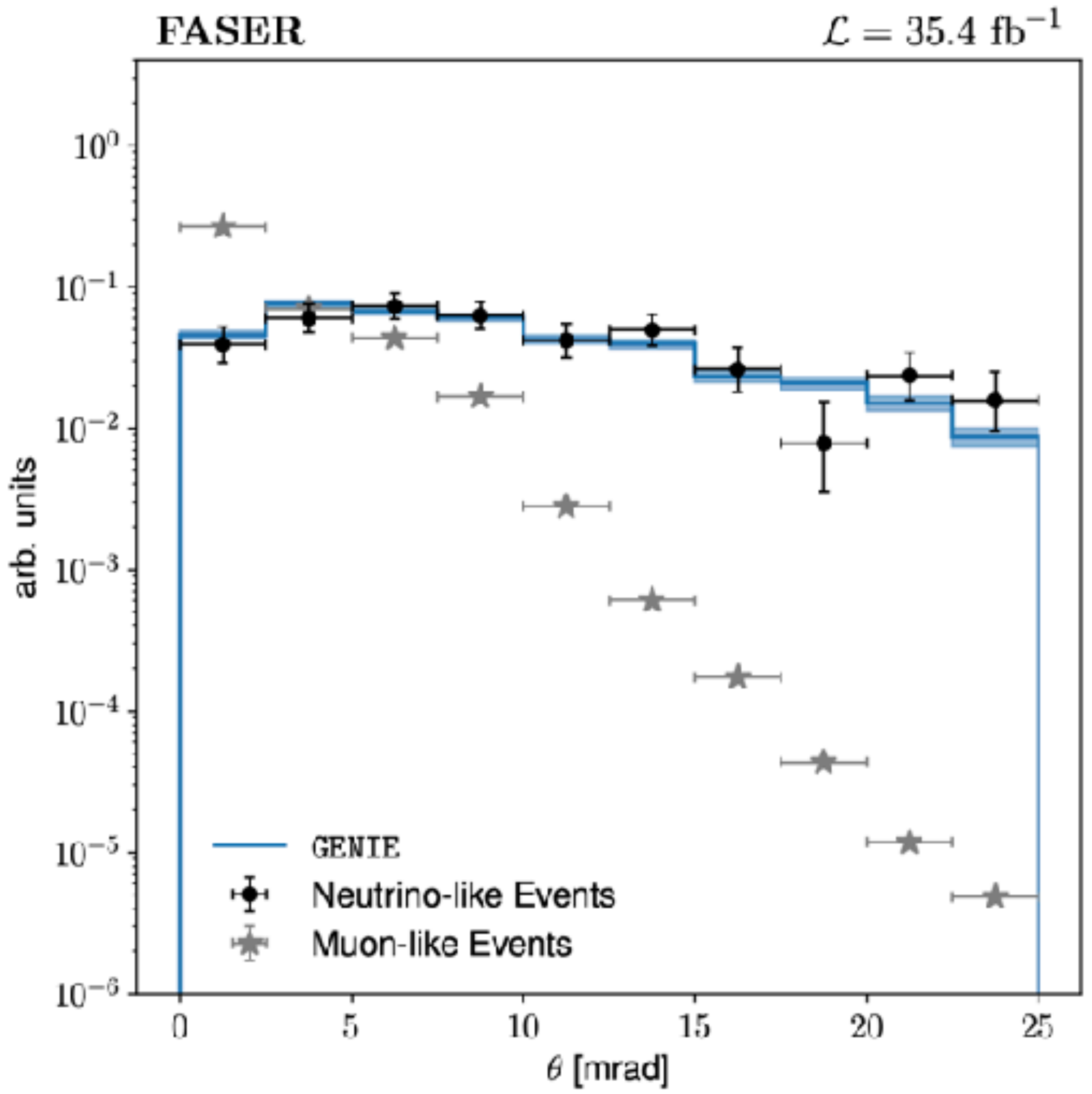
* arXiv:2105.07077

Operations

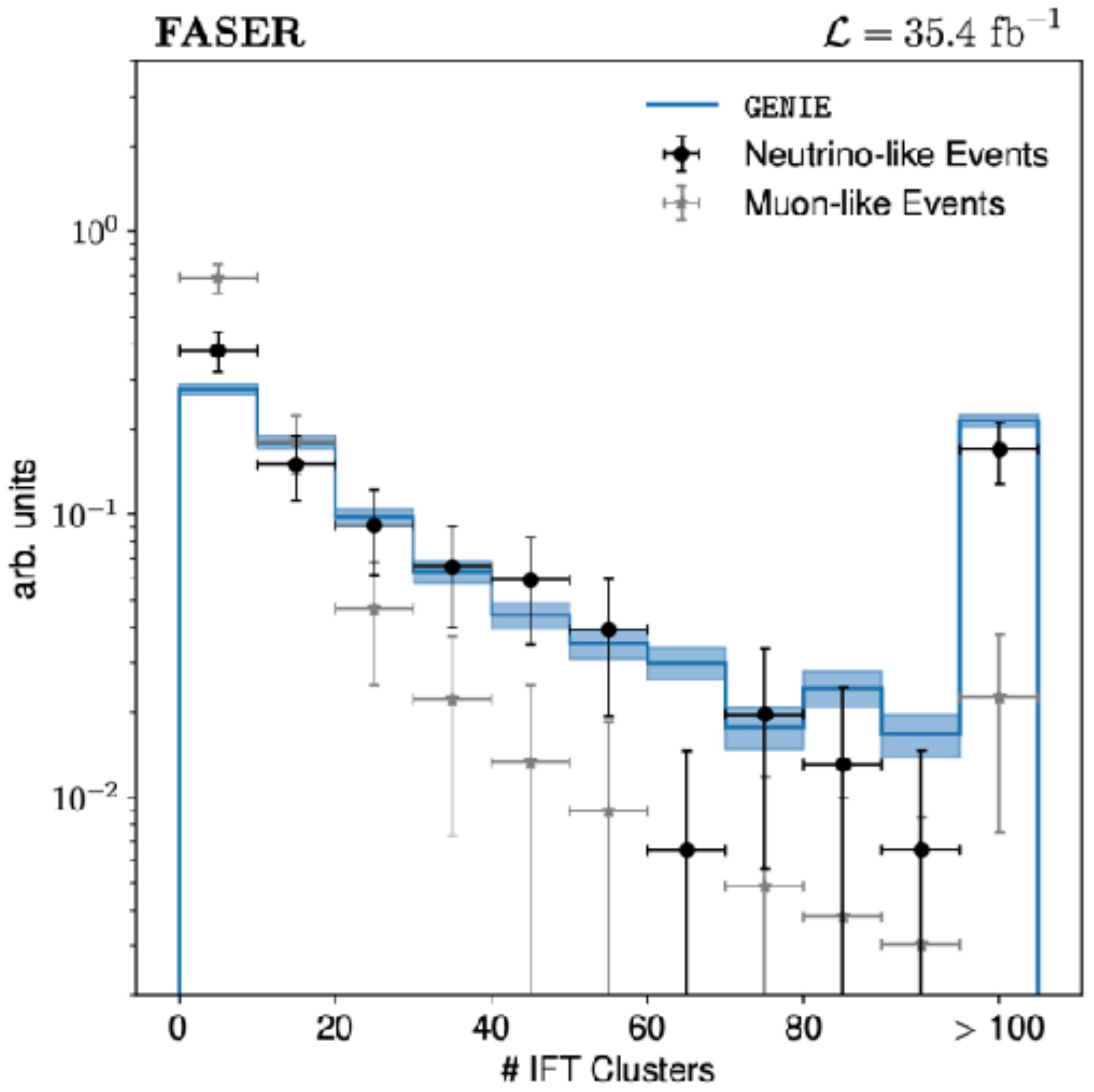
- All detector components performing excellently
  - More than 350M single-muon events recorded
  - Example: muon leaving track passing through full detector - consistent with MIP

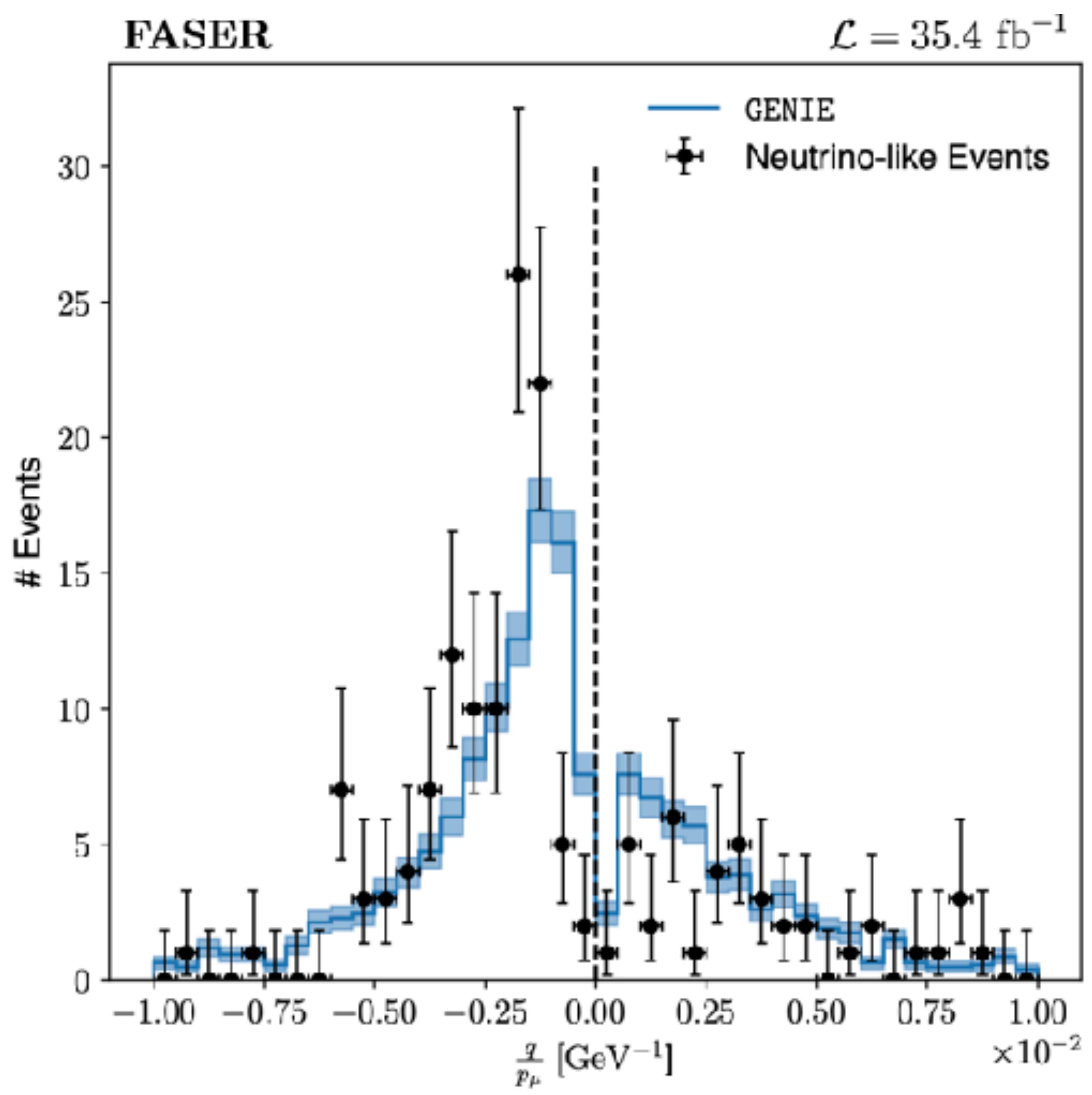
Neutrino analysis | Results

- Candidate neutrino events match expectation from signal
  - High occupancy in front tracker station
  - Most events have high μ momentum
  - More νμ than anti- νμ



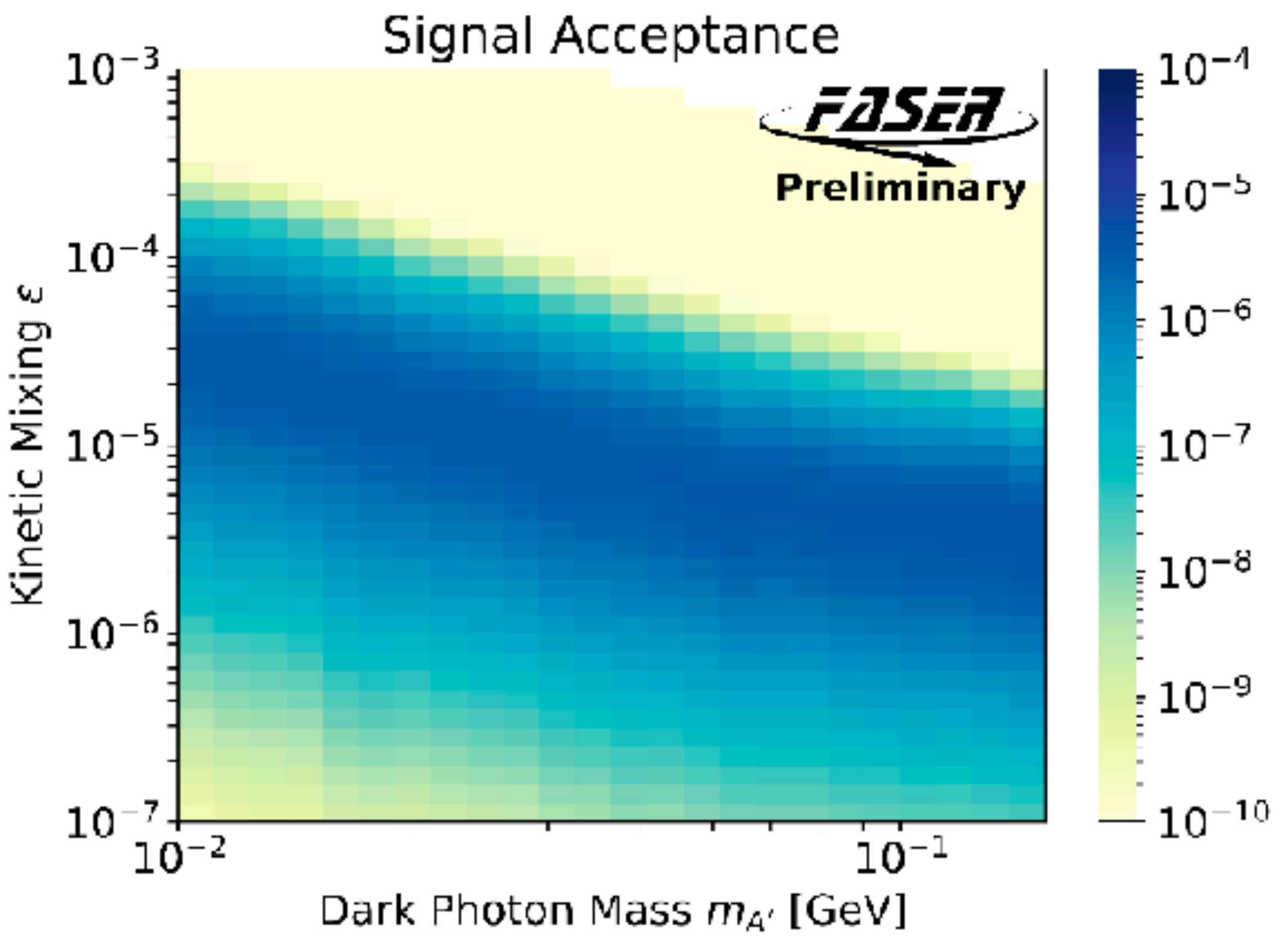
- NB: no acceptance corrections nor any systematic uncertainties in these plots

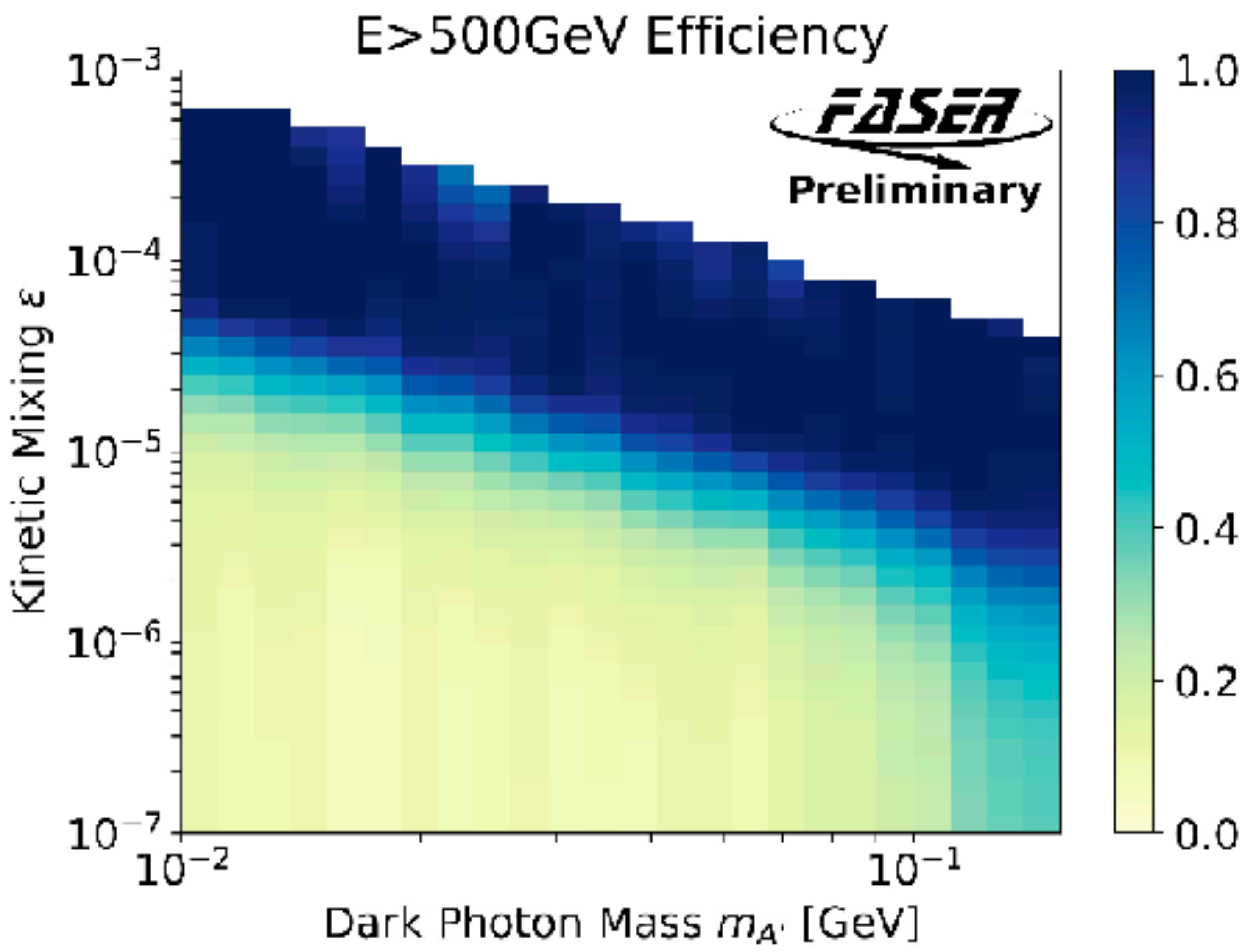




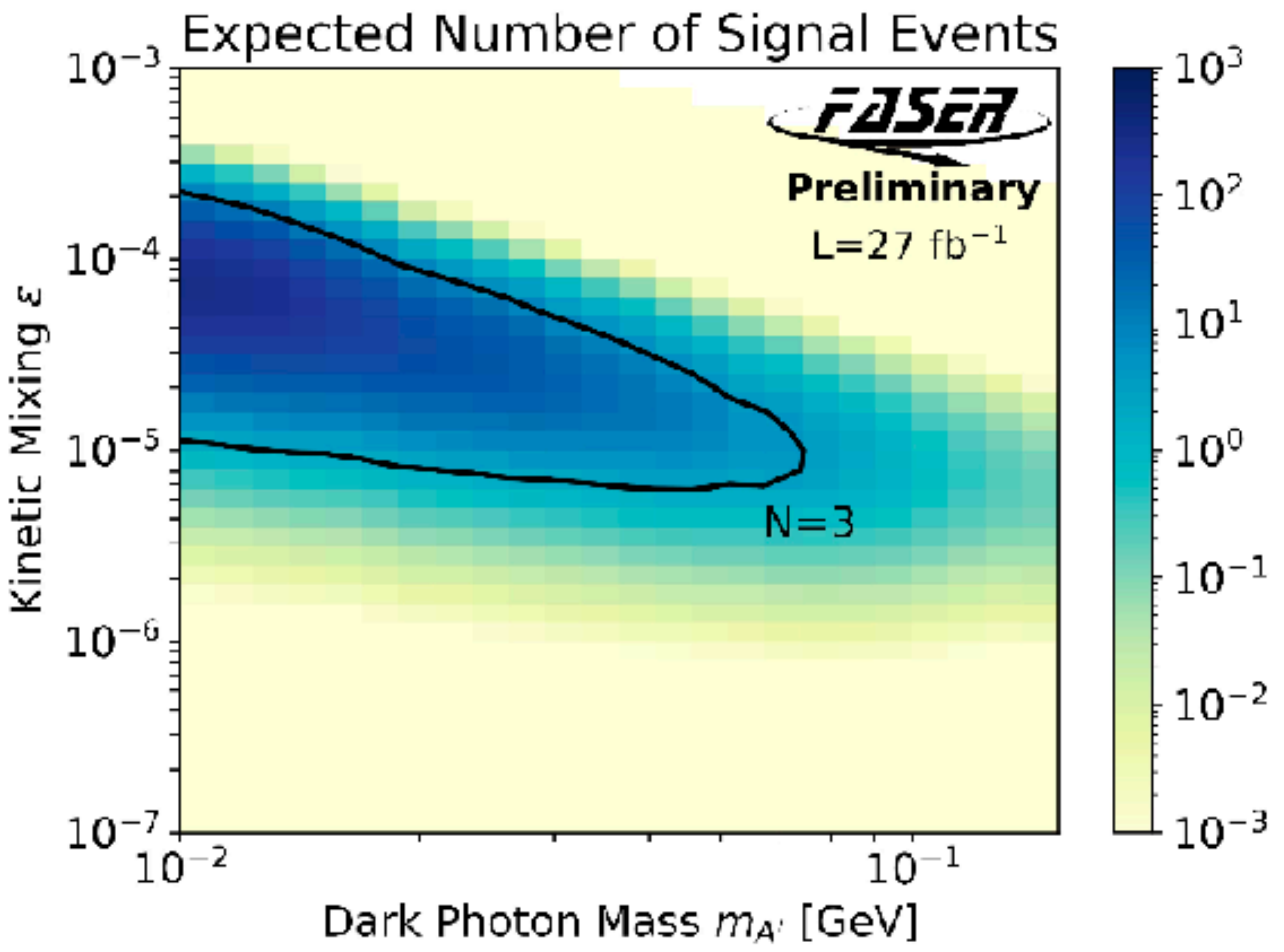
Dark Photon | Signal

- Acceptance 10^-6
- Decay volume 10^-8 solid angle
- P(decay in FASER) = 10^-3





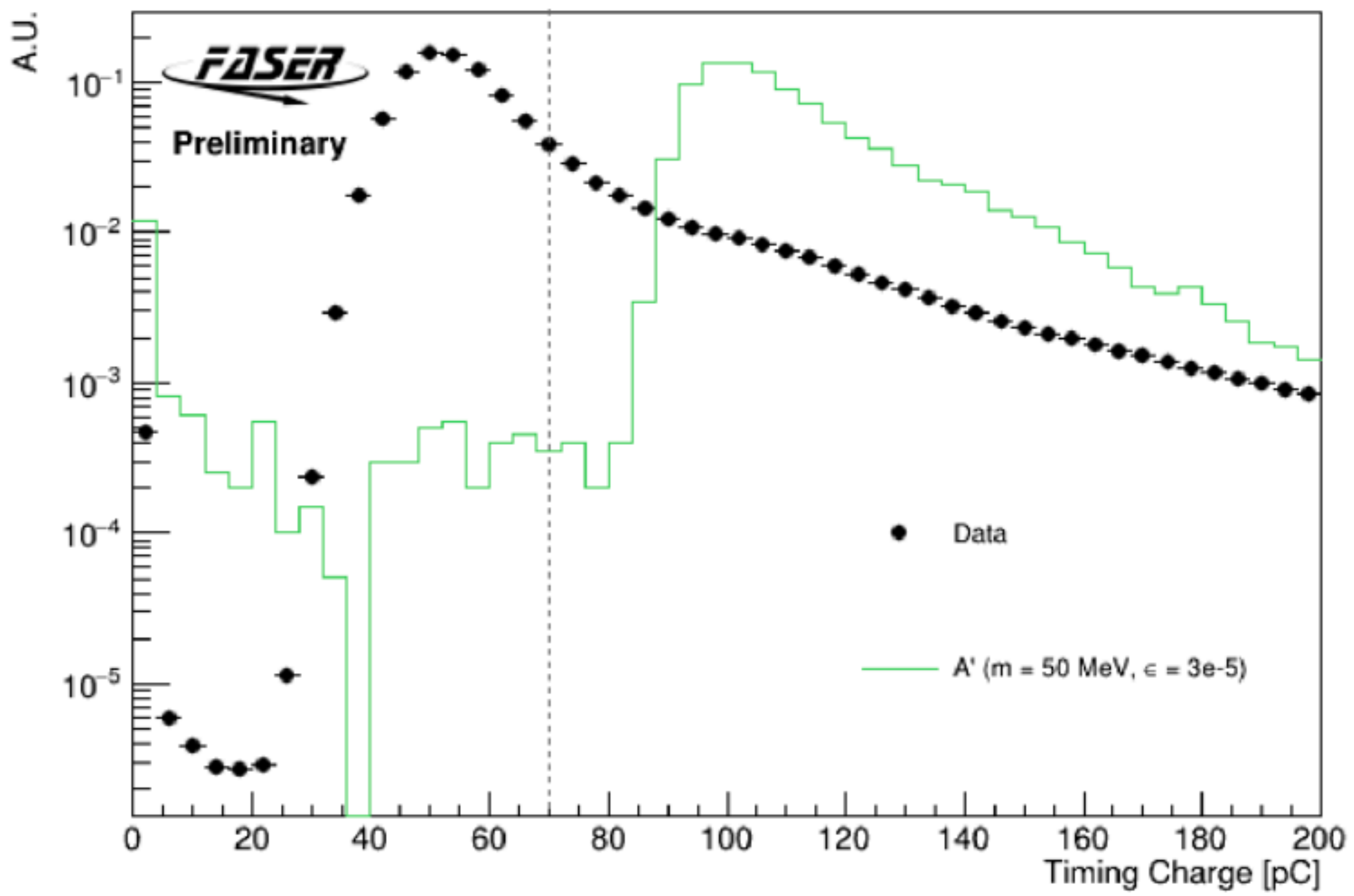
$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$



Dark Photon | Selection

Description	Value
Pre-selecton	
Time consistent with a colliding bunch identifier Timing scintillator trigger	
Scintillator	
Timing station: Top or Bottom Scintillator charge OR Top and Bottom charge	 > 70 pC > 30 pC
Each Preshower scintillator charge Each Veto scintillator charge	>2.5 pC <40 pC
Tracking	
Exactly 2 Good Tracks Momentum χ^2/NDF Number of tracker layers on track Number of tracker hits on track	 > 20 GeV < 25 $>= 7$ $>= 12$
Fiducial selection	
Track extrapolated to all scintillators and tracking stations	< 95mm
Calorimeter	
Calorimeter energy (sum of four channels)	> 500 GeV

TABLE I. Summary of selection requirements.

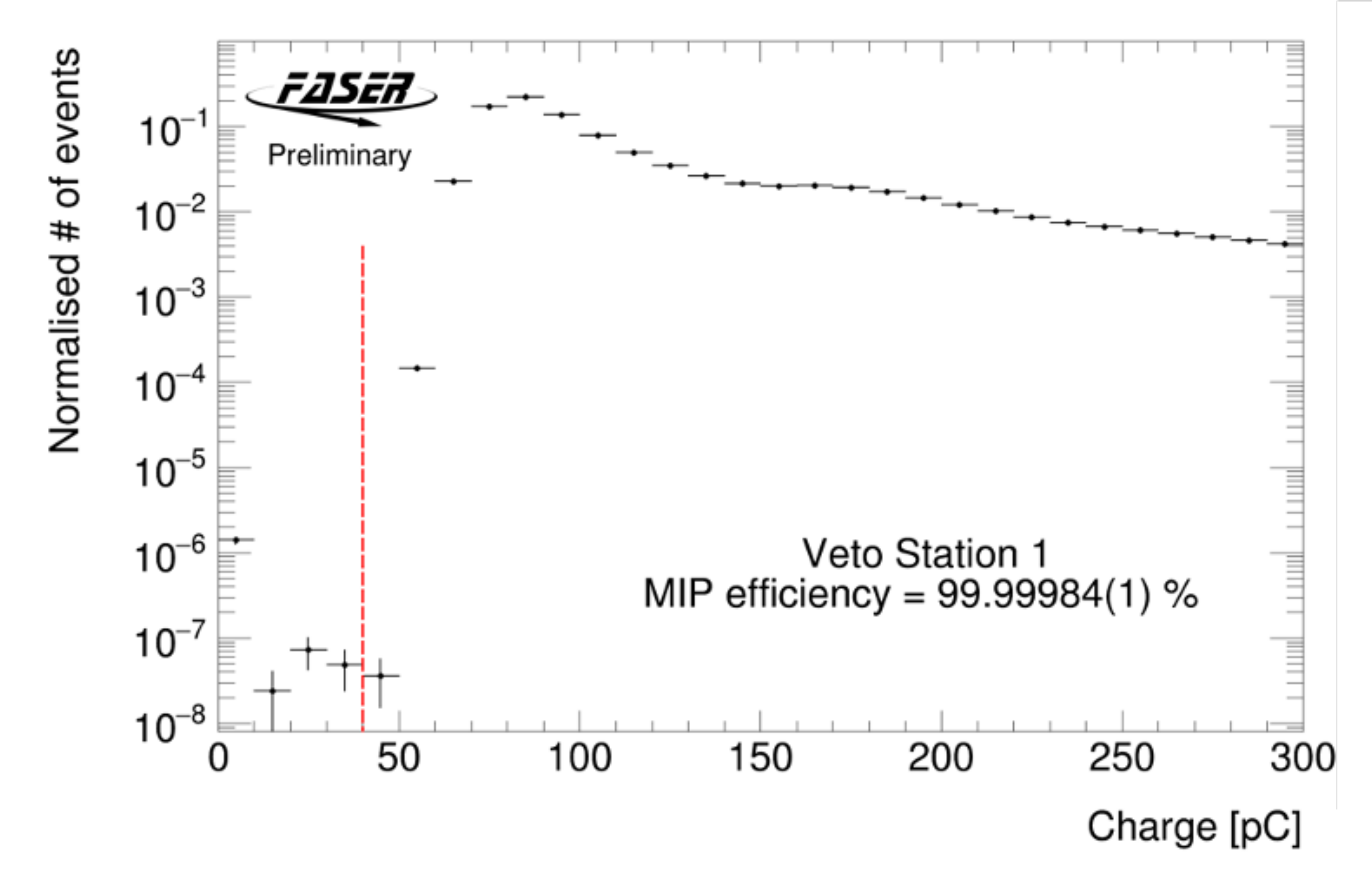


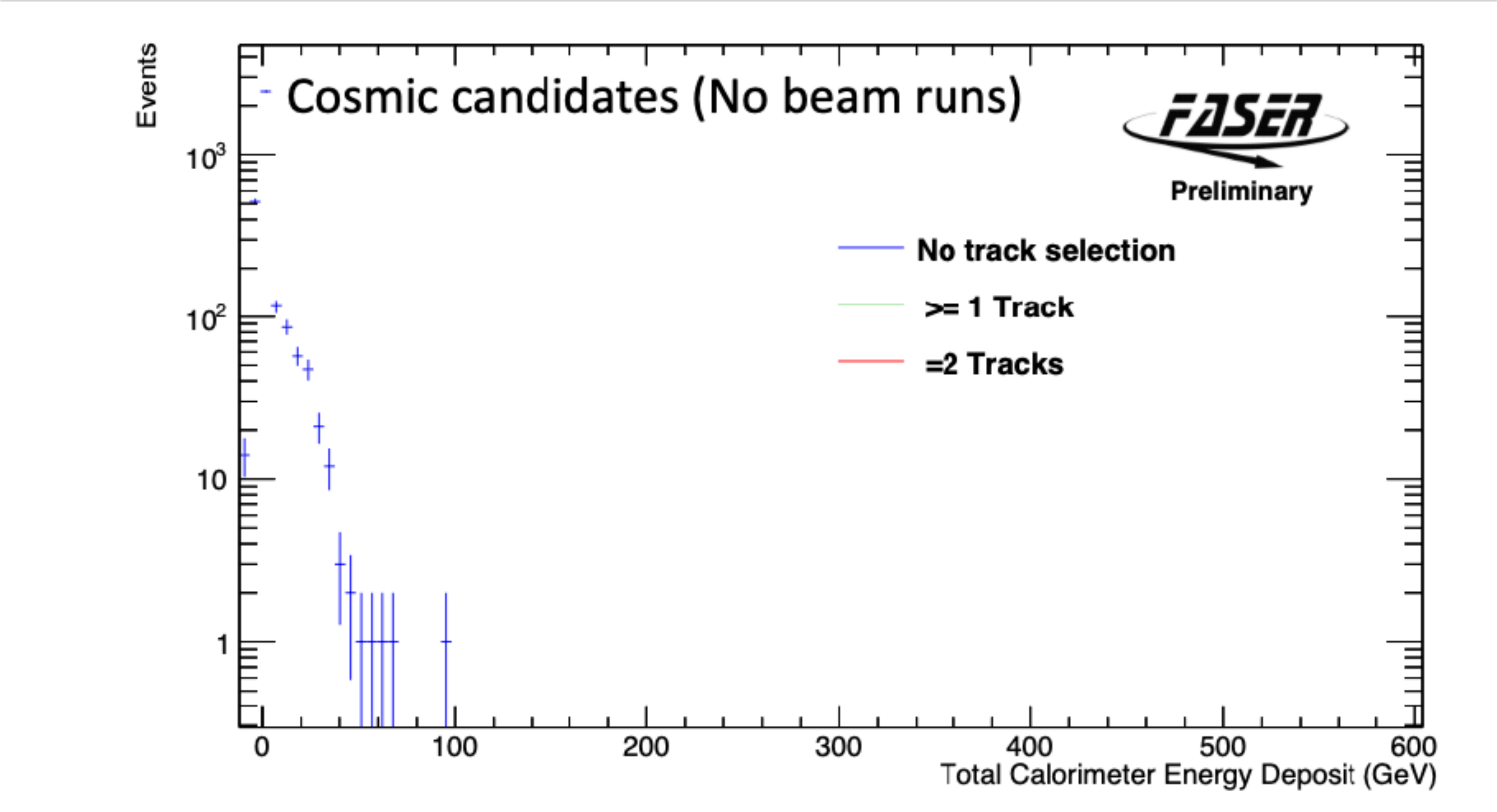
Selection Criteria	Efficiency
Good collision event	99.7%
No Veto Signal	98.4%
Timing/Preshower Signal	97.3%
≥ 1 good track	89.2%
$= 2$ good tracks	44.5% *
Track radius $<$ 95 mm	42.3% *
Calo energy $>$ 500 GeV	41.6% *

$\epsilon = 3 \times 10^{-5}$ $m_{A'} = 25.1$ MeV

Dark Photon | Backgrounds

- Veto inefficiency
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. 10^8 muons to negligible level (even before cuts) ($<10^{-20}$ inefficiency)
- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually

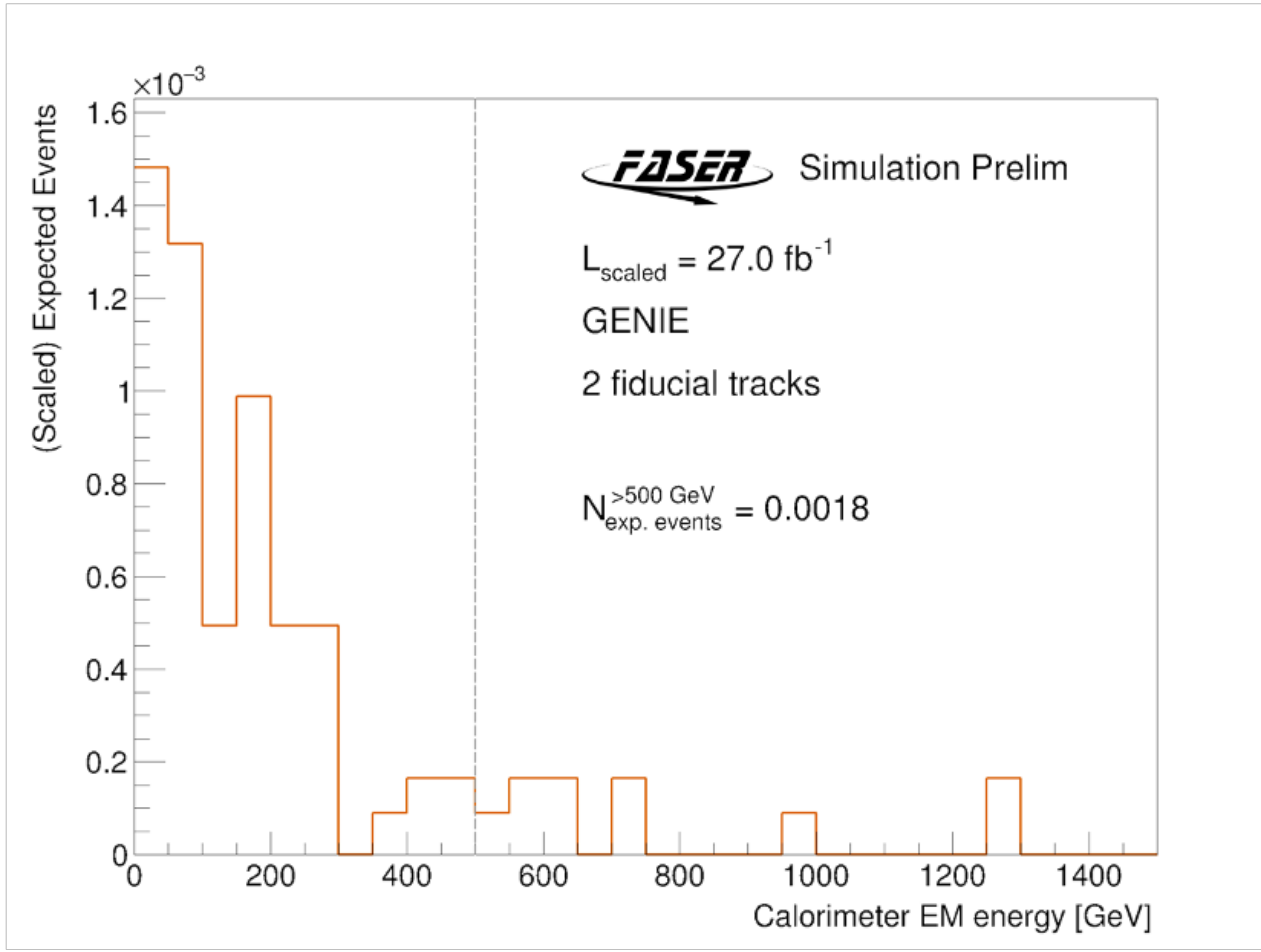




Dark Photon | Backgrounds

- Main background is from Neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab-1)
  - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

N = (1.8 ± 2.4) x 10^{-3}

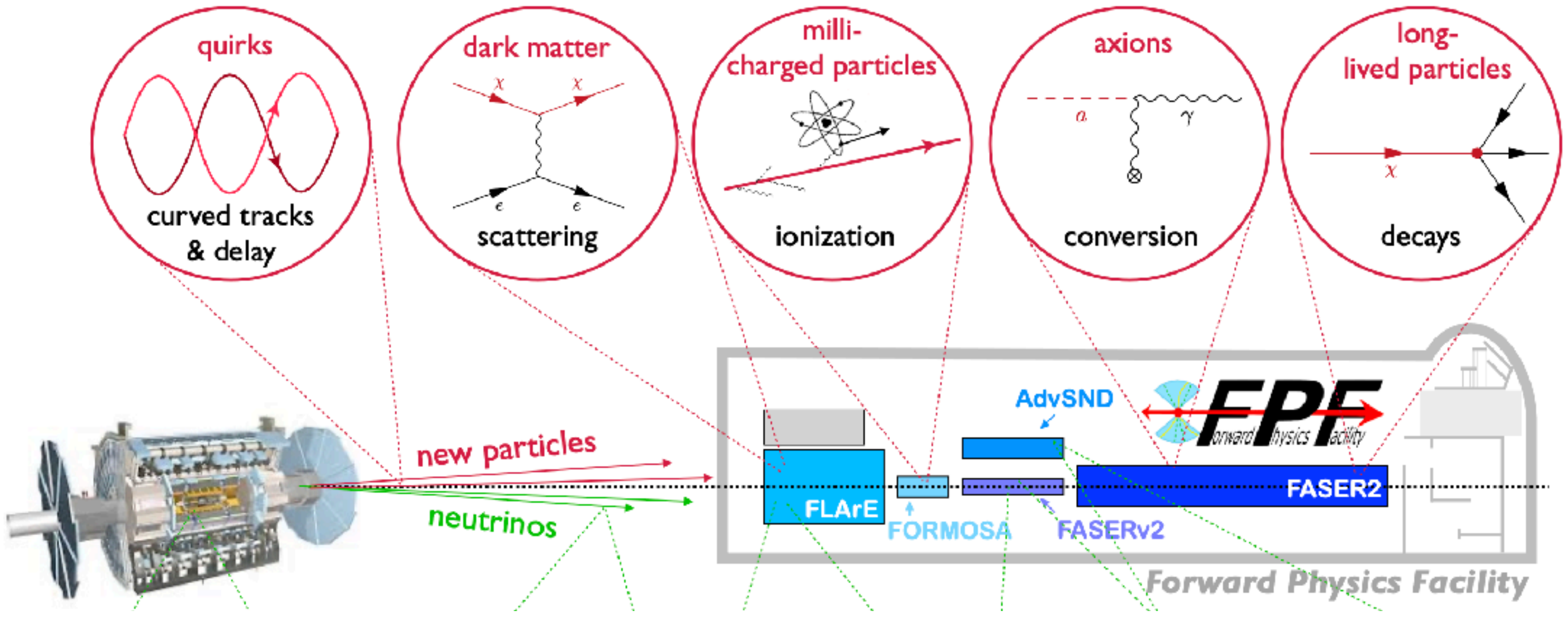


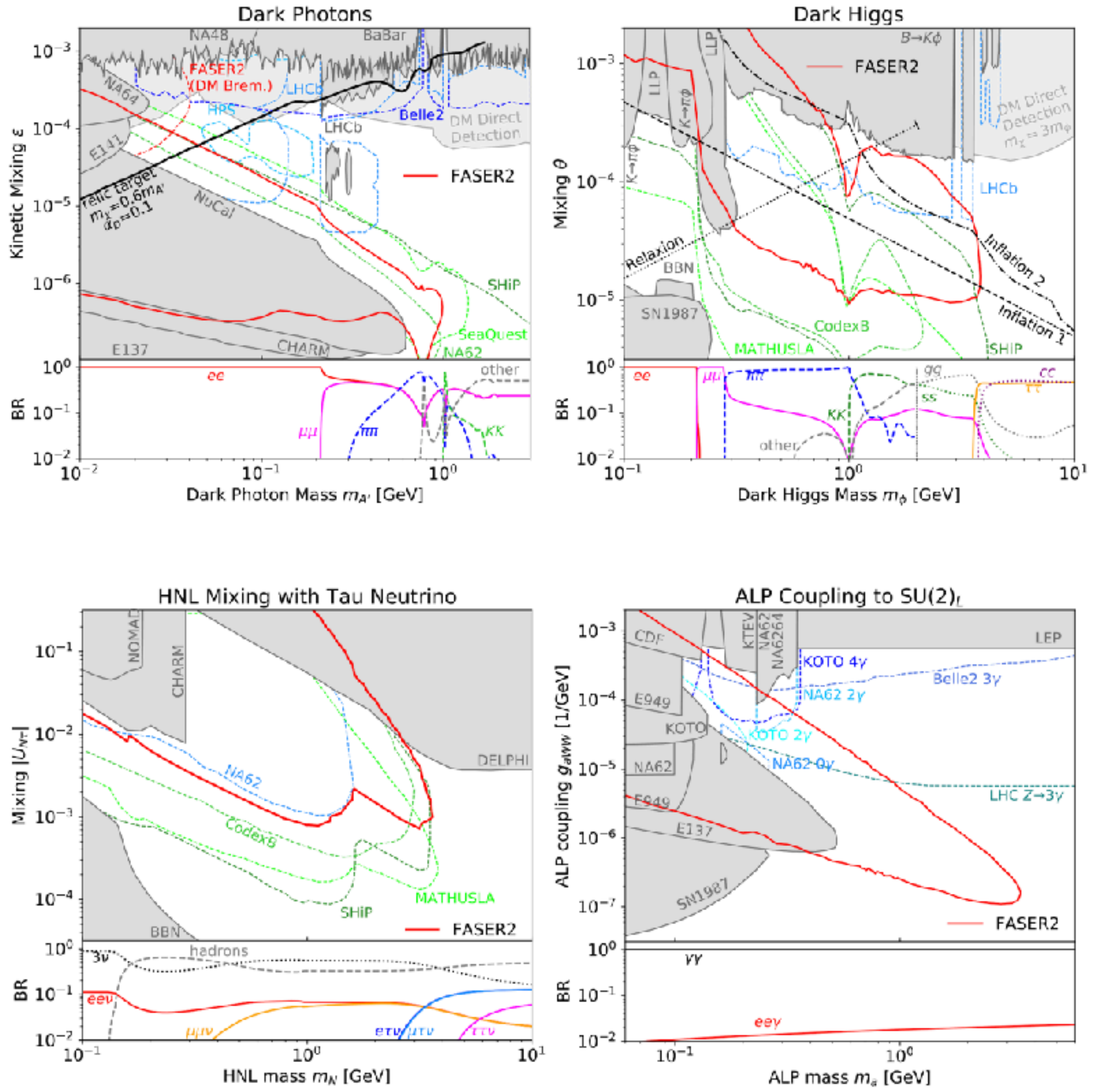
- Neutral hadrons (e.g. Ks) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed since:
    - muon nearly always continues after interaction
    - has to pass through 8 interaction lengths (FASERν)
    - decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2/3 tracks and different veto conditions

N = (2.2 ± 3.1) x 10^{-4}

Forward Physics Facility | BSM

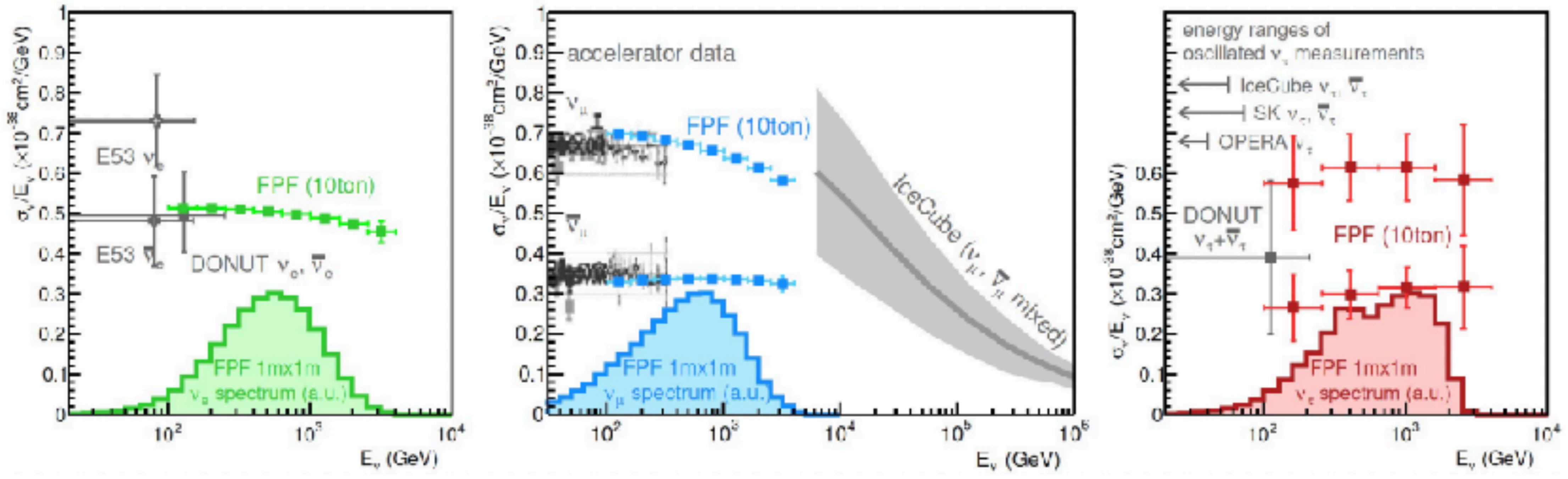
- FPF Papers:
  - FPF "Short" Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)

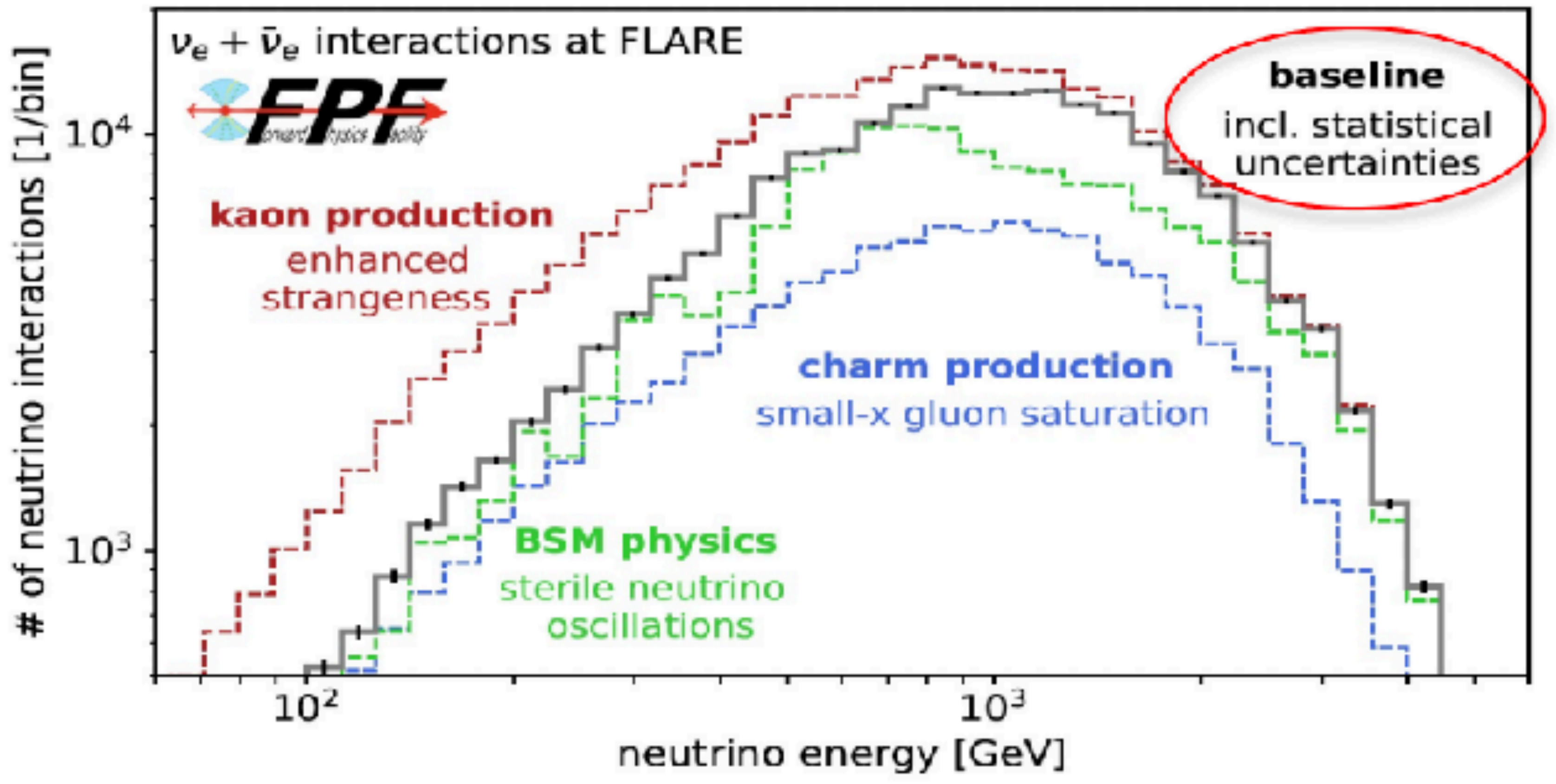


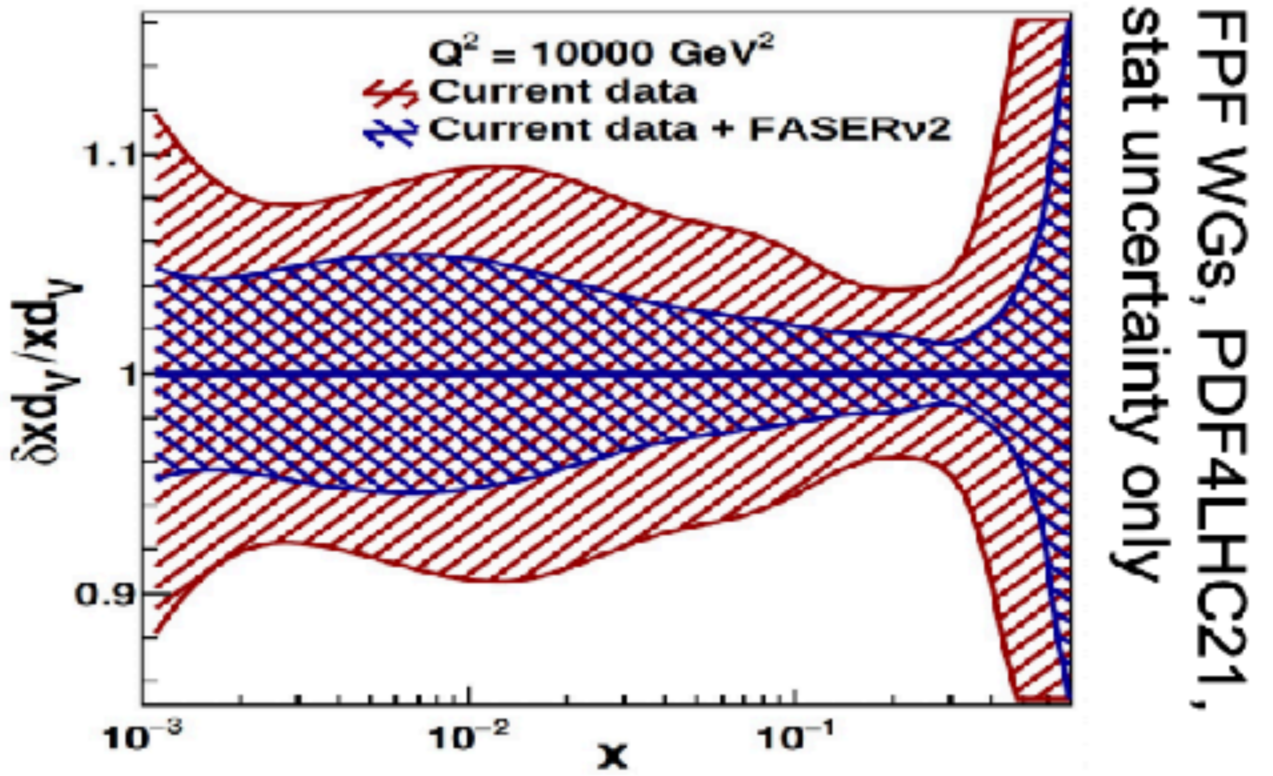


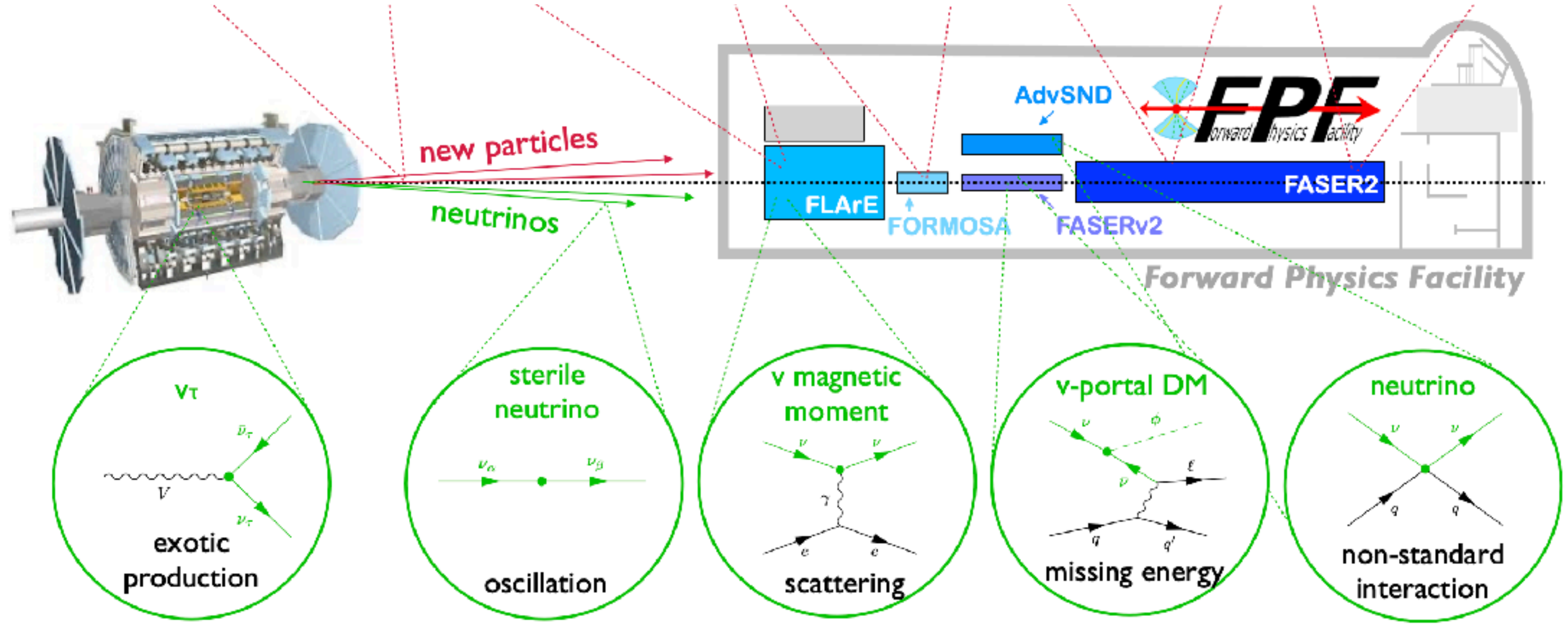
Forward Physics Facility | Neutrinos

- FPF Papers:
  - FPF "Short" Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)



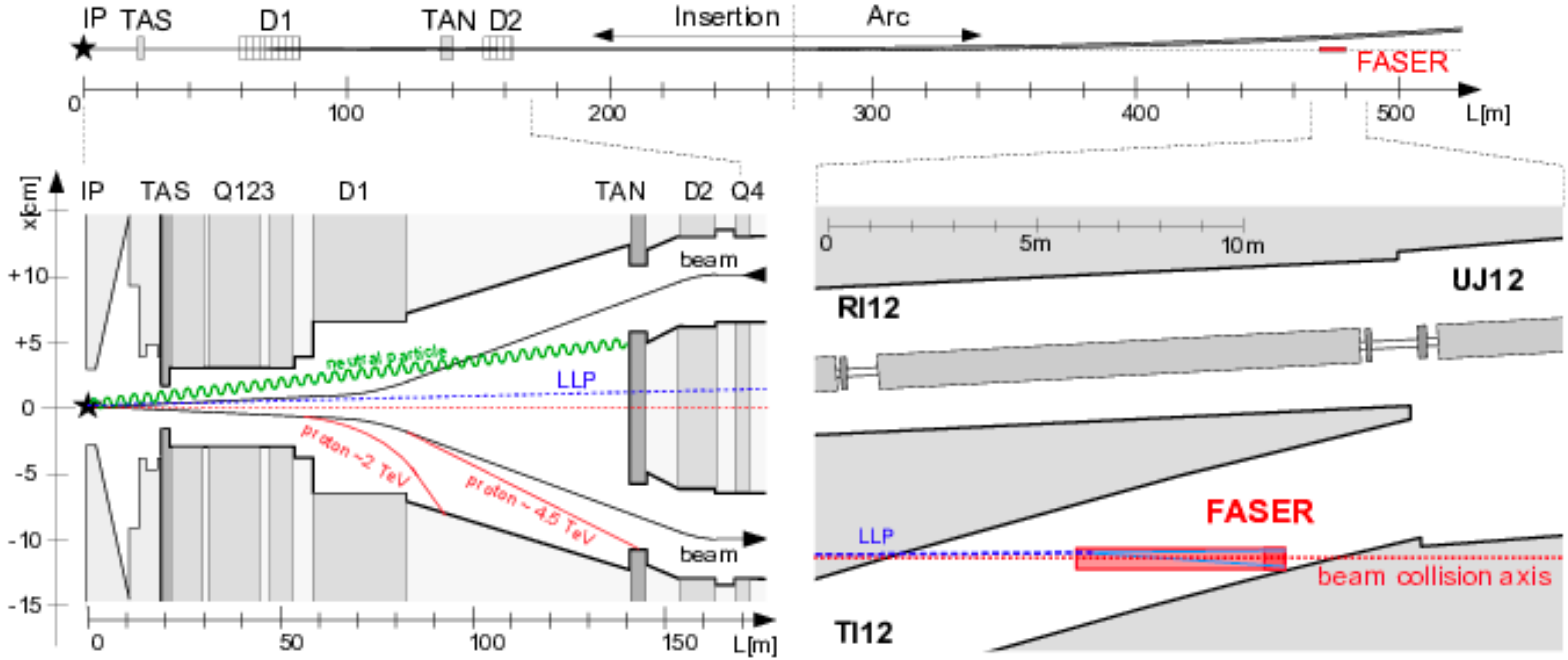






FASER Location

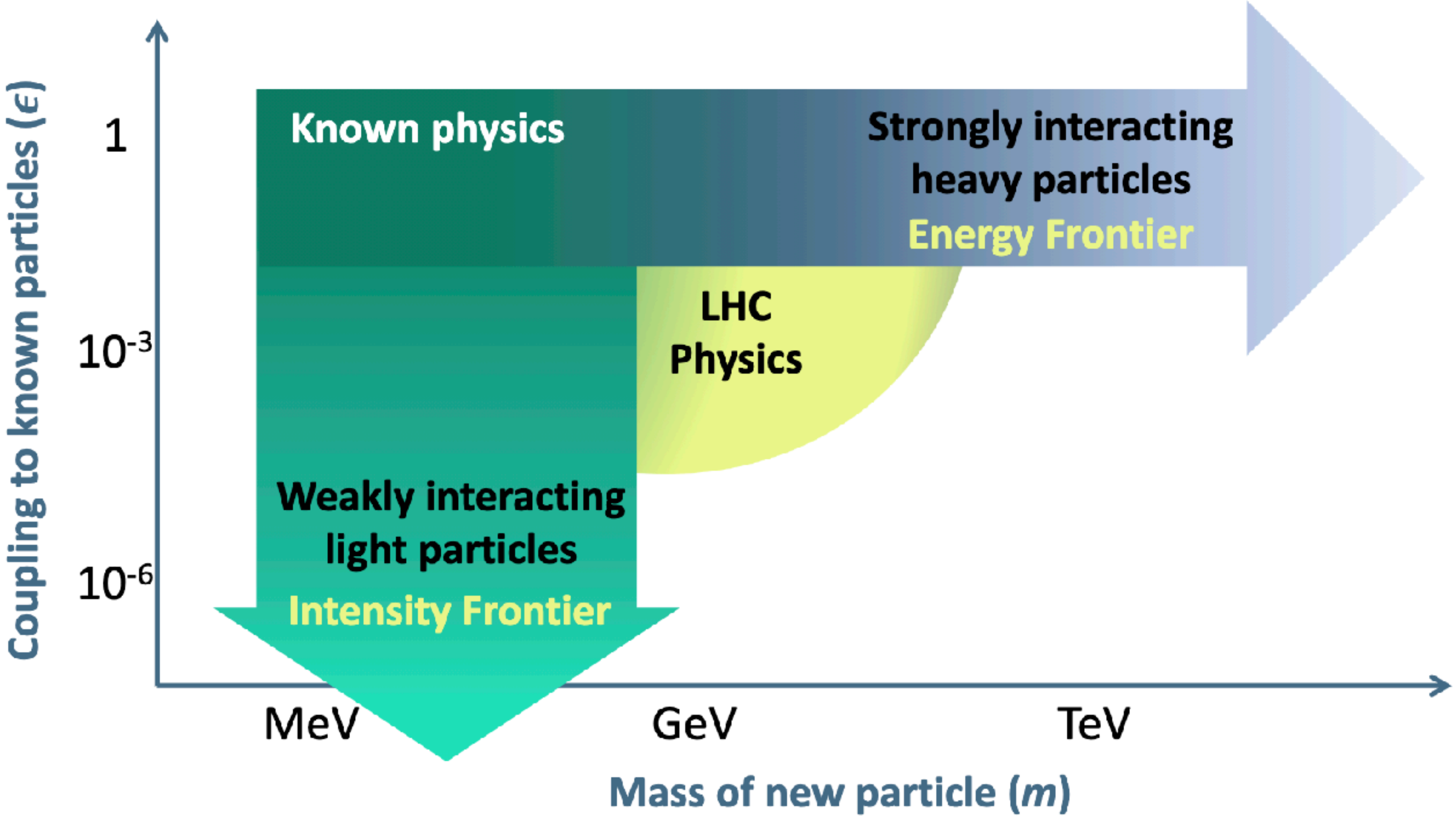
- A closer look at the LHC infrastructure on the line-of-sight:



Physics Motivation

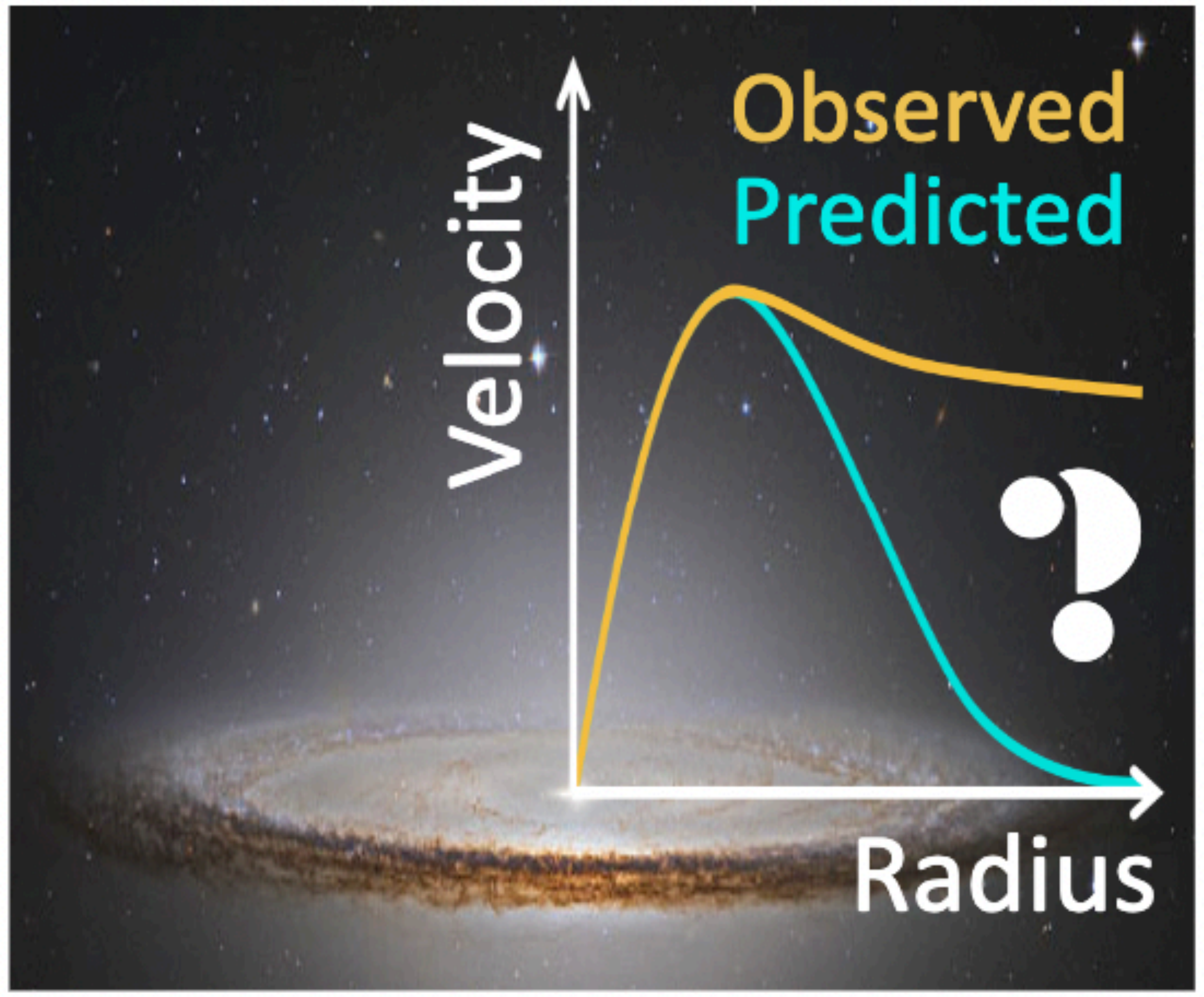
- The **LHC experiments** are producing incredible results, searching in previously unexplored phase spaces and performing increasingly precise measurements.

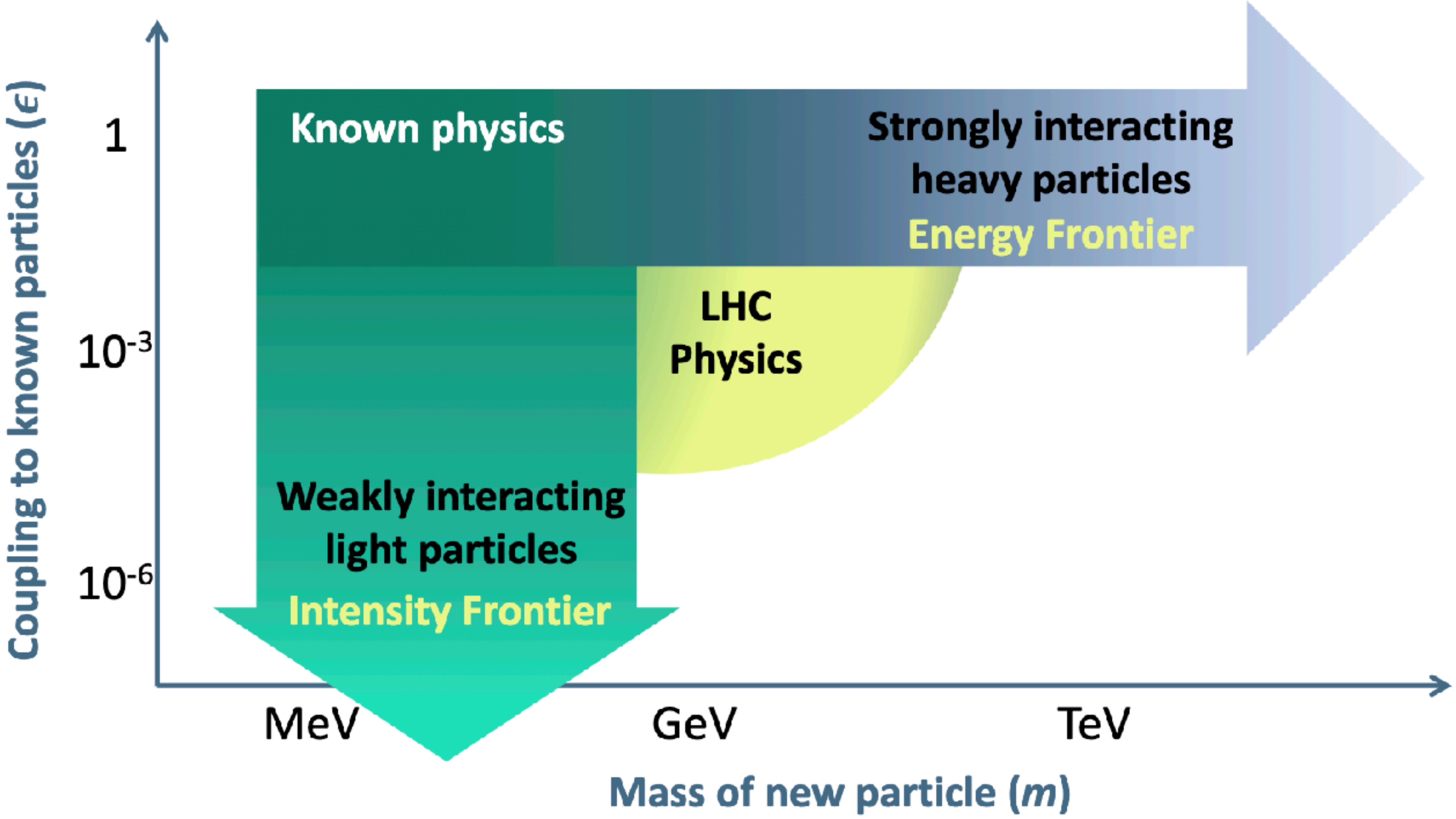
- But the lack of any observation of BSM physics motivates **looking elsewhere** too.



Physics Motivation

- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

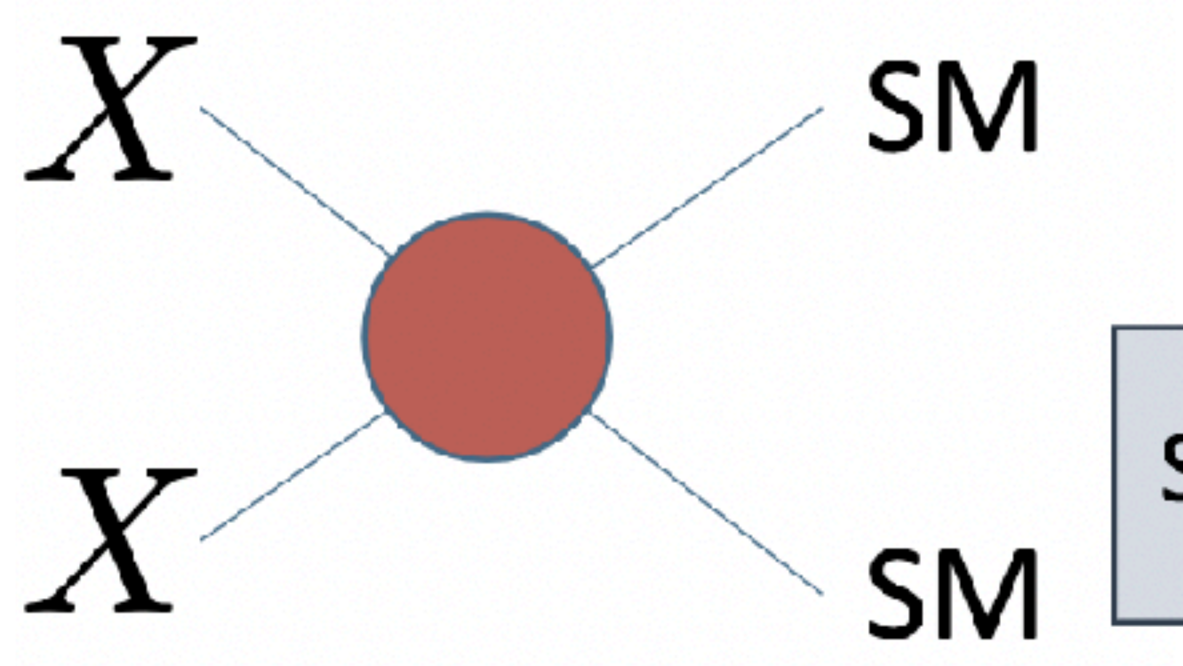


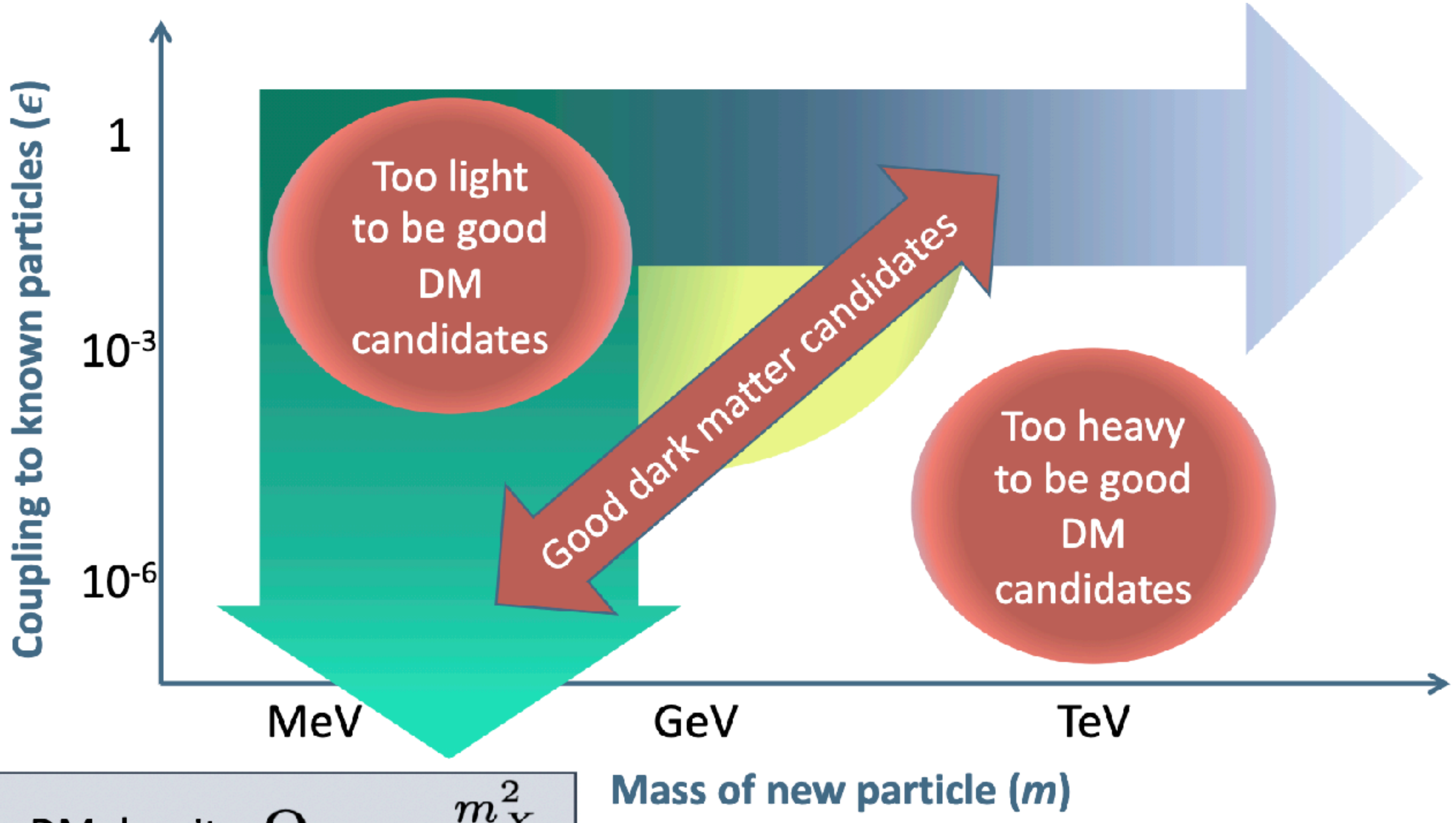


Physics Motivation

- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

- Main region of interest is for new particles that satisfy DM relic density requirements.





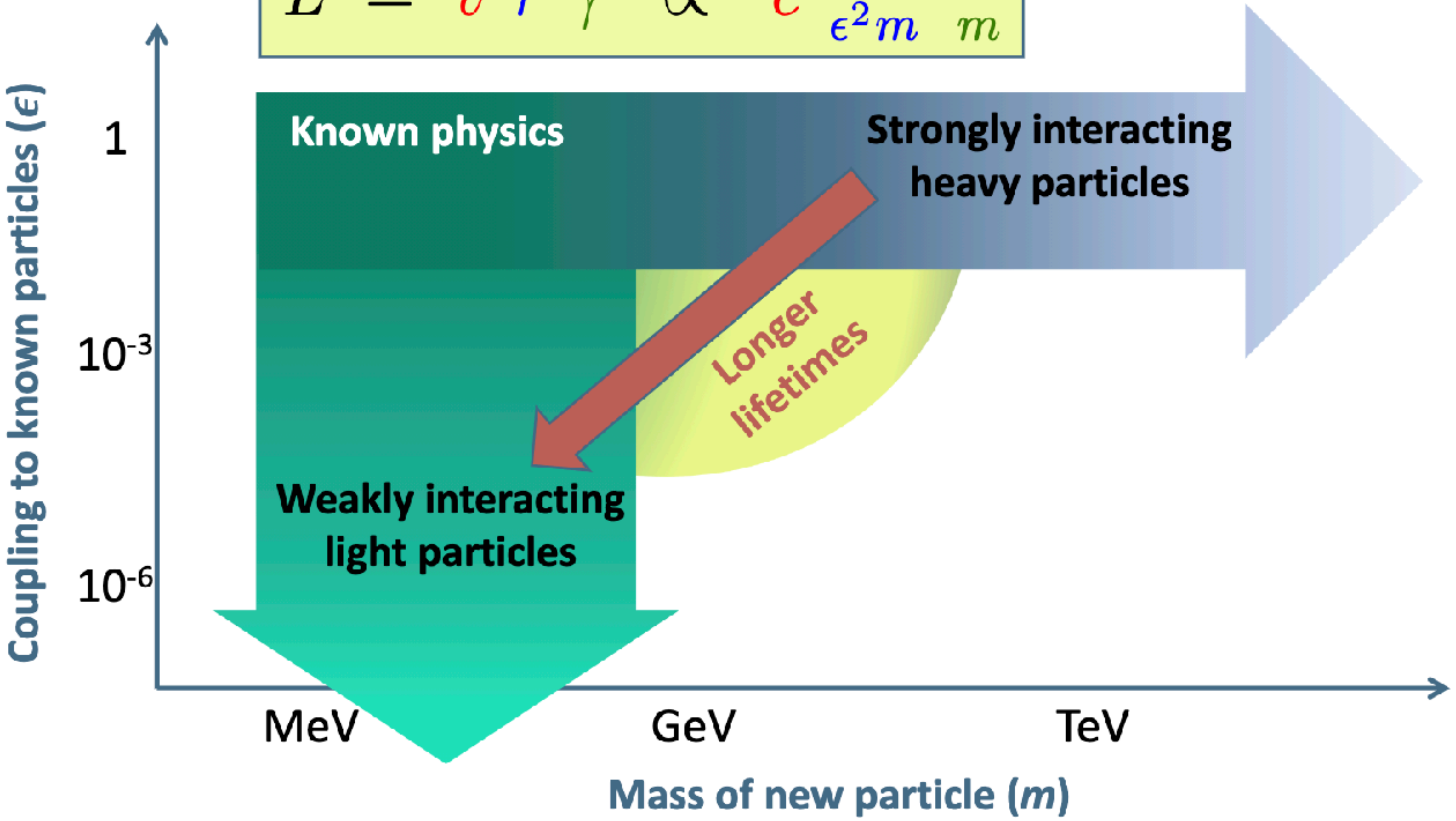
Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

Physics Motivation

- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- Distinct signatures
- Opportunity for exploration!

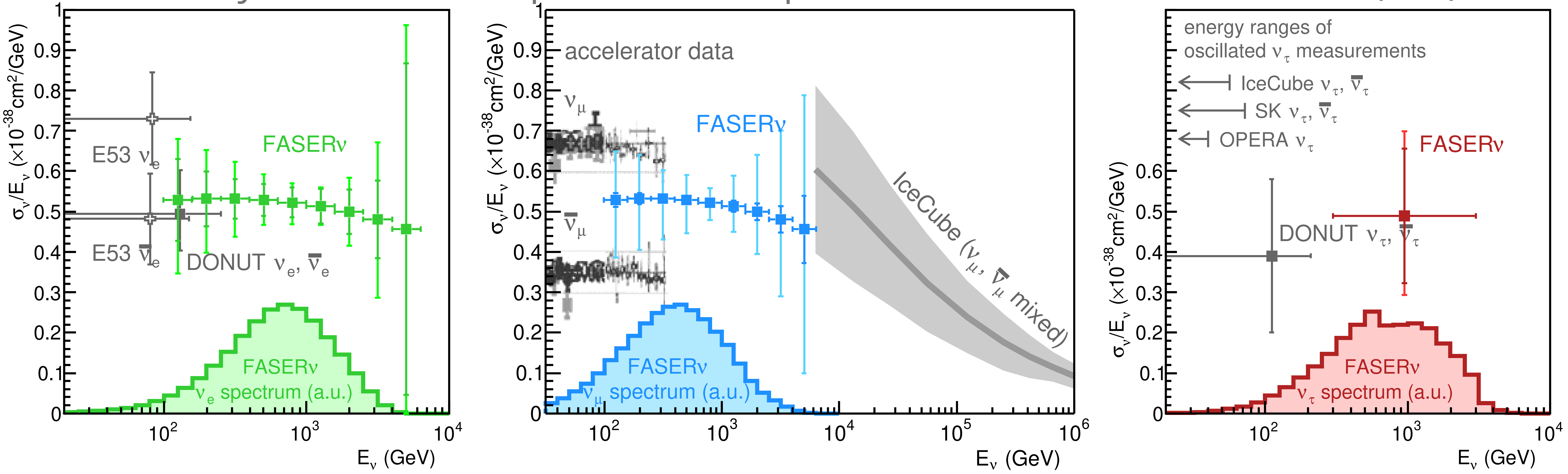
Distance travelled by particles:

$$L = v\,\tau\,\gamma \;\propto\; c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$



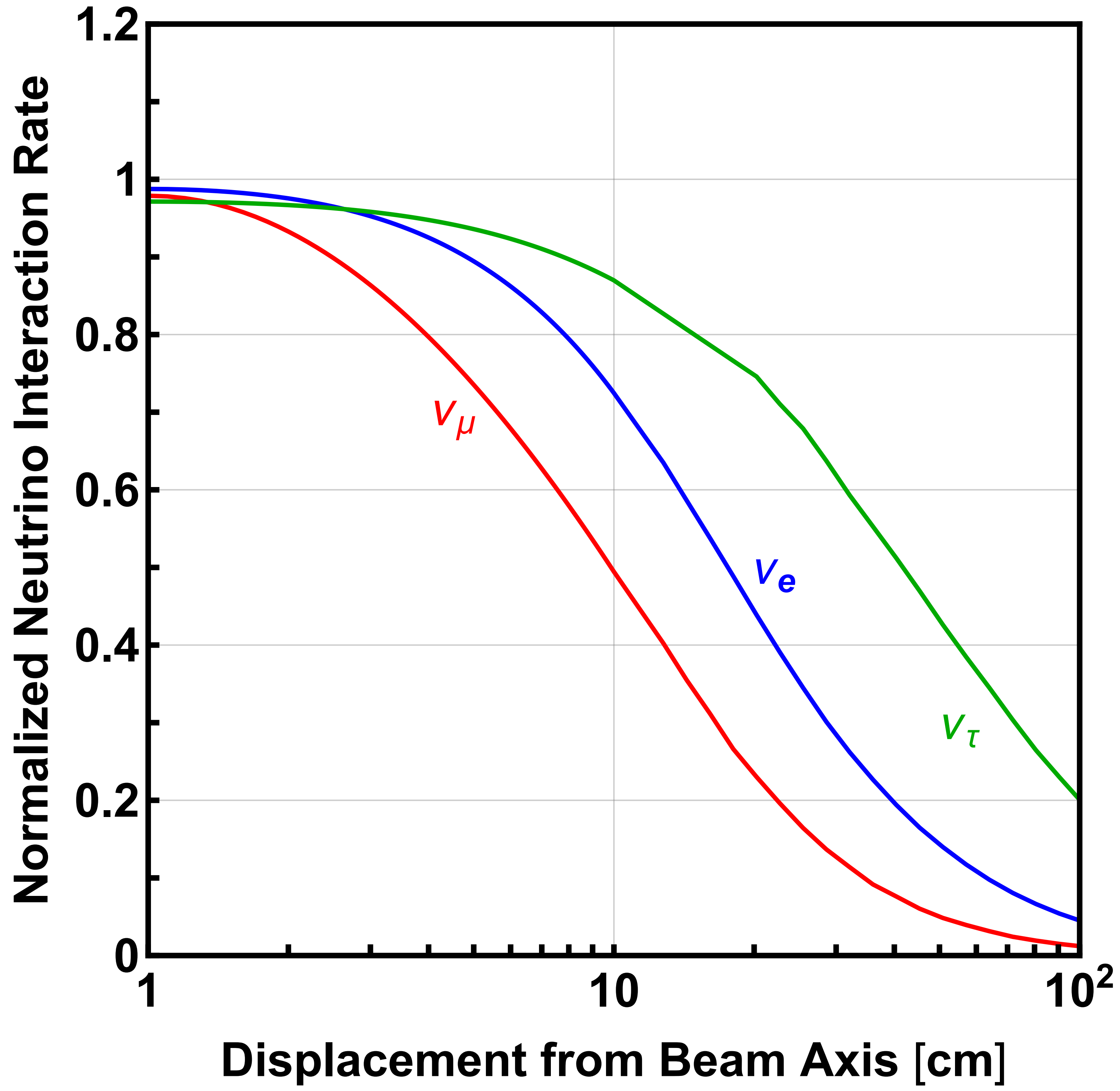
FASERν | Physics case

- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb^{-1}):
  - Uncertainty from neutrino production important. E_ν reco resolution ~30% (sim).



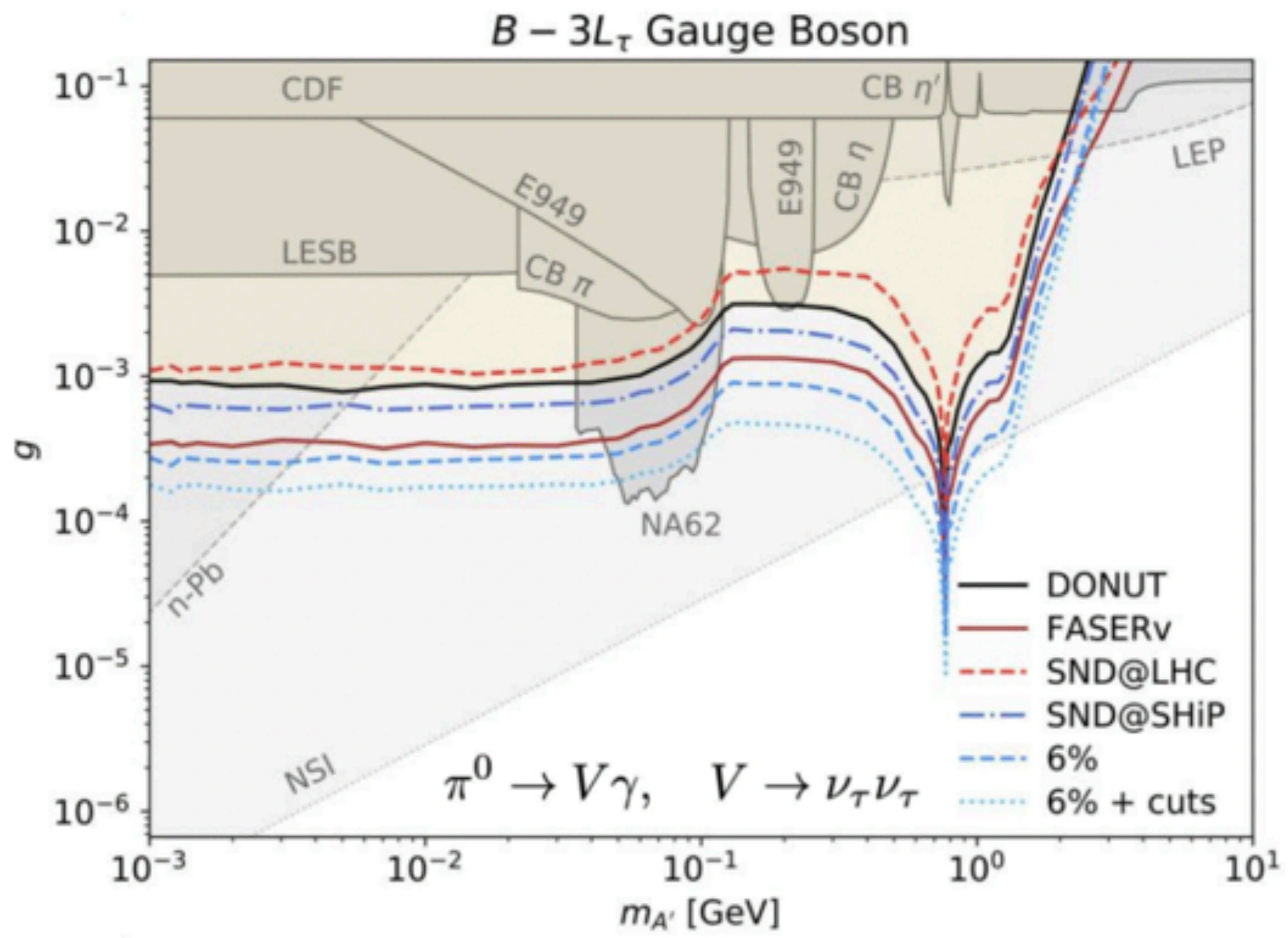
FASERν | Physics case

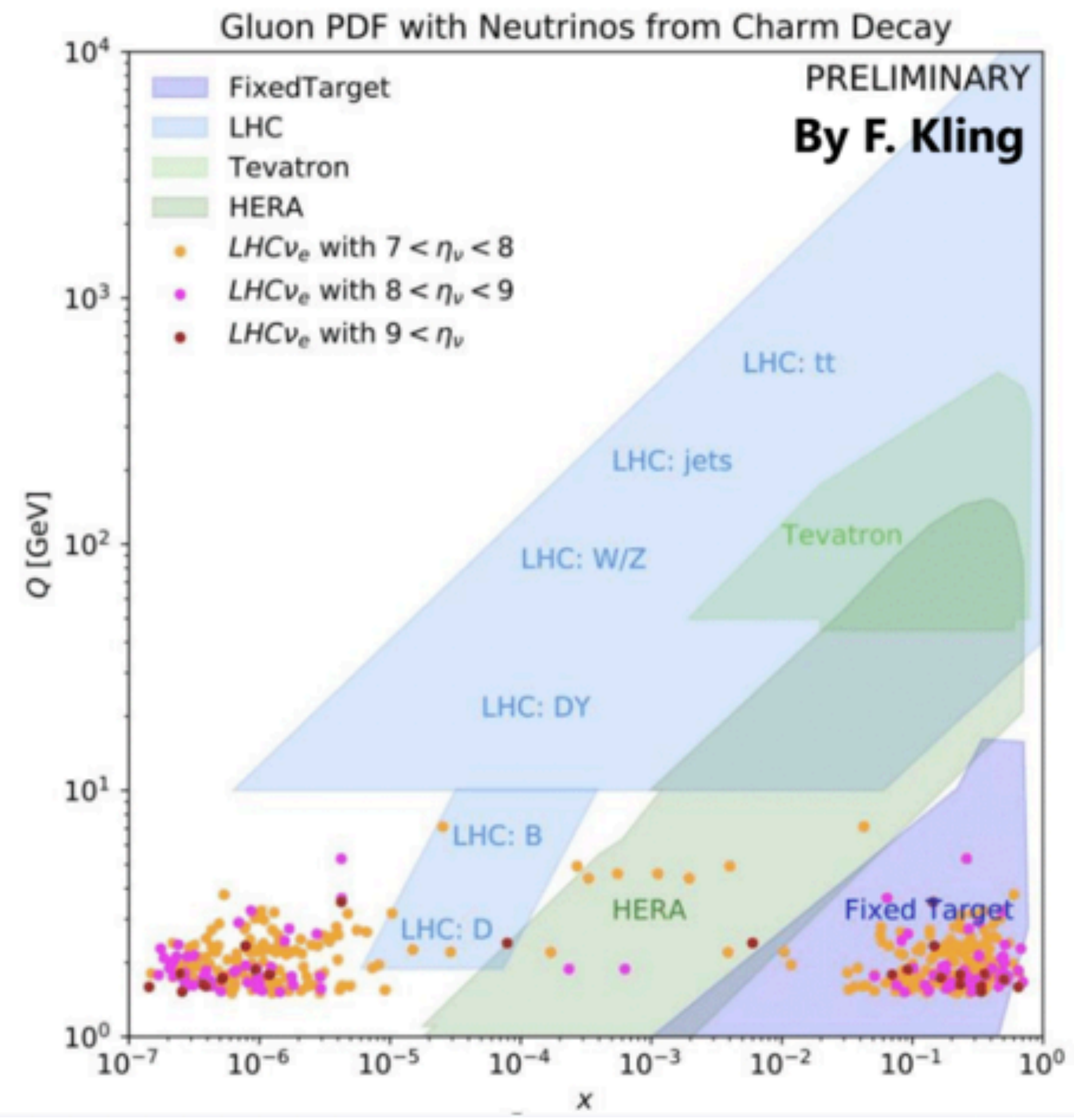
- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb^{-1})
- Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:

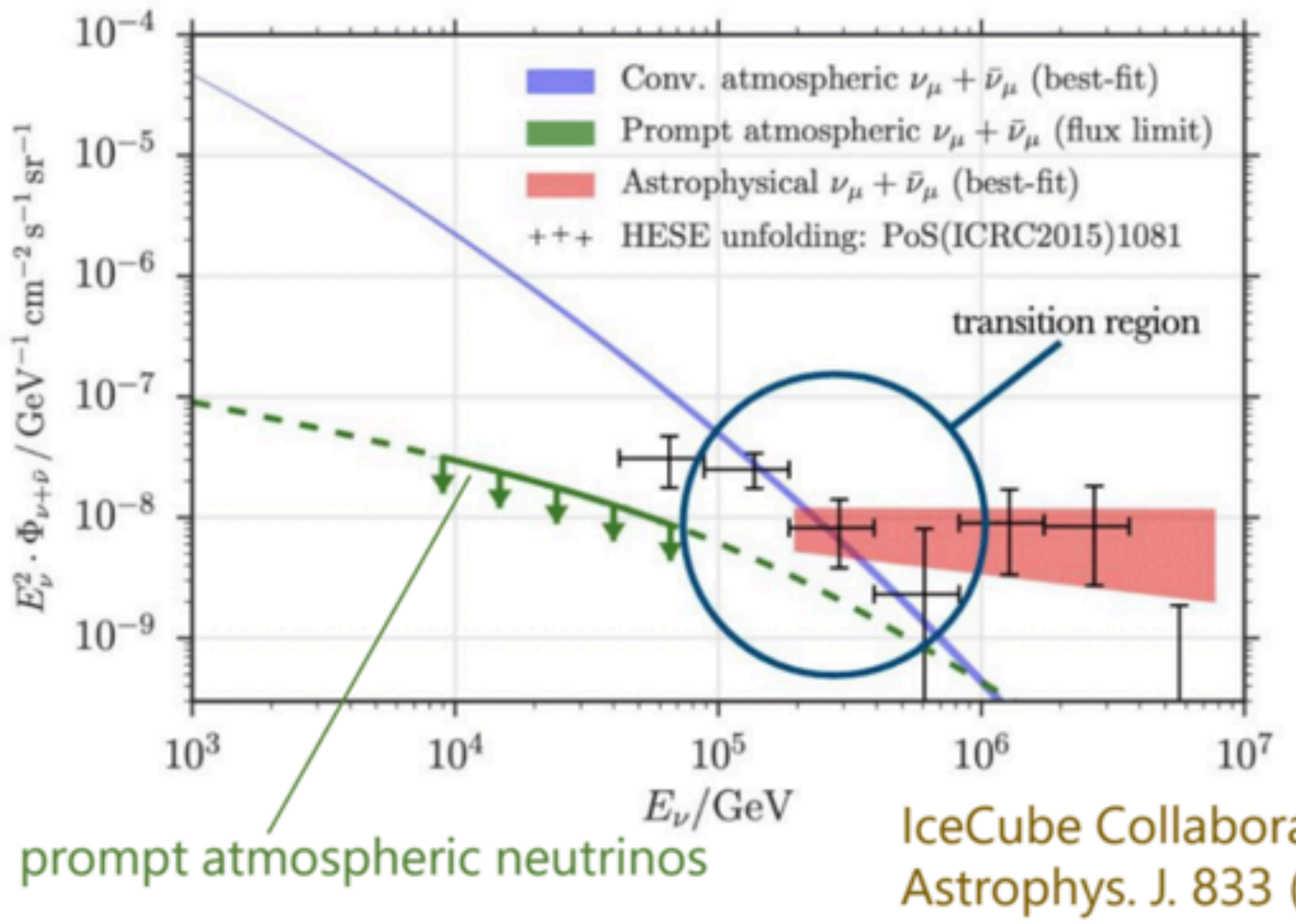


FASERν | Rich neutrino physics program

- BSM physics
  - New light weakly coupled gauge boson (→ν_τ) could enhance ν_τ flux.
  - Sterile neutrinos with mass ~40 eV can cause oscillations at FASER
- QCD
  - FASER's neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
  - Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm
- Cosmic rays and neutrinos
  - IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
  - Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes



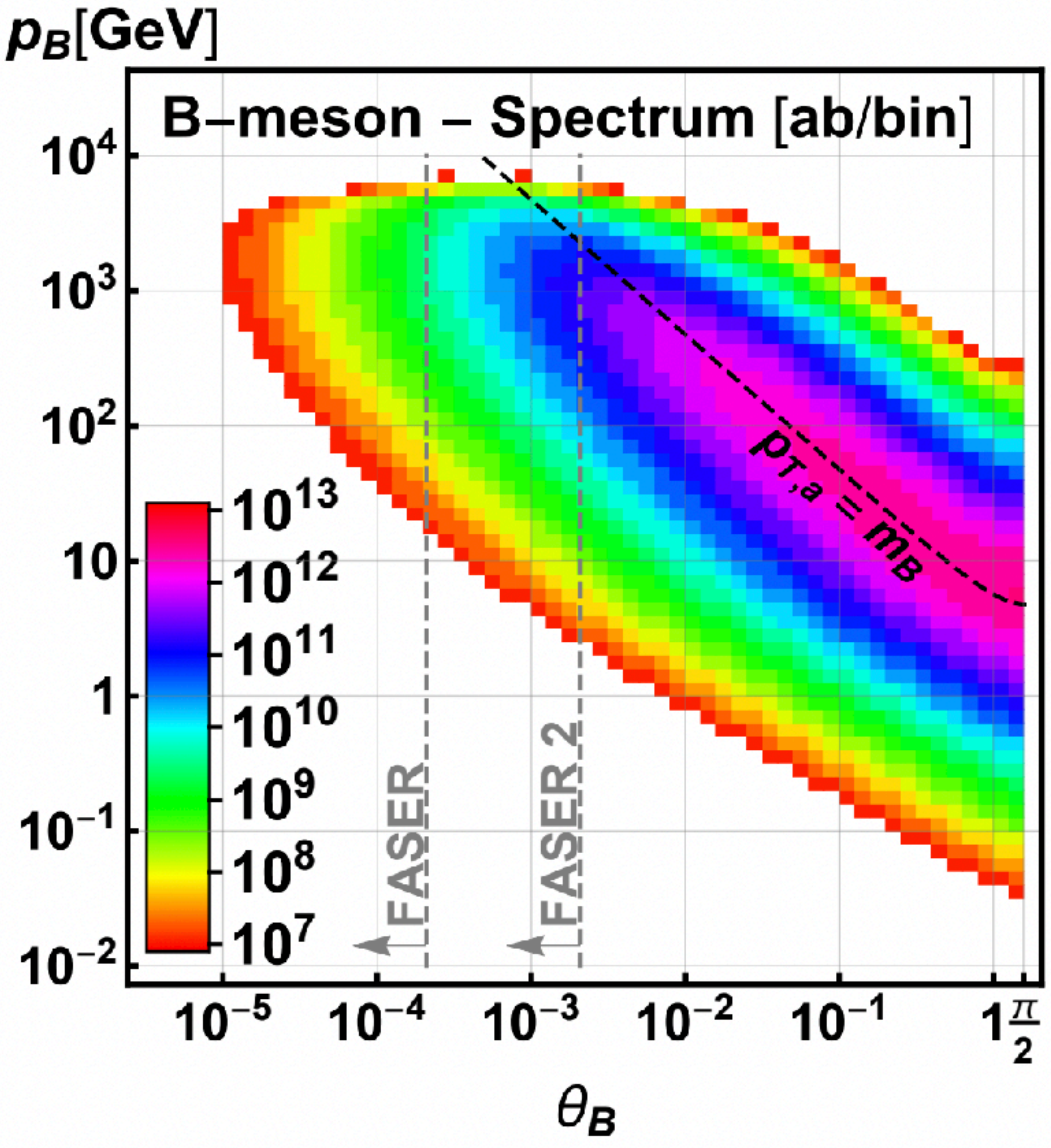




IceCube Collaboration, Astrophys. J. 833 (2016)

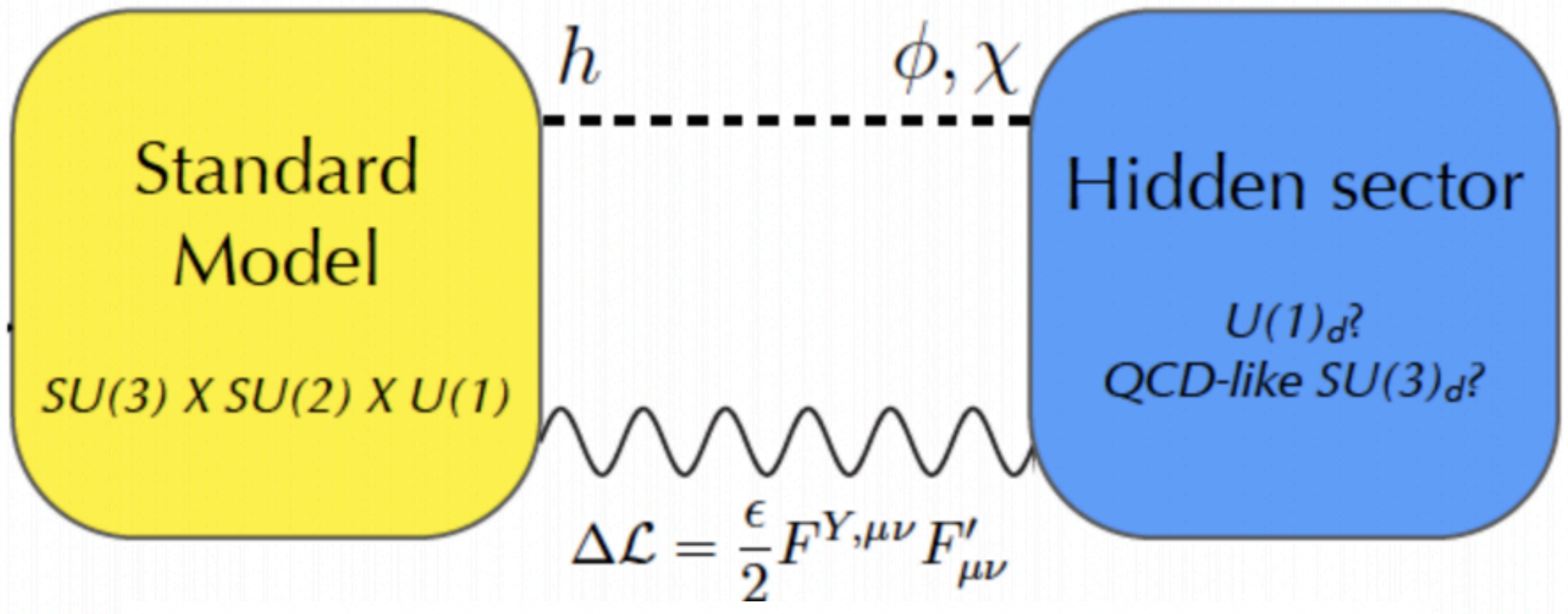
FASER2

- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.



Physics | Dark portal

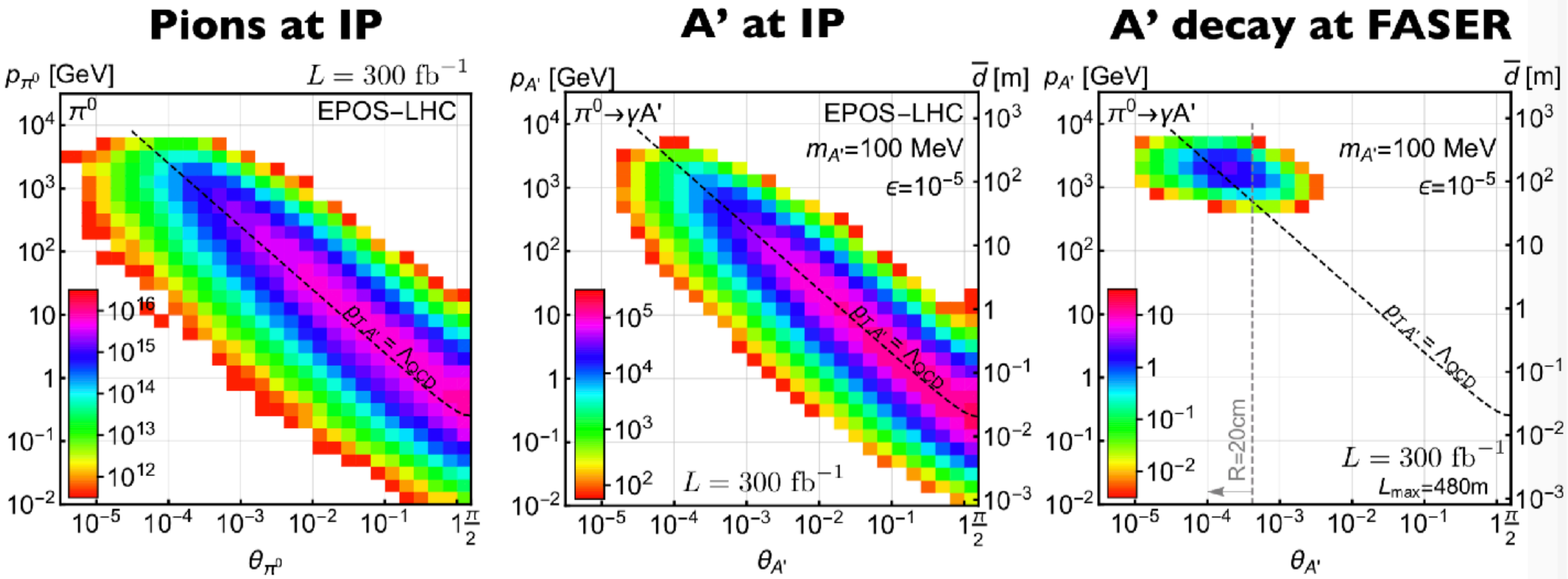
- Hidden sector physics:
  - New mediating particles, couplings to SM via mixing with SM "portal" operator
  - Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations…
  - Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)
- Typically long-lived particles (LLPs) that travel macroscopic distances before decaying to SM particles



$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

Overview | Dark photons



- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ ΛQCD
- enormous event rates N ~ 10^{15} per bin

- production peaks at pT~ ΛQCD
- rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- still rates N~10^5 per bin: LHC could be dark a photon factory

- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

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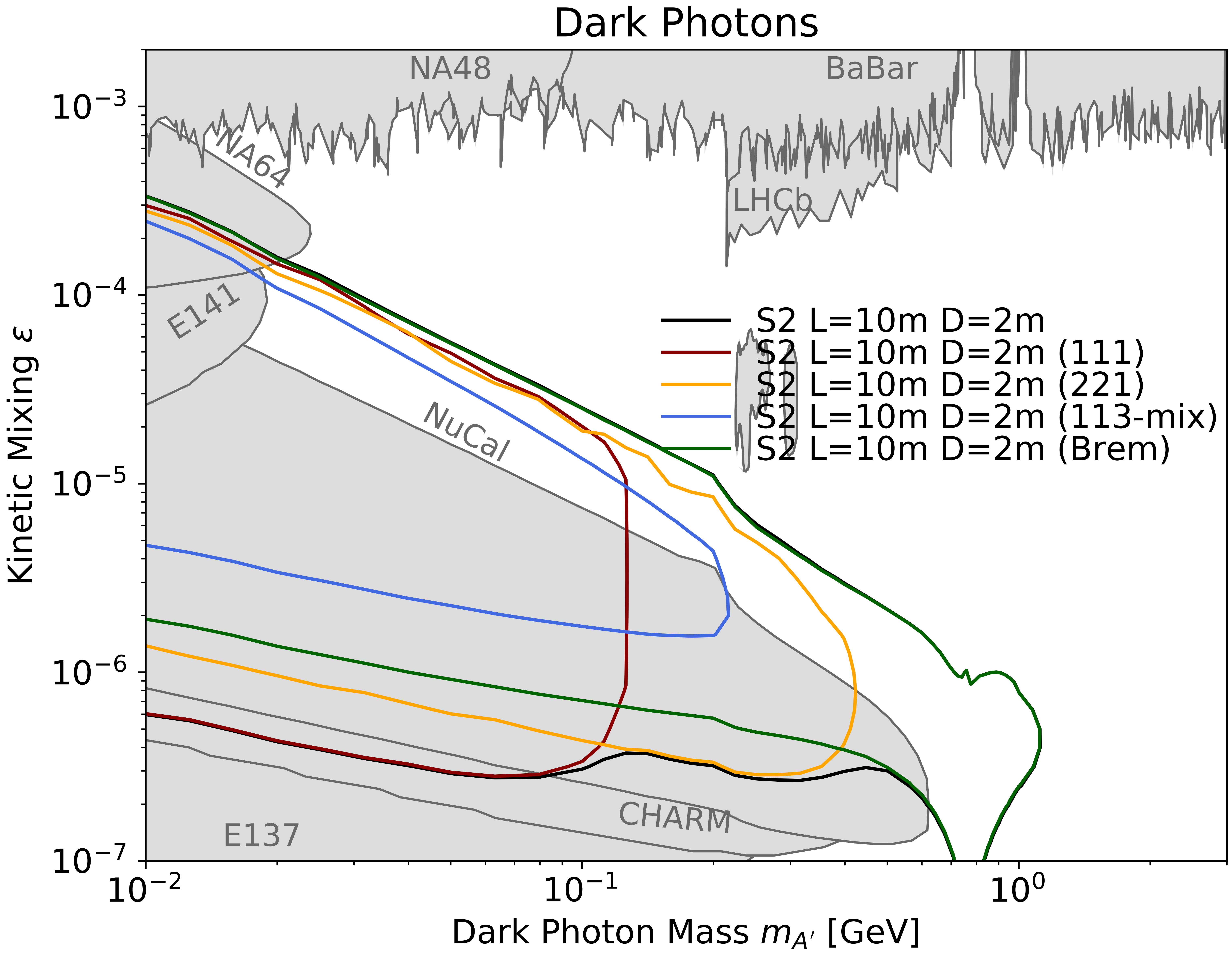
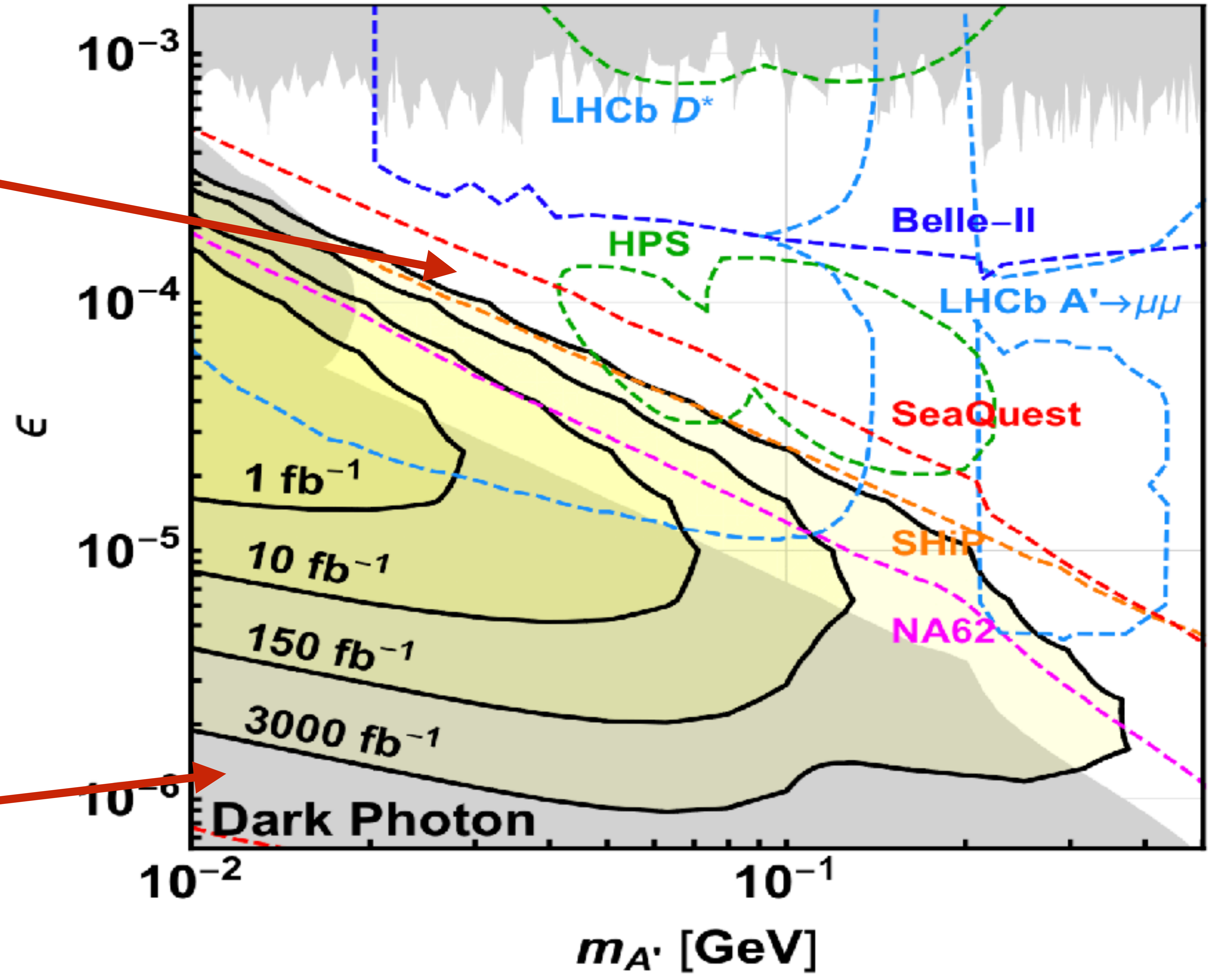
Overview | LLP production modes

Overview | Dark photon reach



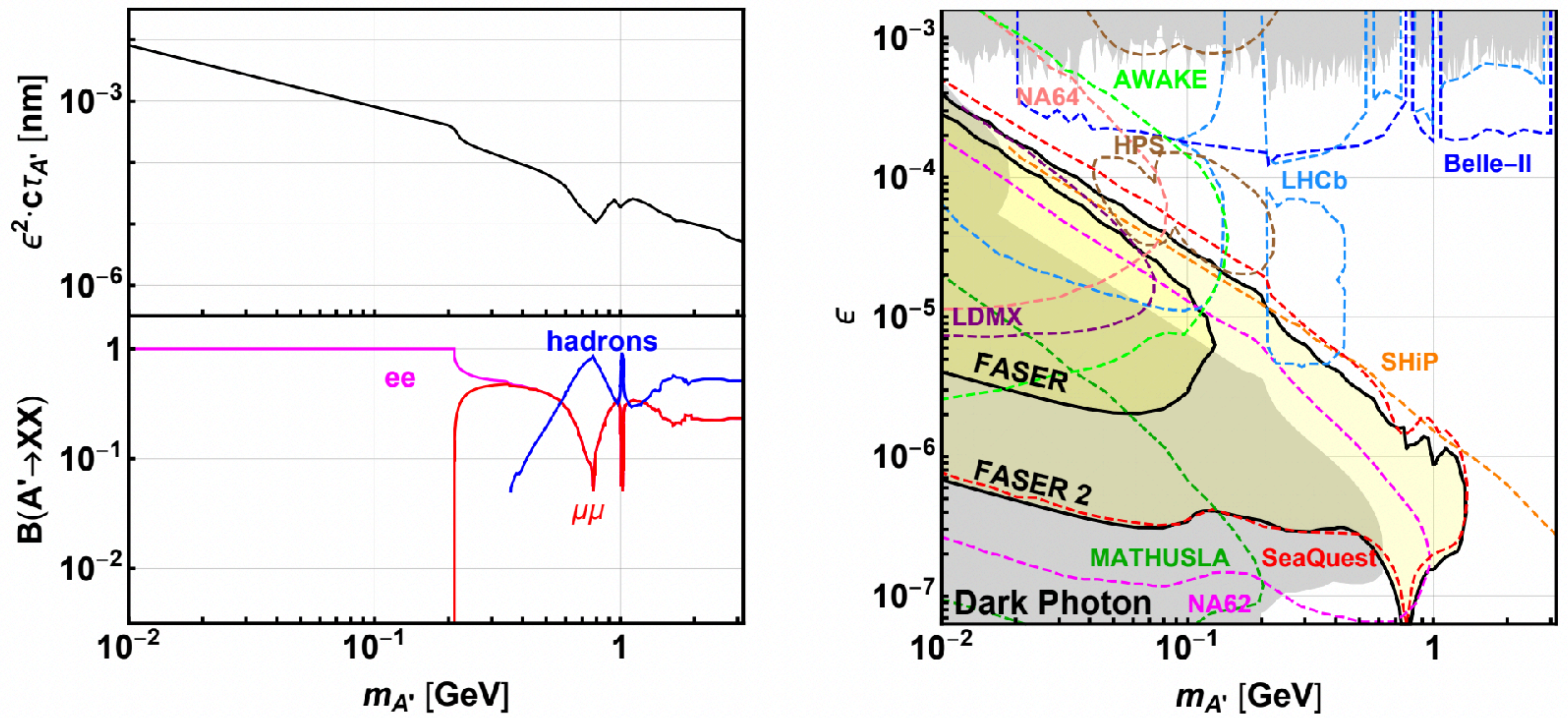
Overview | Dark photon reach

For lower lifetime the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector

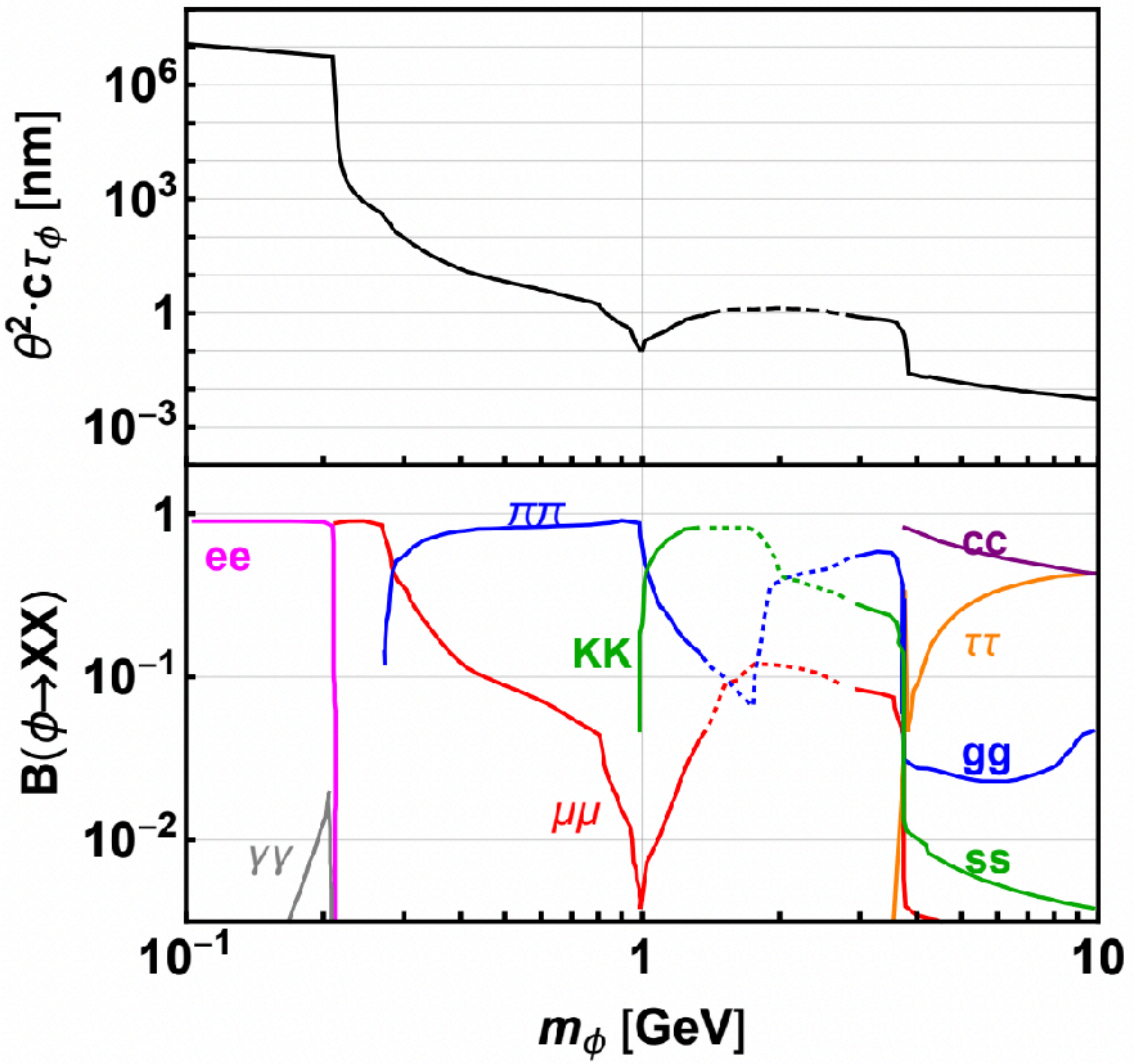


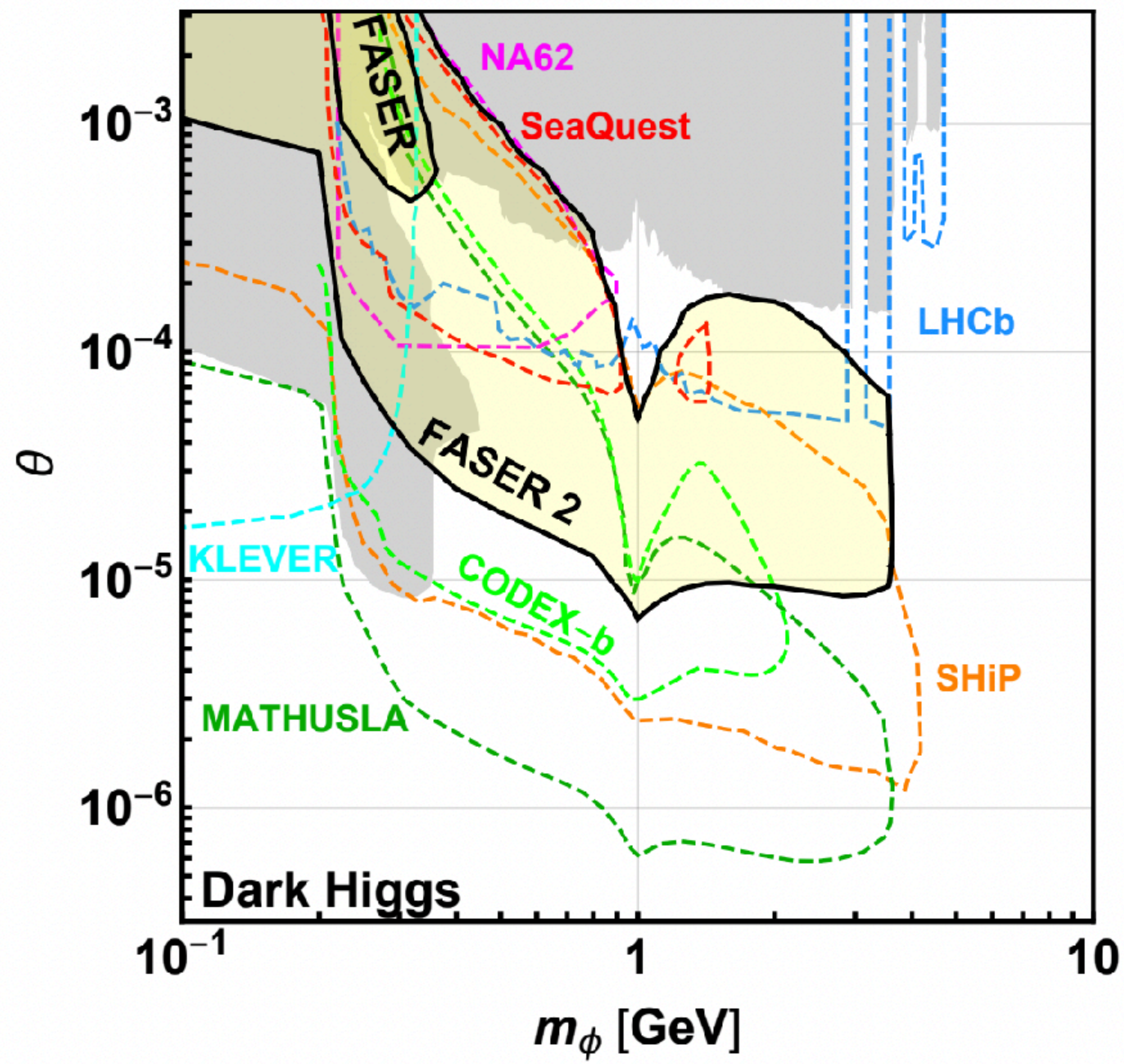
Combining dependence in both production rate and decay width, total number of signal events in the detector scales as ε^4

Target scenarios | Dark Photon

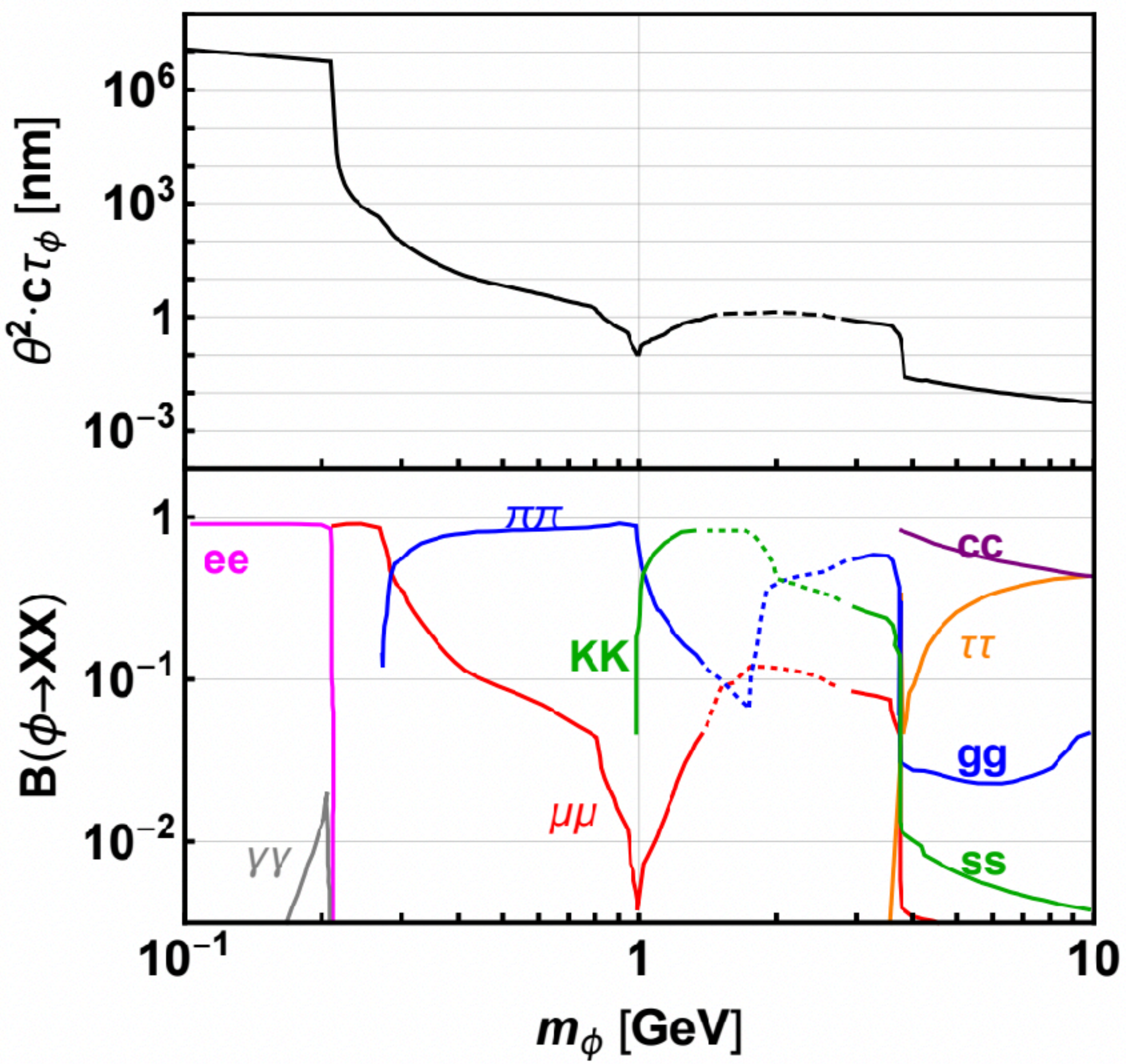


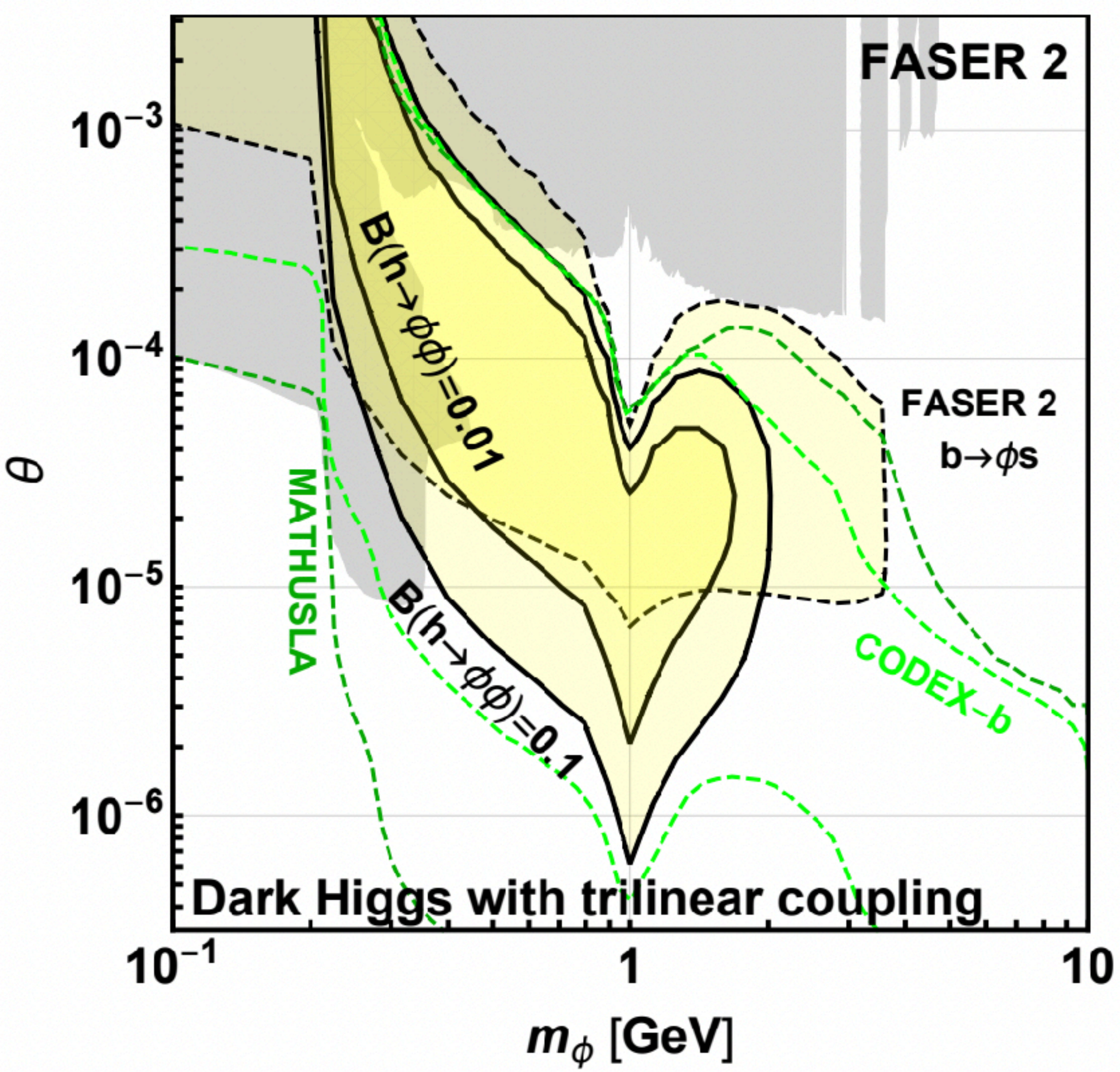
Target scenarios | Dark Higgs



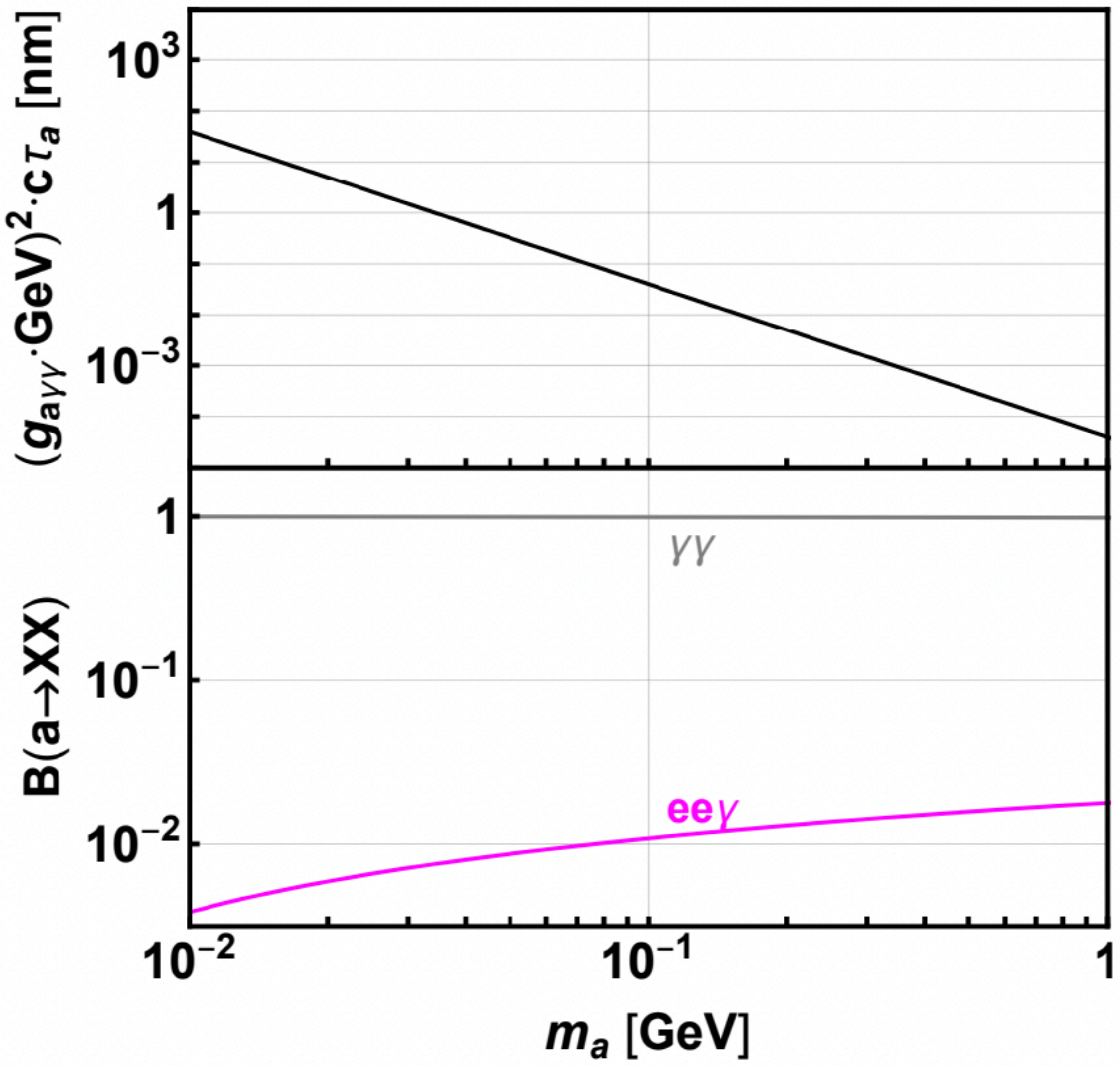


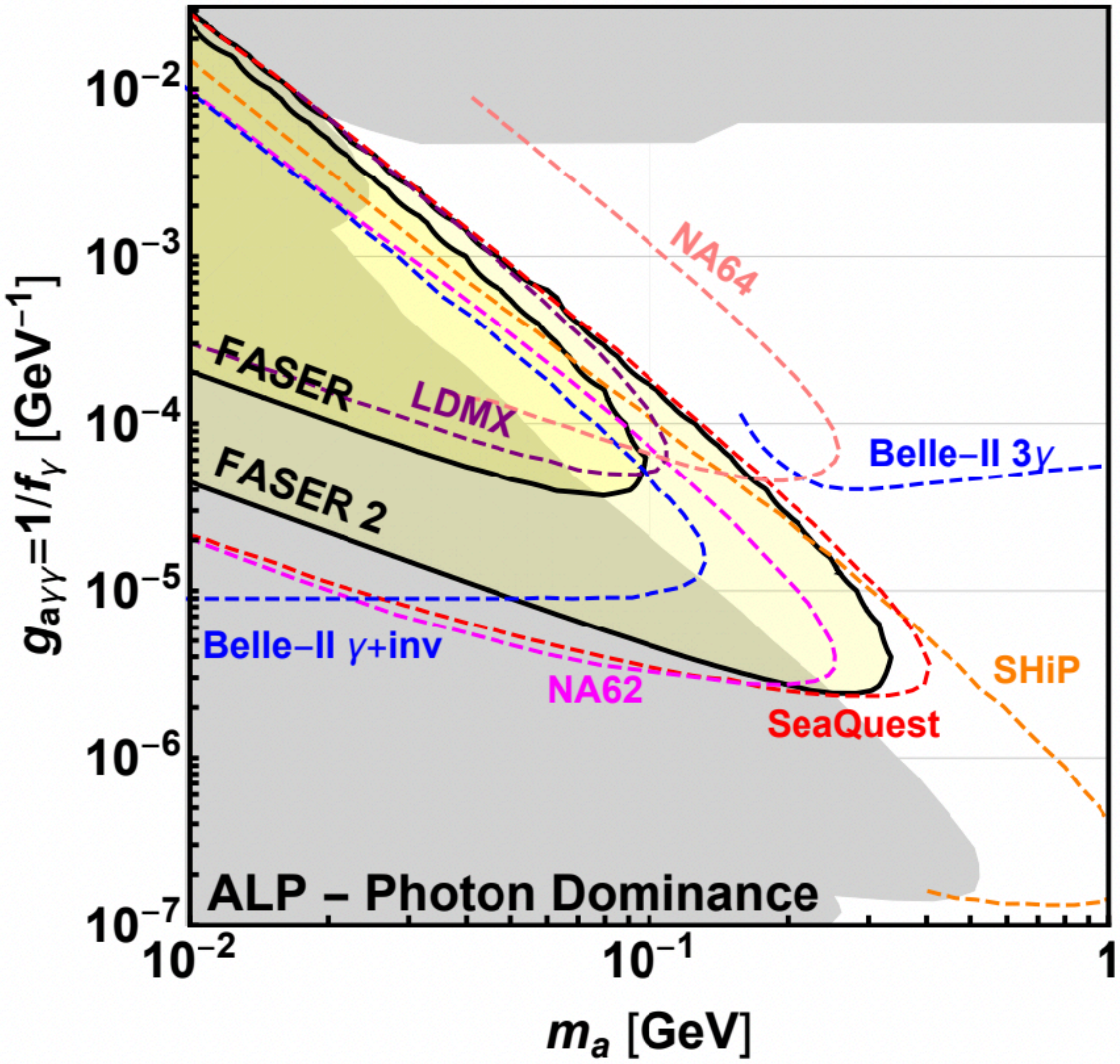
Target scenarios | Dark Higgs



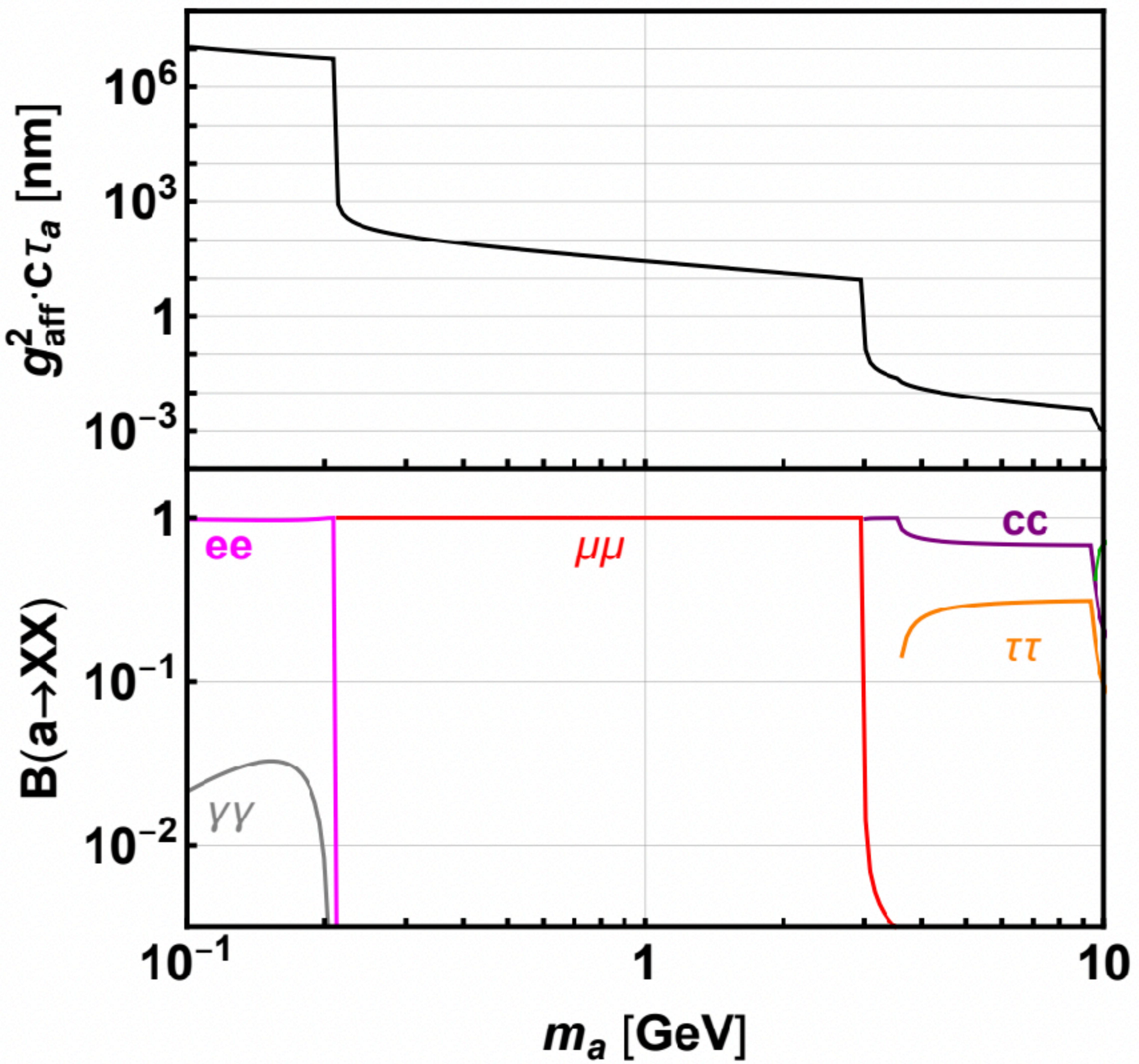


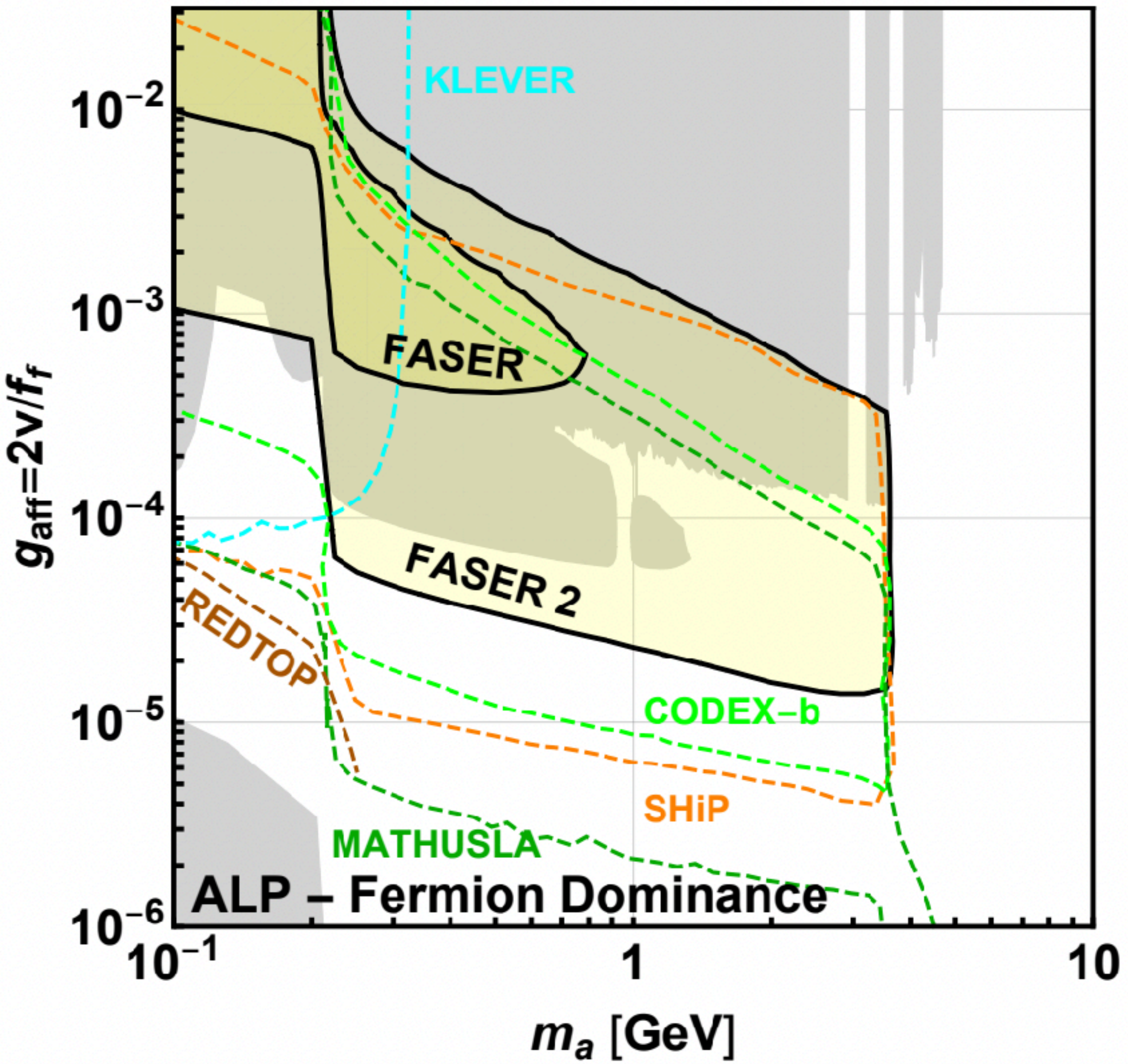
Target scenarios | ALP



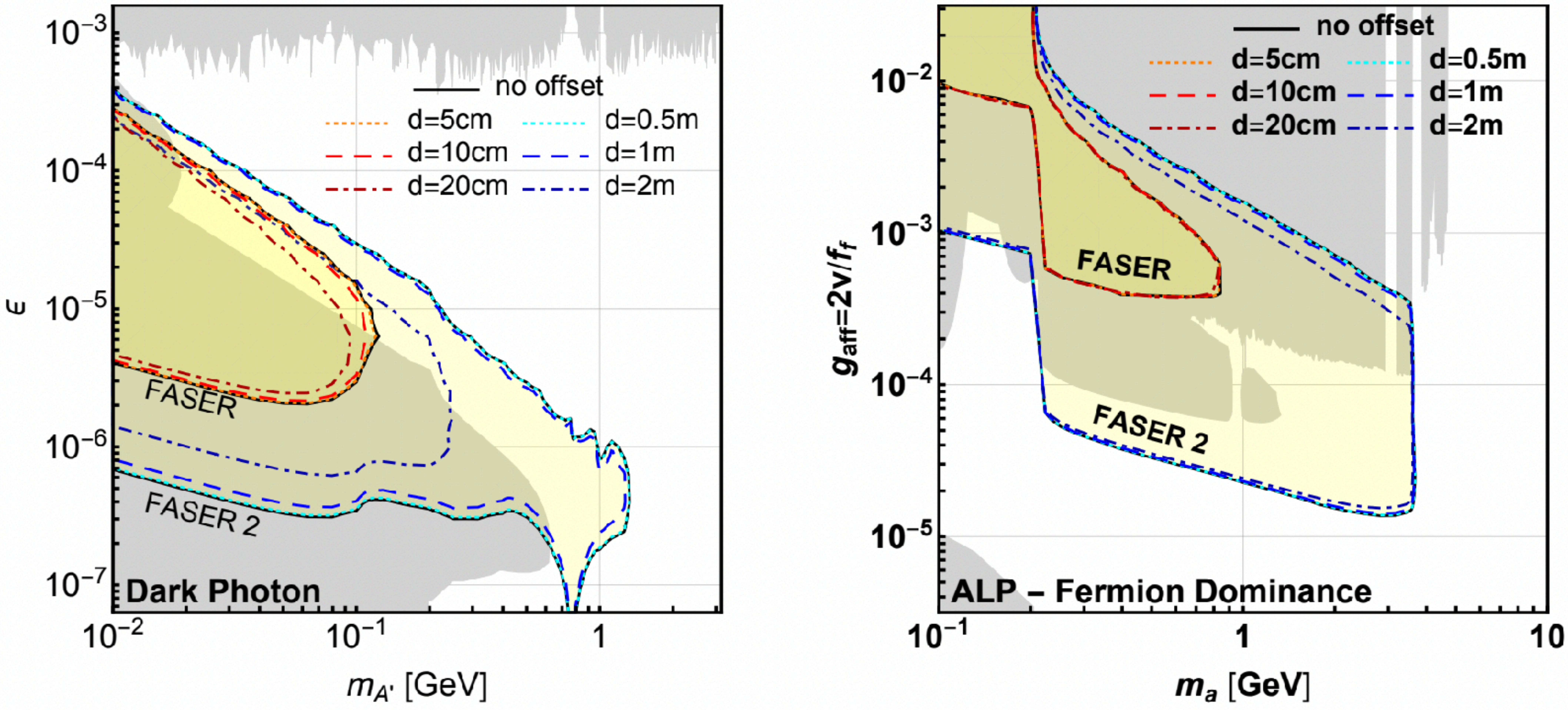


Target scenarios | ALP



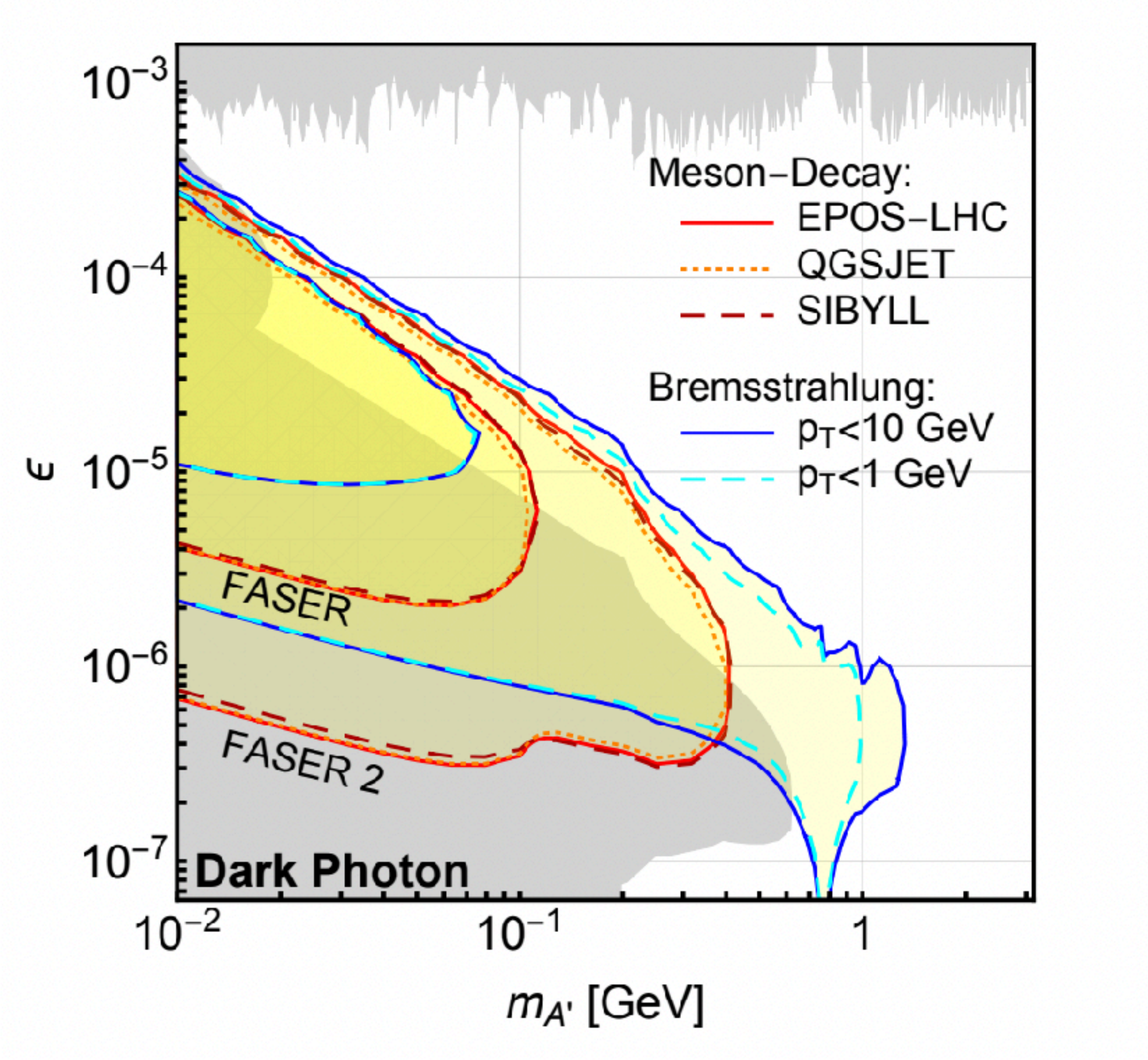


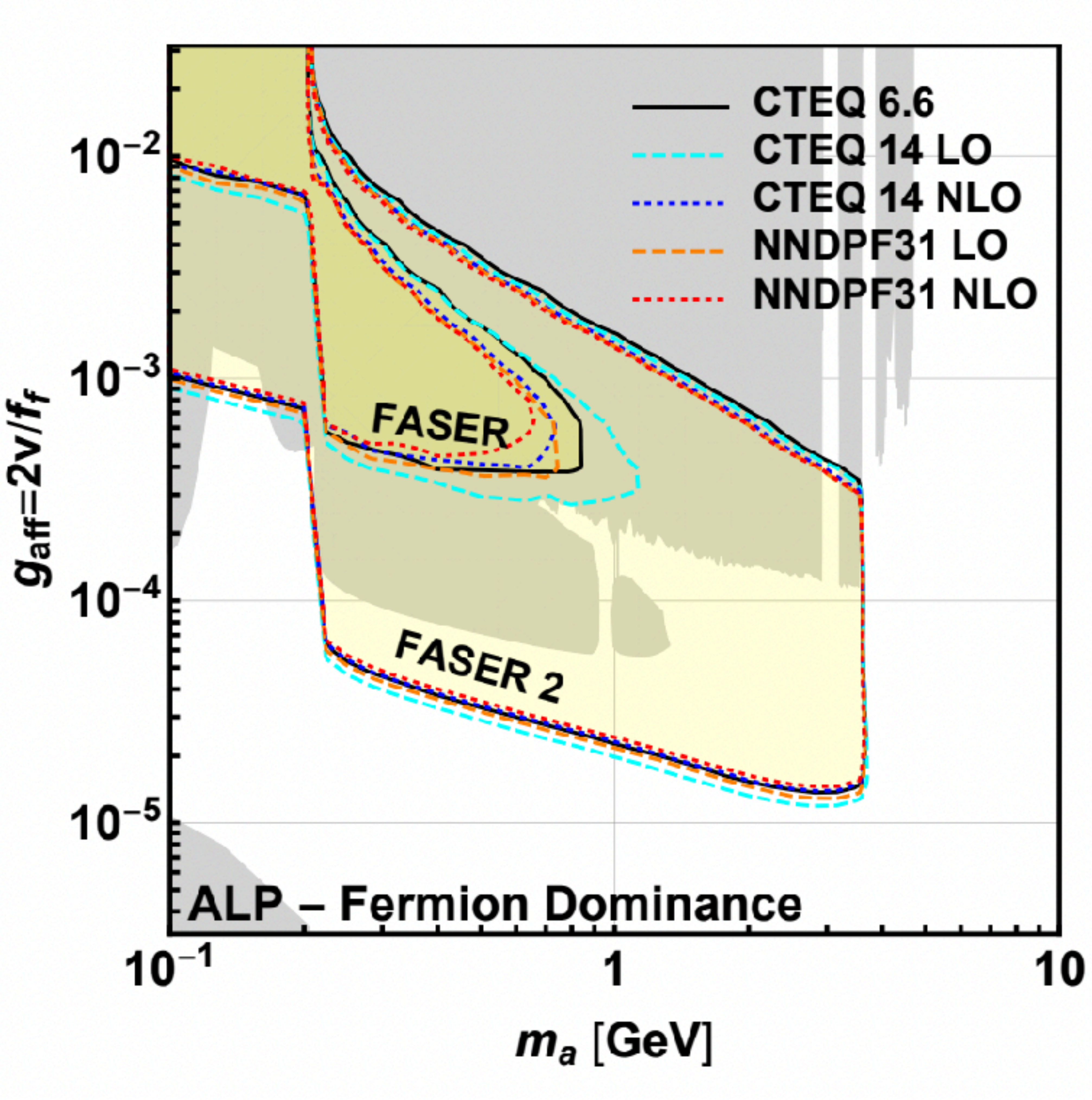
Beam offset



no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
Dark Photon
ε
$m_{A'}$ [GeV]
ALP – Fermion Dominance
$g_{aff}=2v/f_f$
m_a [GeV]

Modelling uncertainties





Energy threshold