Institut
“Jožef Stefan”
Ljubljana, Slovenija

ATLAS
EXPERIMENT

The Bologna Postdoc Experience: Left-Right Symmetry, ALPs, and a Bowl of Tortellini

Blaž Leban, 13. 11. 2025

Outline

- General information
- Physics:
  - Search for lepton number violating processes in the Left-Right Symmetric Model: EXOT-2024-03 (EXOT-2025-14)
  - Search for axion-like particles (ALPs) decaying into a pair of opposite-charge muons in ultra-peripheral collisions: HION-2023-14
  - Other
- Life in Bologna and Italy 🇮🇹🍝

General introduction

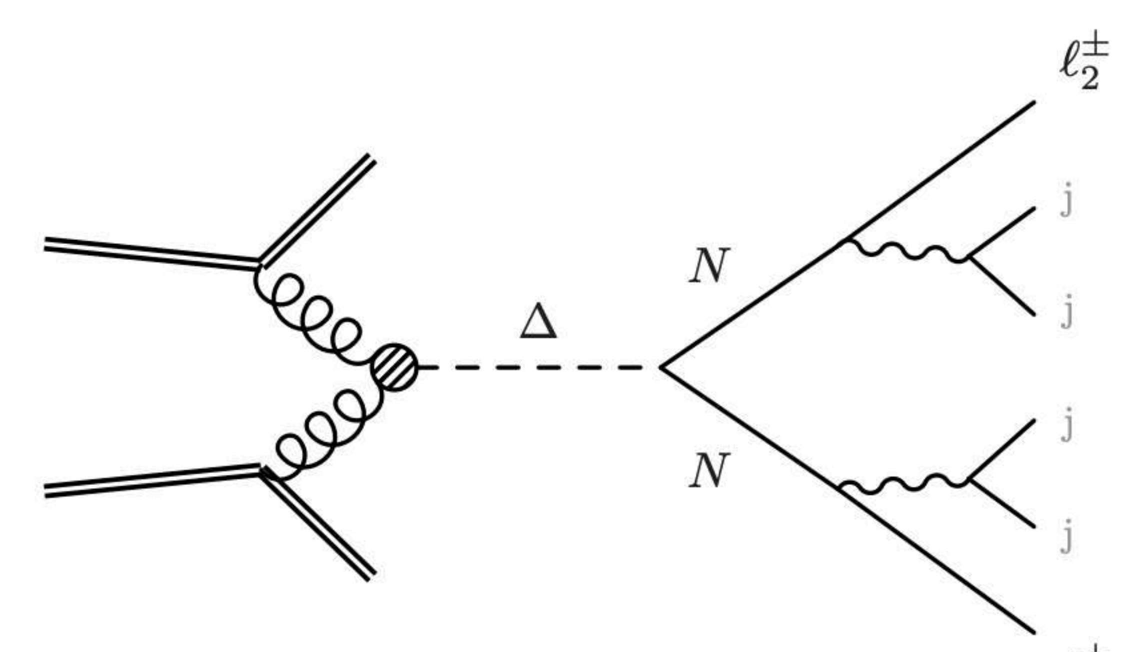
- **Place:** INFN, Sezione di Bologna (ATLAS exotics group)
- **Position:** “Assegno di ricerca” - research grant program aimed at foreign researchers coming to Italy
- **Duration:** 1 (+1) year: 2. 11. 2023 - 31. 10. 2025
  - First year of the contract: our child was born, so we were all able to move to Bologna
  - Second year of the contract: I was allowed to work remotely as our child began kindergarten and my wife’s (MR @O2 IJS) parental leave ended, so we returned to Slovenia.

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI BOLOGNA

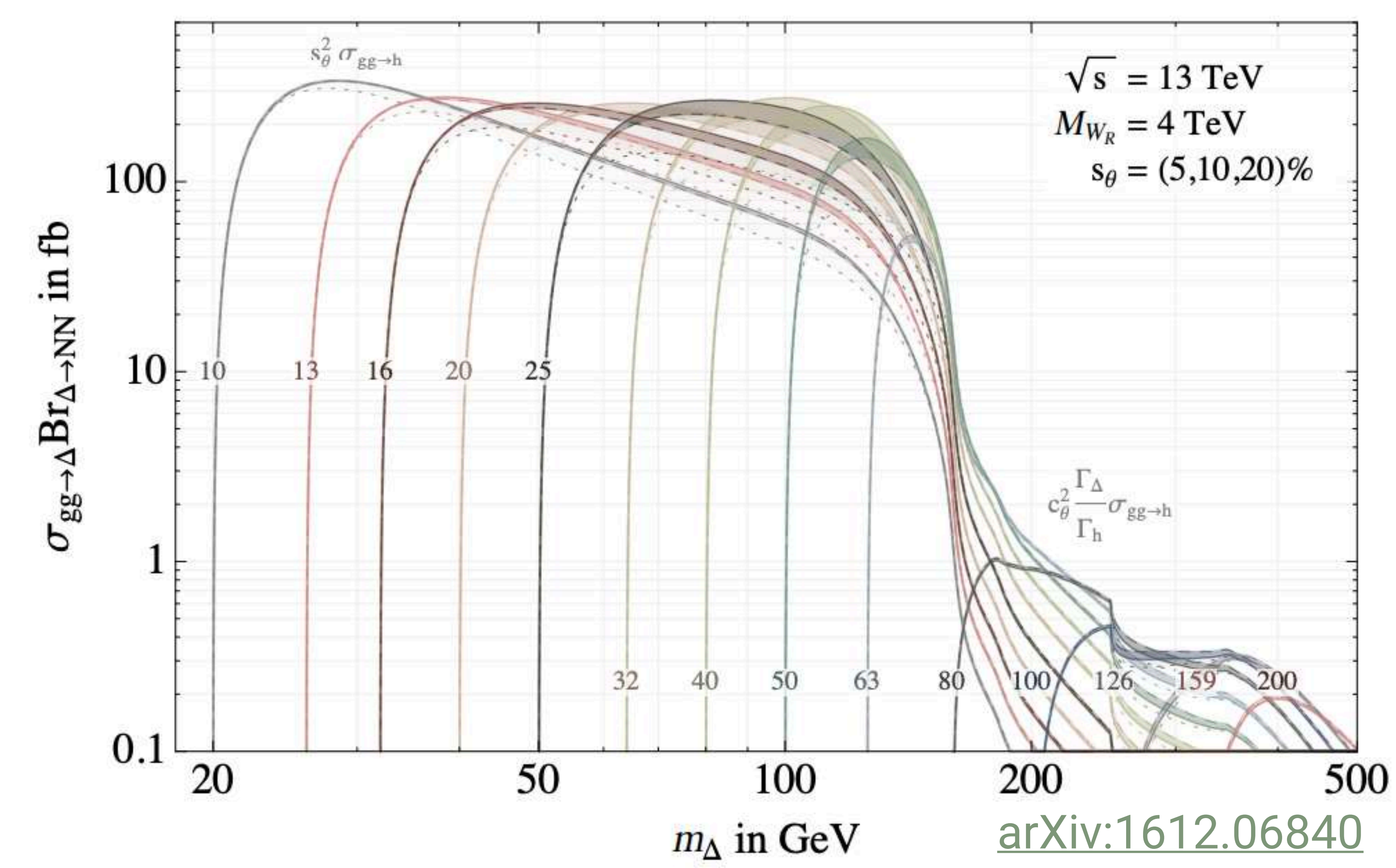
Majorana Neutrinos in the Left-Right Symmetric Model

LRSM analysis

- The model was thoroughly studied by our F1 colleagues, who have now joined ATLAS as short-term associates. arXiv:2403.07756
- Collaborate with the JSI group in the "umbrella" analysis (DCH, T3SS).
- Process characteristics:
  - Majorana heavy neutrino, N, pair production via the gluon fusion and a Δ (triplet "Majorana" Higgs) resonance.
  - It is a **lepton-number-violating** process with $\Delta L = 0,\ 2.$
  - Can lead to **two same-sign leptons** in the final state (+ additional soft jets) $\rightarrow$ low SM background.
  - **Displaced vertices** can be present, which may help reduce the background further.



arXiv:1612.06840

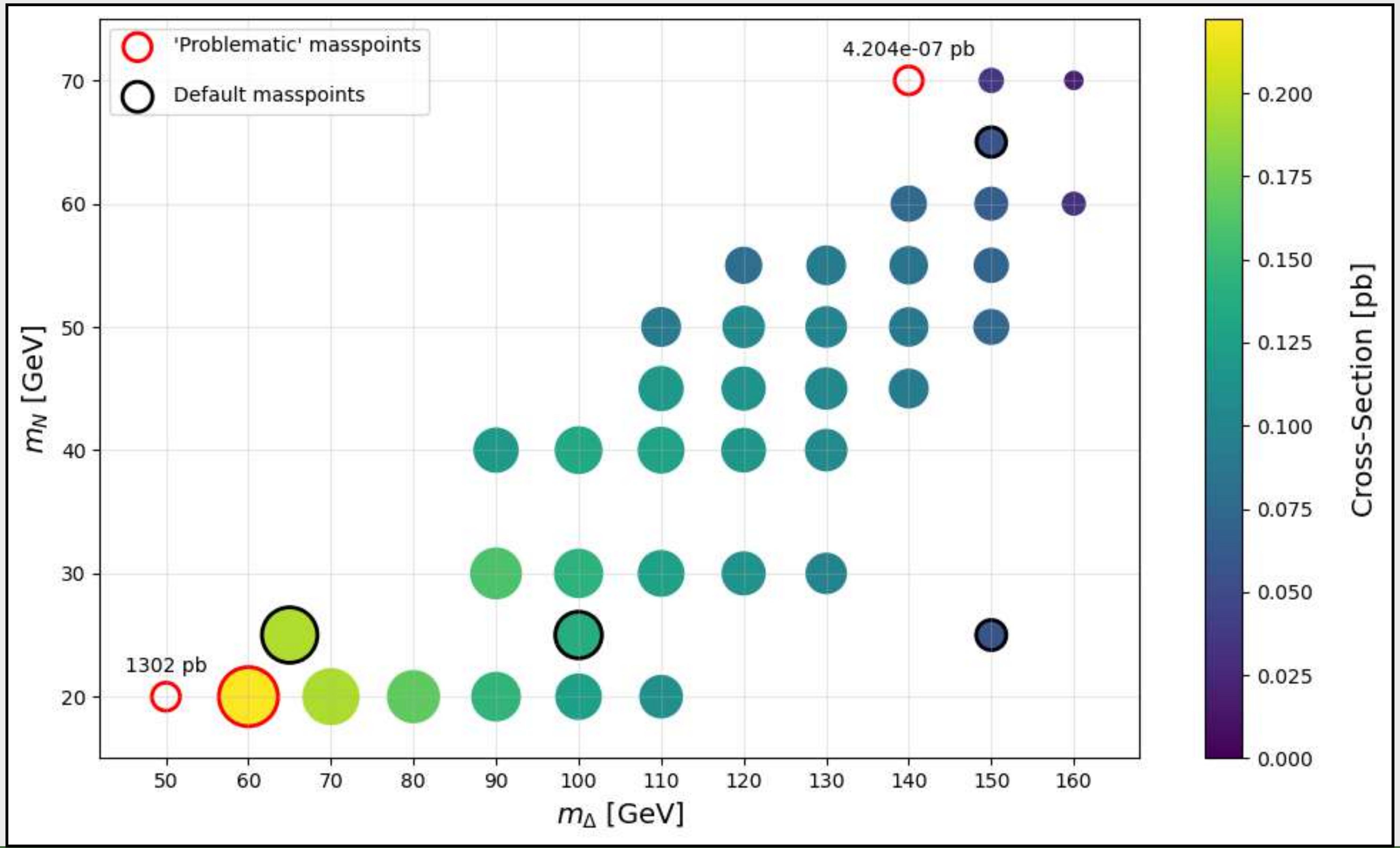


arXiv:1612.06840

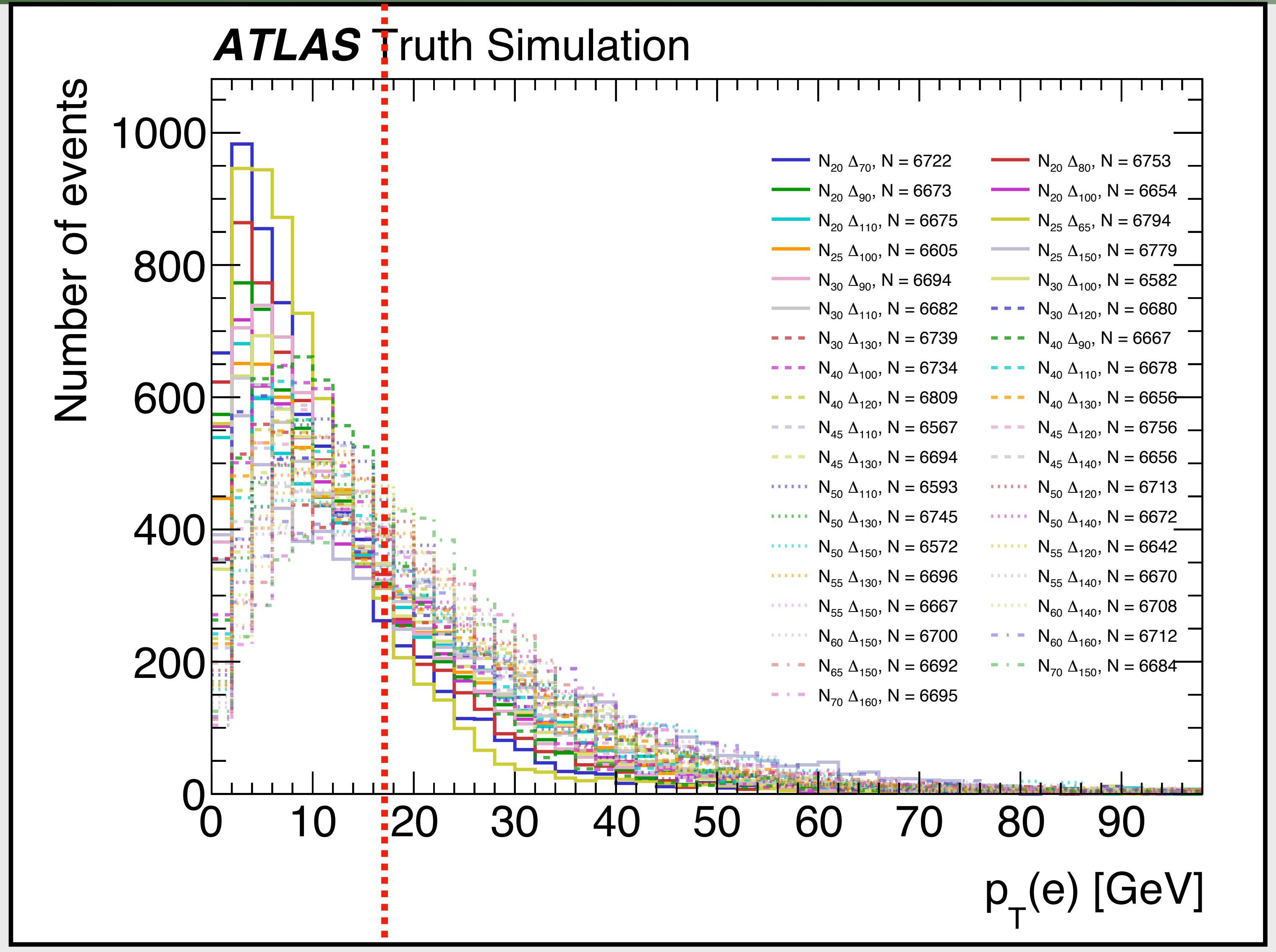
Truth-level studies

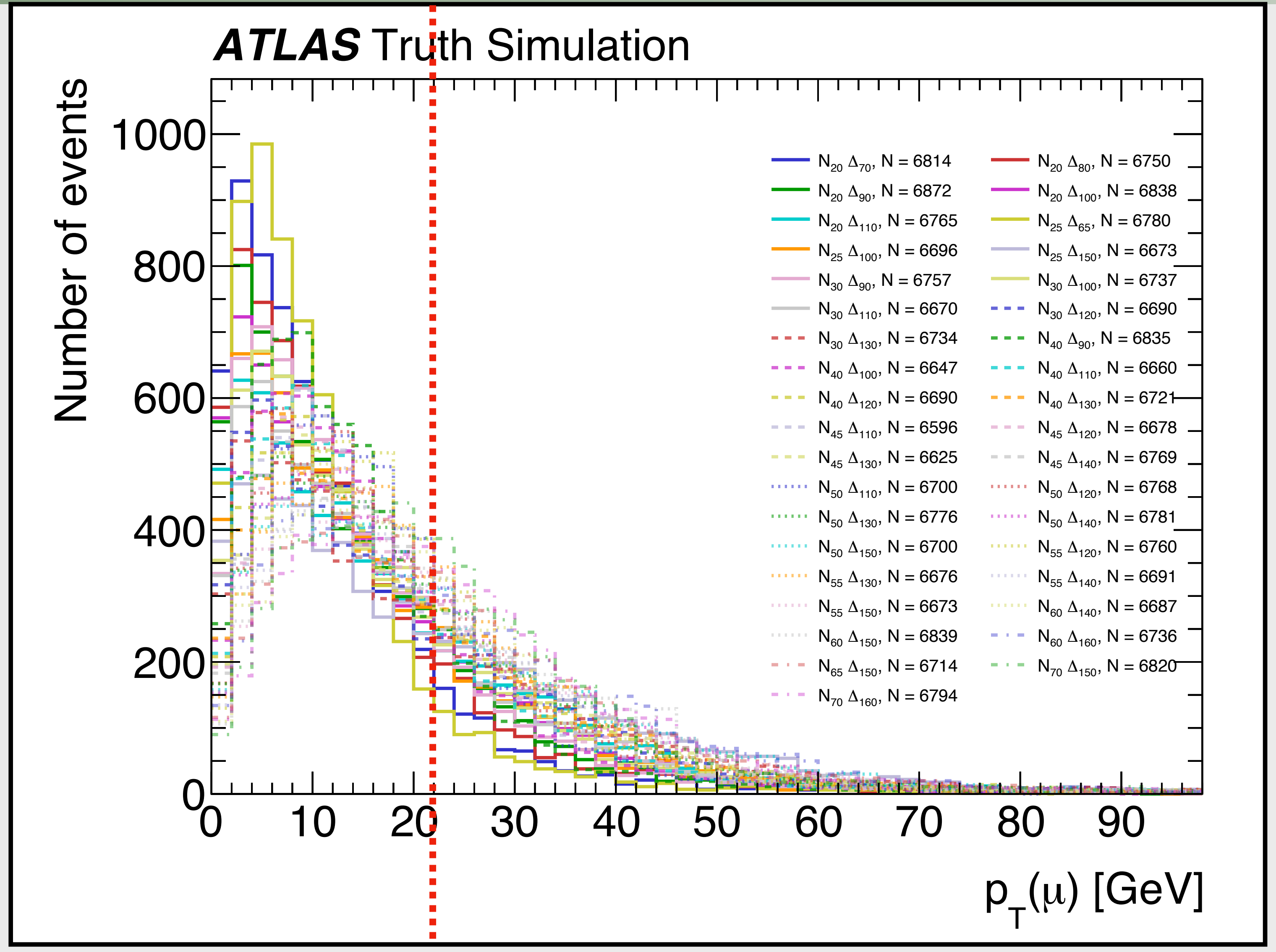
- Wr generated **37 signals** on a grid of m_N and m_Δ, which have sensible cross-sections.
- **Gridpack mode** was used for ME calculation and integration.
- Although the total cross-sections are not unreachable, the final state is very low-energetic. A significant fraction of events is not detected simply due to the **detector acceptance/efficiency**:
  - $p_T(j) > 20$ GeV,
  - $p_T(e) > 17$ GeV,
  - $p_T(\mu) > 22$ GeV.

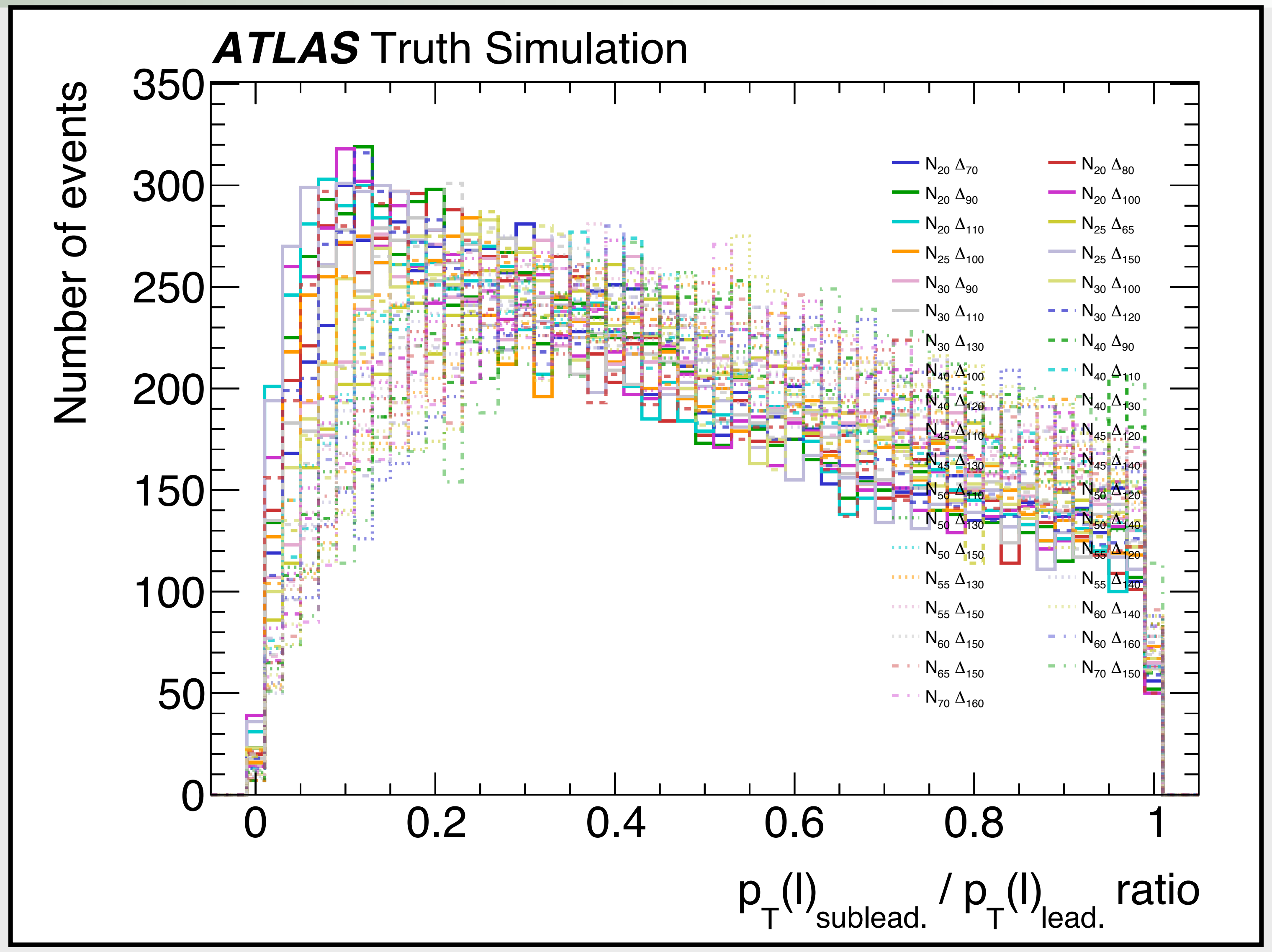
Trigger thresholds

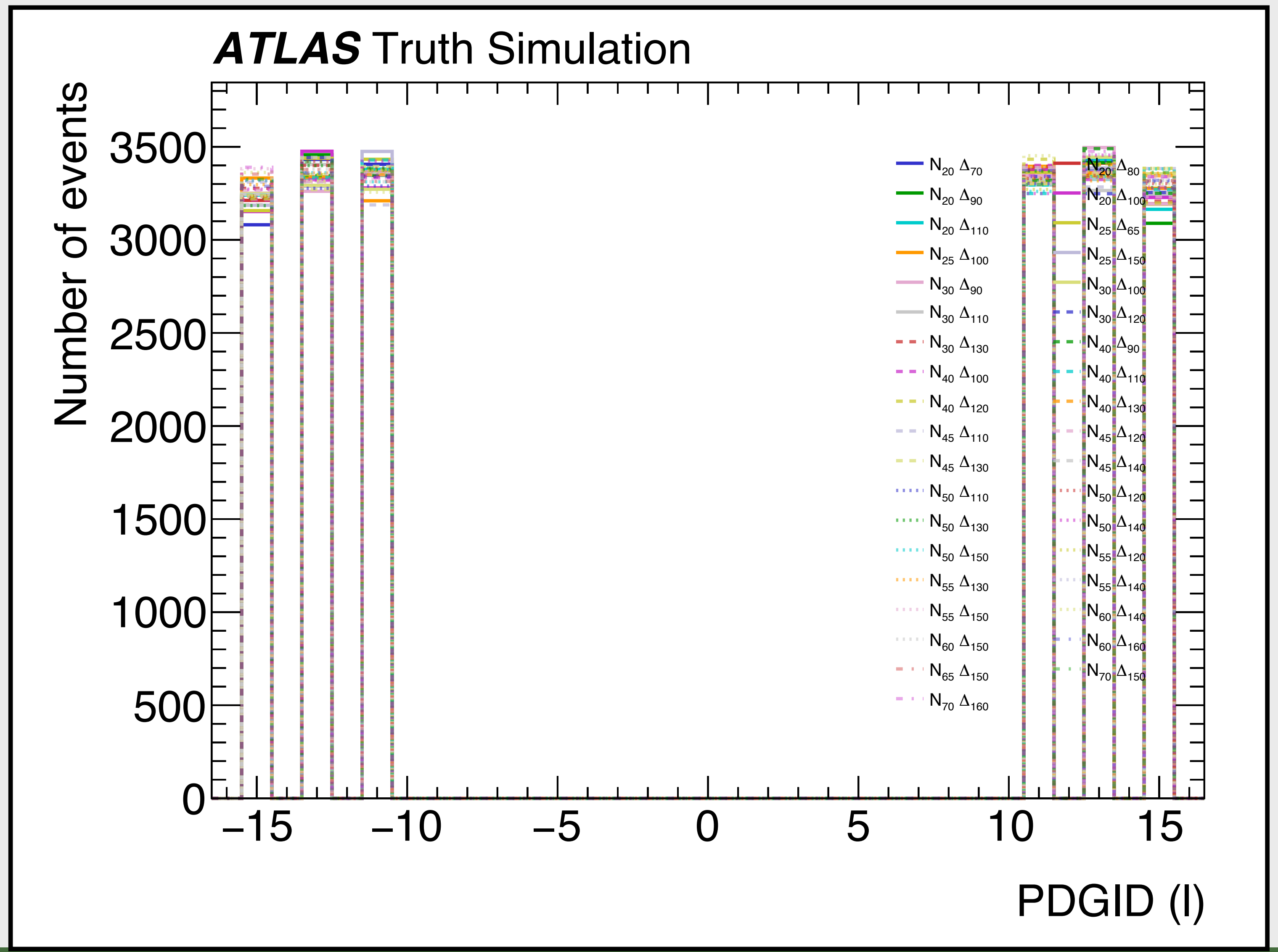


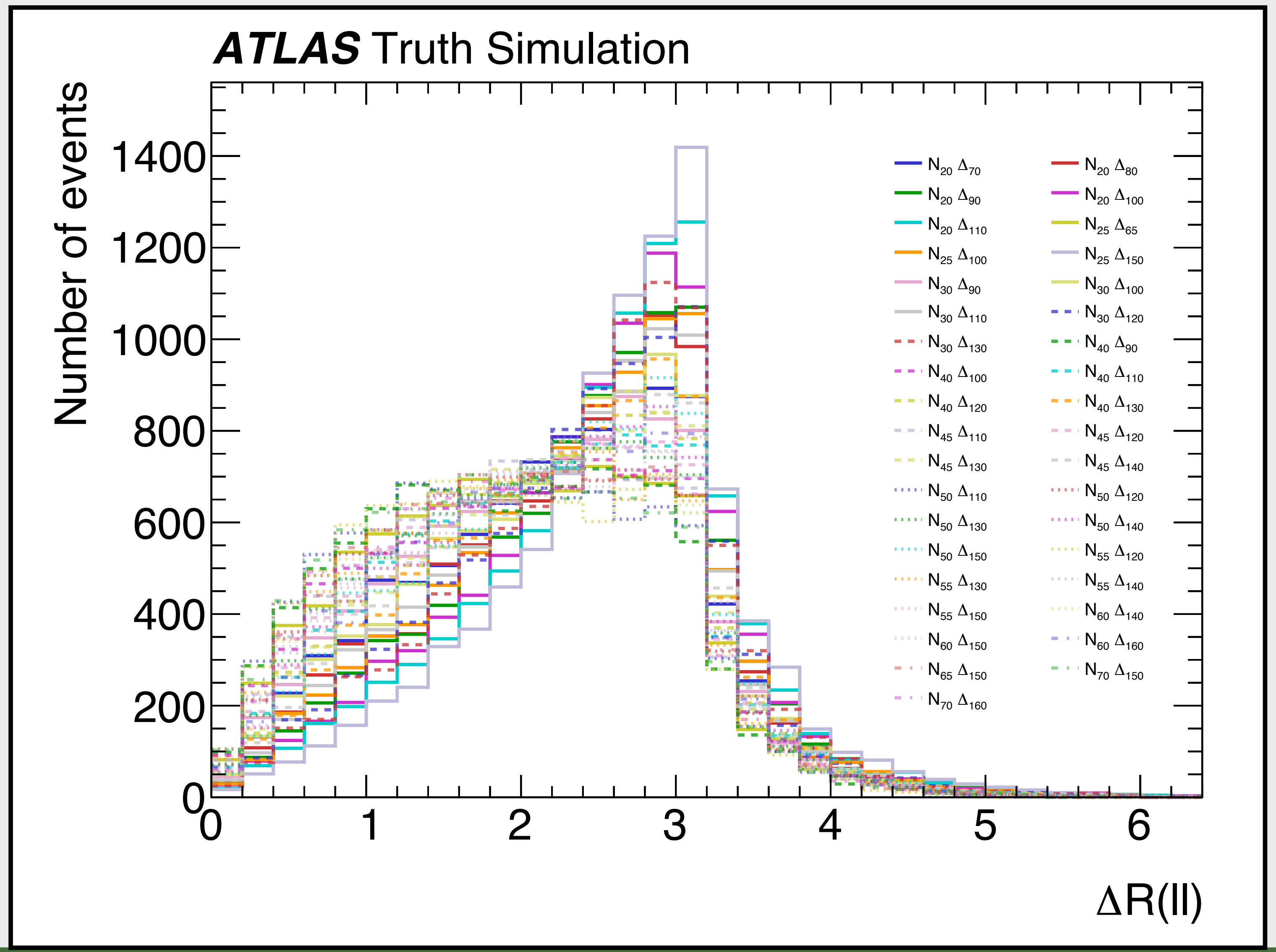
Truth-level studies - leptons

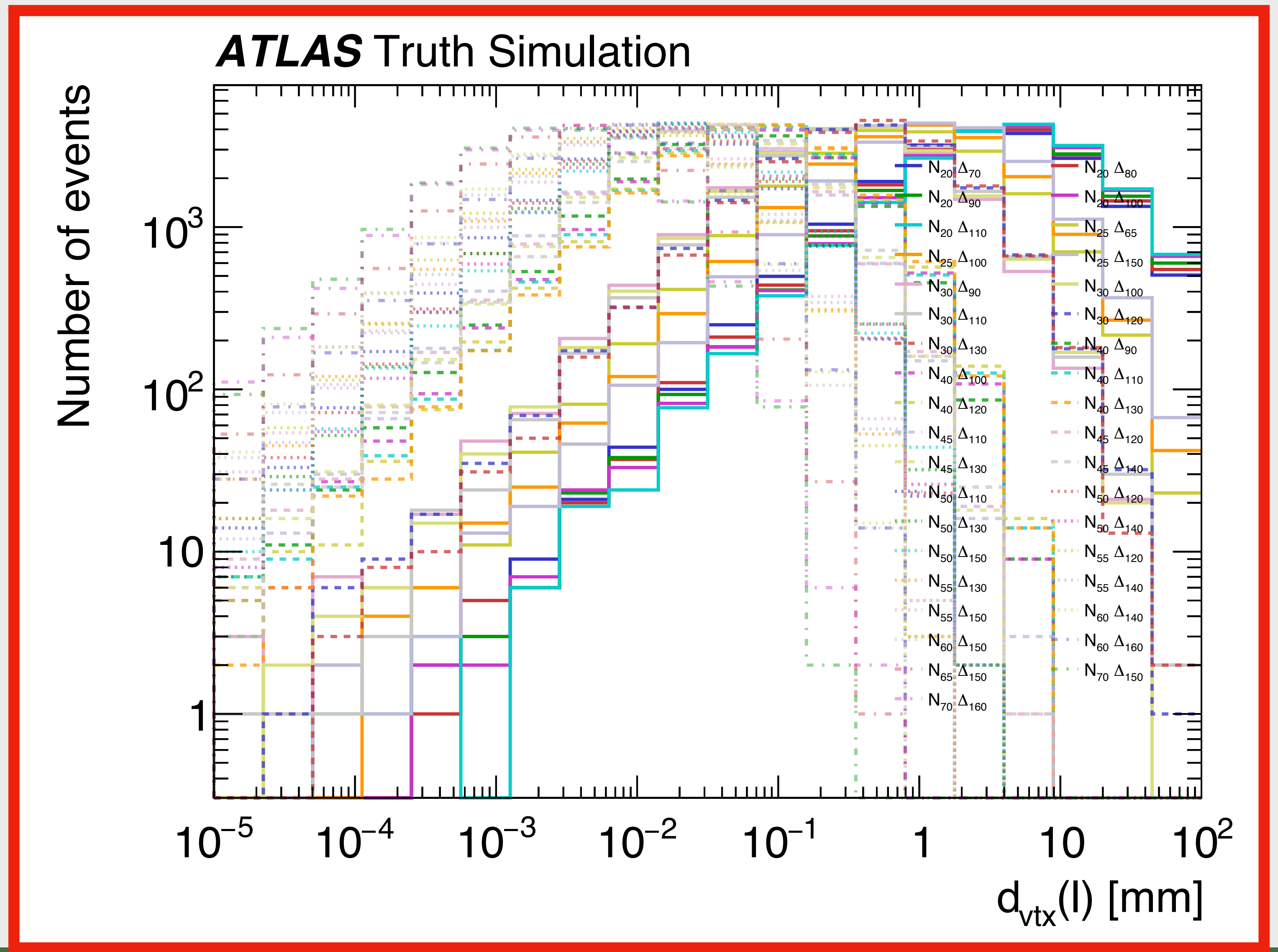




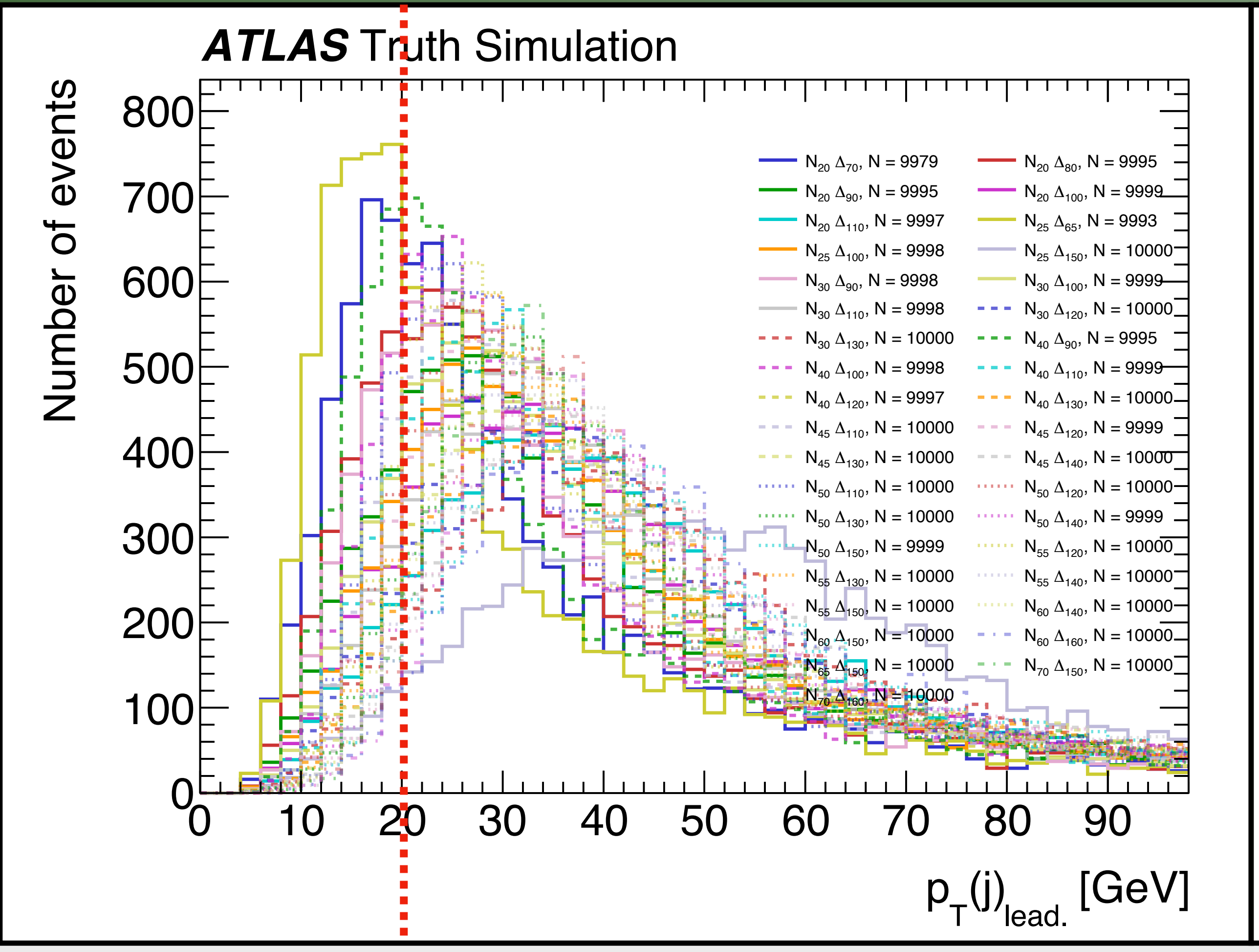


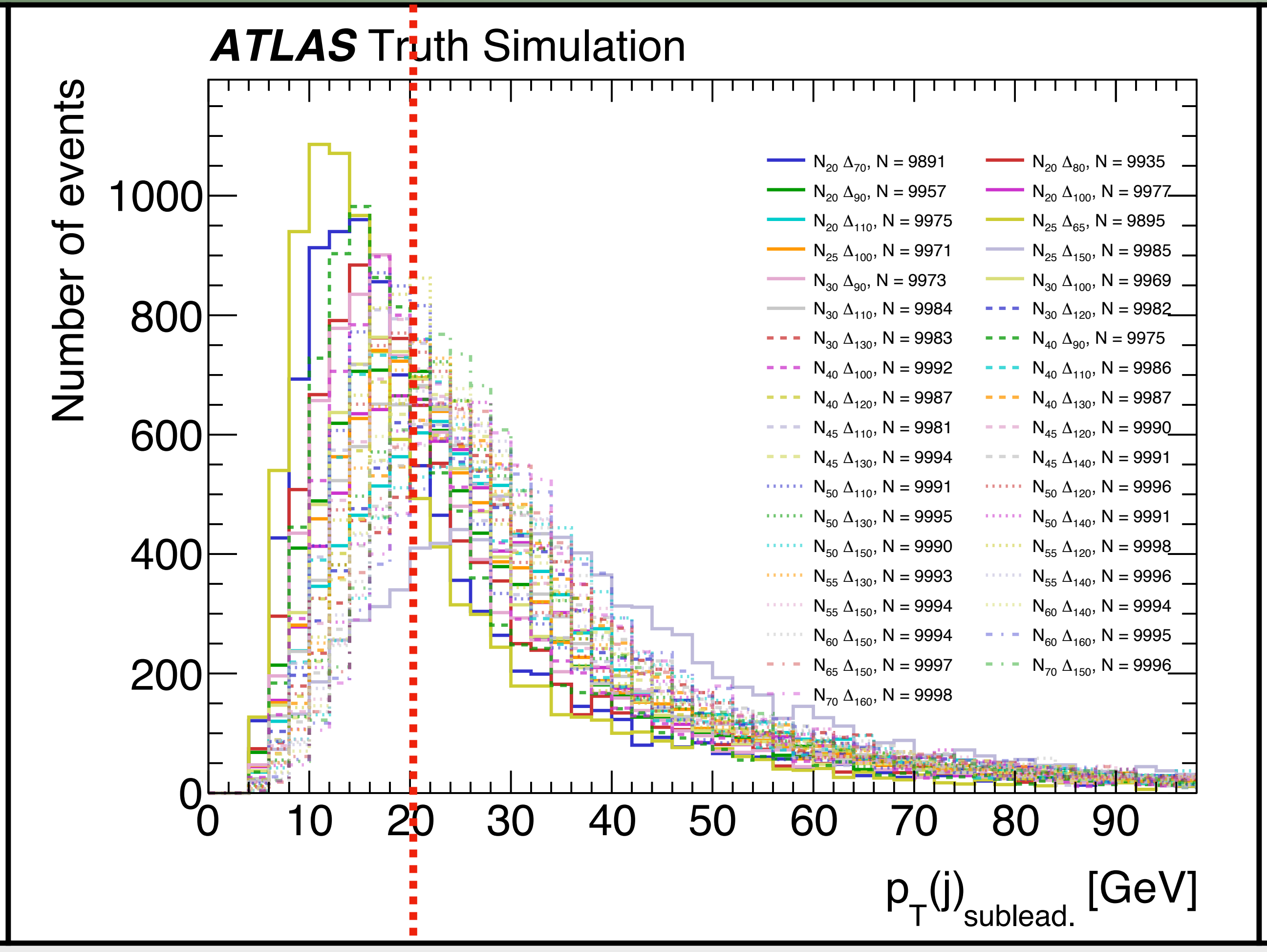


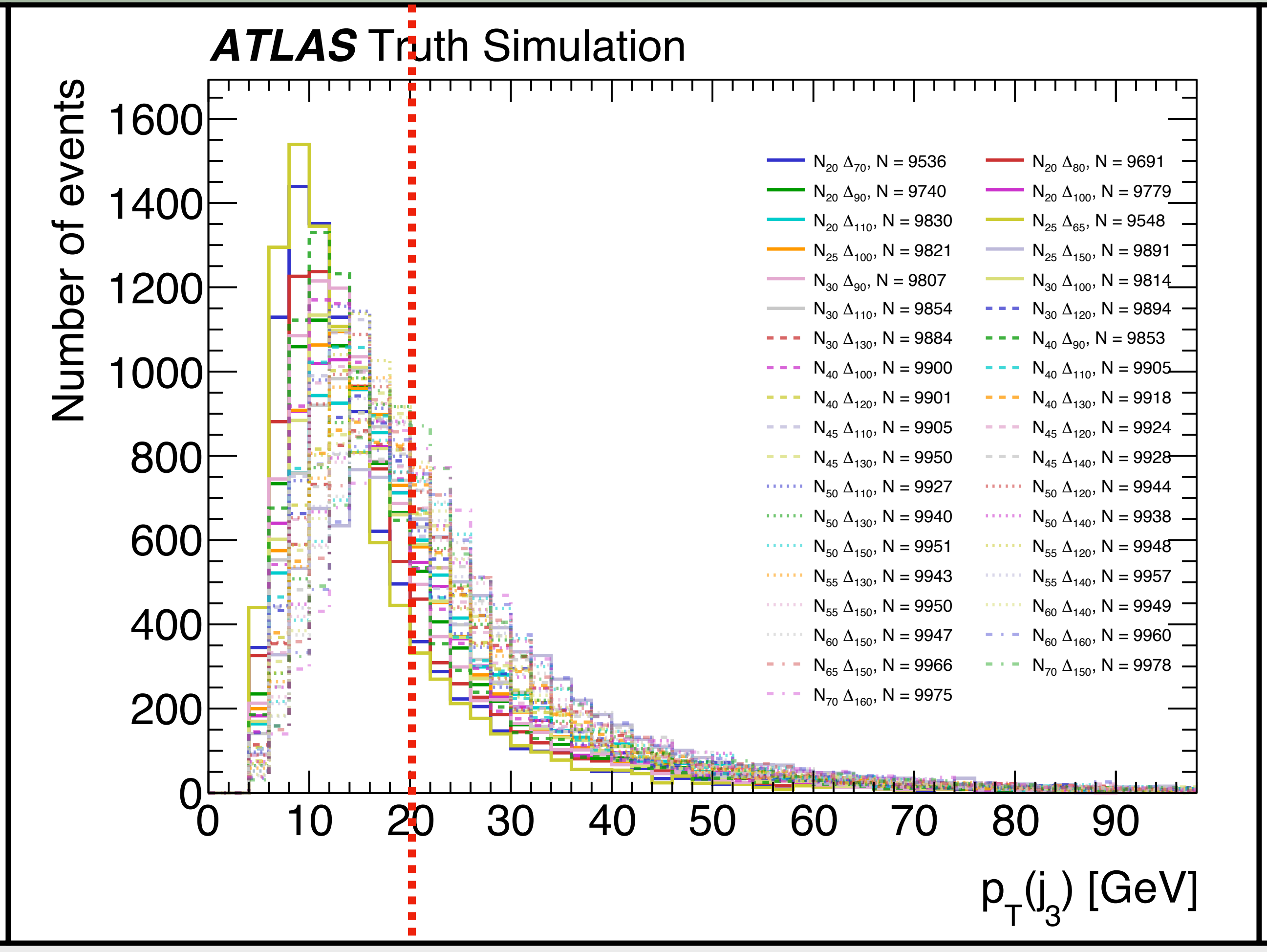


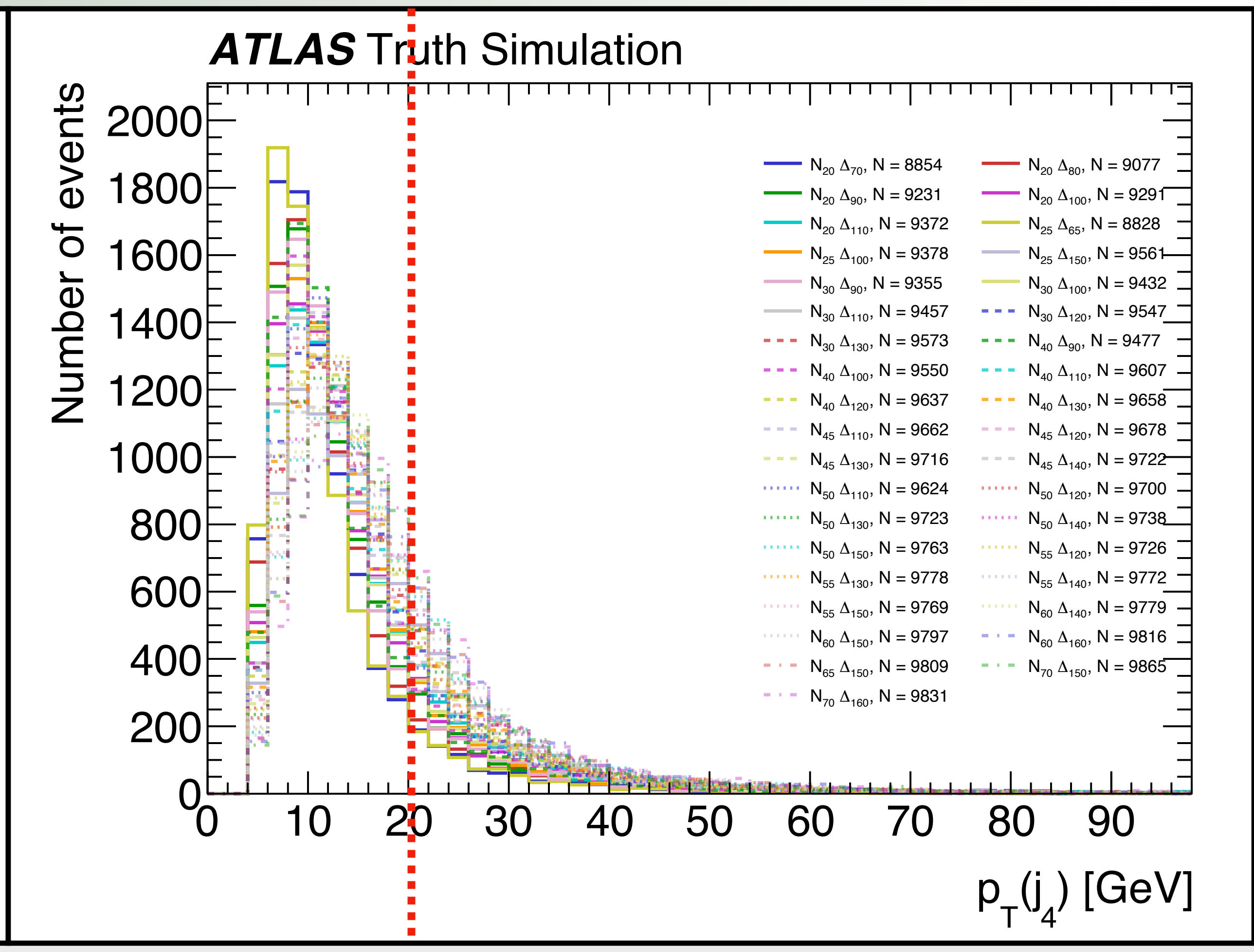


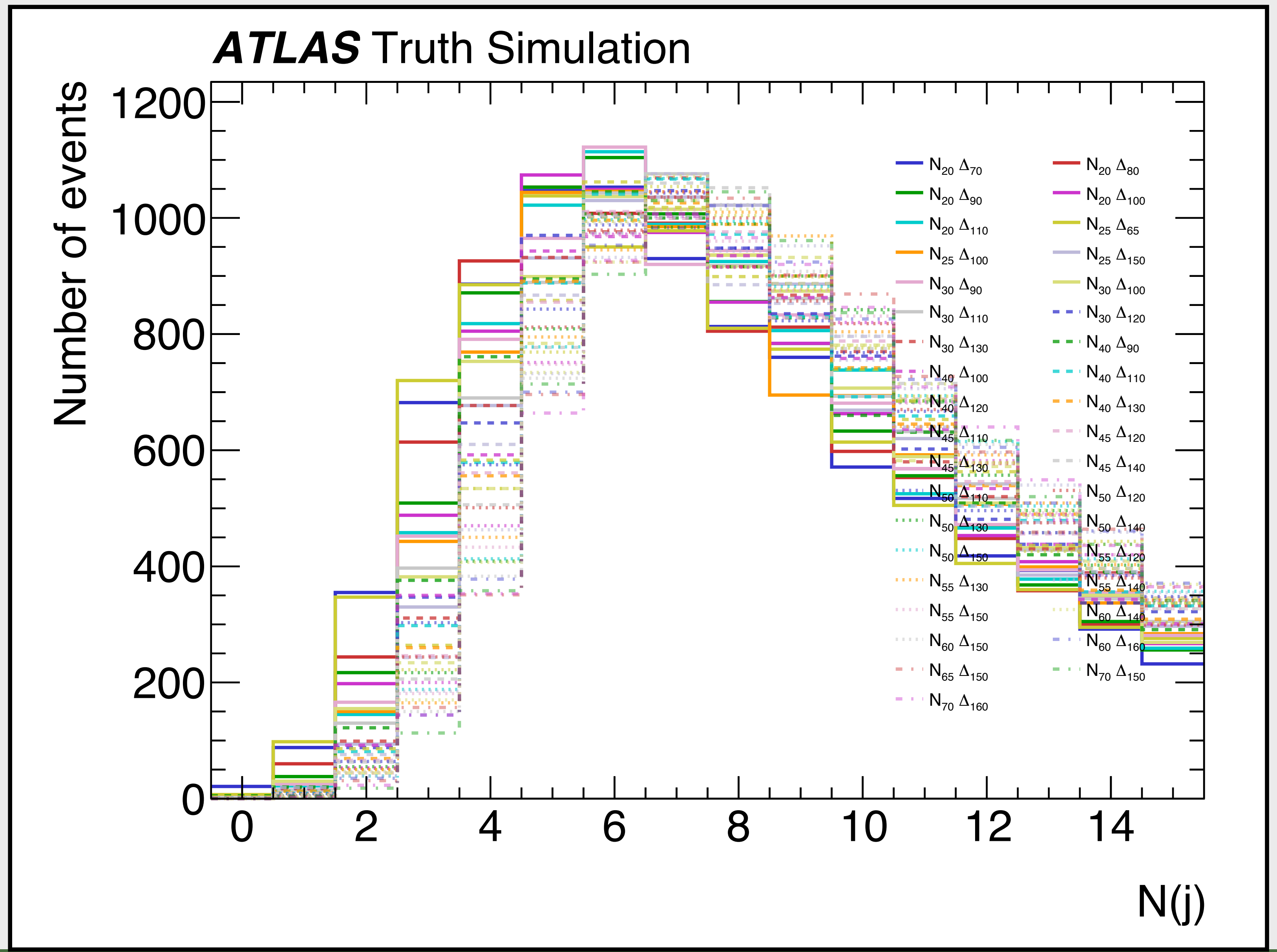
Truth-level studies - jets





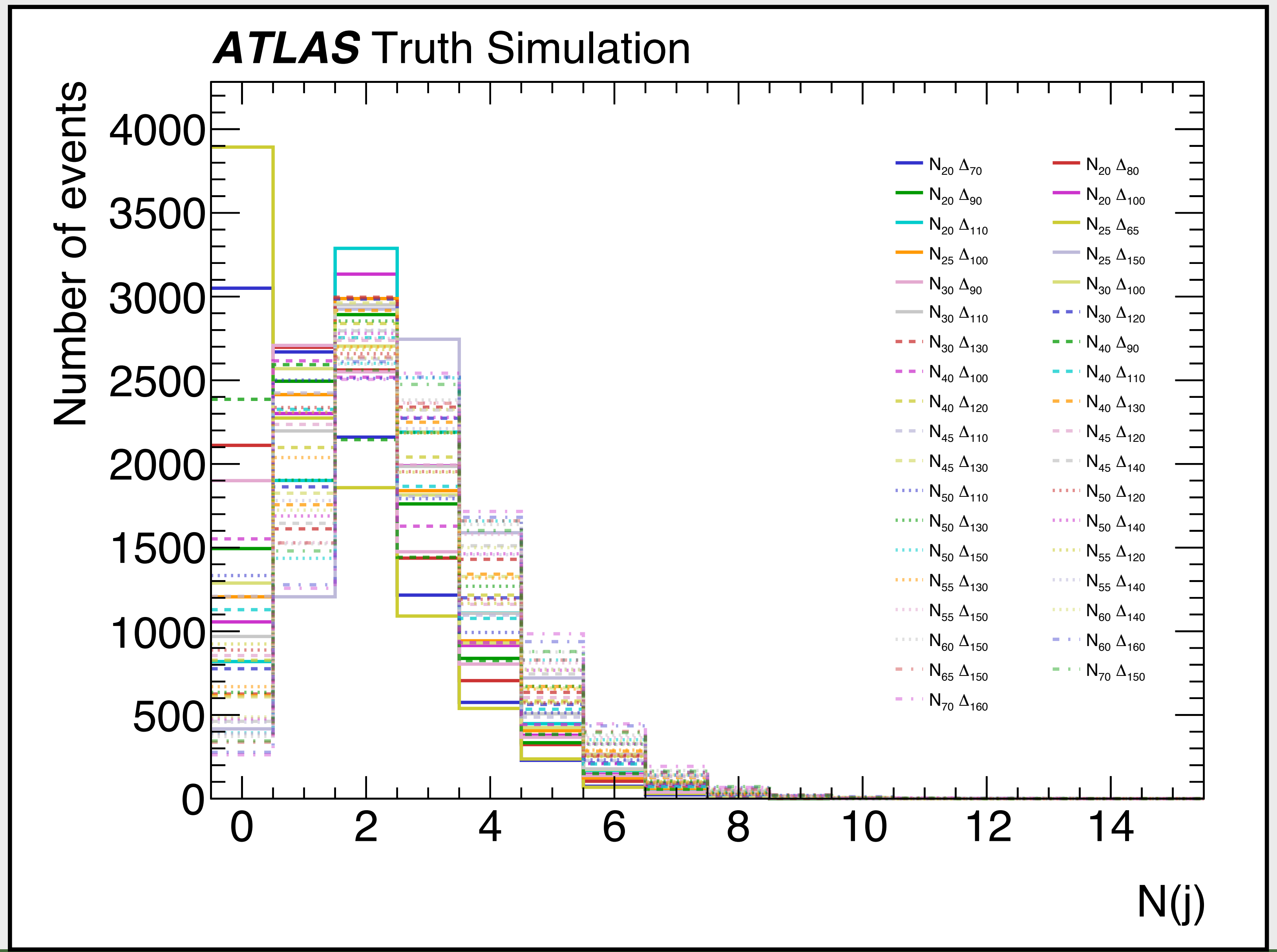






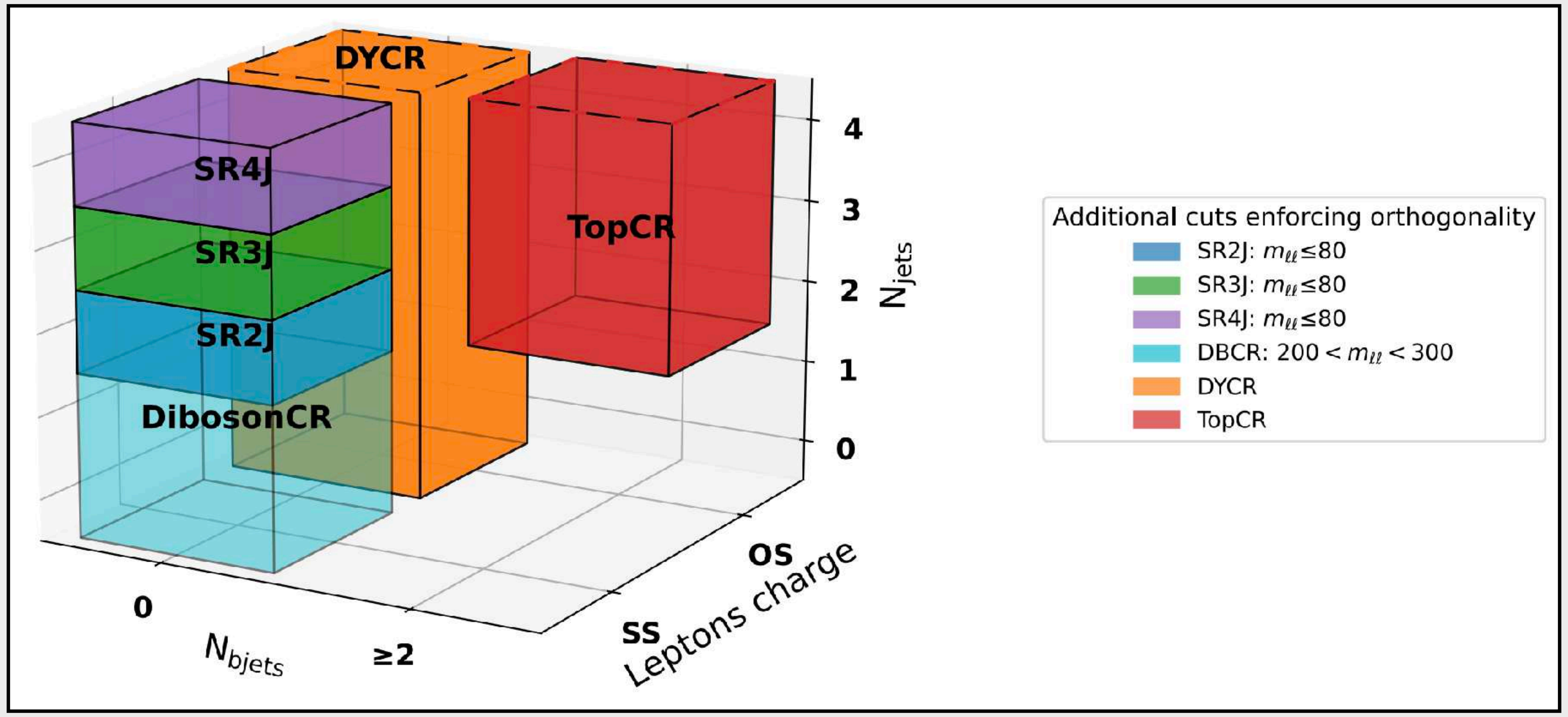
$p_T(j) > 20$ GeV

cut



Analysis strategy

Quantity	SR2J	SR3J	SR4J	TopCR	DBCR	DYCR	TopVR	DBVR	DYVR
$p_T(\ell_{lead})$ [GeV]	< 150	< 150	< 150	–	–	–	–	–	–
$p_T(\ell_{sublead})$ [GeV]	< 100	< 100	< 100	–	–	–	–	–	–
N_{jets}	2	3	4	≥ 2	< 3	–	≥ 2	< 3	–
N_{bjets}	0	0	0	≥ 2	0	0	≥ 2	0	0
Leptons charge	SS	SS	SS	OS	SS	OS	OS	SS	OS
$m_{\ell\ell}$ [GeV]	≤ 80	≤ 80	≤ 80	$130 - 300$	$200 - 300$	$80 - 120$	$300 - 1500$	$300 - 600$	$120 - 1000$
E_T^{miss} [GeV]	< 150	< 150	< 150	–	> 30	–	–	> 30	–
$\Delta(m_{jj\ell})_{min}$ [GeV]	–	–	< 60	–	–	–	–	–	–



Cutflows

Cutflows for signal events (weighted)

SR2J

SR2J $l^\pm l^\pm$, N_{30}, Δ_{90}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.04×10^3
Number of jets	1.11×10^3
Crack veto cleaning	1.11×10^3
Two loose leptons	161
Triggers	129
Bad muon veto	129
Two tight leptons	58.1
Analysis channel	57.4
Charge	26.0
b-jet multiplicity	23.7
Missing E_T	23.6
m_{ll} SS lead. pair	23.2
Leading lepton p_T	23.0
Subleading lepton p_T	22.9
Jet multiplicity	4.81

SR2J $l^\pm l^\pm$, N_{50}, Δ_{150}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.83×10^3
Number of jets	1.86×10^3
Crack veto cleaning	1.86×10^3
Two loose leptons	545
Triggers	467
Bad muon veto	467
Two tight leptons	278
Analysis channel	274
Charge	132
b-jet multiplicity	126
Missing E_T	126
m_{ll} SS lead. pair	93.6
Leading lepton p_T	93.1
Subleading lepton p_T	93.1
Jet multiplicity	26.1

SR2J $l^\pm l^\pm$, N_{70}, Δ_{160}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	621
Number of jets	630
Crack veto cleaning	630
Two loose leptons	202
Triggers	174
Bad muon veto	174
Two tight leptons	104
Analysis channel	103
Charge	50.1
b-jet multiplicity	47.7
Missing E_T	47.5
m_{ll} SS lead. pair	42.6
Leading lepton p_T	42.4
Subleading lepton p_T	42.3
Jet multiplicity	11.9

SR3J

SR3J $l^\pm l^\pm$, N_{30}, Δ_{90}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.04×10^3
Number of jets	1.11×10^3
Crack veto cleaning	1.11×10^3
Two loose leptons	161
Triggers	129
Bad muon veto	129
Two tight leptons	58.1
Analysis channel	57.4
Charge	26.0
b-jet multiplicity	23.7
Missing E_T	23.6
m_{ll} SS lead. pair	23.2
Leading lepton p_T	23.0
Subleading lepton p_T	22.9
Jet multiplicity	2.72

SR3J $l^\pm l^\pm$, N_{50}, Δ_{150}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.83×10^3
Number of jets	1.86×10^3
Crack veto cleaning	1.86×10^3
Two loose leptons	545
Triggers	467
Bad muon veto	467
Two tight leptons	278
Analysis channel	274
Charge	132
b-jet multiplicity	126
Missing E_T	126
m_{ll} SS lead. pair	93.6
Leading lepton p_T	93.1
Subleading lepton p_T	93.1
Jet multiplicity	17.5

SR3J $l^\pm l^\pm$, N_{70}, Δ_{160}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	621
Number of jets	630
Crack veto cleaning	630
Two loose leptons	202
Triggers	174
Bad muon veto	174
Two tight leptons	104
Analysis channel	103
Charge	50.1
b-jet multiplicity	47.7
Missing E_T	47.5
m_{ll} SS lead. pair	42.6
Leading lepton p_T	42.4
Subleading lepton p_T	42.3
Jet multiplicity	9.40

SR4J

SR4J $l^\pm l^\pm$, N_{30}, Δ_{90}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.04×10^3
Number of jets	1.11×10^3
Crack veto cleaning	1.11×10^3
Two loose leptons	161
Triggers	129
Bad muon veto	129
Two tight leptons	58.1
Analysis channel	57.4
Charge	26.0
b-jet multiplicity	23.7
Missing E_T	23.6
m_{ll} SS lead. pair	23.2
Leading lepton p_T	23.0
Subleading lepton p_T	22.9
Jet multiplicity	0.867
$\Delta(m_{jjl})_{\min}$	0.406

SR4J $l^\pm l^\pm$, N_{50}, Δ_{150}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	1.83×10^3
Number of jets	1.86×10^3
Crack veto cleaning	1.86×10^3
Two loose leptons	545
Triggers	467
Bad muon veto	467
Two tight leptons	278
Analysis channel	274
Charge	132
b-jet multiplicity	126
Missing E_T	126
m_{ll} SS lead. pair	93.6
Leading lepton p_T	93.1
Subleading lepton p_T	93.1
Jet multiplicity	9.03
$\Delta(m_{jjl})_{\min}$	5.87

SR4J $l^\pm l^\pm$, N_{70}, Δ_{160}	Yield
Expected yield $\sigma \cdot \mathcal{L}$	621
Number of jets	630
Crack veto cleaning	630
Two loose leptons	202
Triggers	174
Bad muon veto	174
Two tight leptons	104
Analysis channel	103
Charge	50.1
b-jet multiplicity	47.7
Missing E_T	47.5
m_{ll} SS lead. pair	42.6
Leading lepton p_T	42.4
Subleading lepton p_T	42.3
Jet multiplicity	4.36
$\Delta(m_{jjl})_{\min}$	3.06

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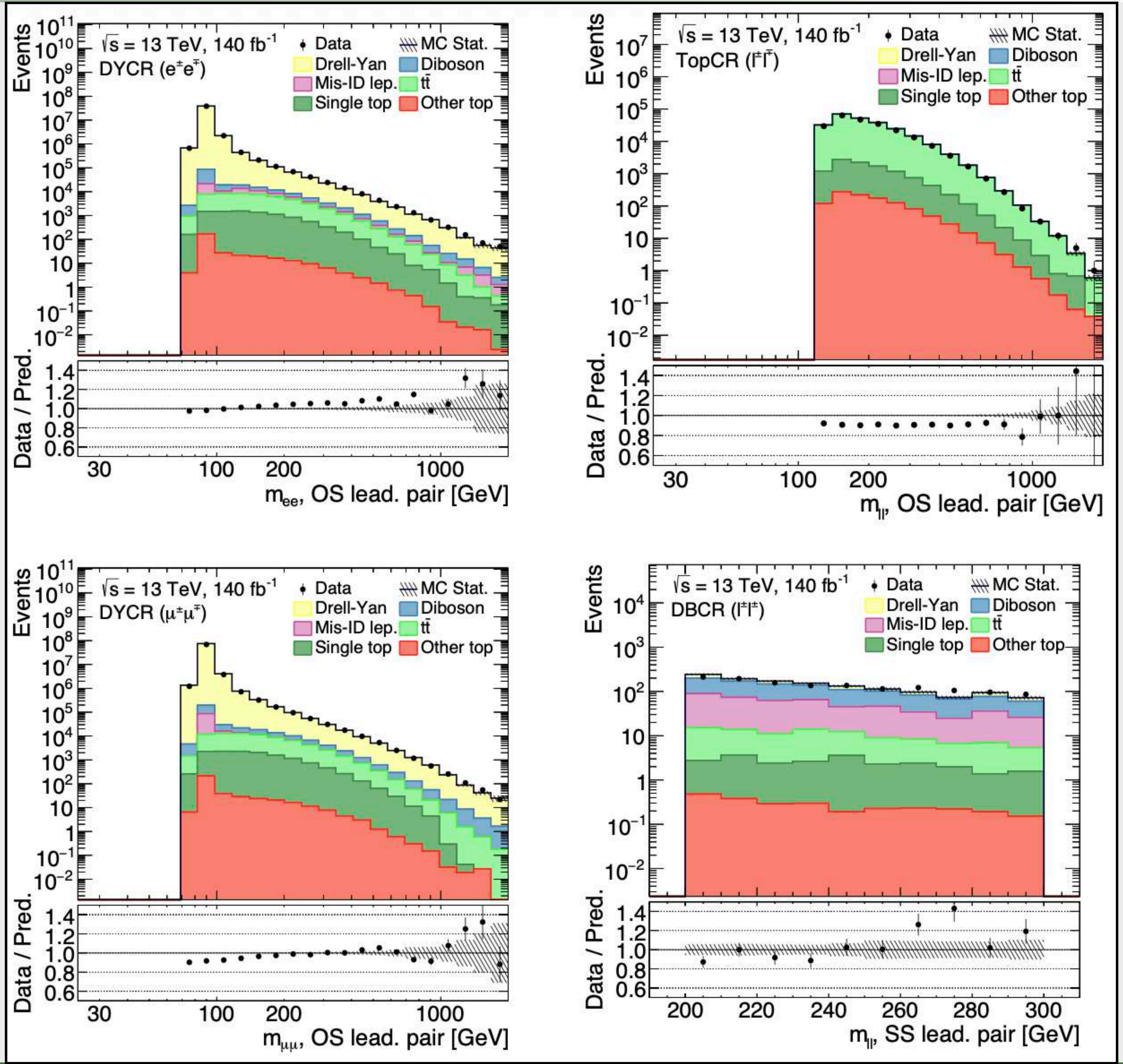
Slide from E. Sanzani

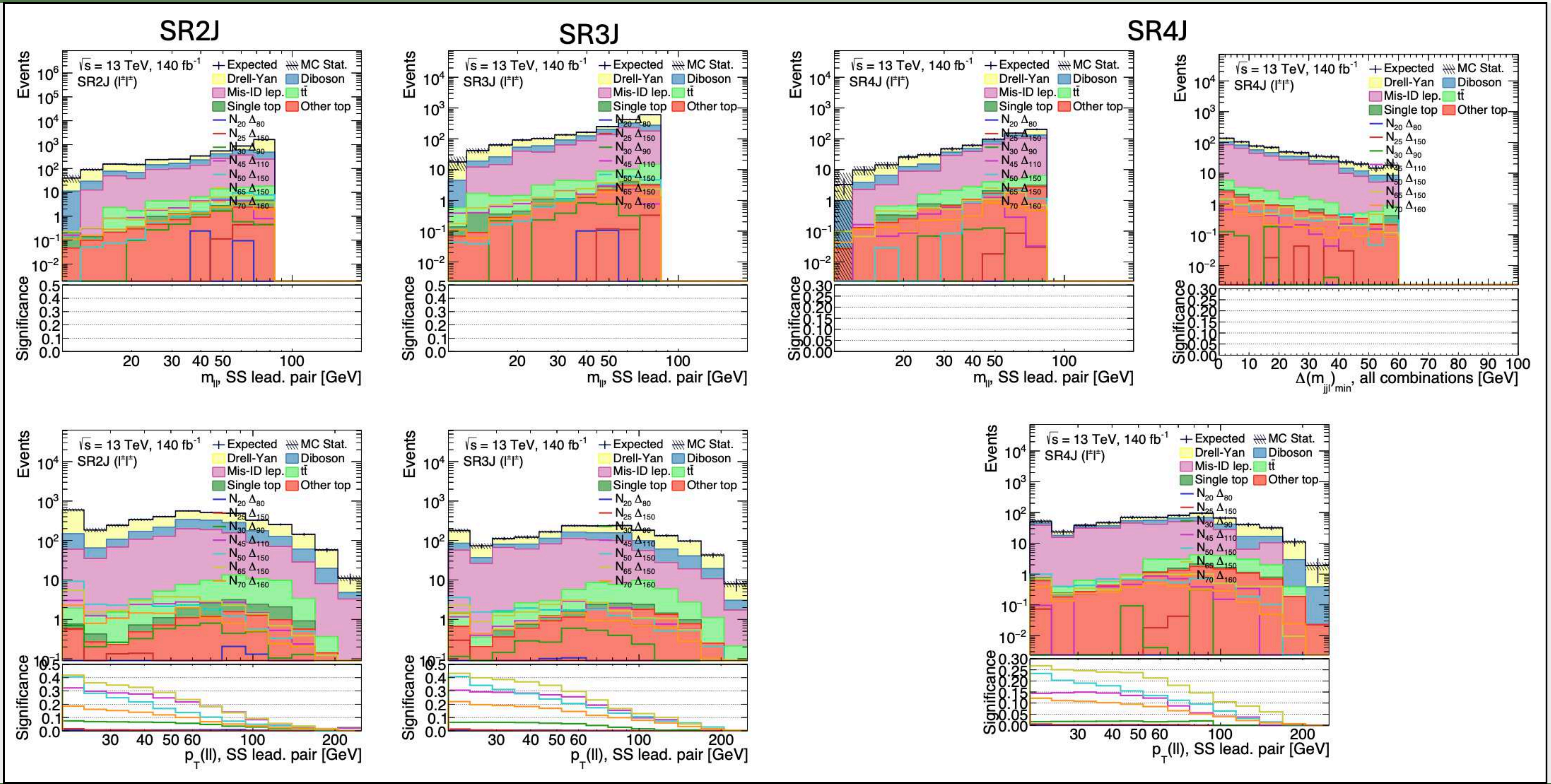
Control regions

- We construct control regions to verify the MC to data agreement.
- At this stage the agreement is good.



Plots from E. Sanzani

Signal regions



$\Delta m_{ljj}^{min} = \min | m(l_1 j_a j_b) - m(l_2 j_c j_d) |$

Plots from E. Sanzani

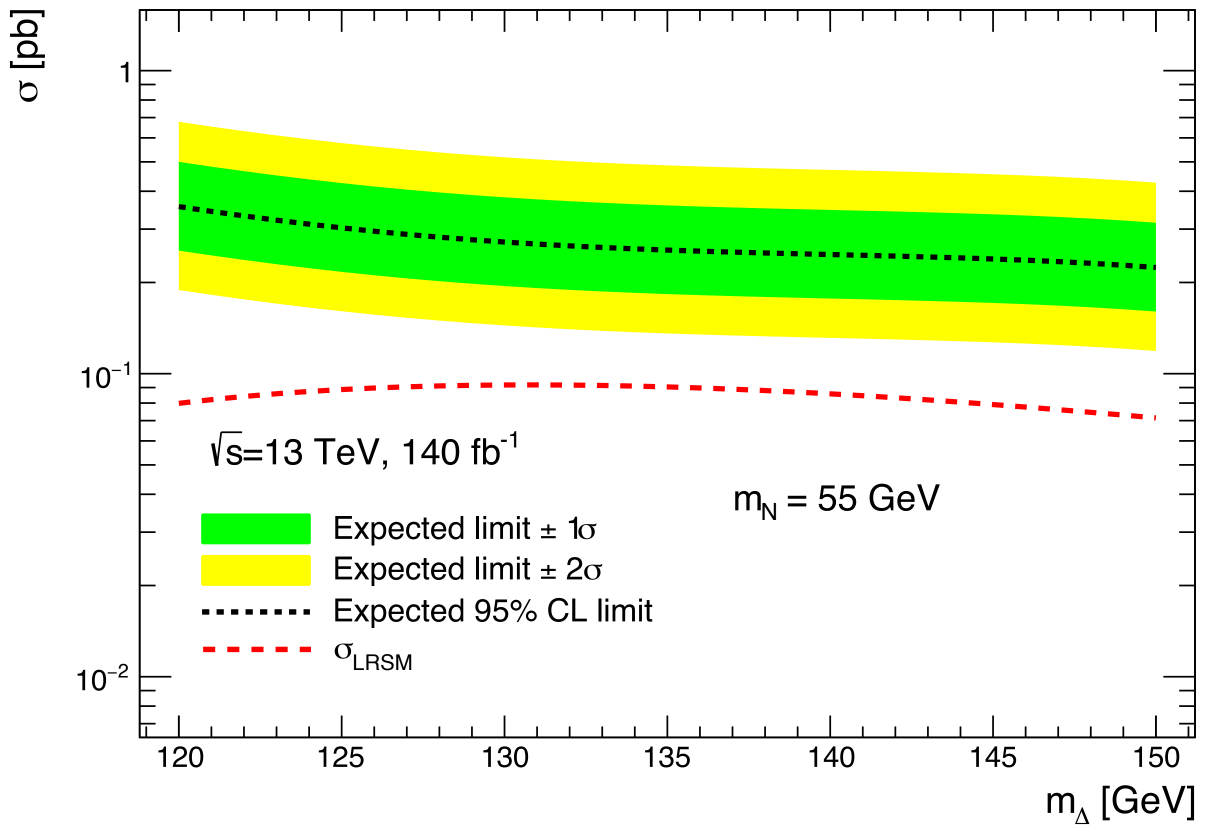
Machine learning approach

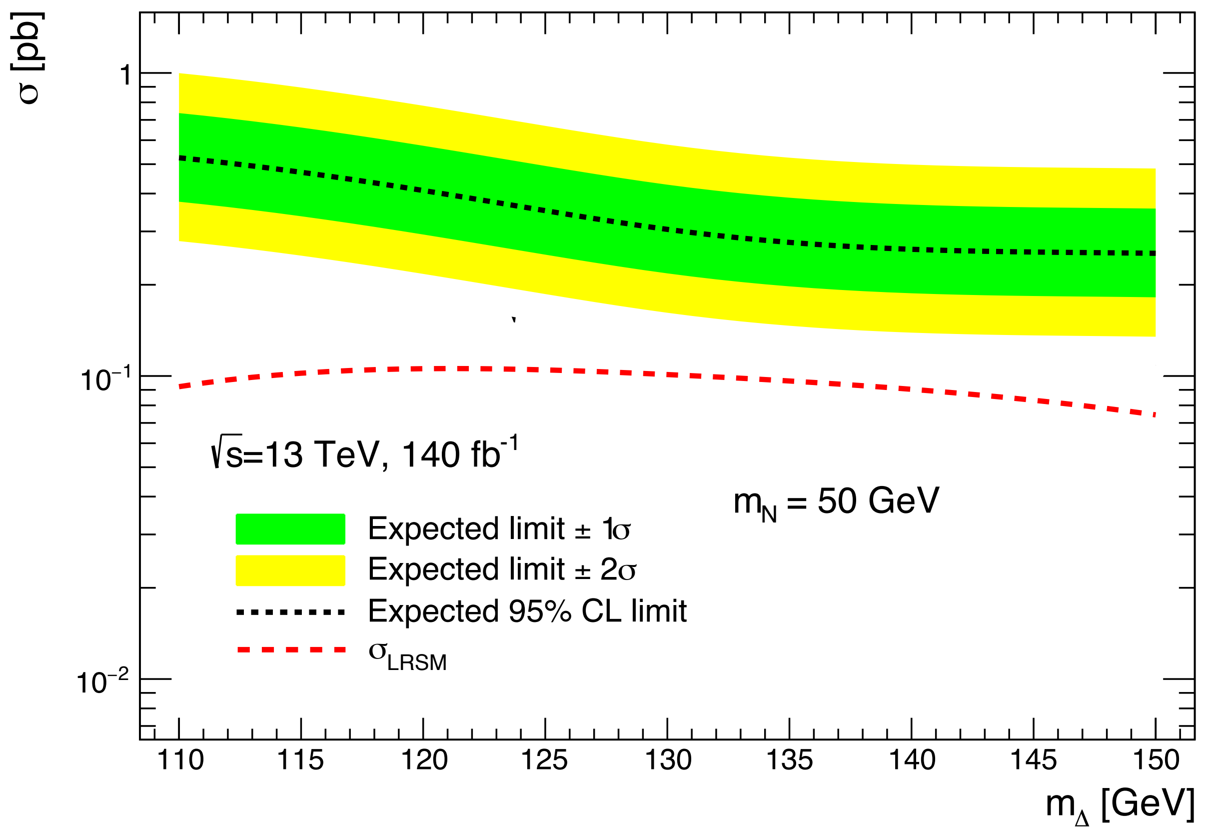
- An alternative approach is to use an MVA method, hoping it will help discriminate the signal from the background. The plan is to:
  - **Loosen the cuts** as much as possible (keep only the targeted kinematics in), to leave the ML algorithm greater phase space for learning.
  - Use the parametrised neural network to interpolate or extrapolate between signal mass points → **one model** to rule them all.
  - Define regions based on the **MVA output score** (control ~ 0, signal ~ 1), which also enters the fit.

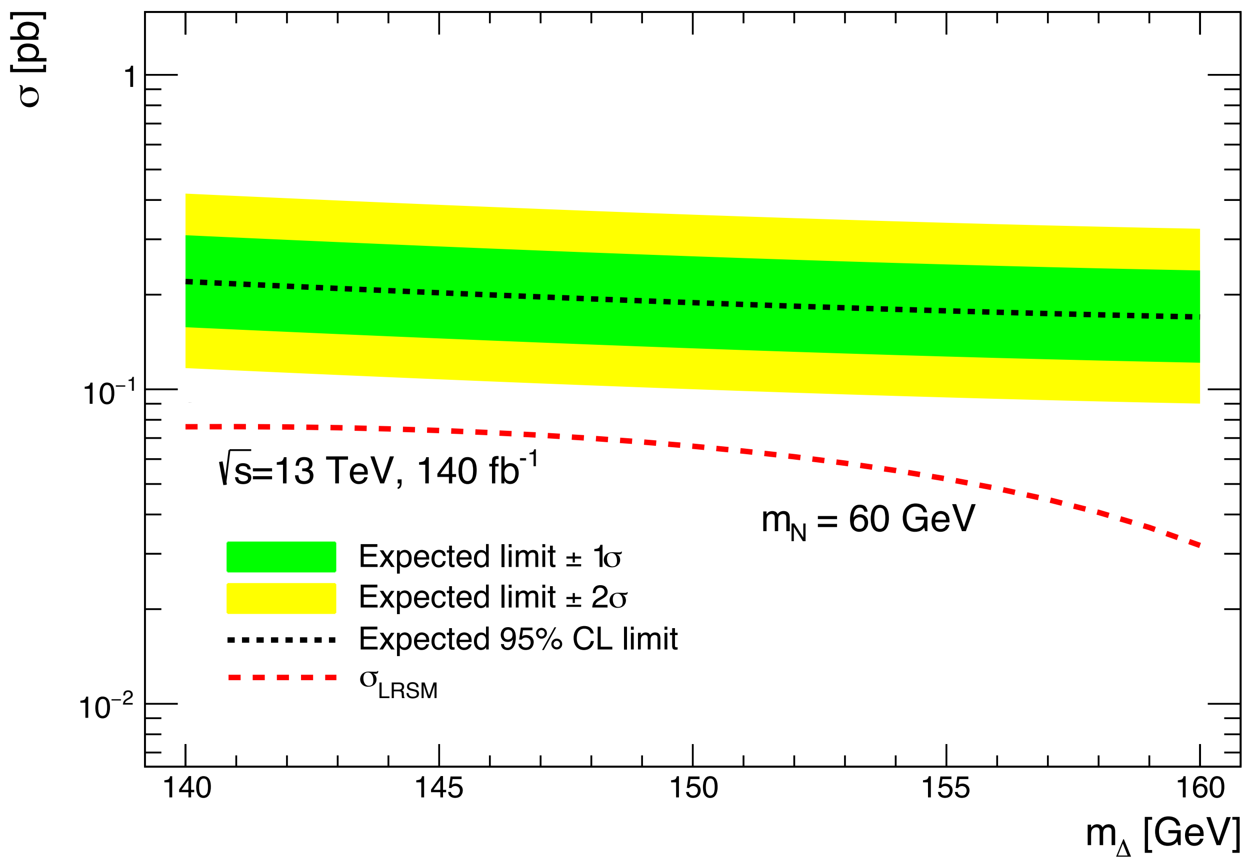
Quantity	SR2J	SR3J	SR4J	TopCR	DBCR	DYCR	TopVR	DBVR	DYVR
$\mathrm{N_{bjets}}$	0	0	0	≥ 2	0	0	≥ 2	0	0
Leptons charge	SS	SS	SS	OS	SS	OS	OS	SS	OS
$\mathrm{N_{jets}}$	$= 2$	$= 3$	$= 4$	≥ 2	< 3	–	–	< 3	–
$m_{\ell\ell}$ [GeV]	≤ 80	≤ 80	≤ 80	> 200	> 200	> 80	–	> 200	> 80
MVA score	> 0.8	> 0.8	> 0.8	< 0.4	< 0.4	< 0.4	$[0.4, 0.8]$	$[0.4, 0.8]$	$[0.4, 0.8]$

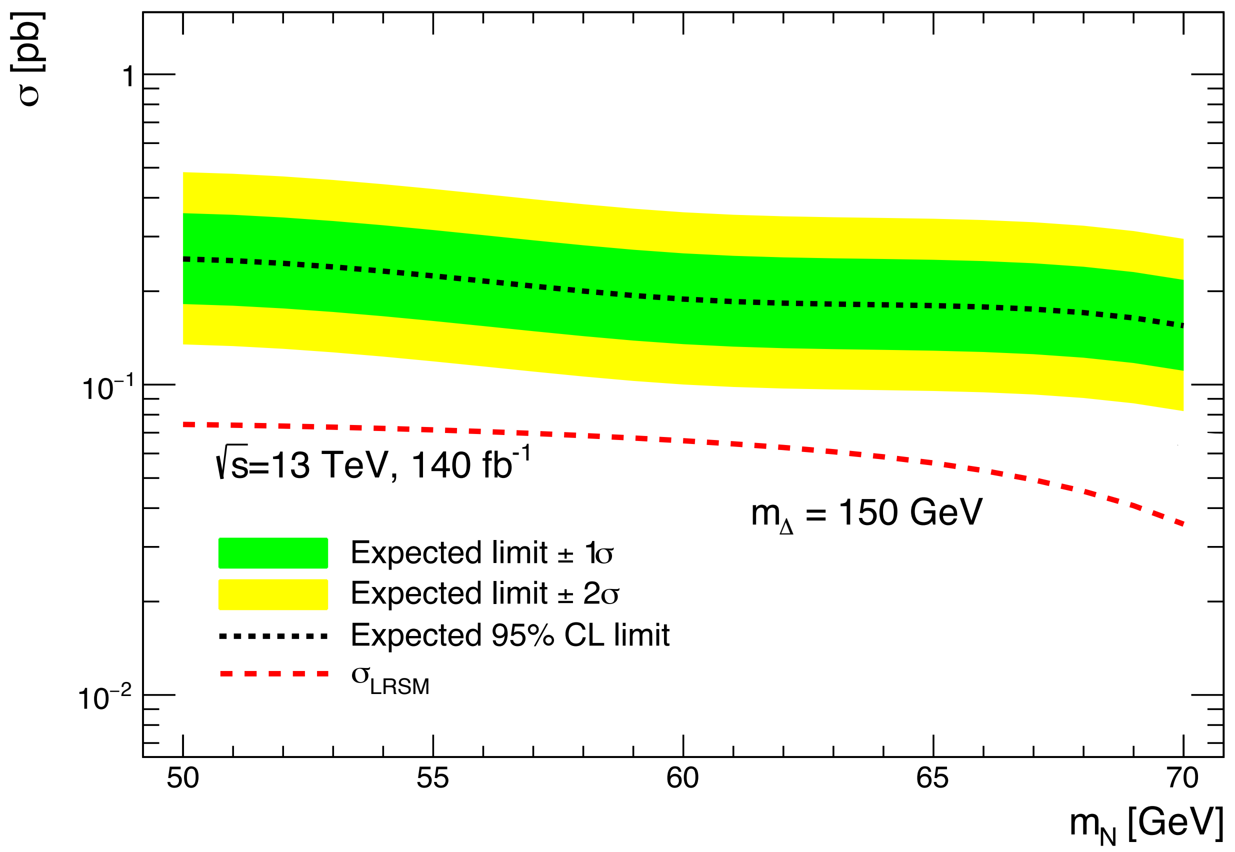
Preliminary results

Fit results









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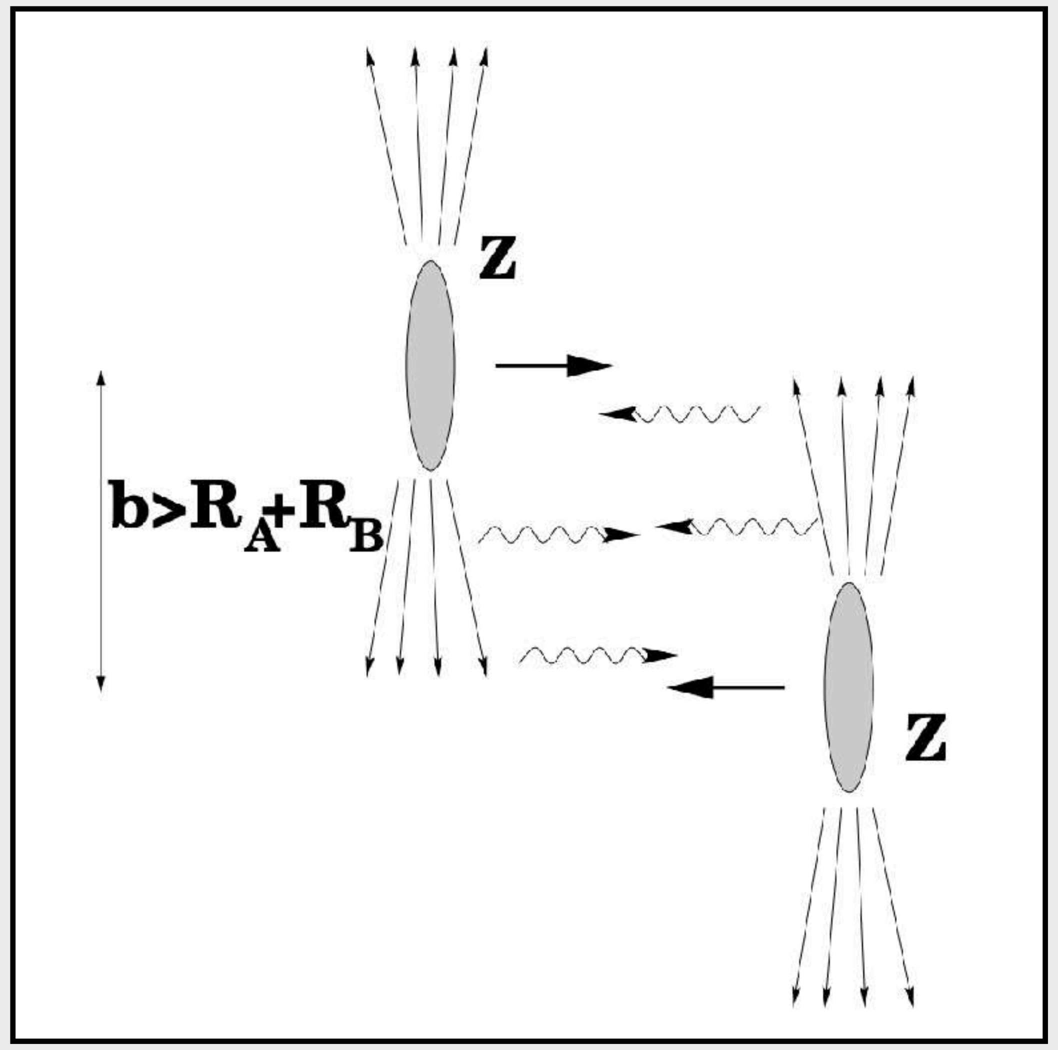
Slide from E. Sanzani

ALPs in Ultra-Peripheral Collisions (UPCs)

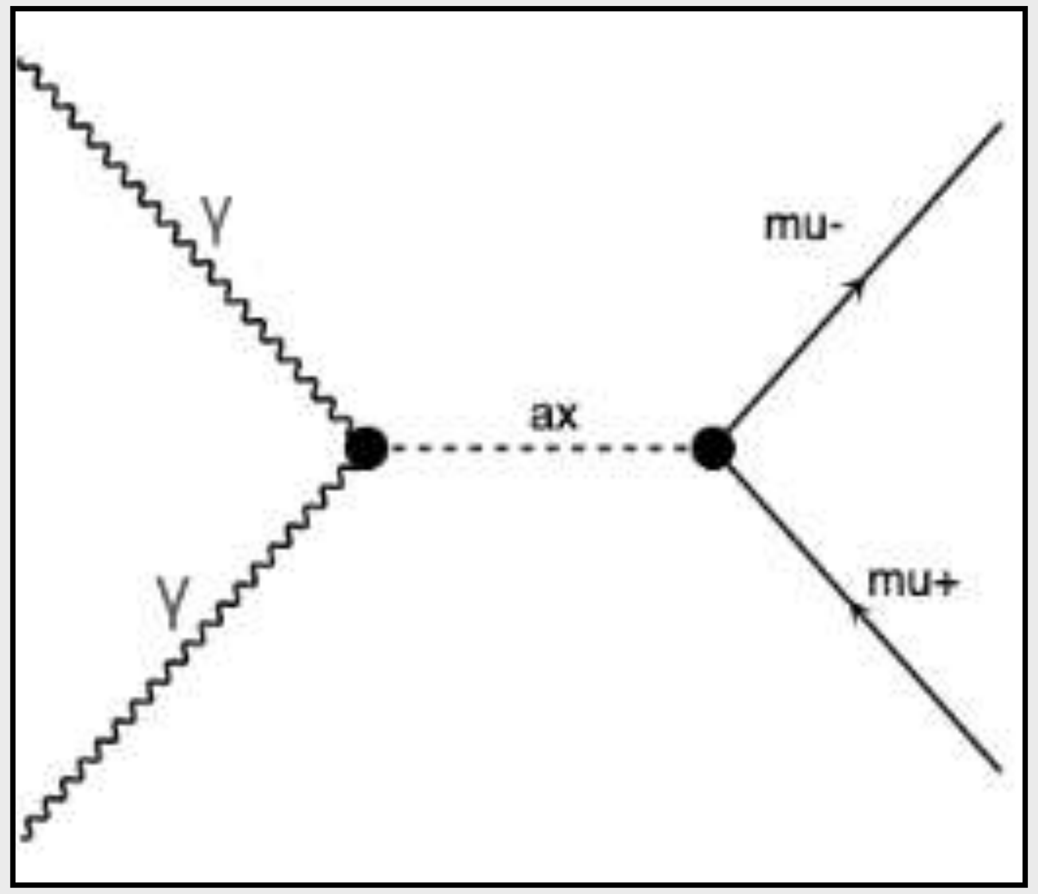
Why the UPCs?

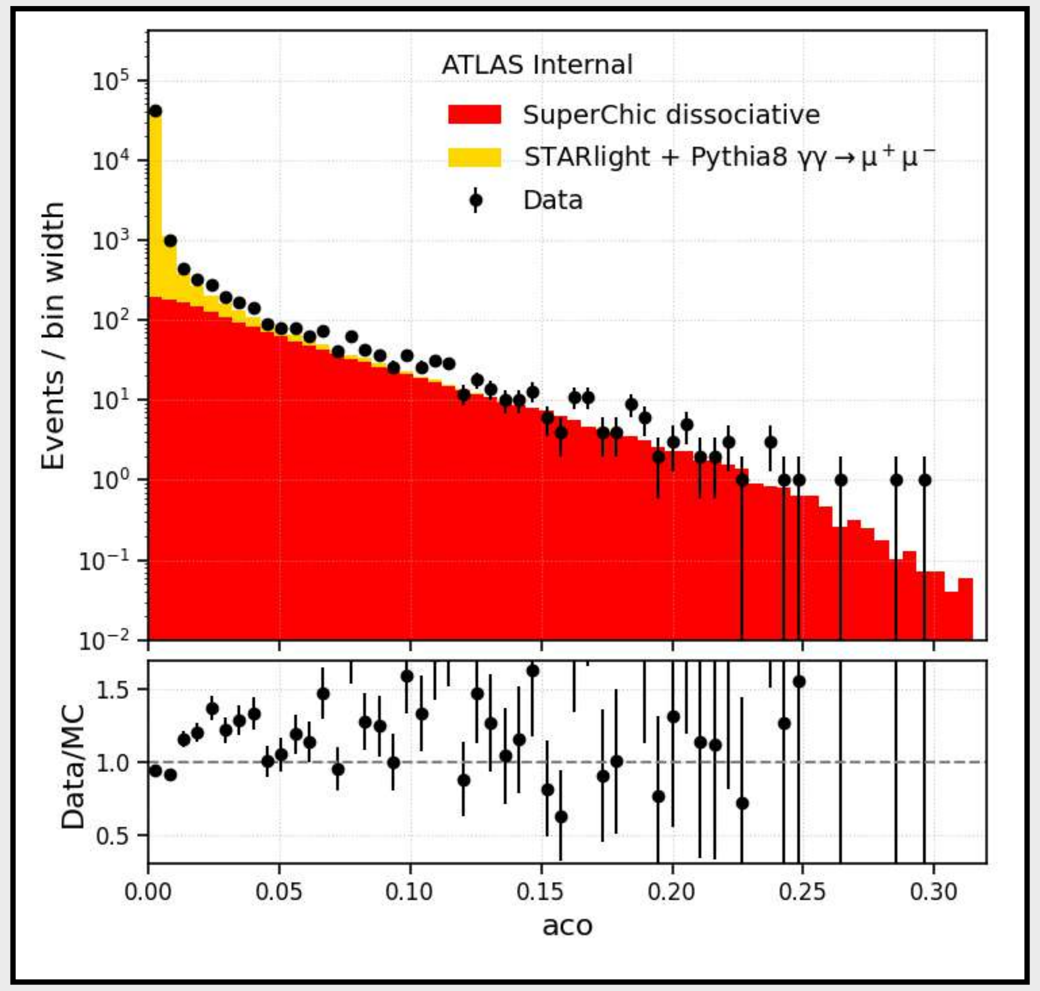
- I was brought into the **heavy ion (+ exotics)** analysis to help a student from Poland (joint PhD AGH University of Kraków and University of Bologna).
- Actually, not the “usual” Pb-Pb analysis, but a study of UPCs:
  - Heavy nuclei at ultra-relativistic energies carry strong electromagnetic fields, which can be viewed as a flux of virtual (nearly real) photons - $N(\gamma) \propto Z^2$.
  - The impact parameter is usually required to be larger than the sum of the two nuclear radii.
  - Photo-nuclear interactions or **photon-photon** interactions can occur.
- Such interactions lead to photons with up to 100 GeV longitudinal boosts (@LHC energies) that can produce a wide variety of exclusive final states: dileptons, dijets, and diphotons.
- Very **low background** and almost **perfectly balanced** in the transverse direction.

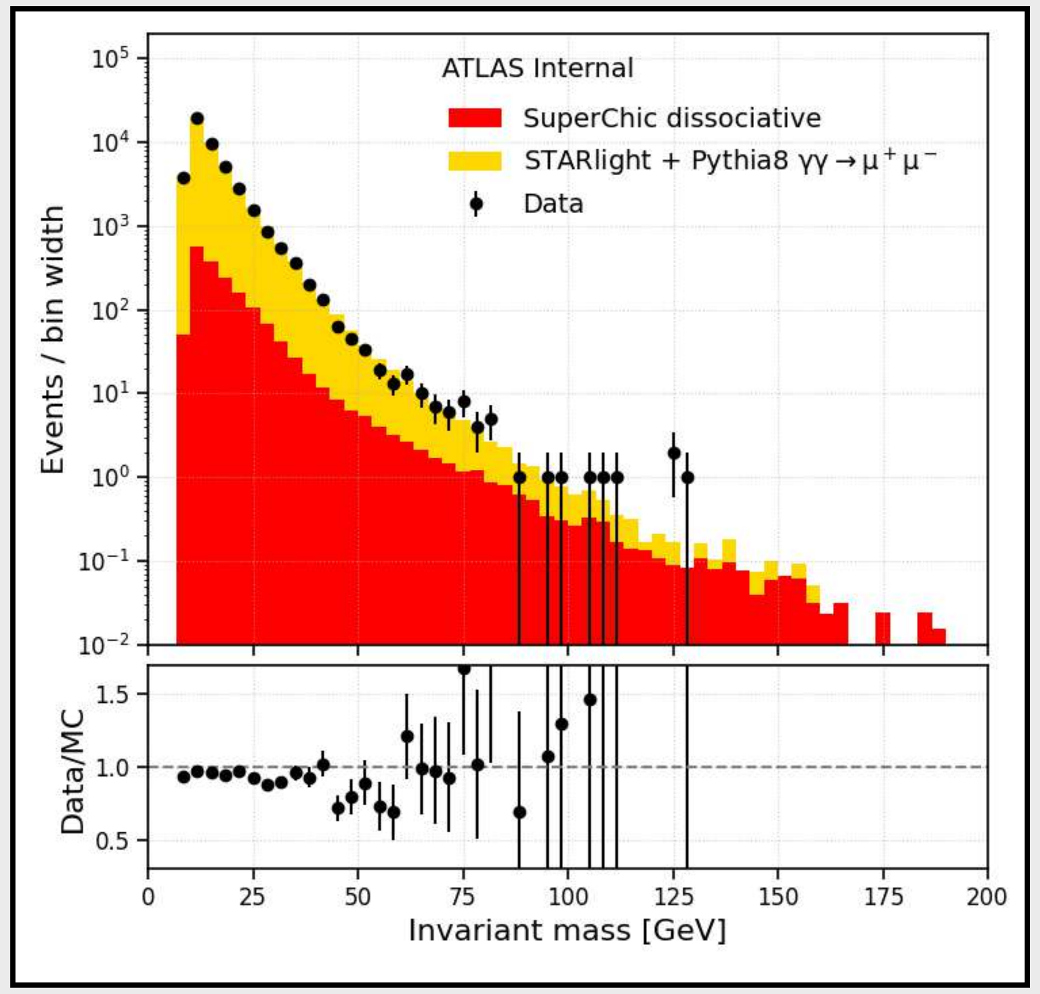


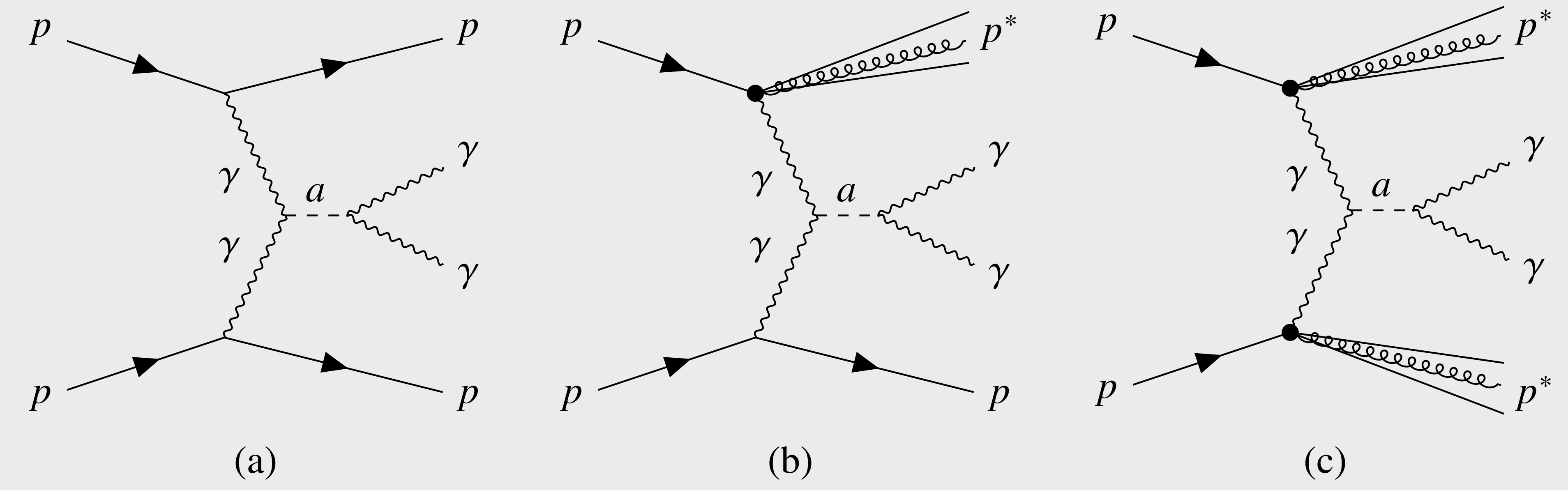
Why the ALPs?

- The student already contributed to the $\gamma\gamma \rightarrow \mu^+\mu^-$ analysis (HION-2016-02) in the past, + she landed in the Exotics group in Bologna:
  - ➡ Study the process $\gamma\gamma \rightarrow a \rightarrow \mu^+\mu^-$, where a is the ALP.
- We are searching for the resonance in the dimuon invariant mass spectrum in the range from 6 GeV to 100 (200) GeV.
- $\gamma\gamma \rightarrow \mu^+\mu^-$ is now the main background, with some contribution of the single- and double-dissociative LbyL scattering*.





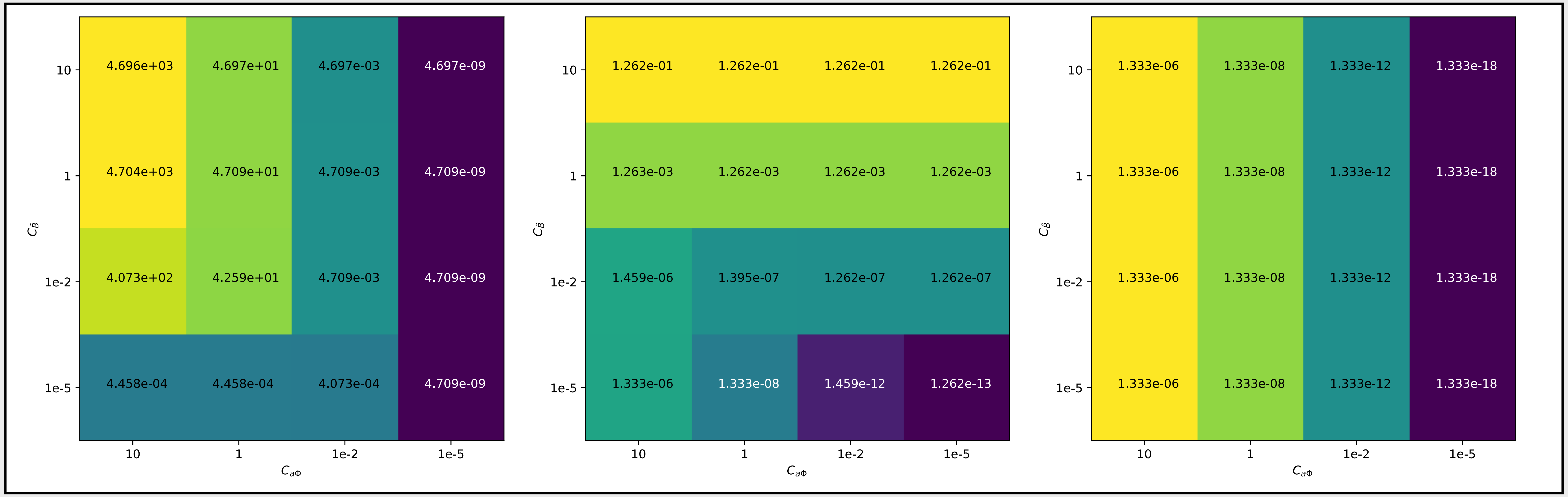




a) exclusive light-by-light scattering, b) single-dissociative (SD) light-by-light scattering, c) double-dissociative (DD) light-by-light scattering.

My feasibility studies

- We were studying different coupling parameters that would give us “observable” cross-sections.
- Displacement could be the key!

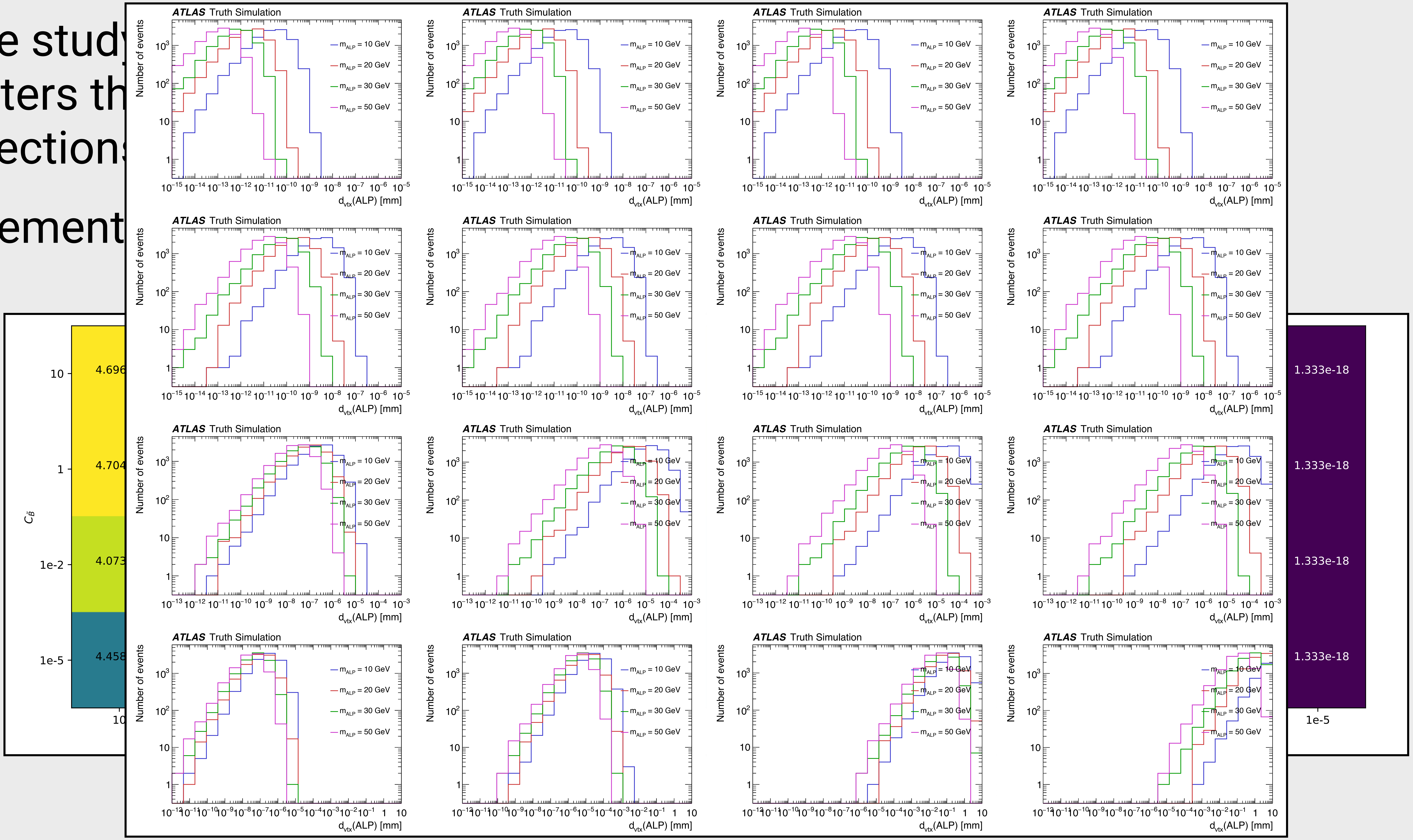


Cross sections [pb], widths [GeV] and partial widths [GeV] as a function of $C_{a\Phi}$ and $C_{\tilde{B}}$ for m_{ALP} = 20 GeV

My feasibility studies

- We were study
parameters th
cross-section

- Displacement



My feasibility studies

- We w
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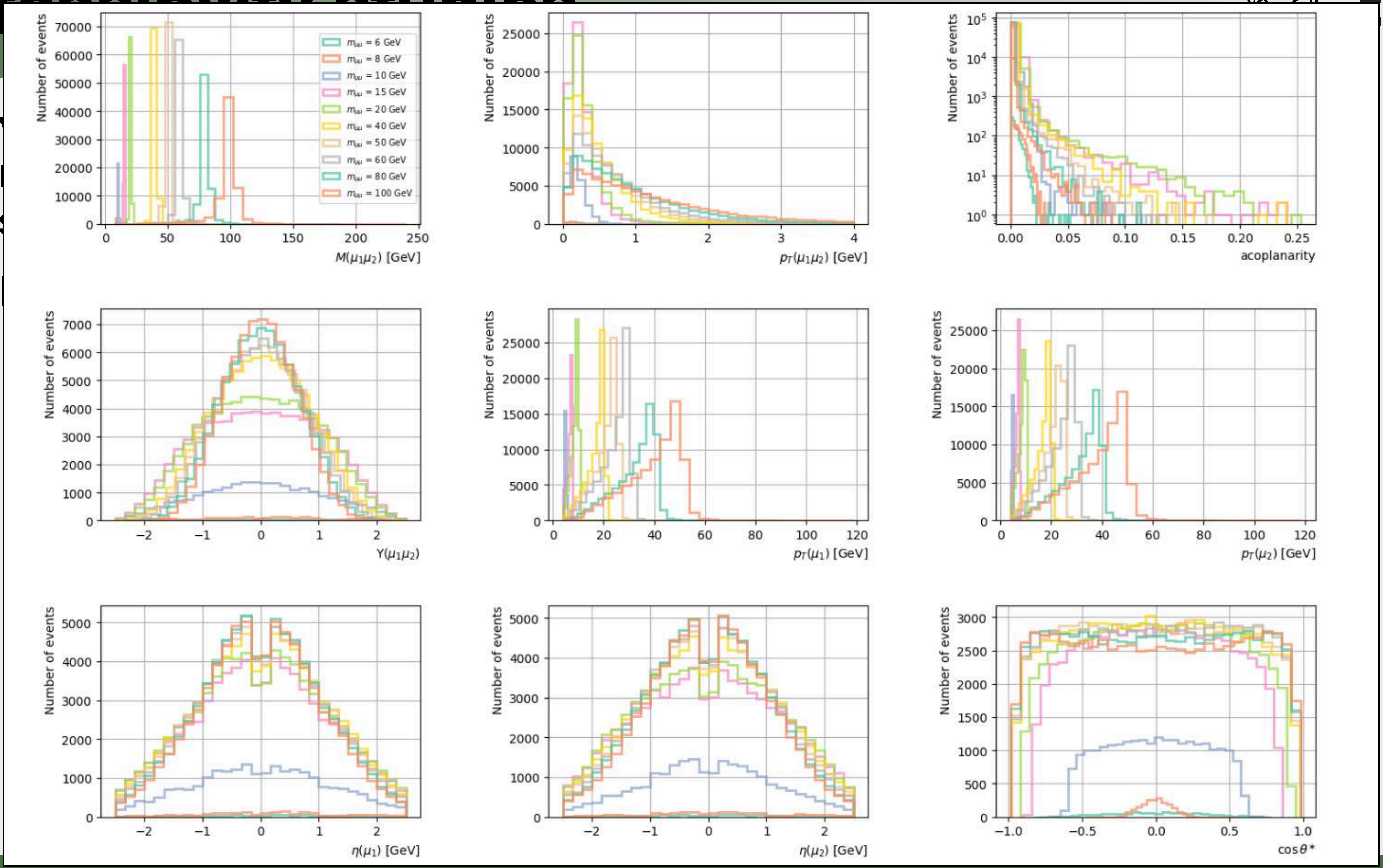
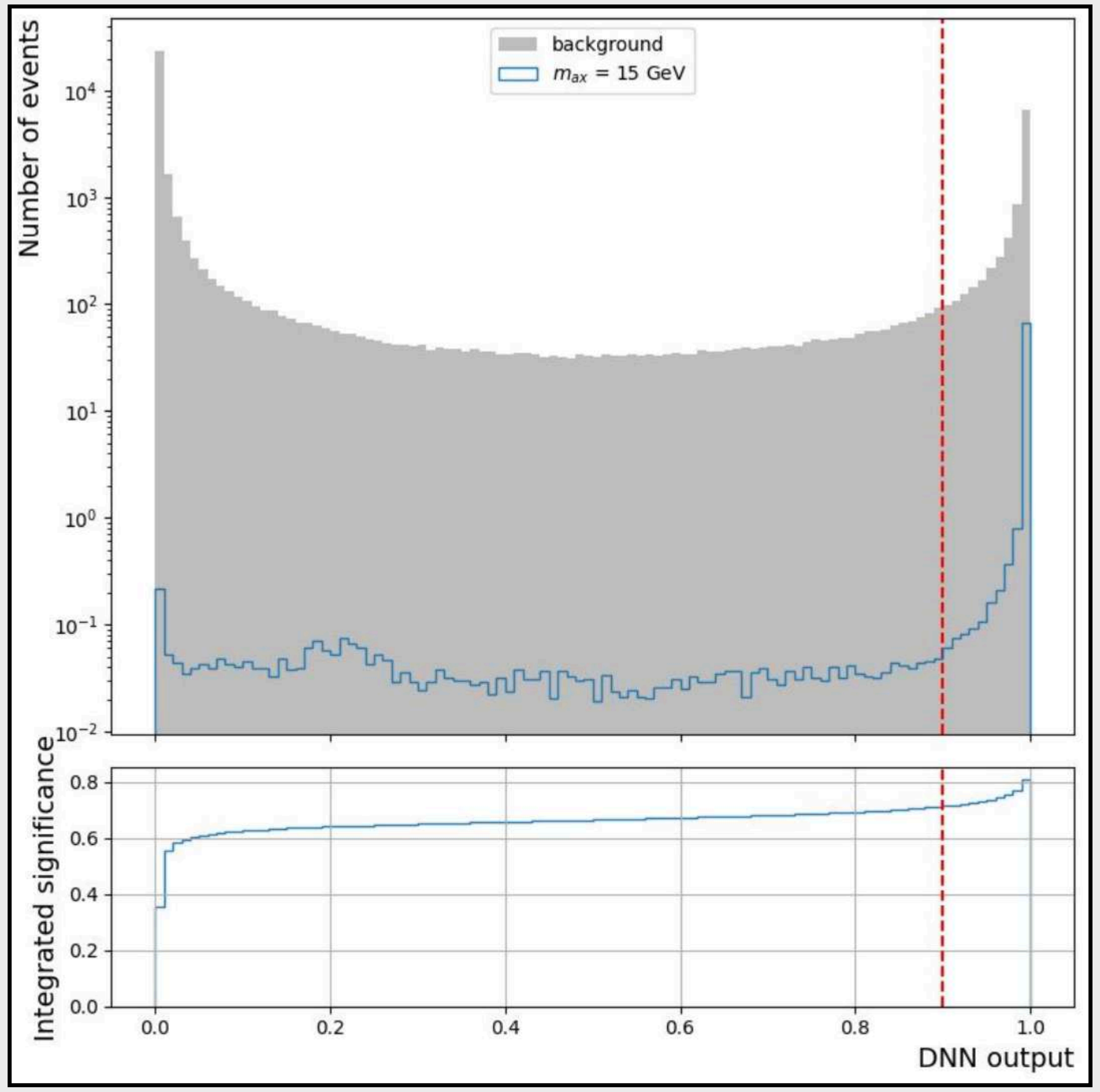
- Displ



Analysis status

- Currently working on parametrised neural network inference and optimising selection.
- Gaussian Process Regression is planned to model the background in the di-muon invariant mass spectrum and then look for the bumps.
- The significance seems to be the highest somewhere in the middle of the invariant mass search window (~50 GeV):
  - **Low mass regime:** High background + preselection cuts
  - **High mass regime:** Tiny cross-sections



- My contributions include developing the “truth” framework (producing and validating the MC samples, as well as preselection optimisation) and the ML infrastructure.

Other work-related activities I

- “BSM Searches Summary” talk at [XVII ATLAS Italia Workshop]() in Rome, and
- “Exotics Run-3 opportunities: new tools and methods” talk at [ATLAS Exotics workshop](), which we also organised in October 2024 in Bologna.

Other work-related activities II

- Helped at the "**Art & Science across Italy**" outreach event in Ferrara.
- It is a project by INFN in collaboration with CERN that invites high school students to create **artworks inspired by scientific topics**.
- Works are exhibited regionally, and winners proceed to a national competition. The best are given the opportunity to **visit CERN** or INFN labs.

Life in Italy 🇮🇹🍝

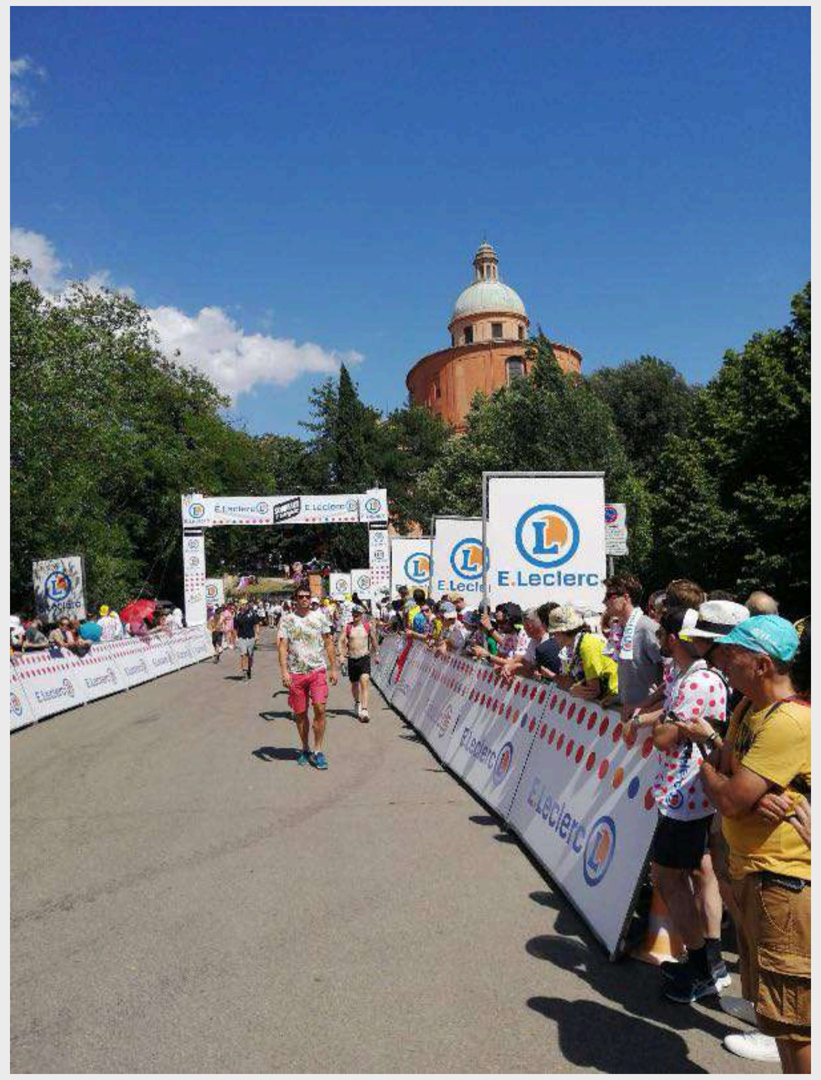
A lot of food

A lot of cycling 🚴

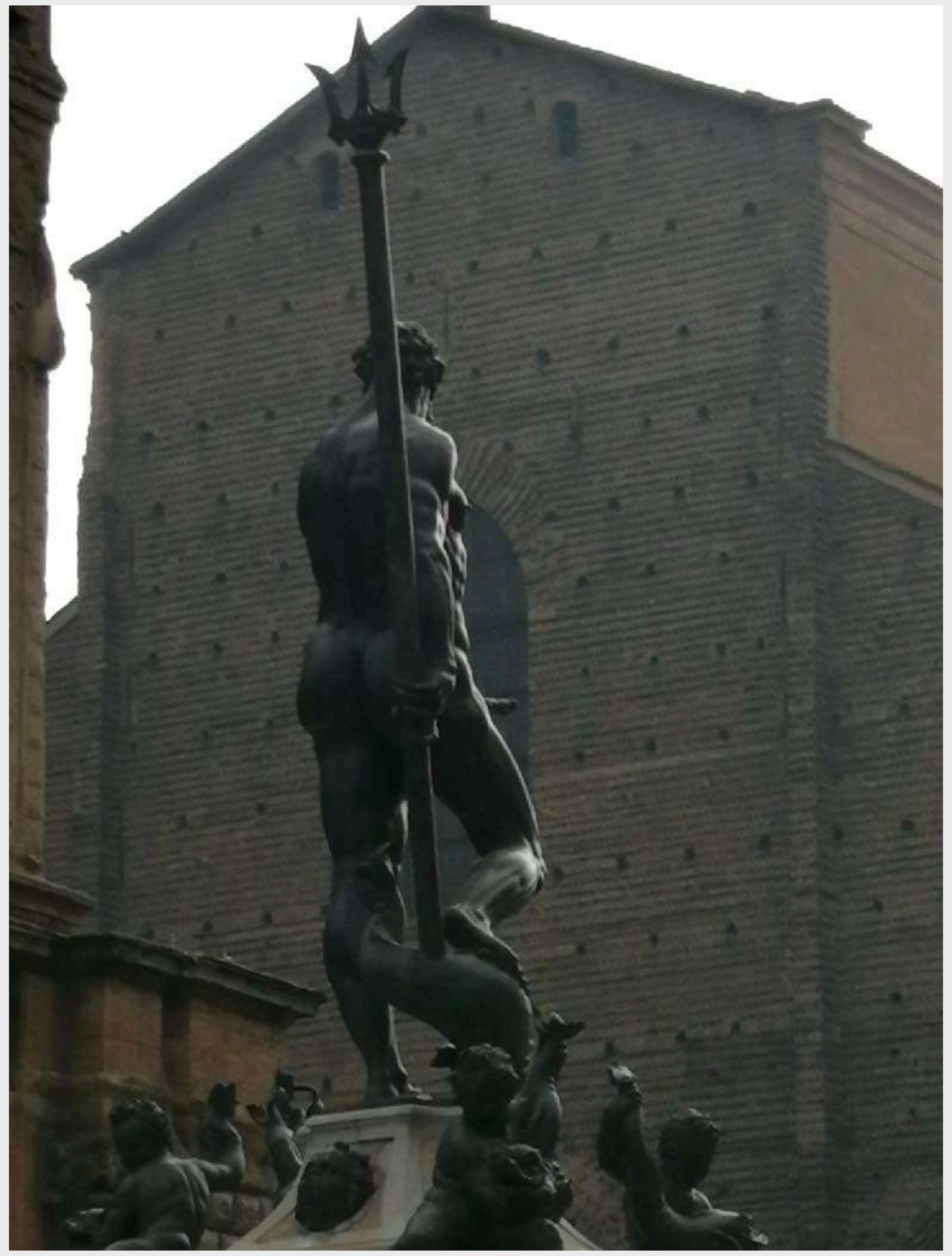
ATLAS EXPERIMENT IJS

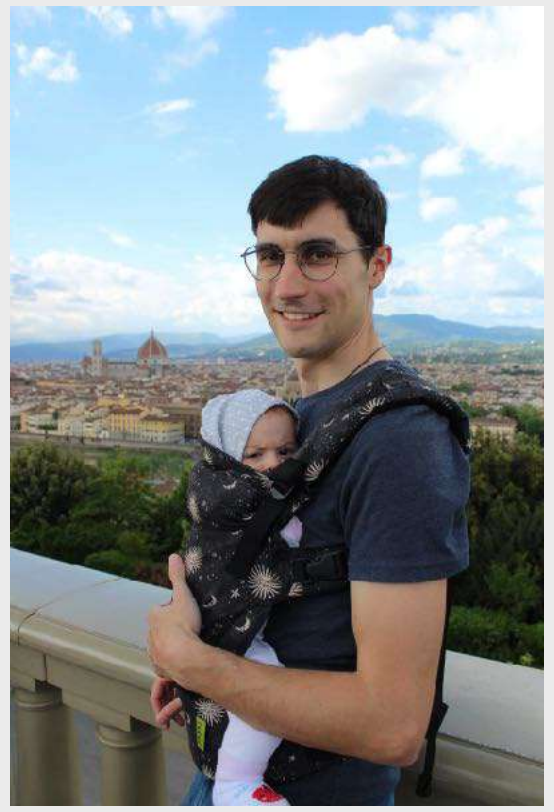
- Strade Bianche (Siena) 🏆 T. P. 🇸🇮
- Giro d'Italia (Monte Grappa stage) 🏆 T. P. 🇸🇮
- Tour the France (Bologna stage) 🏆 K. V. 🇫🇷
- Giro dell'Emilia (Bologna) 🏆 T. P. 🇸🇮

➡ 75% win efficiency 😜

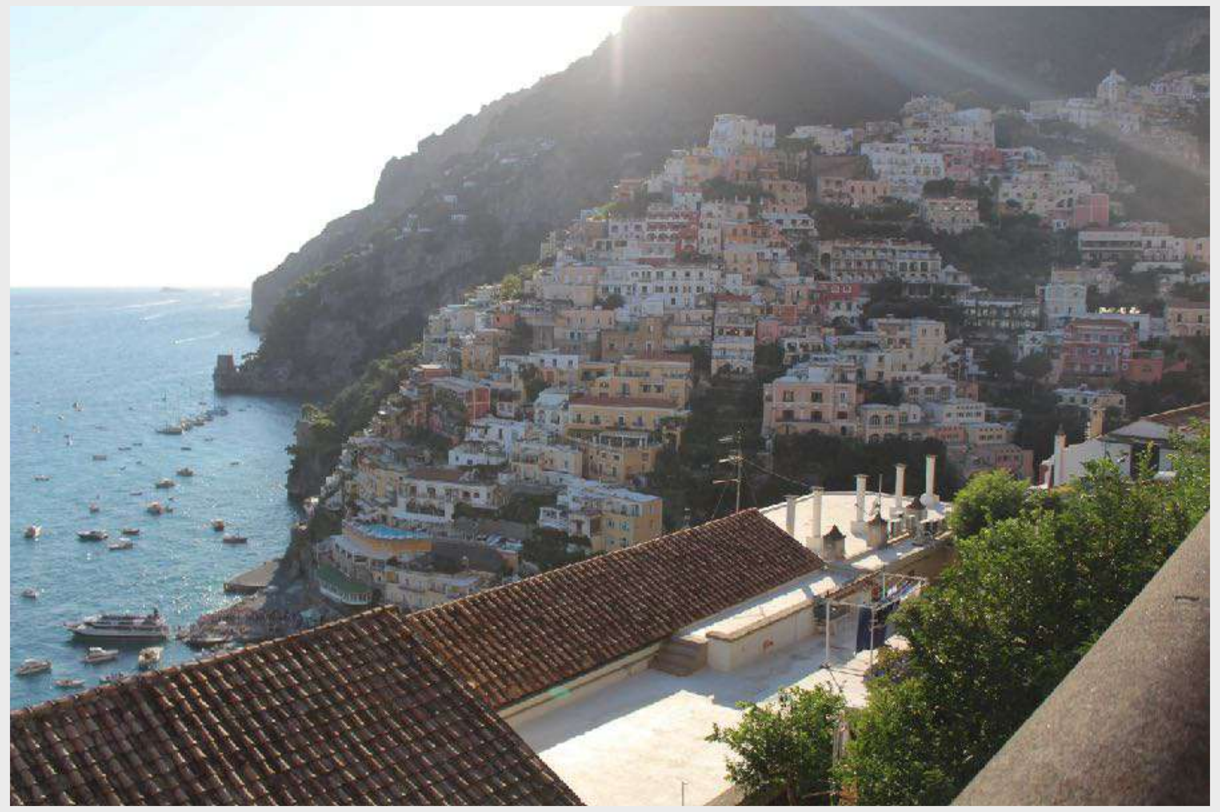


Much to see 👀



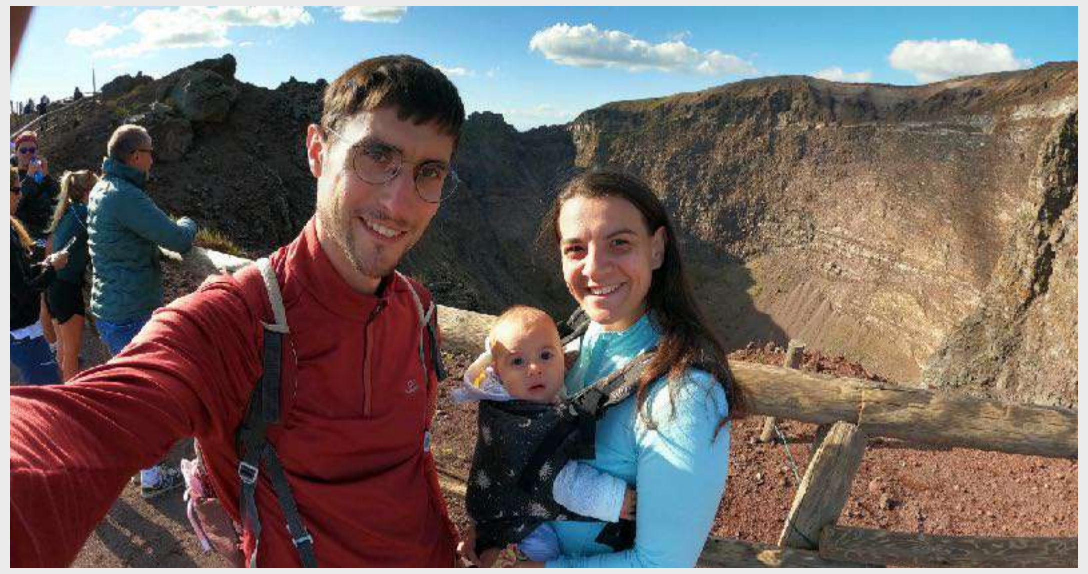


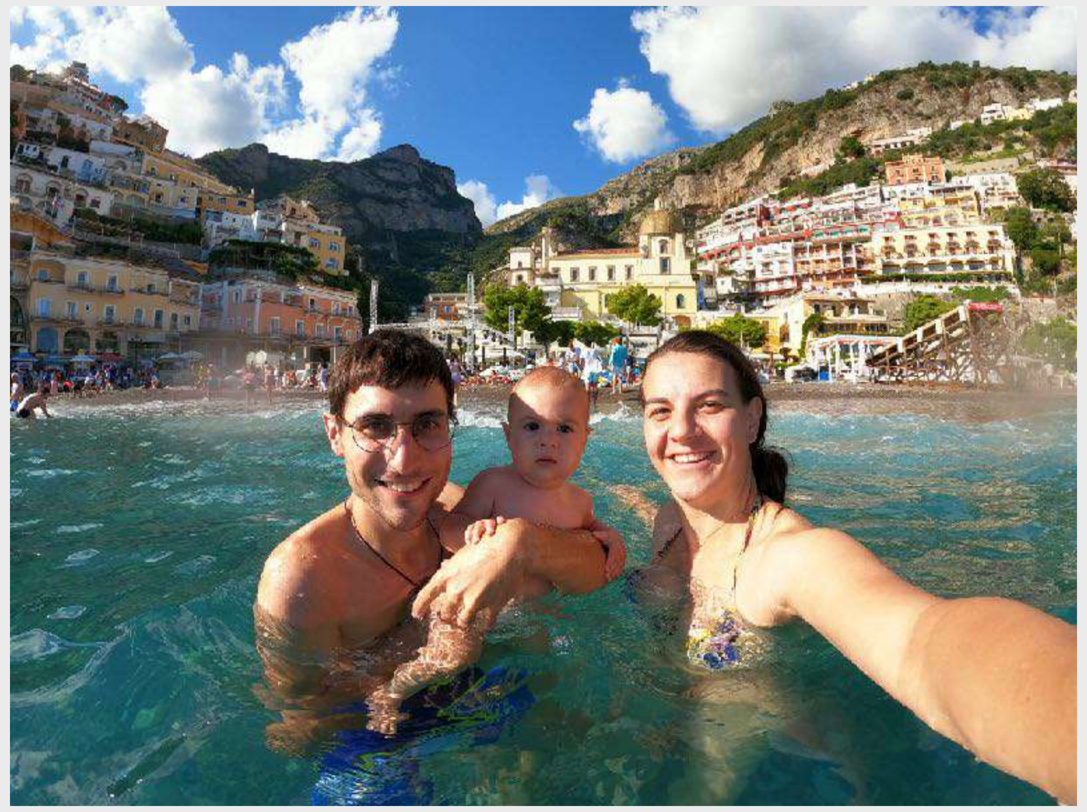
Much to see





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