Designing collider analyses and reinterpreting the results of the LHC

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Outline

1. Introduction

2. Designing a phenomenological analysis at colliders

3. LHC recasting

4. Summary

New physics at the LHC

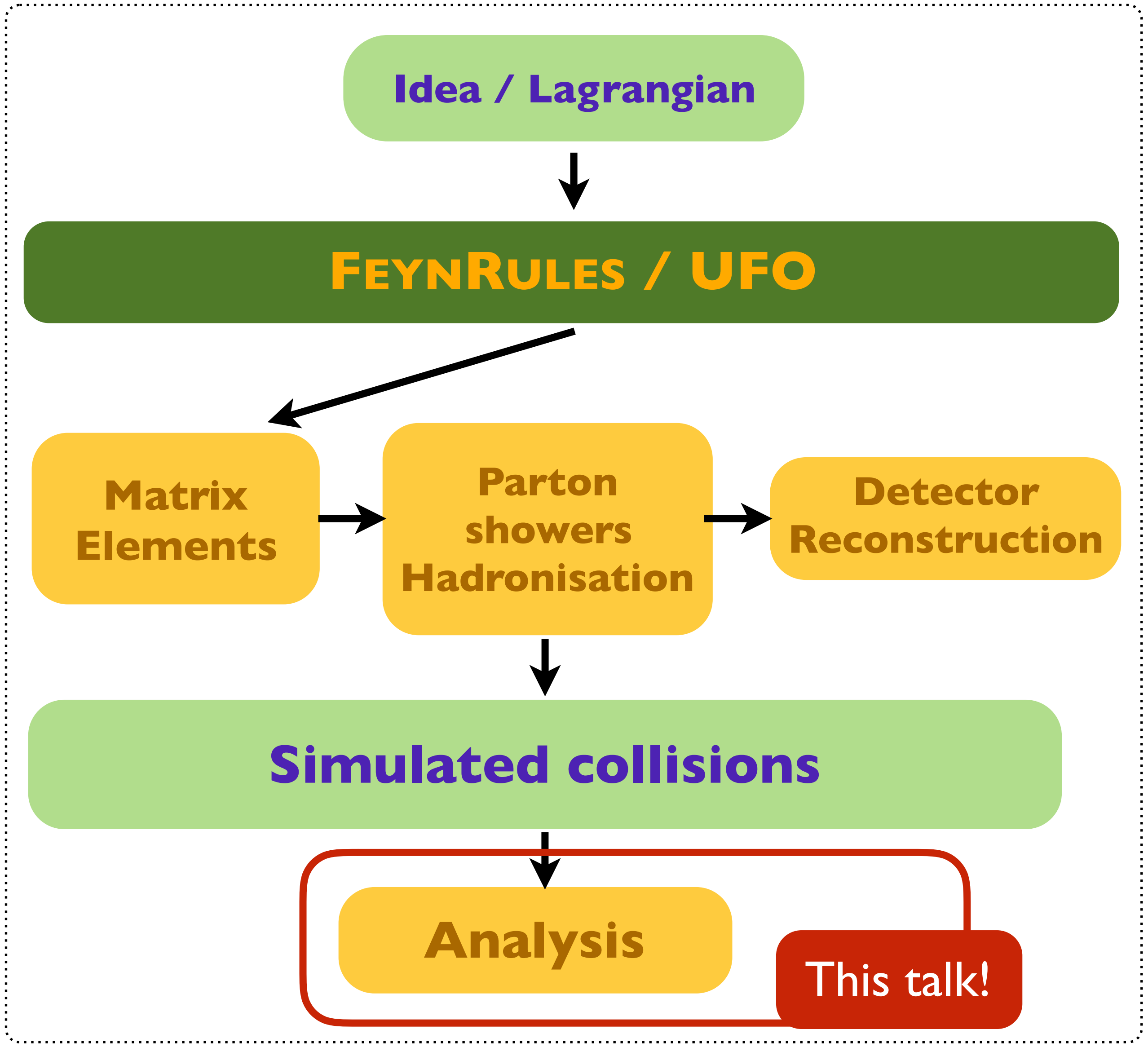
- ✦ Path towards the characterisation of new physics
  - ✤ Fitting and interpreting deviations
  - ✤ Predictions of associated signatures/signals
    - → Monte Carlo simulations play a key role
- ✦ Final words on any potential new physics at the LHC
  - ✤ Accurate measurements ⊕ precision predictions (NLO QCD + PS)
    - → Monte Carlo simulations play a key role

- ✦ More on the new physics nature at the LHC
  - ✤ Fitting deviations by new physics signals
    - → Reinterpretation of LHC results (confronting models to data)
  - ✤ Designing new analyses to probe new ideas
    - → from signal and background predictions

Making new physics a standard

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]

✦ Tools connecting an idea to simulated collisions



- From Lagrangian to model files
  - ★ FEYNRULES
  - ★ UFO
- Matrix element generation
  - ★ MG5_AMC → predictions at LO/NLO
- Parton showers / hadronisation
  - ★ PYTHIA
- Detector simulation
  - ★ DELPHES 3 / MADANALYSIS 5
- Event analysis
  - ★ MADANALYSIS 5

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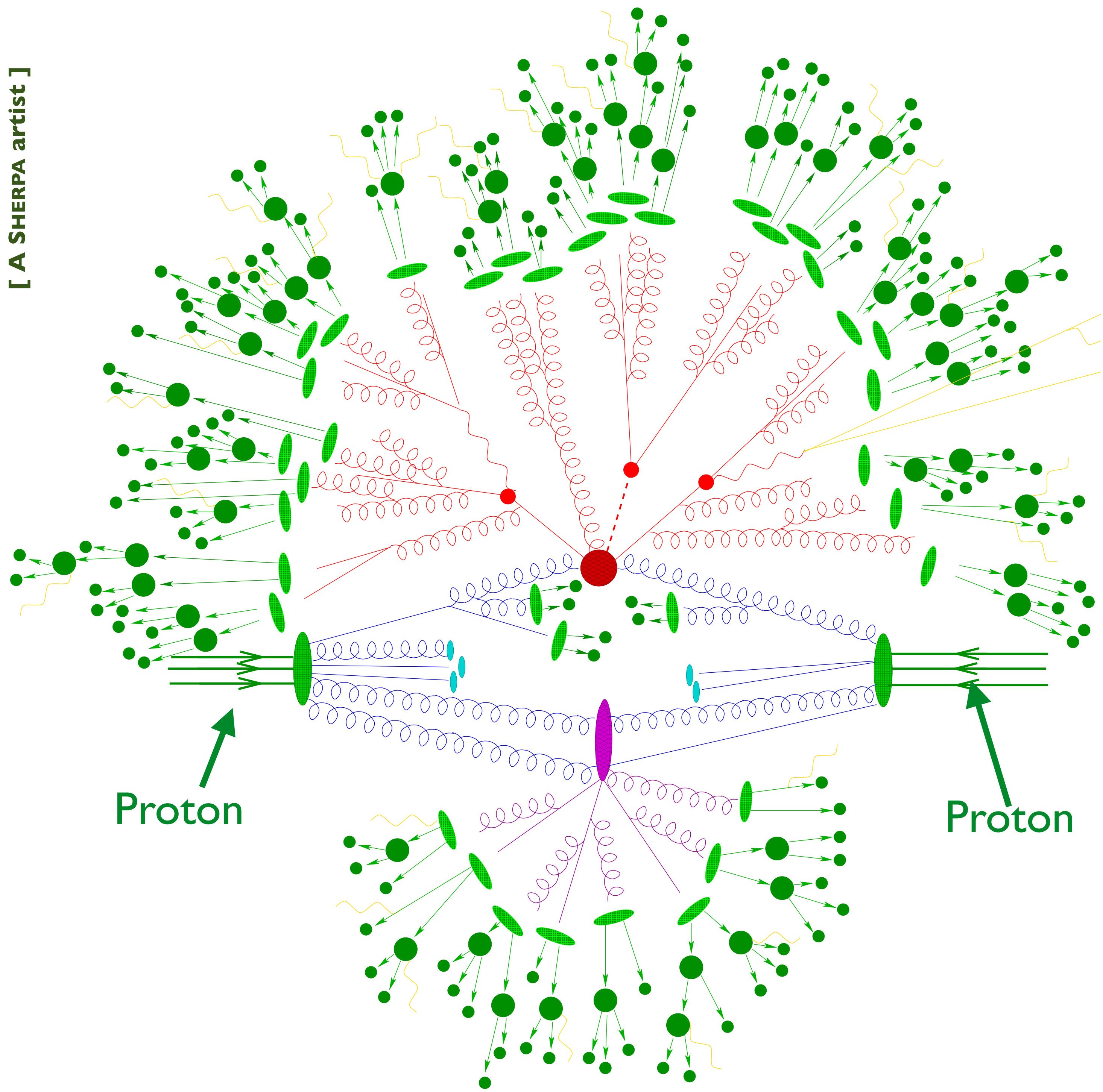

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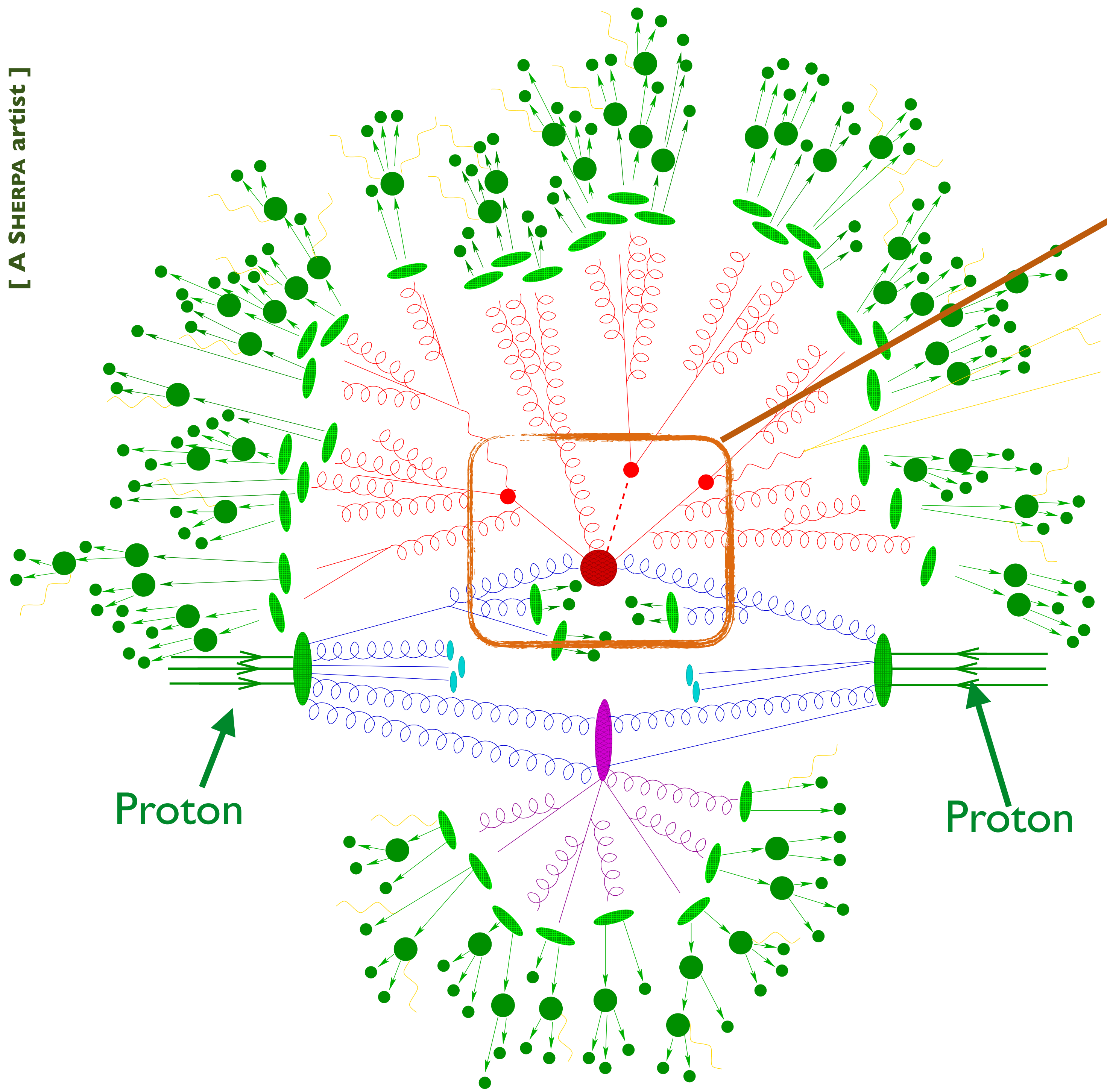

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  - ✤ Any final-state particle
  - ✤ BSM / SM

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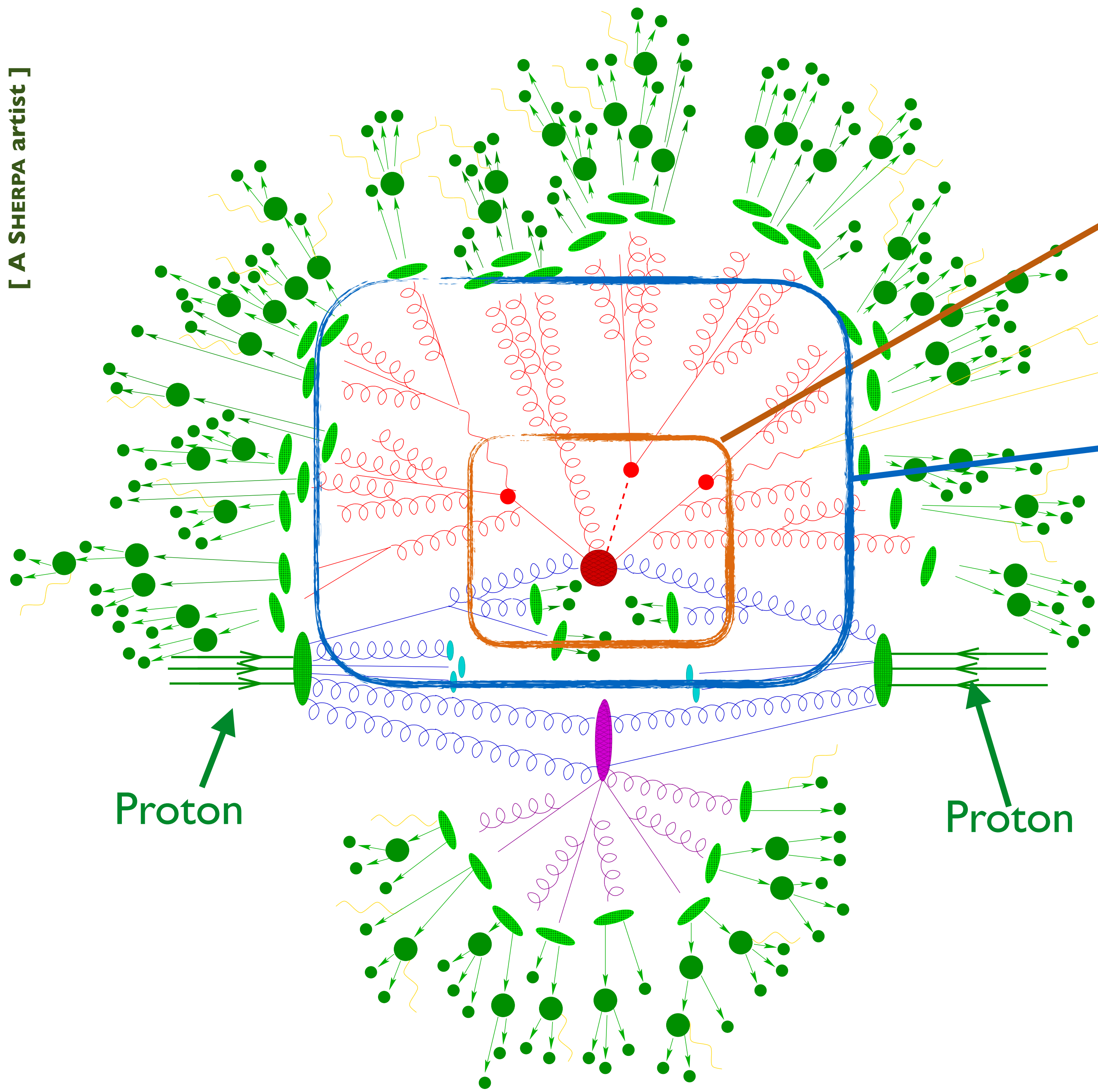

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- ✤ QCD partons
- ✤ Electrons, muons, photons
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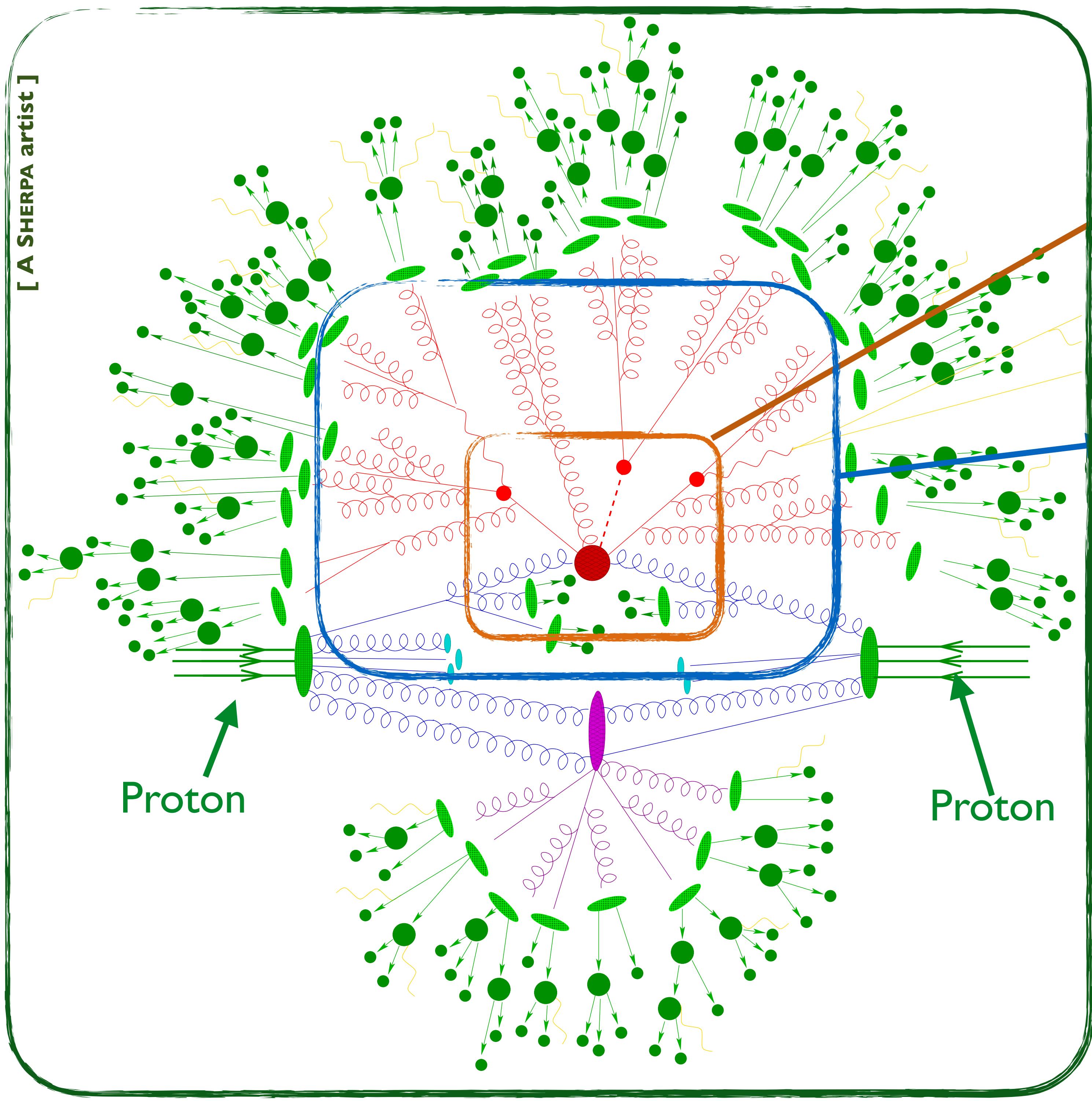

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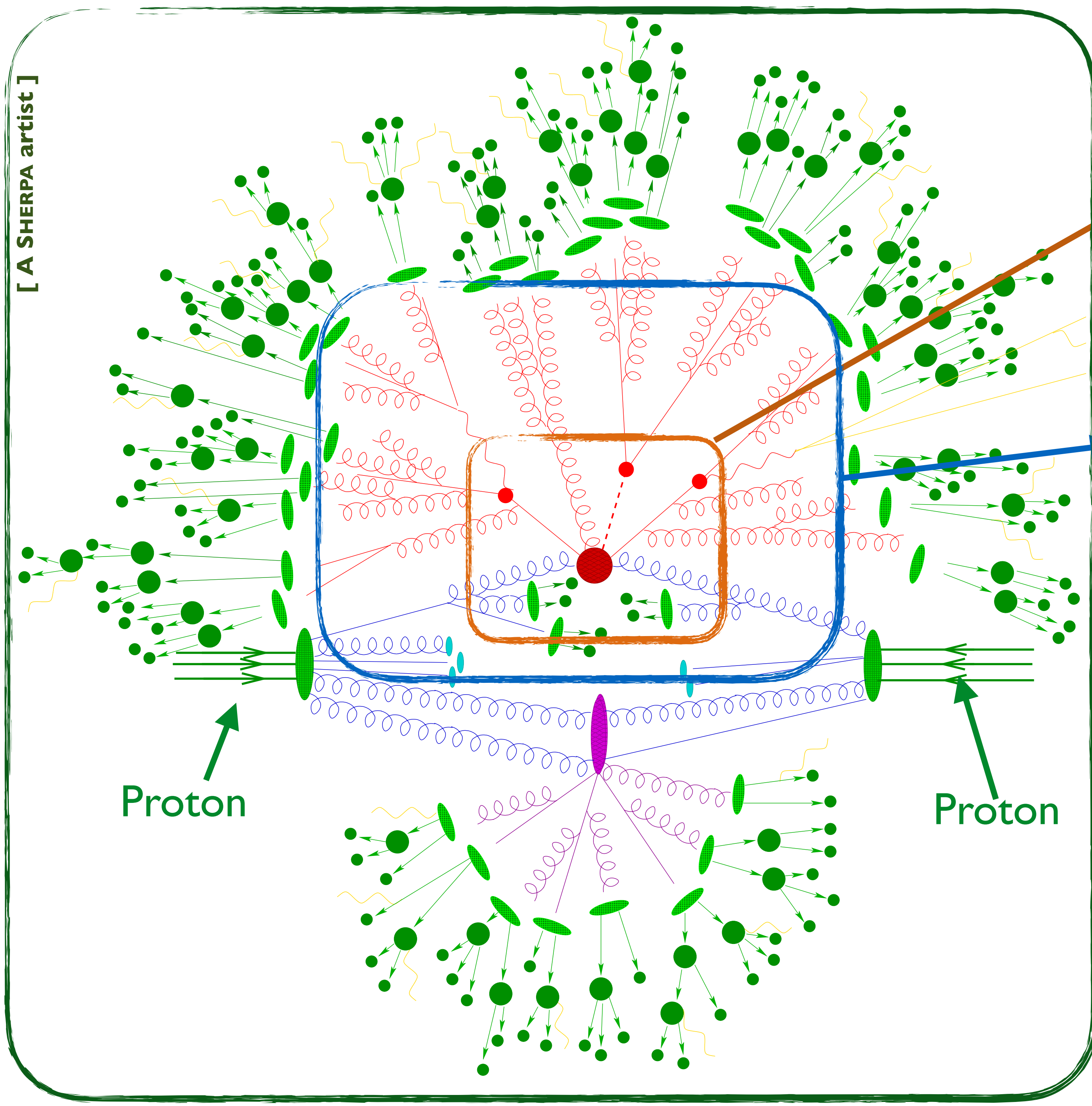

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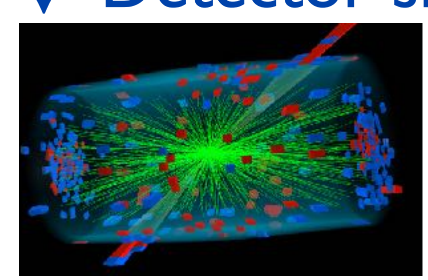
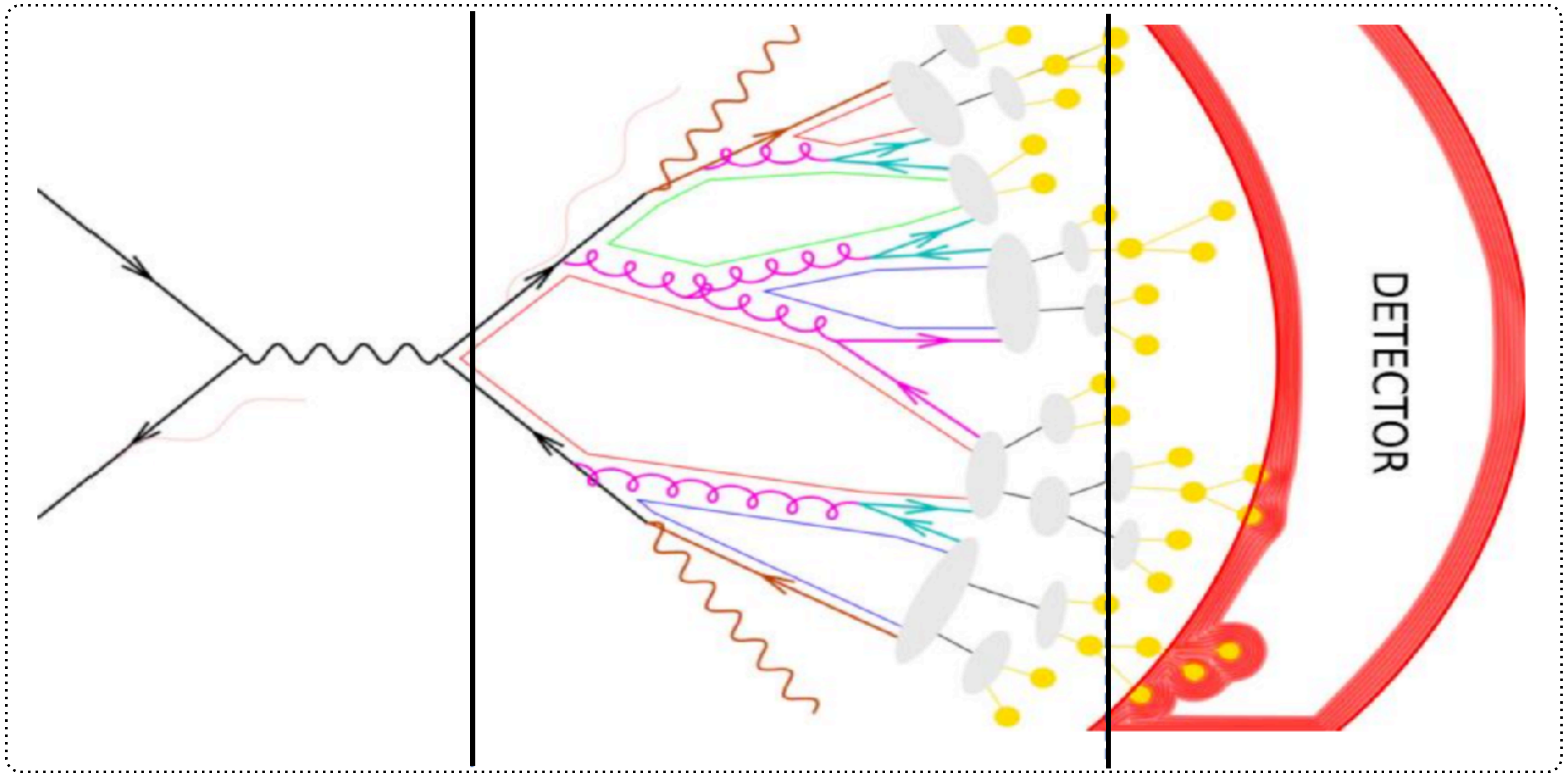


- ✤ Hits
- ✤ Tracks

Event reconstruction

✦ Object clustering (into a smaller number of objects)



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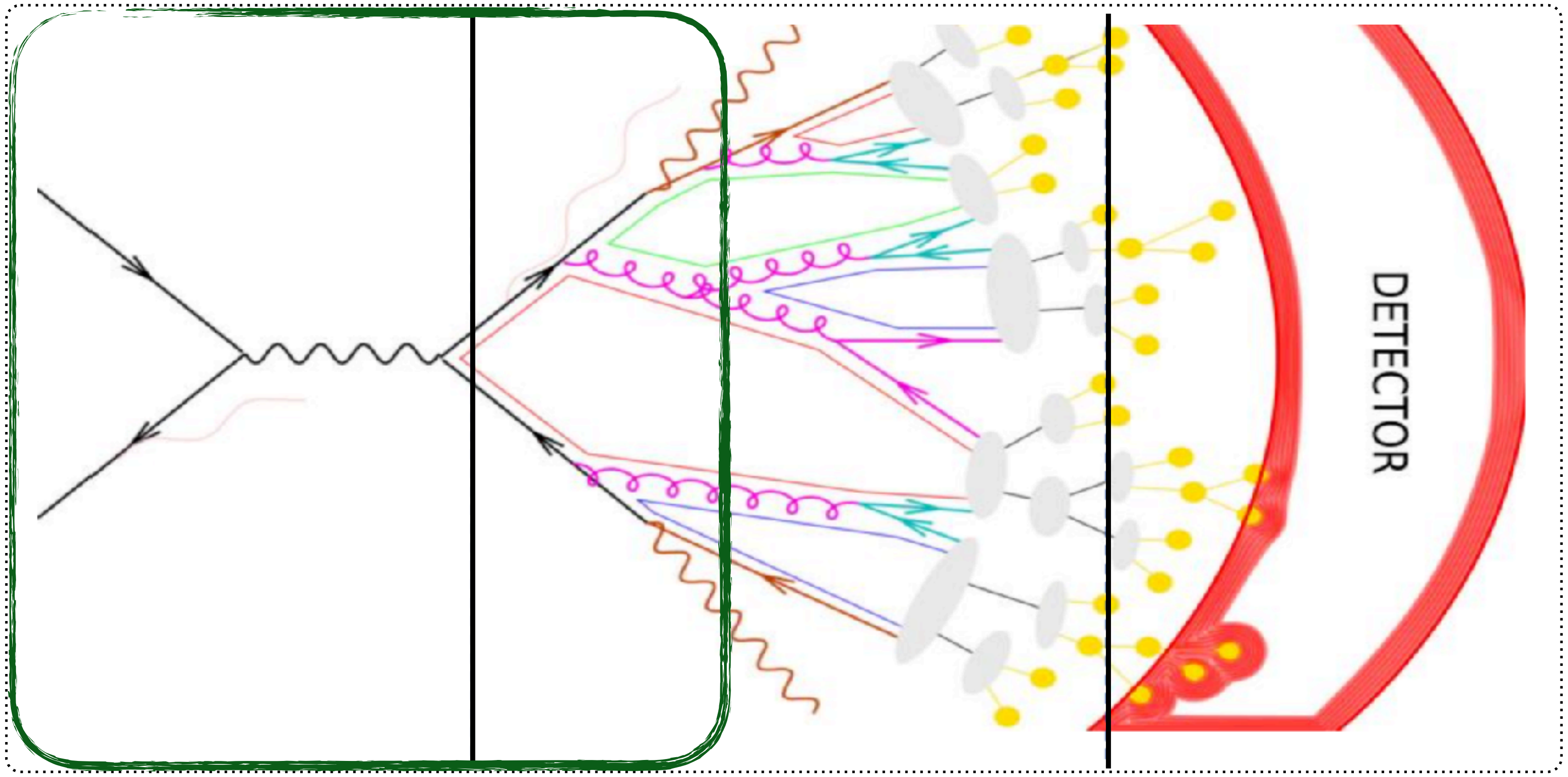

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  - → However possible
- ★ "Stable" tops, gluinos, *etc.*

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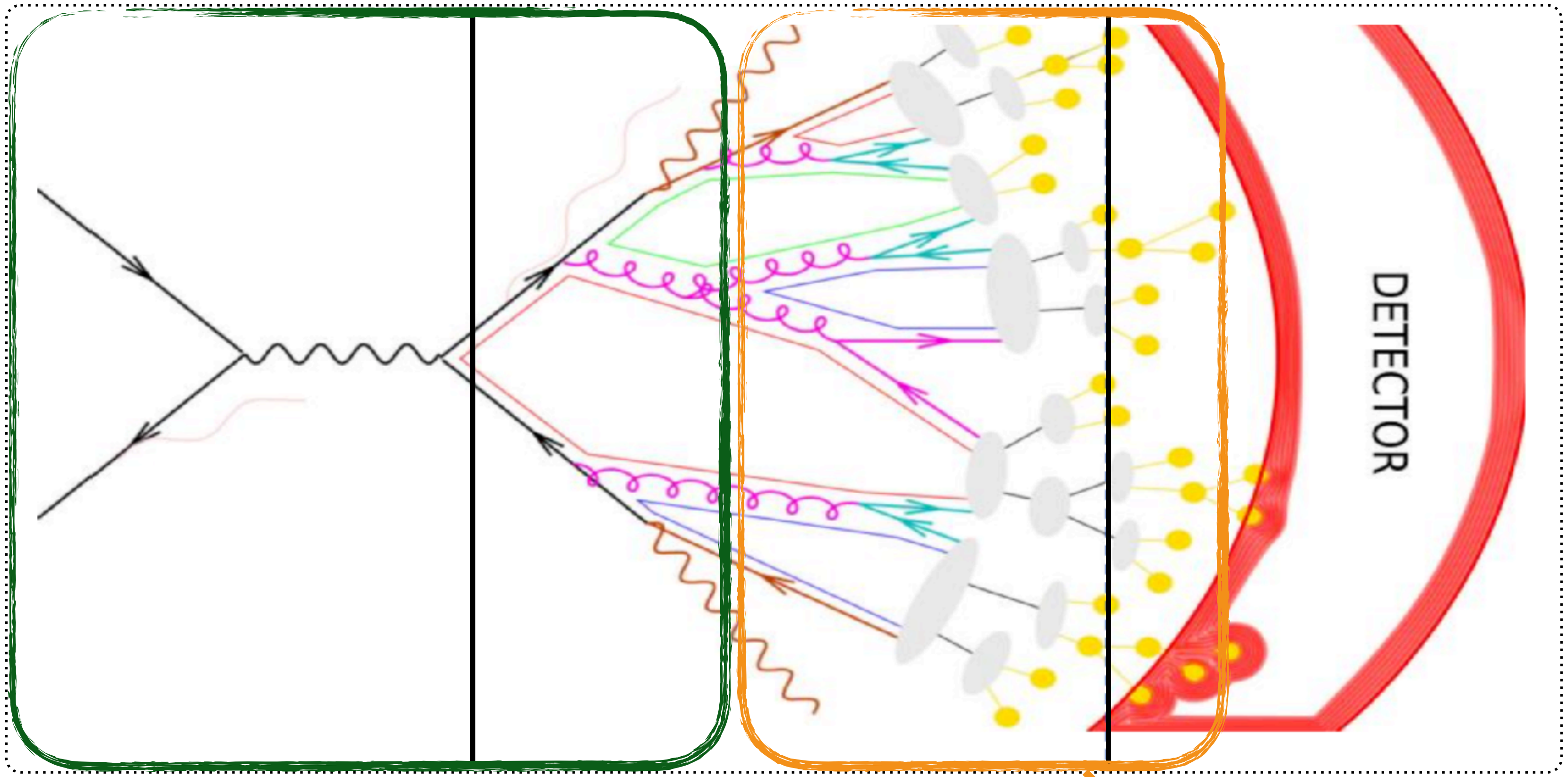

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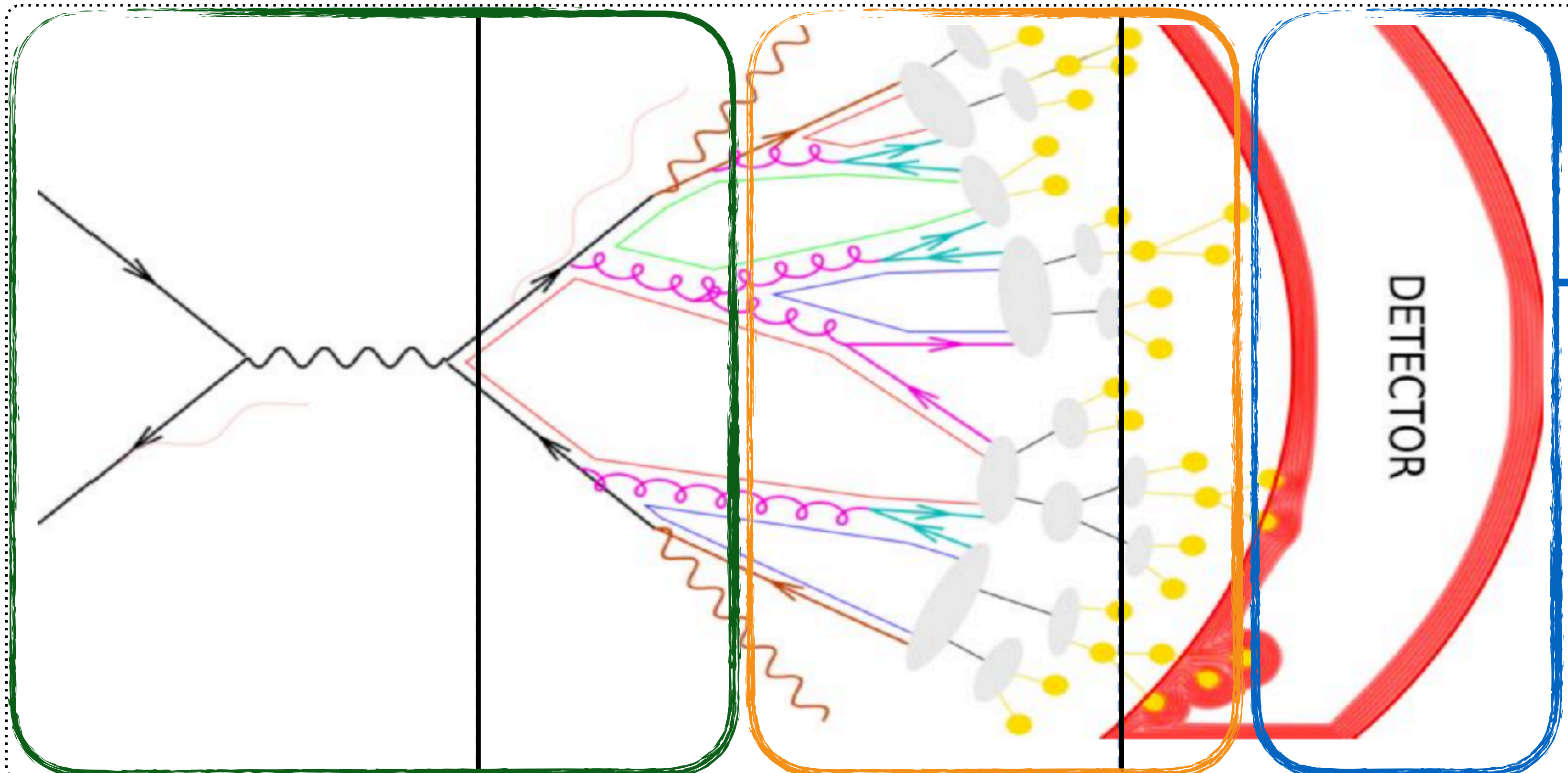

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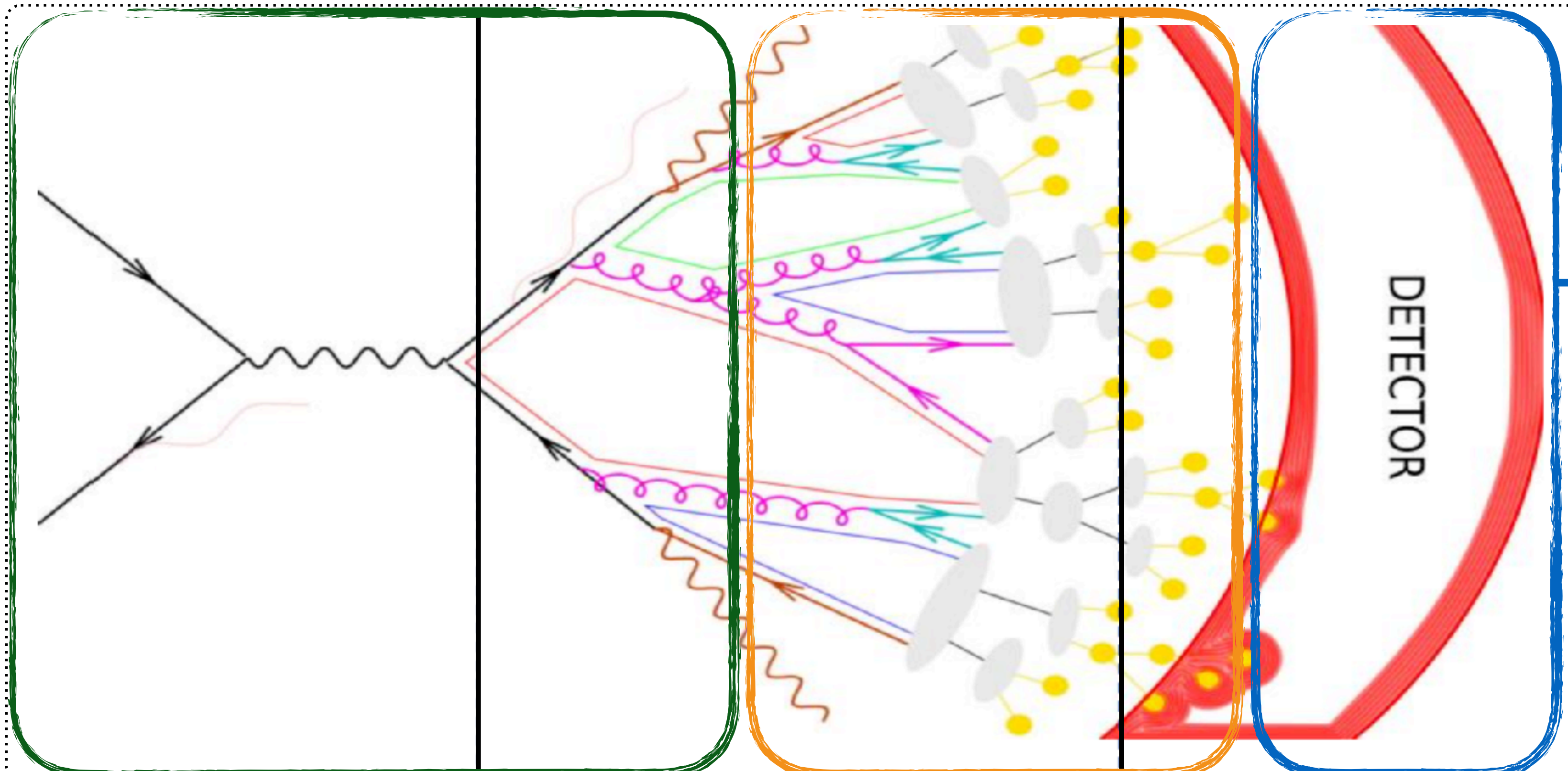

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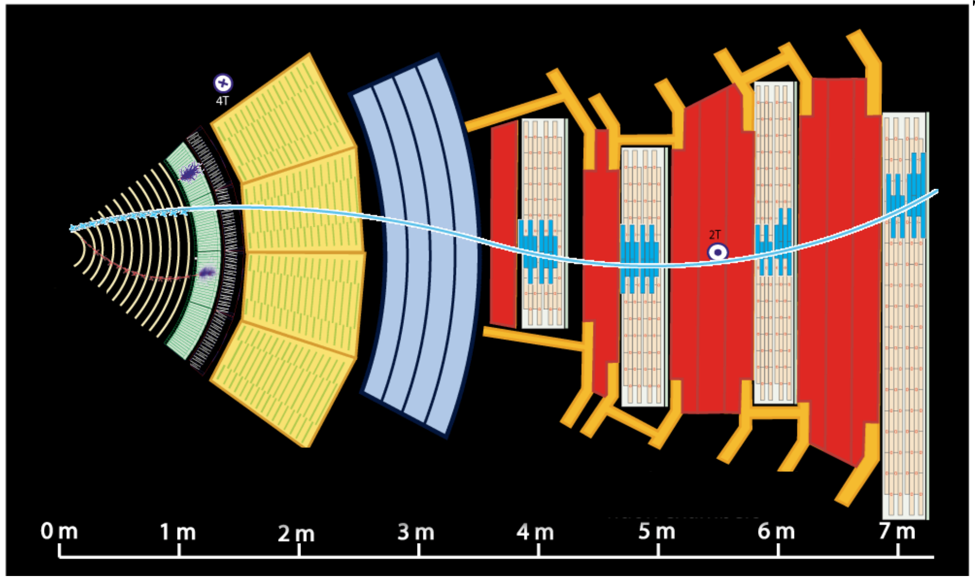
Reconstructed objects in a nutshell

- **Directly observable objects**
  - Truely stable: electrons, γ's
  - Stable on detector scales: muons
- **Other unstable particles**
  - Observable through decays
  - SM and BSM



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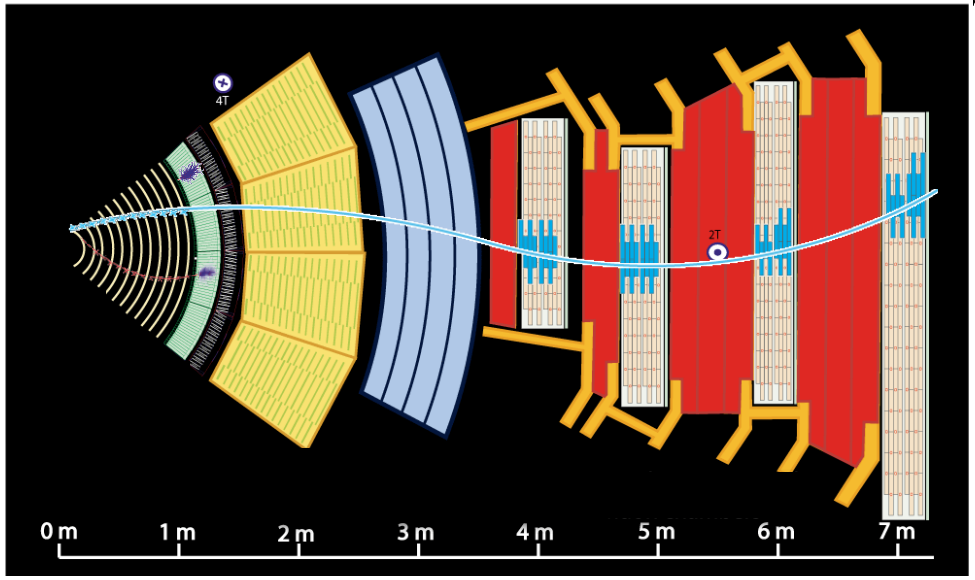

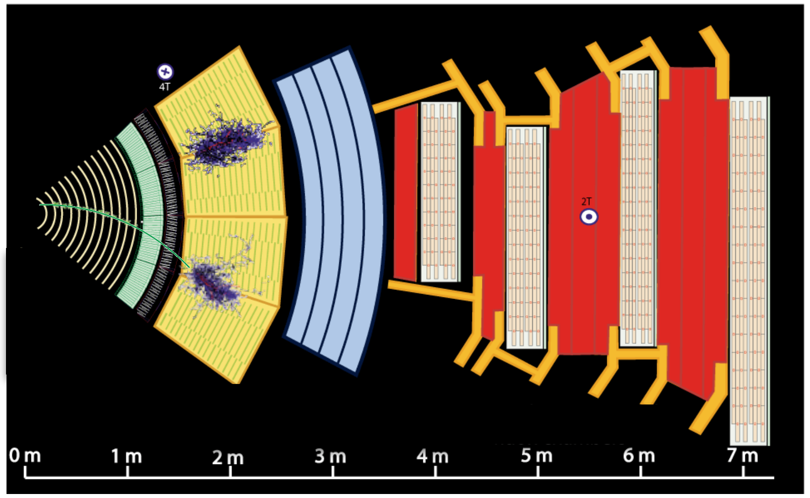

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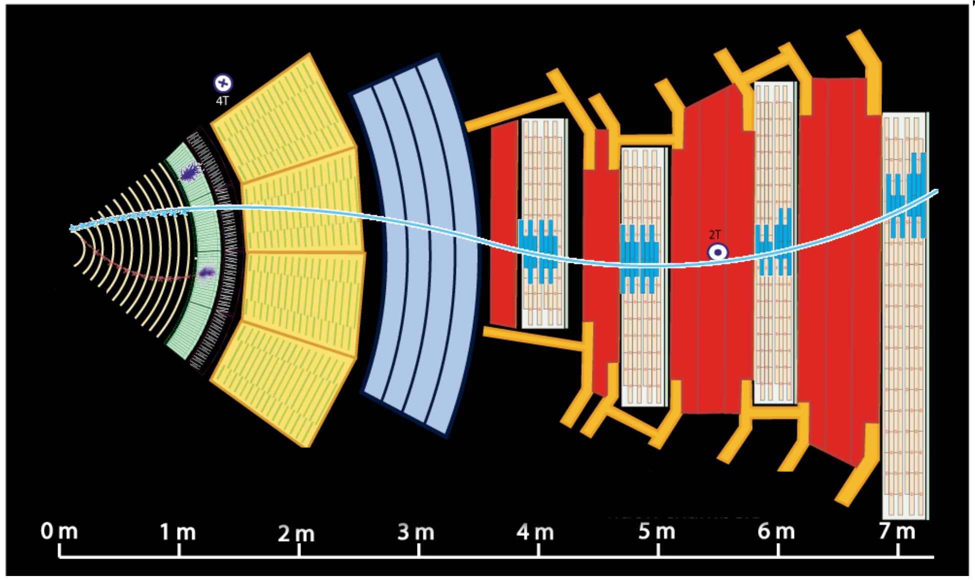

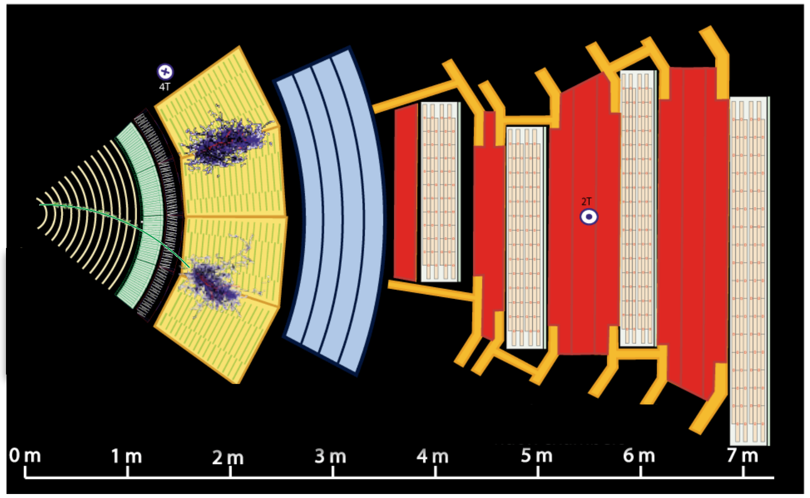

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- ✦ The invisible
  - ✤ Energy-momentum conservation
    - → reconstructing the invisible (neutrinos & more)

Designing an analysis

- ✦ Basic selection requirements
  - ✤ Good quality objects (→ proper reconstruction of the properties)
  - ✤ Within the detector acceptance
- ✦ Analysis itself
  - ✤ Increase the signal/background ratio

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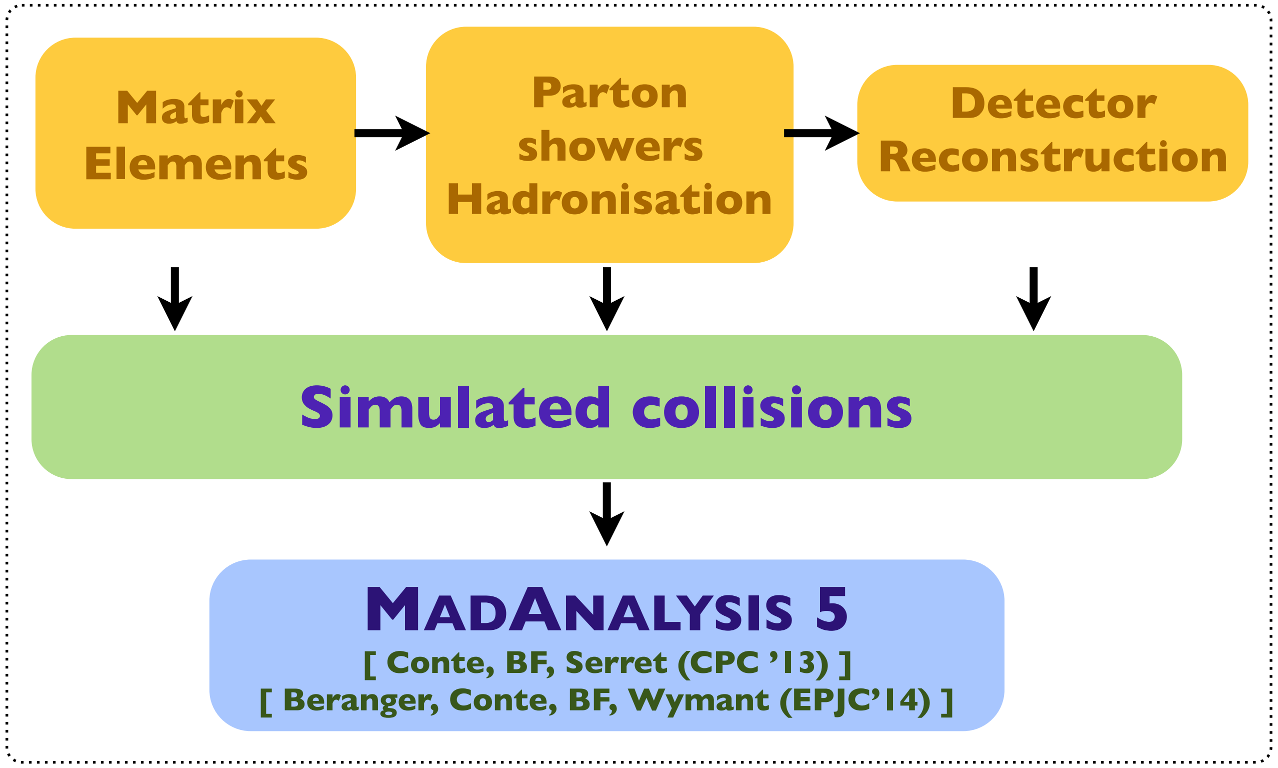
✦ Analysing events with MadAnalysis 5



- ✤ Collider physics made easy
- ✤ Intuitive commands
  → Python interface
- ✤ Analysis behind the scenes
  → C++ black box
- ✤ Human readable output

Toy event samples

✦ Setup (generator level)

- LHC collider at a center-of-mass energy of 13 TeV, 2.3 fb^{-1}
- No lepton cut (pseudorapidity, transverse momentum, *etc.*)
- Jet cuts: $p_T > 20$ GeV, $\Delta R_{jj} > 0.4$, no pseudorapidity cut

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- ✤ WW: two leptonic decays $W^+W^- \to (\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
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✦ NLO cross sections (LO generation, NLO normalisation)

- ✤ Top-antitop pairs ≈ 33 pb
- ✤ WW ≈ 4.2 pb
- ✤ ZZ ≈ 0.3 pb

Getting closer to a detector (at parton-level)

- ✦ We have not simulated any detector response
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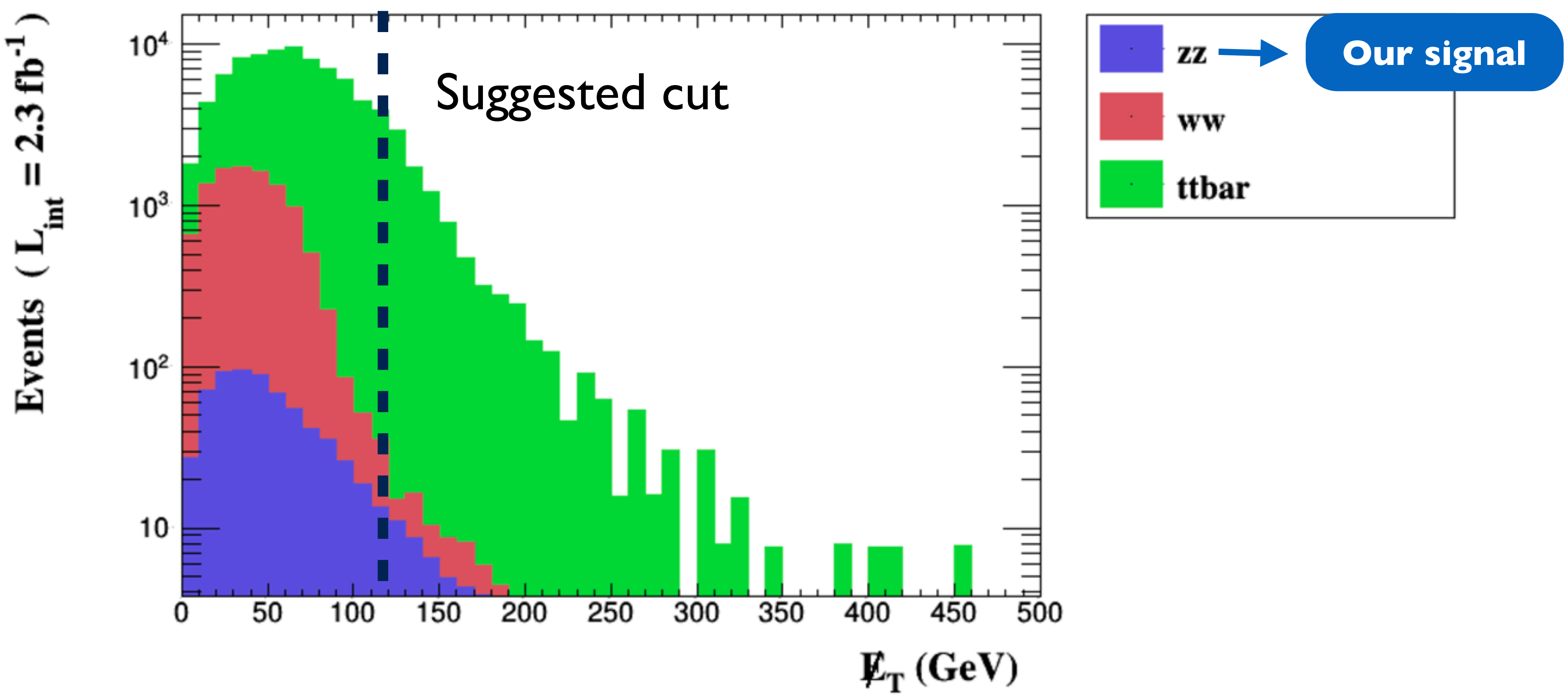
How to get the signal out of the background?

Some example: missing energy

✦ Missing energy distribution



✦ Statistics information for each histogram

Dataset	Integral	Entries / events	Mean	RMS	%Underflow	%Overflow
zz	690	1.0	57.9969	47.37	0.0	0.05
ww	9660	1.0	39.7918	21.81	0.0	0.0
ttbar	75899	1.0	73.7078	39.9	0.0	0.0

Selection cut

✦ Implementing the missing energy cut

$$\not{E}_T < 125 \text{ GeV}$$

How to choose a cut?
- ★ Large signal efficiency
- ★ Small background efficiencies

Dataset	Events kept: K	Rejected events: R	Efficiency: K / (K + R)	Cumul. efficiency: K / Initial
zz	640.80 +/- 6.76	49.20 +/- 6.76	0.9287 +/- 0.0098	0.9287 +/- 0.0098
ww	9633.9 +/- 5.1	26.1 +/- 5.1	0.997300 +/- 0.000528	0.997300 +/- 0.000528
ttbar	68826.1 +/- 80.1	7073.9 +/- 80.1	0.90680 +/- 0.00106	0.90680 +/- 0.00106

✦ Signal *vs* background evolution

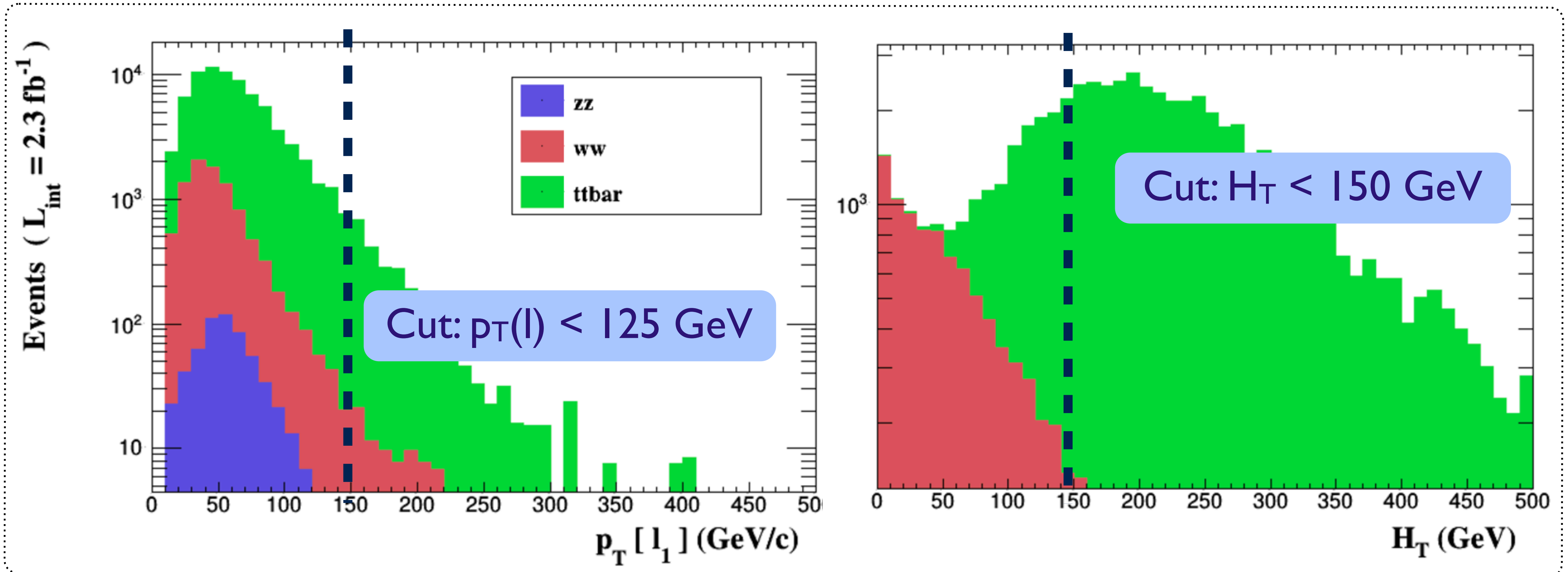
Cut-flow chart

- How to compare signal (S) and background (B): S/sqrt(S+B).

Cuts	Signal (S)	Background (B)	S vs B
Initial (no cut)	690	85559	2.35
Cut 6	640.80 +/- 6.76	78460.1 +/- 80.3	2.278 +/- 0.024

Other examples for cuts

✦ p_T of the leading lepton / total hadronic activity



✤ H_T distribution: the signal is hidden (*cf. y*-axis range), but at low H_T

✦ Cutflow chart after a few cuts

Cuts	Signal (S)	Background (B)	S vs B
Initial (no cut)	690	85559	2.35
Cut 6	624.32 +/- 7.71	70481 +/- 110	2.3413 +/- 0.0288
Cut 7	611.39 +/- 8.35	65997 +/- 121	2.3689 +/- 0.0323
Cut 8	562.3 +/- 10.2	18996 +/- 102	4.0209 +/- 0.0727

Designing an LHC analysis

✦ Defining selection cuts

- ✤ Barely affecting the signal
- ✤ Reducing the background

✦ Not excluded signals are hiding in corners of the parameter space

- ✤ Overwhelming background
- ✤ Use of complex variables (e.g. transverse variables, razor)
- ✤ Machine learning

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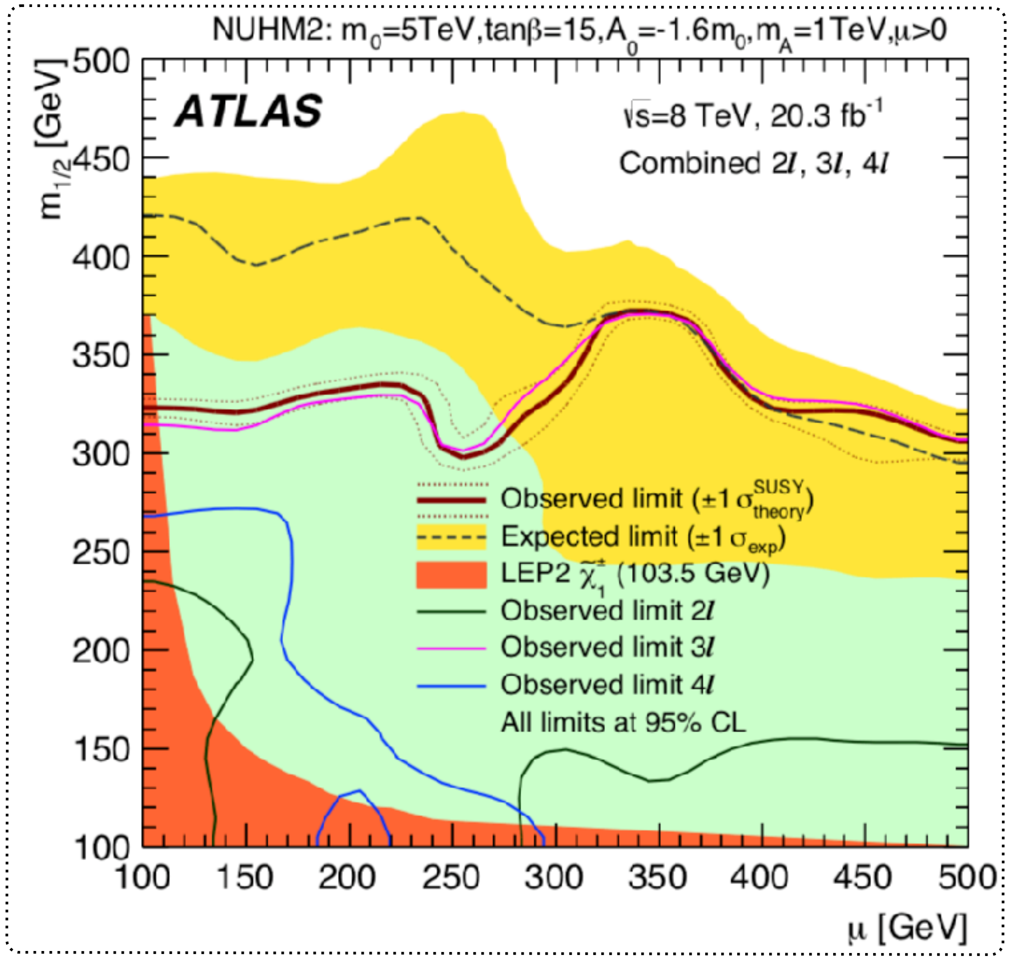
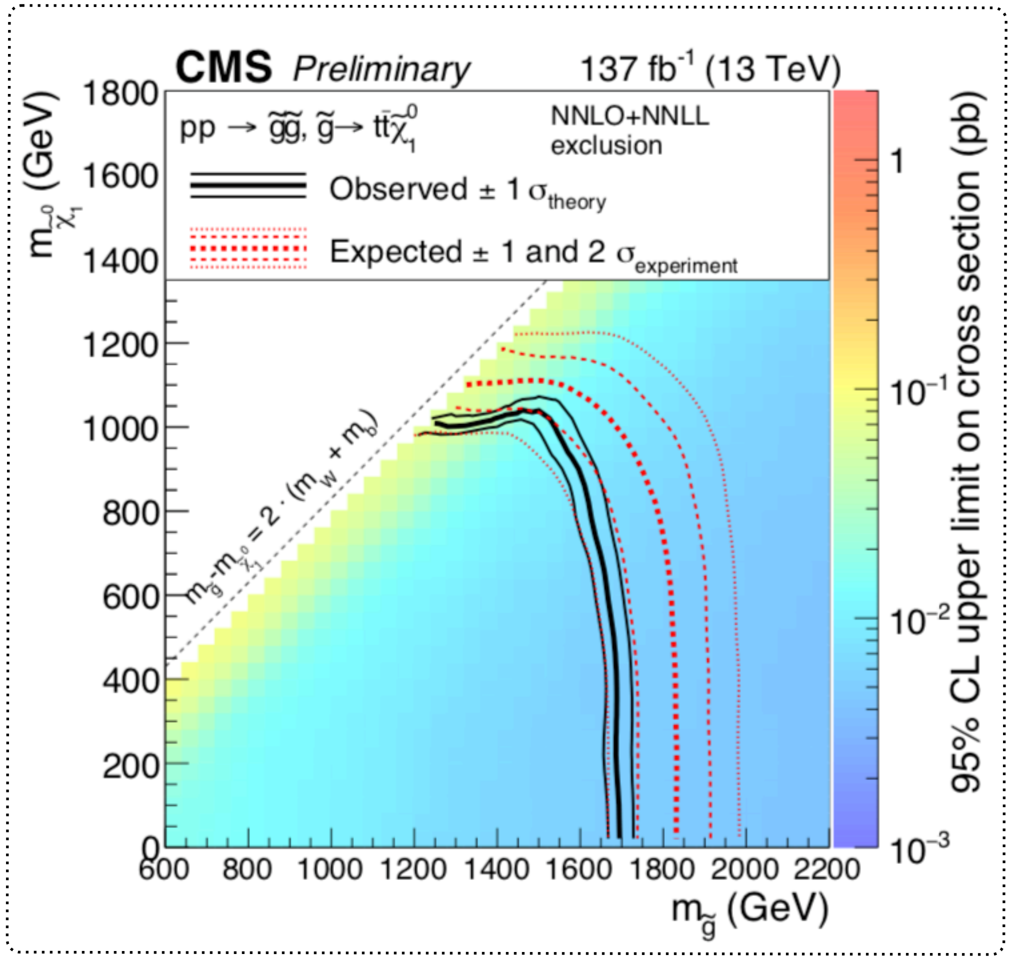
Reinterpreting the LHC results

- Exploit the full potential of the LHC (for new physics)
  - Designing new analyses → probing new ideas — Prospectives (based on MC simulations)
  - Recasting LHC analyses → studying new models — The LHC legacy
- Data preservation in high-energy physics is mandatory
  - Going beyond raw data → analyses
- Related tools need to be supported by the entire community [Kraml *et al.* (EPJC'12)]
  - Both theorists and experimentalists

New physics results at the LHC

- LHC ≡ discovery machine
  - Many ATLAS and CMS searches for new physics
  - Interpretation within popular frameworks and simplified models (SMS)





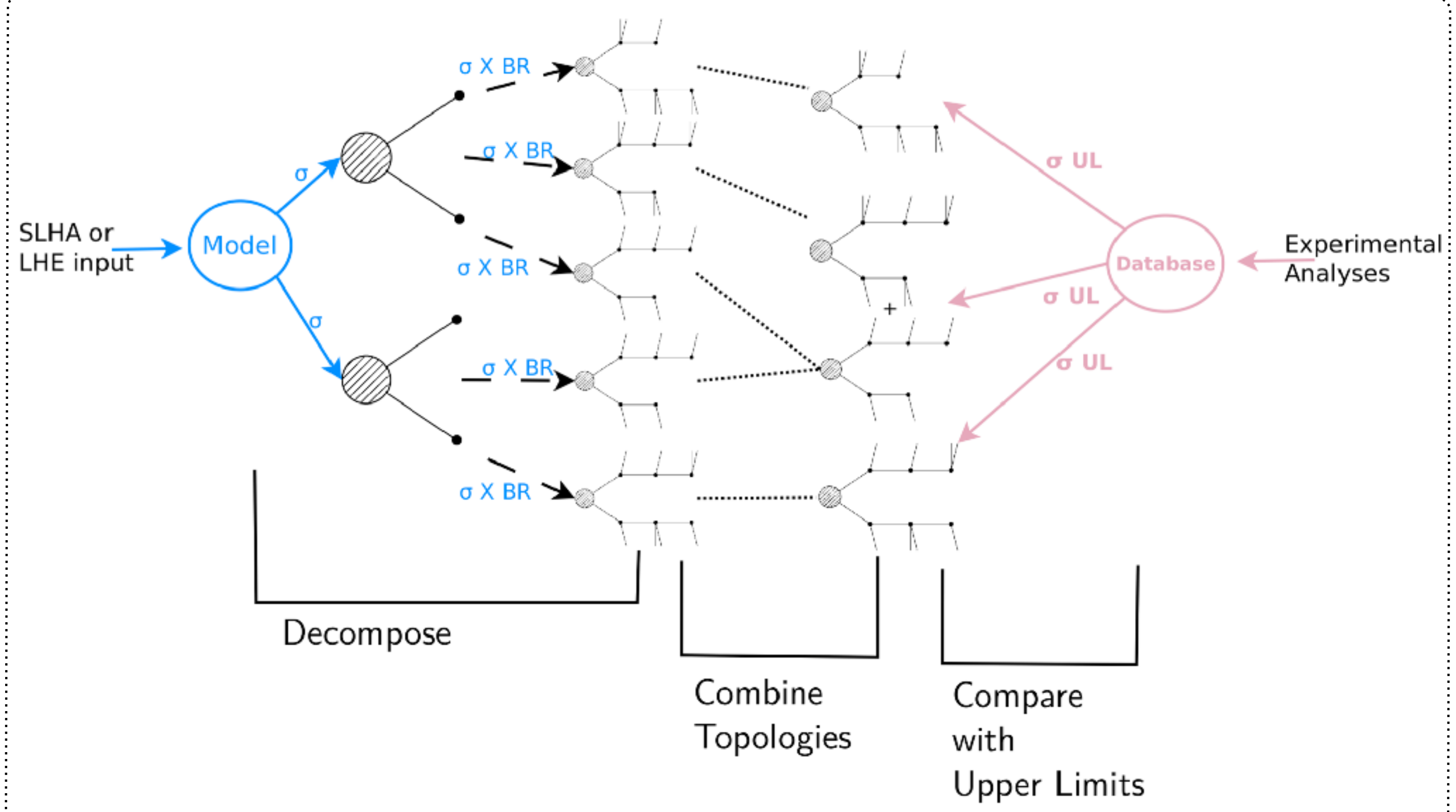
- Need for reinterpretations in all kinds of models

Simplified Model Spectra (SMS)

✦ The SMS-based reinterpretation framework

- ✤ Decomposition of all signatures of a theory into SMS signatures
- ✤ Fiducial cross sections are calculated on the basis of public efficiency maps
- ✤ Comparisons to published upper bounds are made

✦ Main features



- ✤ Extremely fast
- ✤ Low accuracy
  - ★ Different kinematics
  - ★ Asymmetric decays

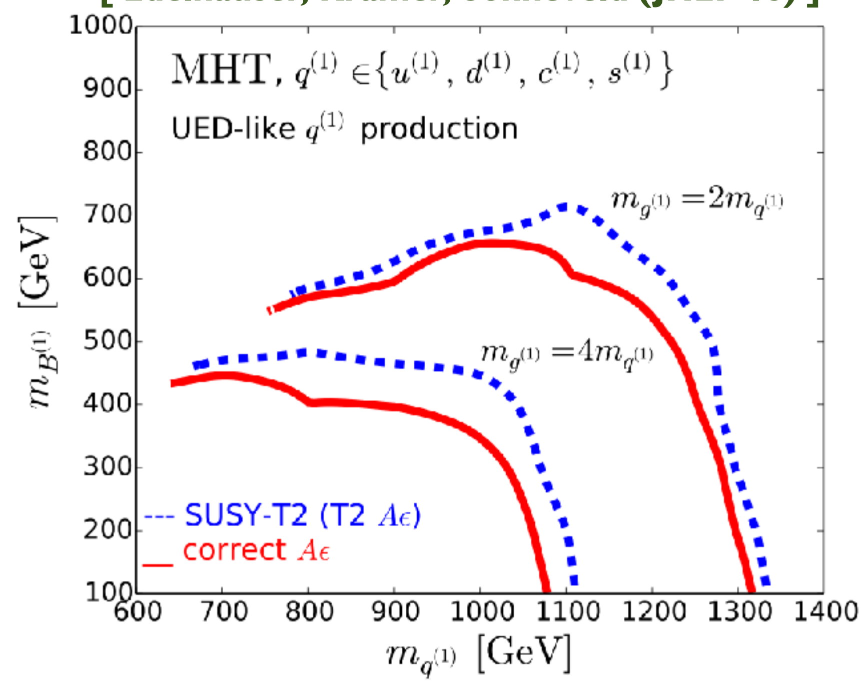
SMS reinterpretation tools

✦ Existing tools: SMODELS (FASTLIM, XQCAT)

[Kraml *et al.* (EPJC'14)] **[Papucci, Sakurai, Weiler & Zeune (EPJC'14)]** **[Barducci *et al.* (CPC'15)]**

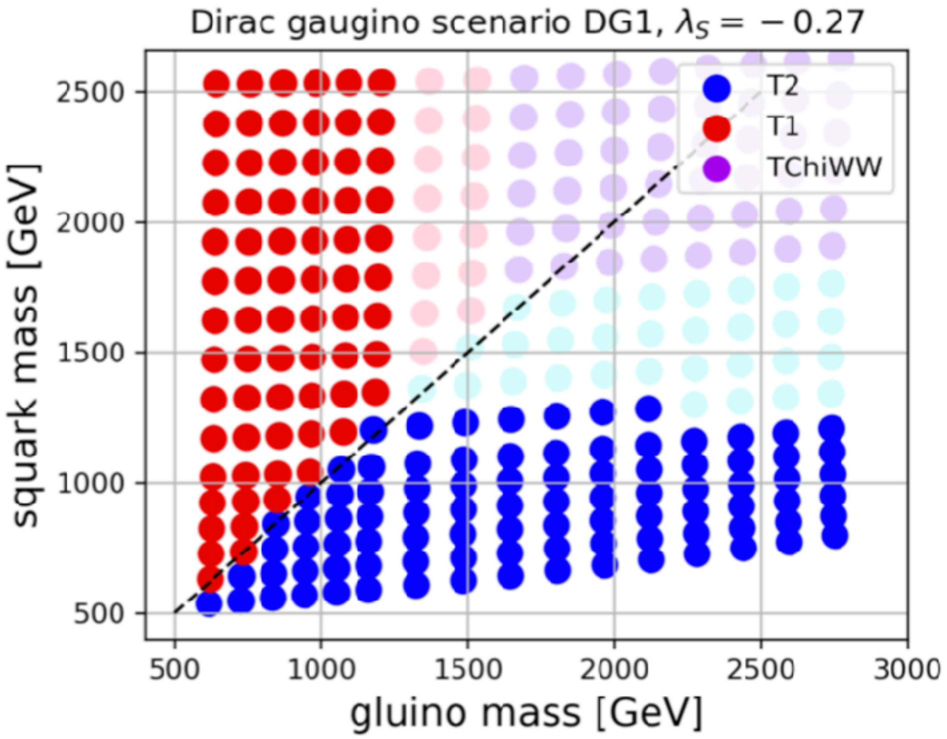
✦ Examples

[Edelhäuser, Krämer, Sonneveld (JHEP'15)]



Limitations (using SMODELS): SUSY *versus* UED

[Chalons *et al.* (JHEP'19)]



Dirac gauginos with SMODELS

Beyond the SMS approach

✦ Plethora of new physics realisations deserving to be studied

- ✤ Experimentalists cannot study all options
- ✤ SMS often not sufficient
  - → detector simulator mimicking ATLAS and CMS
  - → framework for LHC analysis re-implementations

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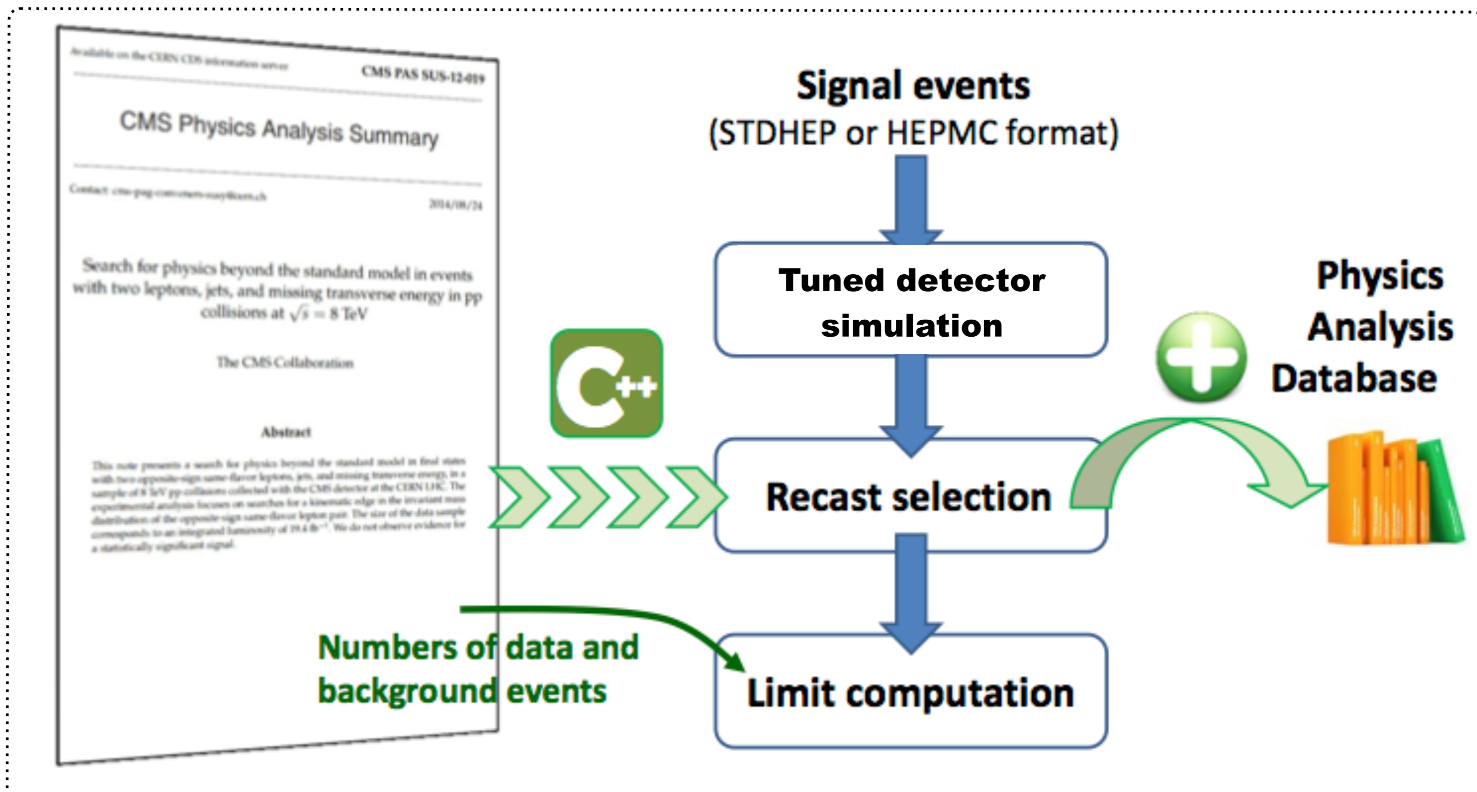
✦ Another recasting strategy



- ✤ 2 options for detector effects
  - ★ DELPHES 3 / PGS (resolutions, efficiencies, *etc.*)
  - ★ RIVET / MADANALYSIS 5 (transfer functions)

Detector modelling

✦ Detector simulation

- ✤ Starting point: hadron-level MC information
- ✤ Extraction of calorimetric and track information →
- ✤ Object reconstruction with efficiencies and smearing
  - ★ Information on isolation, *etc.*

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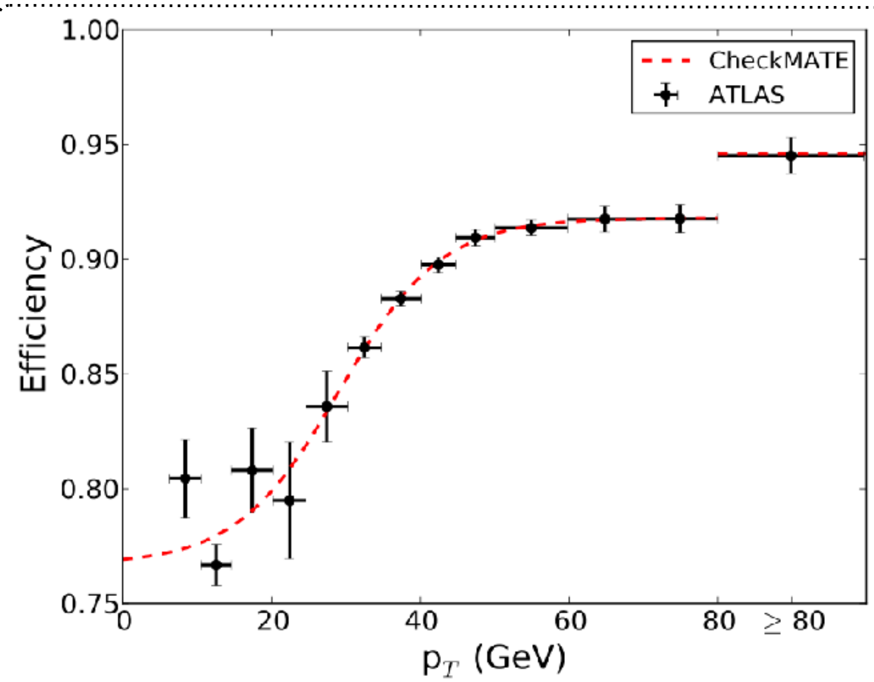
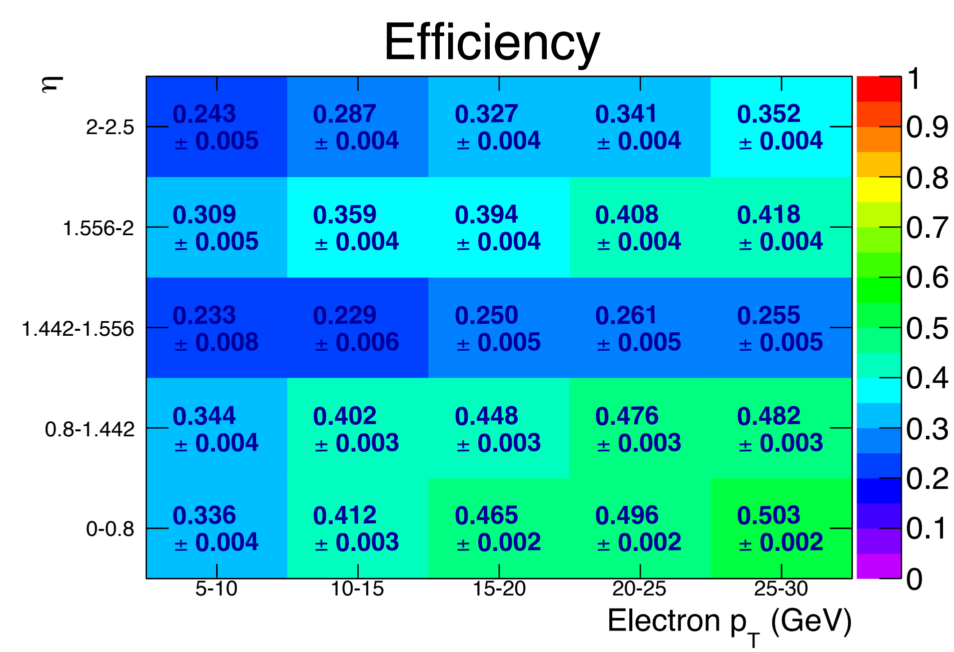


Medium electron efficiency in CHECKMATE



η \ Electron p_T (GeV)	5-10	10-15	15-20	20-25	25-30
2-2.5	0.243 ± 0.005	0.287 ± 0.004	0.327 ± 0.004	0.341 ± 0.004	0.352 ± 0.004
1.556-2	0.309 ± 0.005	0.359 ± 0.004	0.394 ± 0.004	0.408 ± 0.004	0.418 ± 0.004
1.442-1.556	0.233 ± 0.008	0.229 ± 0.006	0.250 ± 0.005	0.261 ± 0.005	0.255 ± 0.005
0.8-1.442	0.344 ± 0.004	0.402 ± 0.003	0.448 ± 0.003	0.476 ± 0.003	0.482 ± 0.003
0-0.8	0.336 ± 0.004	0.412 ± 0.003	0.465 ± 0.002	0.496 ± 0.002	0.503 ± 0.002

Soft electron efficiency in MADANALYSIS 5 (SFS) and RIVET

Current existing public programs

- Using DELPHES: CHECKMATE and MADANALYSIS 5
  [Drees *et al.* (CPC'14); Derks *et al.* (CPC`17) ] [ Dumont, BF, Kraml *et al.* (EPJC`15); Conte & BF (IJMPA`19)]
- Using transfer functions: RIVET, GAMBIT and MADANALYSIS 5
  [Buckley *et al.* (CPC`13) ] [ Balazs et *al.* (EPJC`17)] [Araz, BF & Polykratis (to appear)]
- CONTUR: Standard Model searches [Butterworth *et al.*]

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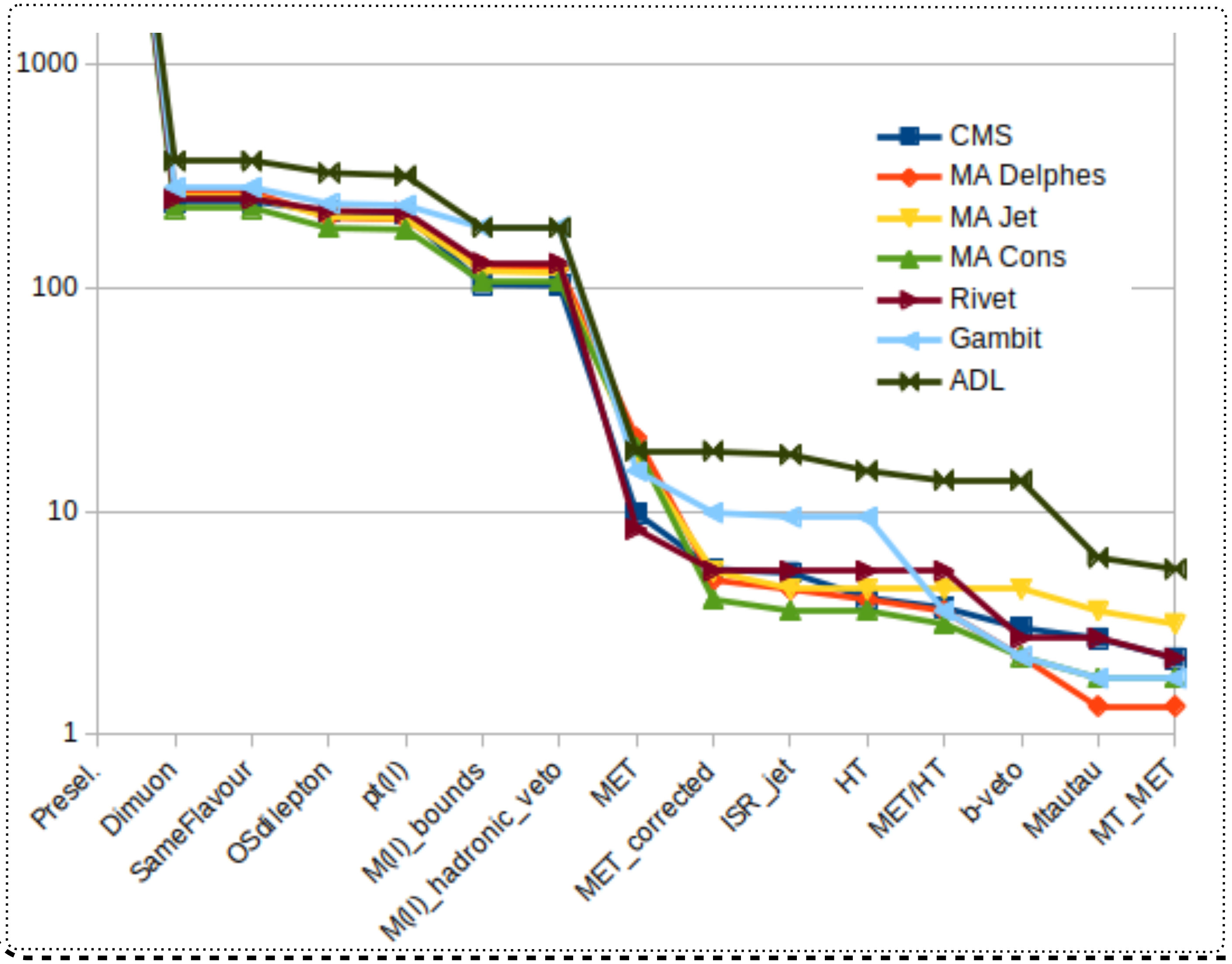
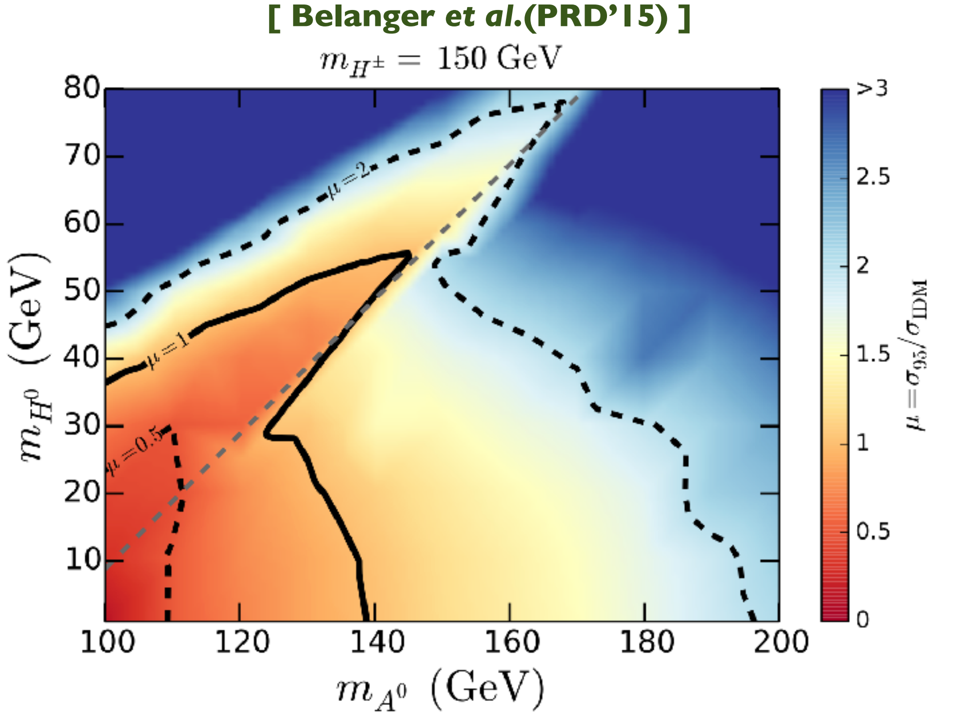


✦ Example: LH 2019

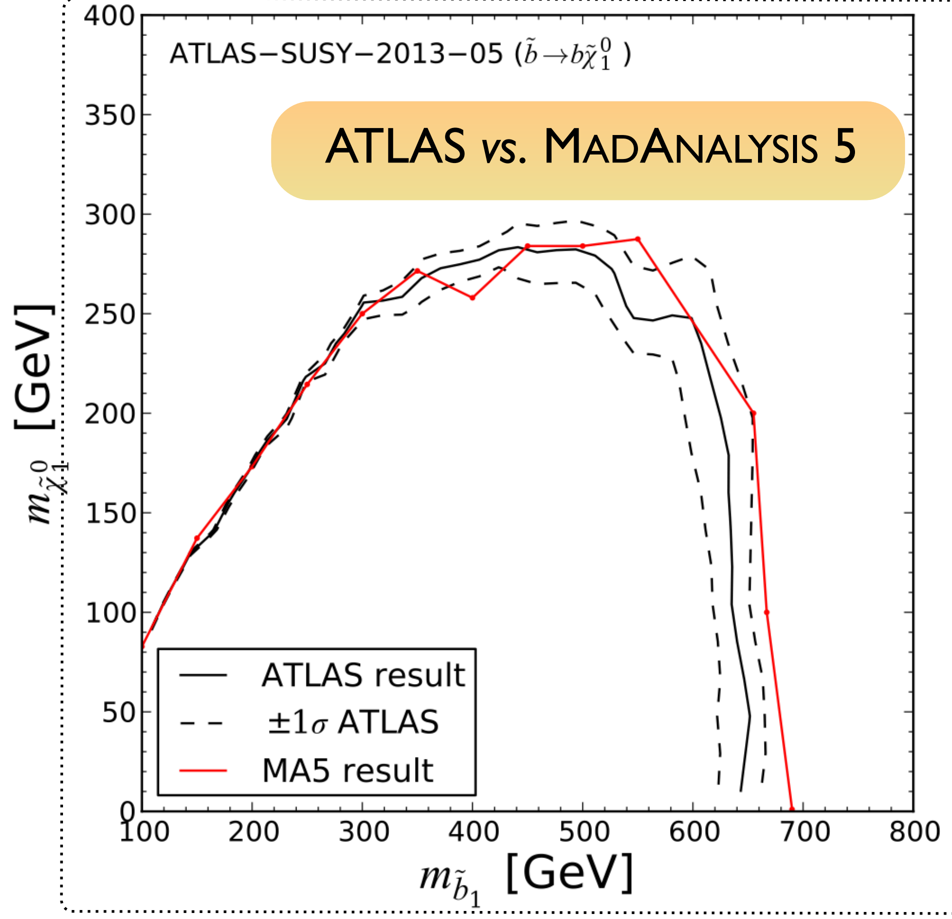
- ✤ CMS-SUS-16-048
- ✤ SUSY with soft leptons
  →sleptons/ewkinos
- ✤ Reasonable agreement with CMS

Crucial to have different frameworks (transfer functions work better)

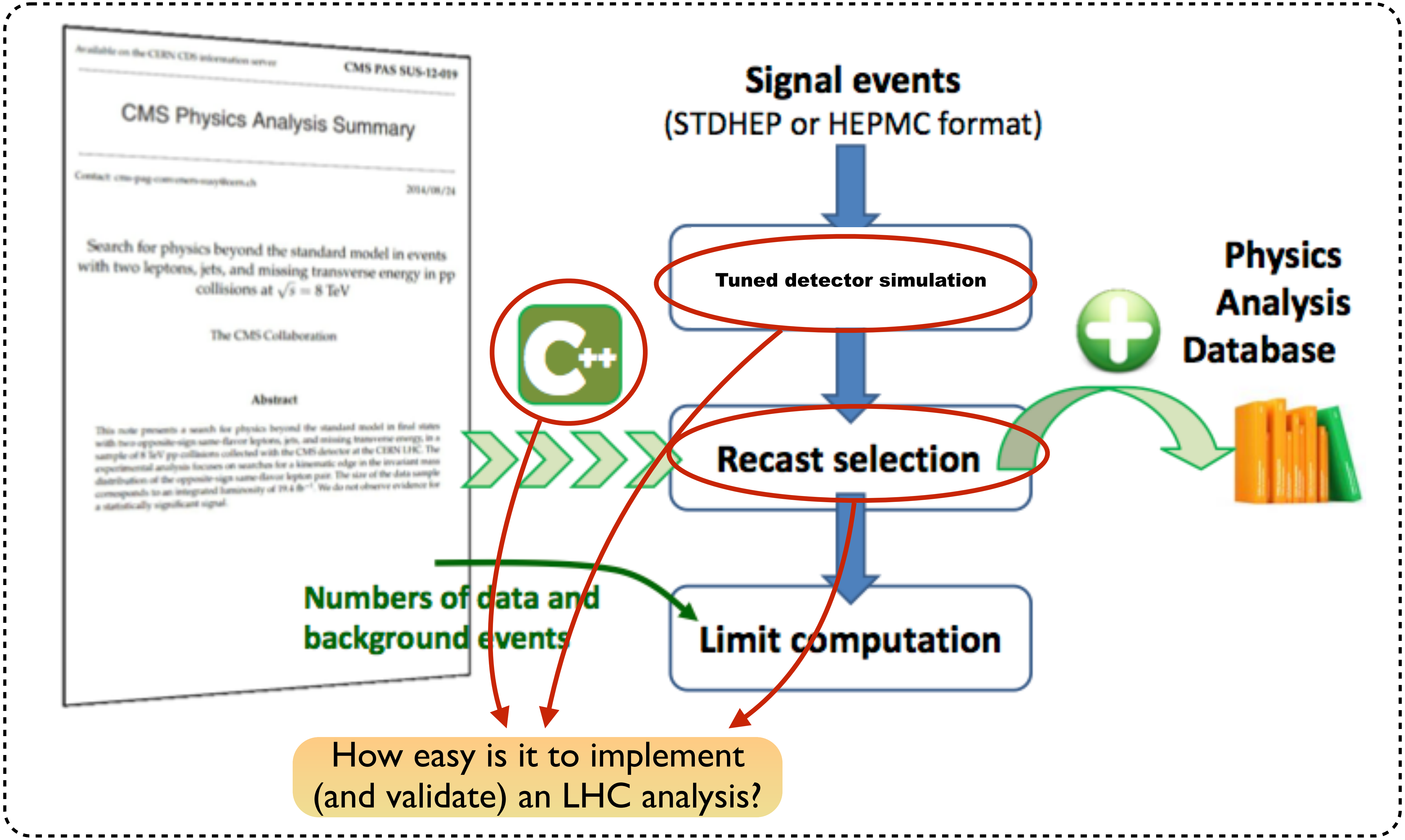
More examples



Constraining the inert Higgs doublet model with SUSY searches and MADANALYSIS 5



Reimplementing an analysis: the challenges



Implementing a new analysis

✦ Picking up an experimental publication

- ✤ Reading
- ✤ Understanding

✅ Relatively easy

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  - ✤ Reading
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- ✦ Writing the analysis code in the tool internal language

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- ✦ Getting accurate information for a proper validation
  - ✤ Efficiencies (trigger, electrons, muons, *b*-tagging, JES, *etc.*)
    - ★ Including p_T and/or η dependence
  - ✤ Detailed cutflows for some well-defined benchmark scenarios
    - ★ Region per region information
    - ★ Exact definition of the benchmarks (spectra)
    - ★ Event generation information (cards, tunes, *etc.*)
  - ✤ Digitised histograms (e.g. on HEPDATA)

⚠️ Essential
❌ Often difficult!

Discussions with experimentalists

Implementing a new analysis

- Picking up an experimental publication
  - Reading
  - Understanding

✅ Relatively easy

- Writing the analysis code in the tool internal language

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⚠ Essential
✗ Often difficult!

Discussions with experimentalists

- Comparing theory tools and real life

Example: CMS-SUS-17-001 in MadAnalysis 5

[Bein, Choi, BF, Jeong, Kang, Li & Sonneveld ('18)]

- CMS search for dark matter in the ttbar + MET channel
  - Dileptonic final state
  - Cutflows and Monte Carlo information for given benchmarks
- Validation at a very good level, cut by cut

Cut	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1)$ GeV		$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300)$ GeV	
	CMS	MA5	CMS	MA5
n(OS μ or e)$= 2$	-	-	-	-
$m_{\ell\ell} > 20$ GeV	0.99	0.99	0.99	0.97
$\lvert m_Z - m_{\ell\ell}\rvert > 15$ GeV	0.95	0.94)	0.89	0.89
$N_j \geq 2$	0.87	0.93)	0.85	0.89
$N_b \geq 1$	0.73	0.84)	0.83	0.83
$E_T^{\rm miss} > 80$ GeV	0.94	0.95	0.89	0.88
$S > 5\ {\rm GeV}^{1/2}$	0.98	0.92	0.96	0.91
$c_1 < 0.80$	0.9	0.97	0.92	0.97
$c_2 < 0.96$	1.0	0.96	1.0	0.94
$M_{T2}(\ell_1\ell_2) > 140$ GeV	0.49	0.42	0.17	0.16
All cuts	0.24	0.25	0.083	0.075

MADANALYSIS 5 analyses on INSPIRE

- ✦ Re-implementations can be uploaded on INSPIRE
  - ✤ DOI are assigned → citations, INSPIRE searches, *etc.*

Information | Citations (2) | Files

Files are versioned, can be downloaded

Madanalysis5 implementation of CMS-SUS-17-001

Bein, Samuel; Choi, Soo-Min; Fuks, Benjamin; Jeong, Soomin; Kang, Dong Woo; Li, Jinmian; Sonneveld, Jory

Description: Cite as: Bein, S., Choi, S.-M., Fuks, B., Jeong, S., Kang, D. W., Li, J. & Sonneveld, J. (2018). Madanalysis5 implementation of CMS-SUS-17-001 code. doi: 10.7484/INSPIREHEP.DATA.MMM1.876Z

Record added 2018-04-16, last modified 2018-11-23

DOI and citations

The Public Analysis Database of MADANALYSIS

- A database with MADANALYSIS 5 implementations of LHC analyses exists
  - http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase

CMS analyses, 13 TeV

Analysis	Short Description	Implemented by	Code	Validation note	Version
CMS-SUS-16-033	Supersymmetry in the multijet plus missing energy channel (35.9 fb-1)	F. Ambrogi and J. Sonneveld	Inspire	PDF	v1.7/Delphes3
CMS-SUS-16-039	Electroweakinos in the SS2L, 3L and 4L channels (35.9 fb-1)	B. Fuks and S. Mondal	Inspire	PDF	v1.7/Delphes3
CMS-SUS-16-052	SUSY in the 1l + jets channel (36 fb-1)	D. Sengupta	Inspire	PDF	v1.6/Delphes3
CMS-SUS-17-001	Stops in the OS dilepton mode (35.9 fb-1)	S.-M. Choi, S. Jeong, D.-W. Kang, J. Li *et al.*	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-010	Mono-Z-boson (2.3 fb-1)	B. Fuks	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-012	Mono-Higgs (2.3 fb-1)	S. Ahn, J. Park, W. Zhang	Inspire	PDF	v1.6/Delphes3
CMS-EXO-16-022	Long-lived leptons (2.6 fb-1)	J. Chang	Inspire	PDF	v1.6_tracks/Delphes3
CMS-TOP-17-009	SM four-top analysis (35.9 fb-1)	L. Darmé and B. Fuks	Inspire	PDF	v1.7/Delphes3

Delphes card for CMS-EXO-16-010 and CMS-SUS-17-001
Delphes card for CMS-EXO-16-012
Delphes card for CMS-SUS-16-039
Delphes card for CMS-SUS-16-041
Delphes card for CMS-SUS-16-052
Delphes card for CMS-TOP-17-009

Dedicated DELPHES cards

Code from INSPIRE

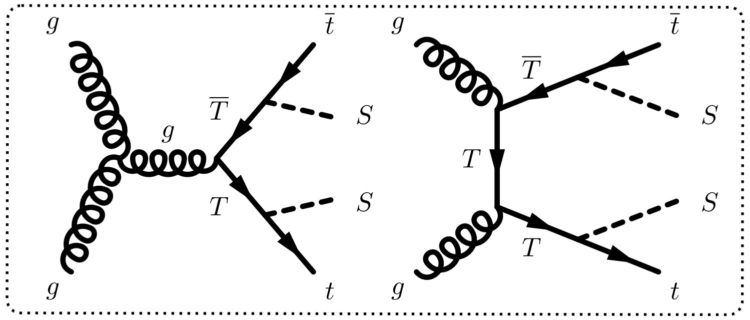
Validation information (cutflows, distributions, *etc.*)

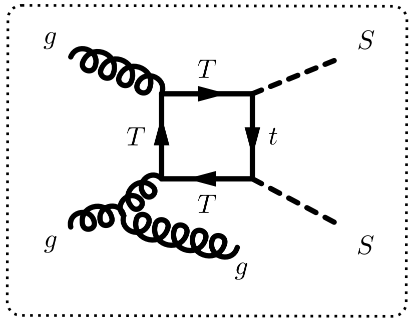
- Can be automatically installed within MADANALYSIS 5

Top-philic scalar dark matter at the LHC

[Colucci, BF, Giacchino, Lopez Honorez, Tytgat & Vandecasteele (PRD`18)]

✦ Simplified model: SM + VLQ + DM





$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \Big[\tilde{y}_t\, S\, \bar{T} P_R t + {\rm h.c.}\Big]$$

✤ Multijet and top-antitop plus MET probes

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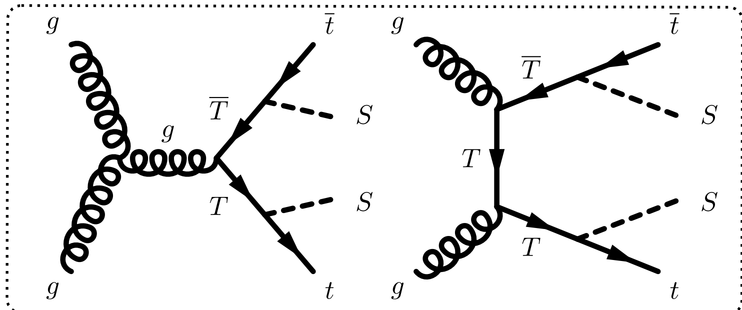

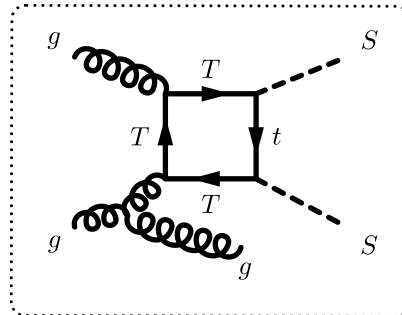

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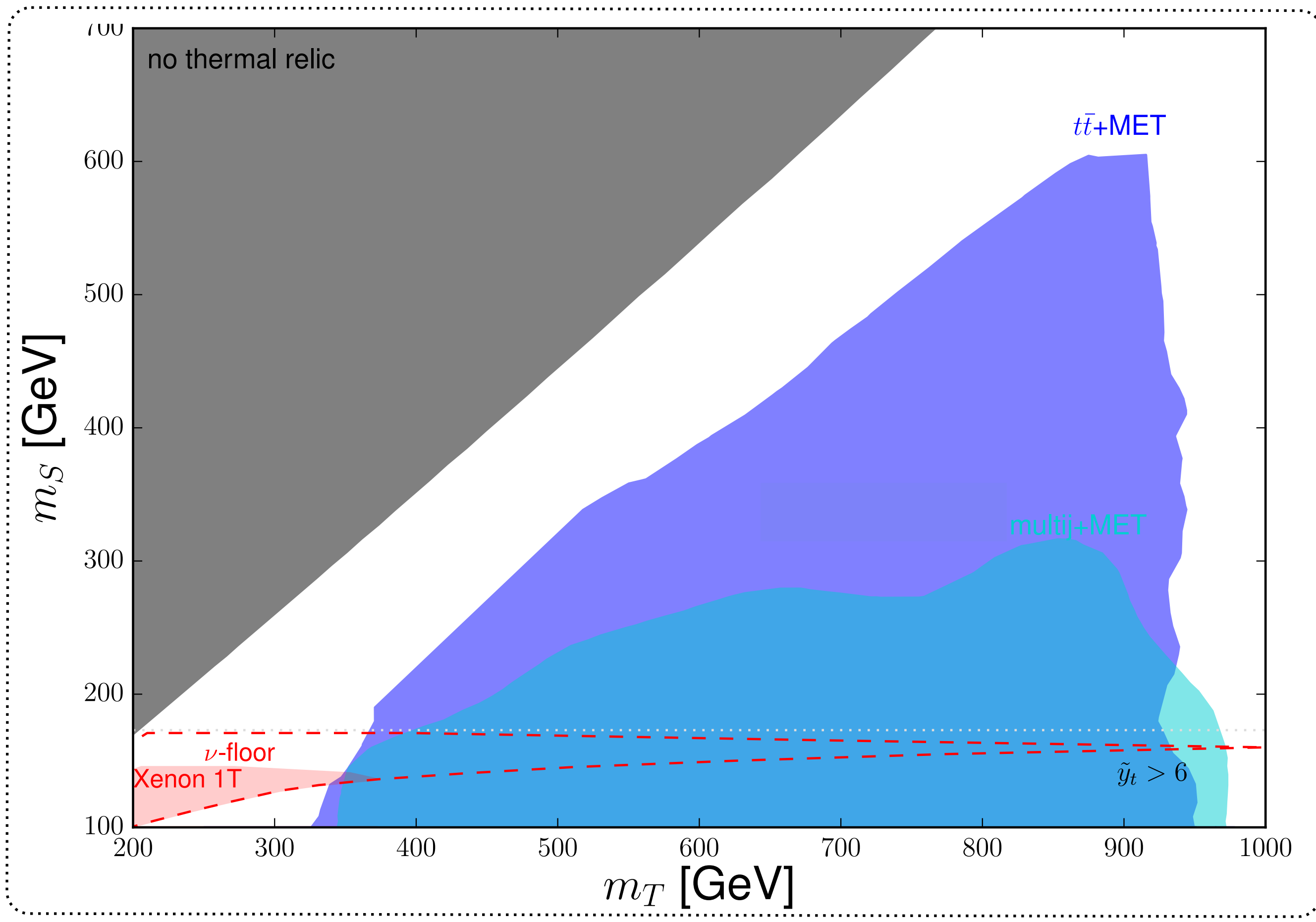


✤ General features

- ★ Γ_T must be larger than $\Lambda_{\rm QCD}$ (no LLP)
- ★ Bounds independent of the Yukawa
  → monojet production negligible

✤ Multijet probes

- ★ Monojet-inspired (at least one very hard jet)
- ★ Loss of sensitivity ⇔ decay phase space

✤ Top-antitop plus MET

- ★ Well adapted to our topology
- ★ Best constraints (and chance of discovery)

$t\bar{t}$+MET constraints on top-philic dark matter

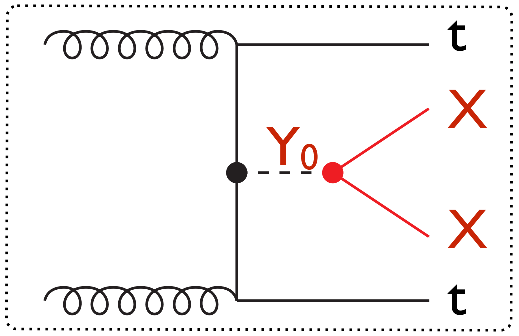
[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ A simplified model for top-philic dark matter

- ✤ A dark sector with a fermionic dark matter candidate X
- ✤ A (scalar) mediator Y_0 linking the dark sector and the top

$$\mathcal{L}_{t,X}^{Y_0} = -\Big(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\Big) Y_0$$

- ✤ Could be probed with $t\bar{t}$+MET events (CMS-B2G-14-004)



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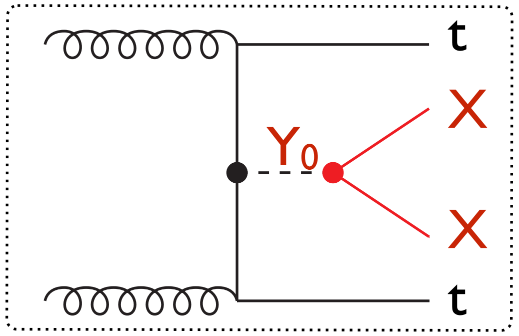

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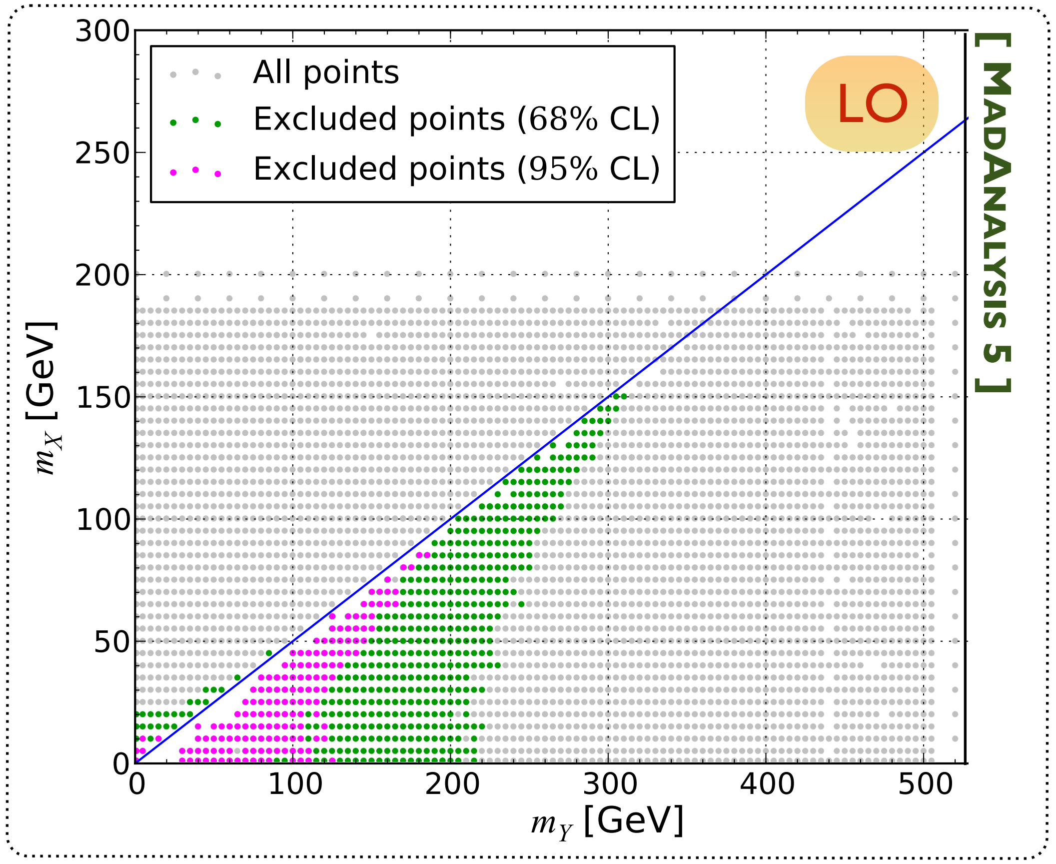
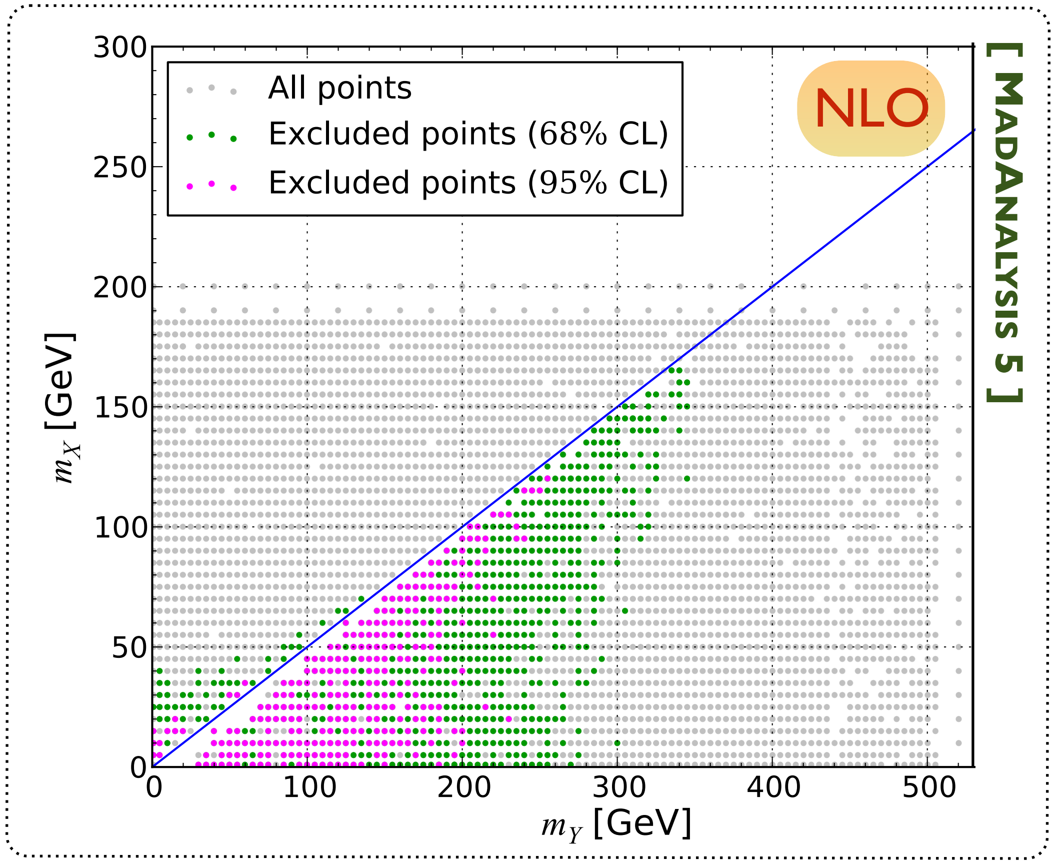
✦ For central scales: mild (but visible) NLO effects on the exclusions





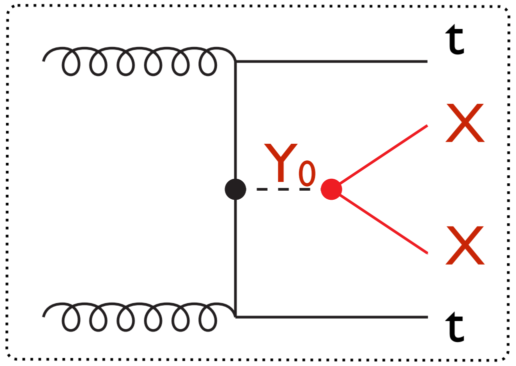
- ✤ How is the picture changing when including scale variations?

NLO effects on a CLs: top-philic dark matter

[Arina, Backovic, Conte, BF, Guo *et al.* (JHEP'16)]

✦ There are theoretical uncertainties on a CLs number

	(m_Y, m_X)	σ_{LO} [pb]	CL_{LO} [%]	σ_{NLO} [pb]	CL_{NLO} [%]
I	(150, 25) GeV	$0.658^{+34.9\%}_{-24.0\%}$	$98.7^{+0.8\%}_{-13.0\%}$	$0.773^{+6.1\%}_{-10.1\%}$	$95.0^{+2.7\%}_{-0.4\%}$
II	(40, 30) GeV	$0.776^{+34.2\%}_{-24.1\%}$	$74.7^{+19.7\%}_{-17.7\%}$	$0.926^{+5.7\%}_{-10.4\%}$	$84.2^{+0.4\%}_{-14.4\%}$
III	(240, 100) GeV	$0.187^{+37.1\%}_{-24.4\%}$	$91.6^{+6.4\%}_{-18.1\%}$	$0.216^{+6.7\%}_{-11.4\%}$	$86.5^{+8.6\%}_{-5.5\%}$



✤ An excluded point (95% CL) may not be excluded when accounting for errors

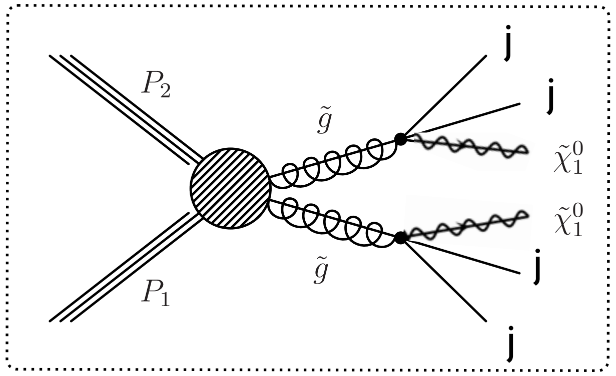
✤ The CLs number can increase / decrease at NLO

✤ The error band is reduced

Impact of the uncertainties → future colliders

[Araz, Frank & BF (1910.11418)]

- ✦ Constraining gluino pair production and decay @ LHC
  - ✤ NLO impact on the shapes of the distributions
  - ✤ Impact on the limits?
  - ✤ Impact of the theory uncertainties?



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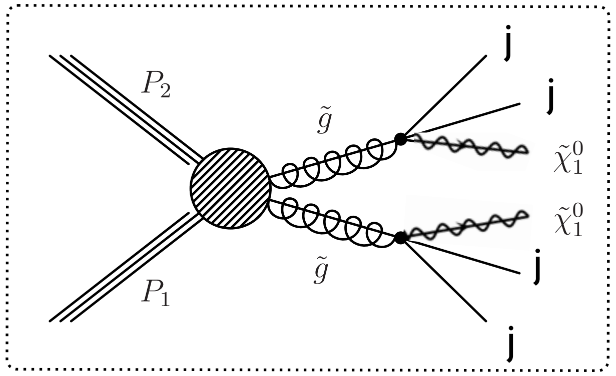
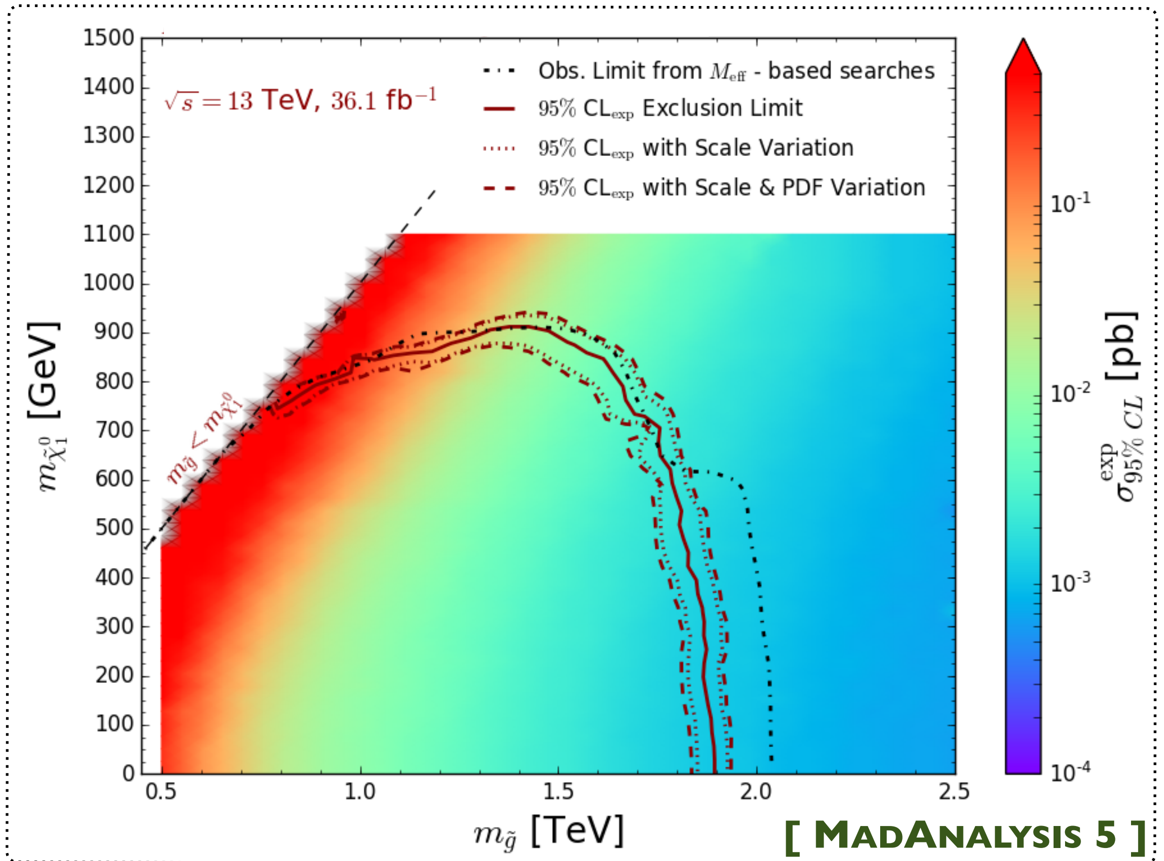
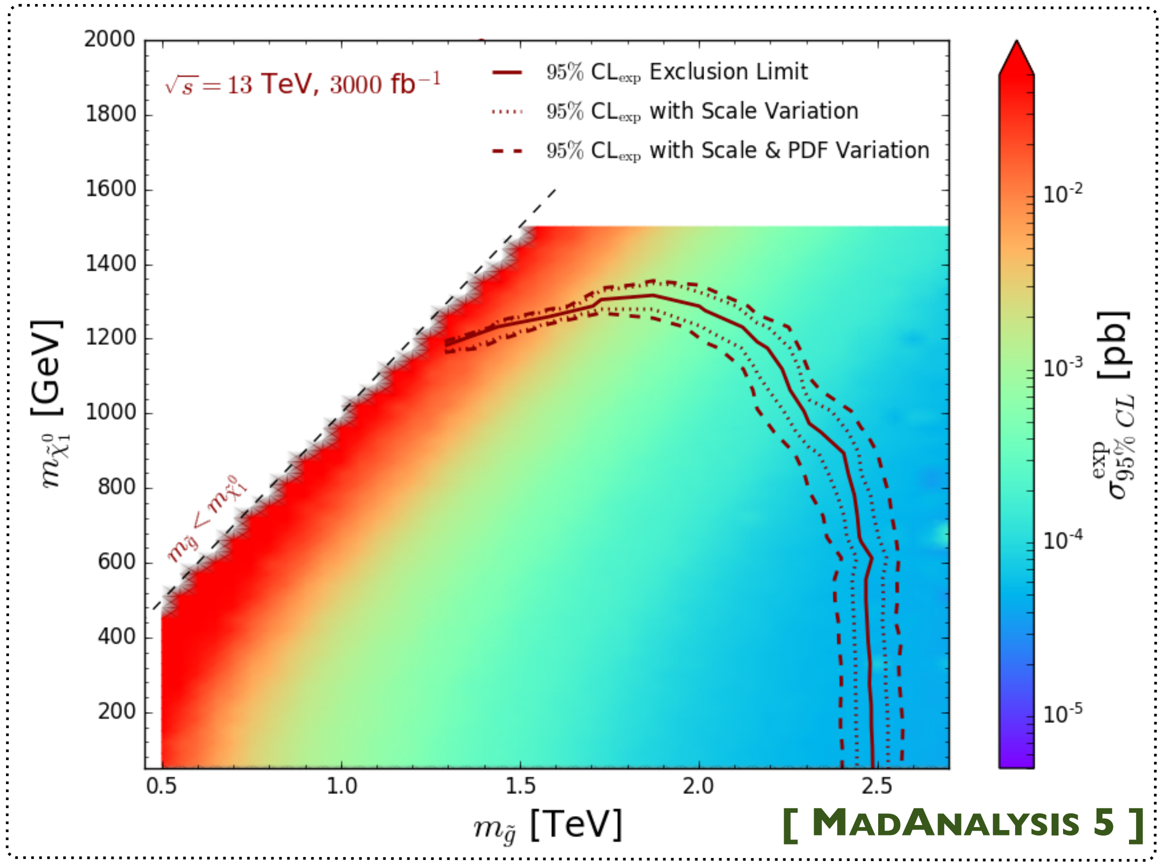


✦ Recasting ATLAS multijet + MET analysis (ATLAS SUSY 2016-07)

- ✤ Left: reproduction of the ATLAS results (LO-merged; $\sigma_{NLL/NLO}$) with NLO signals
- ✤ Right: extrapolation for HL-LHC → impact of the errors





Outline

1. Introduction

2. Designing a phenomenological analysis at colliders

3. LHC recasting

4. **Summary**

Summary

✦ Designing analysis at collider is an art

- Current constraints → BSM is hiding
- Use of clever methods to suppress the backgrounds (without killing the signal)
- Machine learning is routine

✦ The LHC legacy

- It is crucial to be able to reinterpret the LHC results in any theoretical context
- This is a very active field of the last few years: several tools are available
- **Reproducibility** is the ability of an entire experiment to be reproduced, (possibly by an independent theoretical study)