LHC recasting from A to Z

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LPTHE / Sorbonne Université

The second MadAnalysis 5 workshop on LHC recasting @ Korea

KIAS (Seoul, Korea) - 13 February 2020

Outline

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)
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✦ 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

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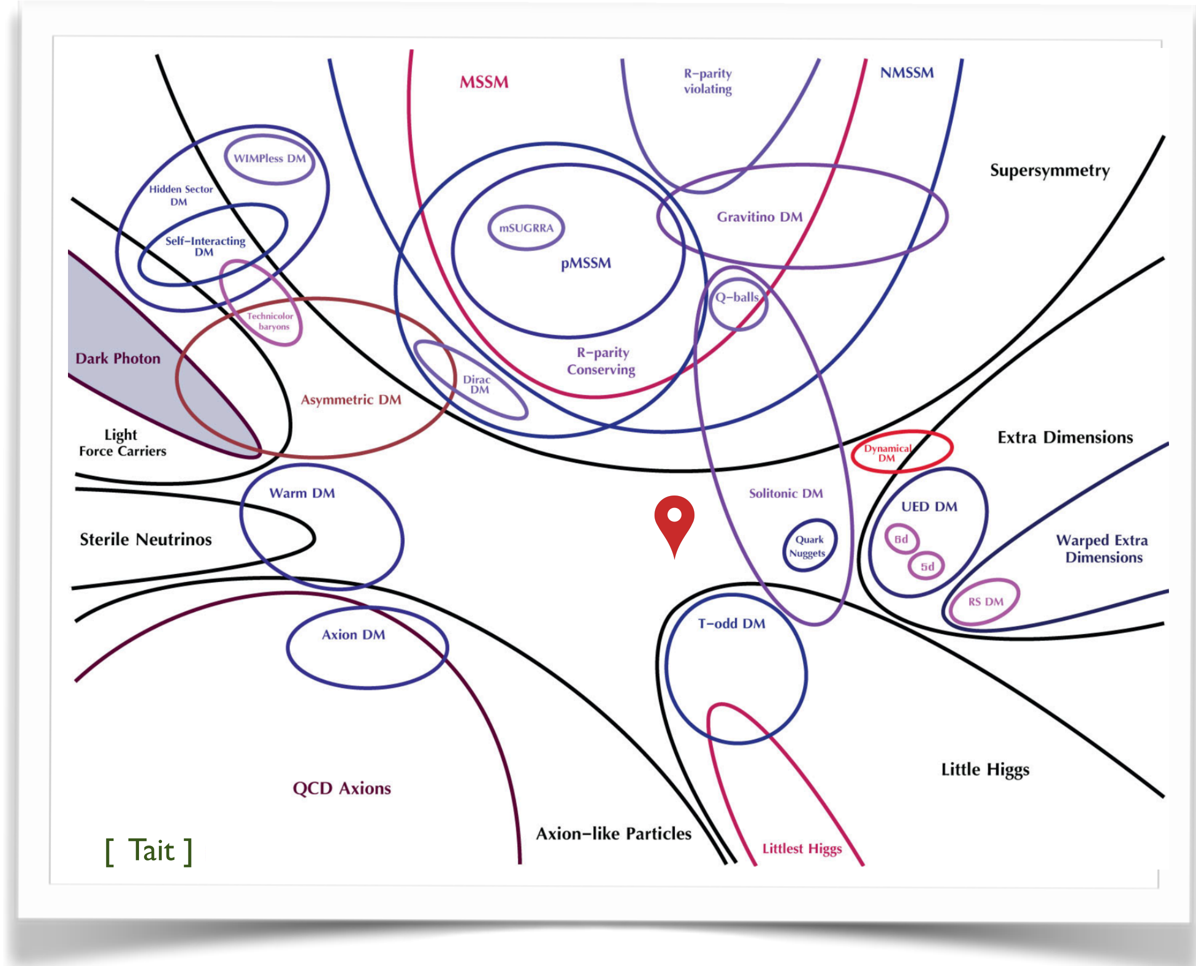
BSM simulations?

BSM simulations: where are we?

- ✦ New physics simulations - a challenge
  - ✤ No sign of new physics
  - ✤ SM-like measurements
    - → no leading candidate theory
  - ✤ Plethora of models to consider
    - → many implementations in tools



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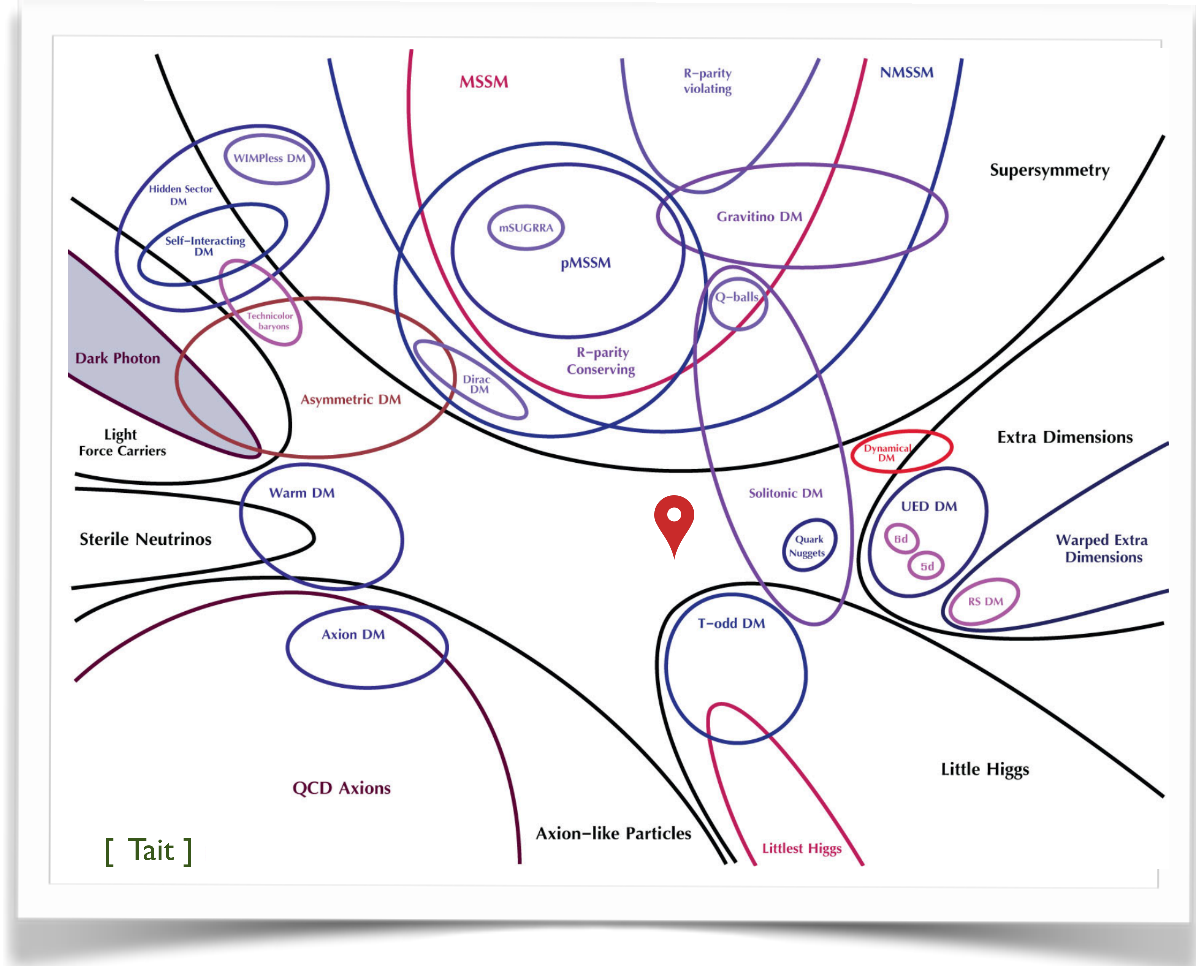
Despite of this, new physics is standard today



✦ New physics is standard

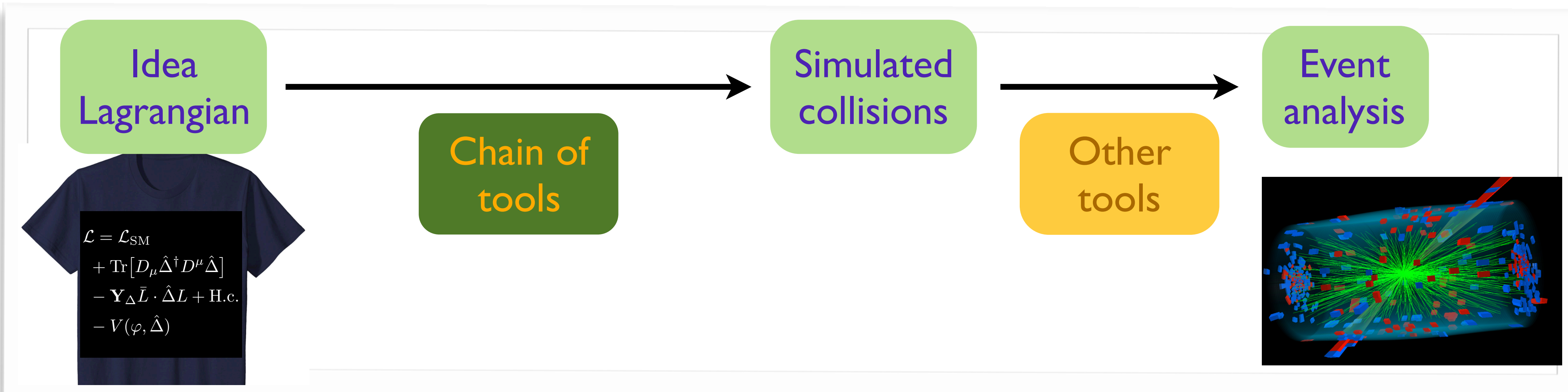
- ✤ 20-25 years of developments → LO simulations are bread and butter
- ✤ Simulations at the NLO QCD accuracy easily achieved
  - ★ For any model/process (→ MADGRAPH5_aMC@NLO)

From Lagrangians to events

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

✦ Streamlining the connection of a physics models to events

- ✤ Any new physics model can be implemented
- ✤ Easy to validate and maintain



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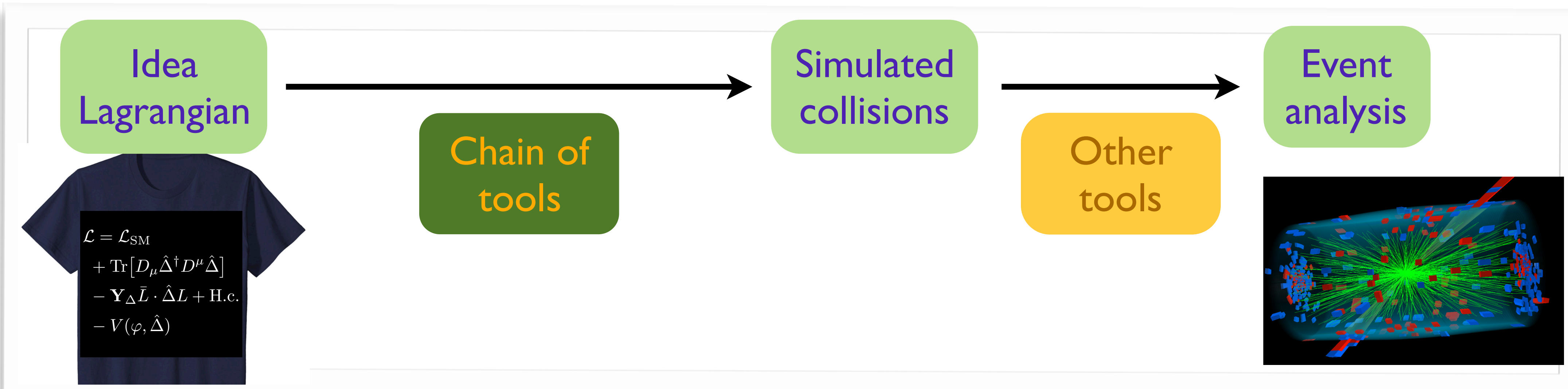

✦ Why a chain of several tools?

- ✤ Phenomena at colliders occur at different scales → factorisation

See Richard’s talk

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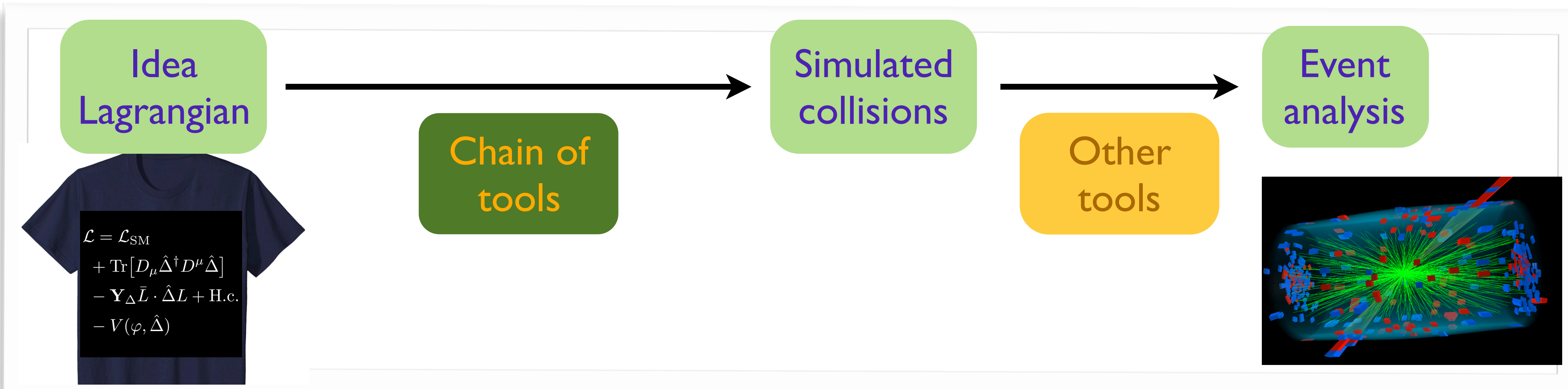

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Let's reverse the chain…

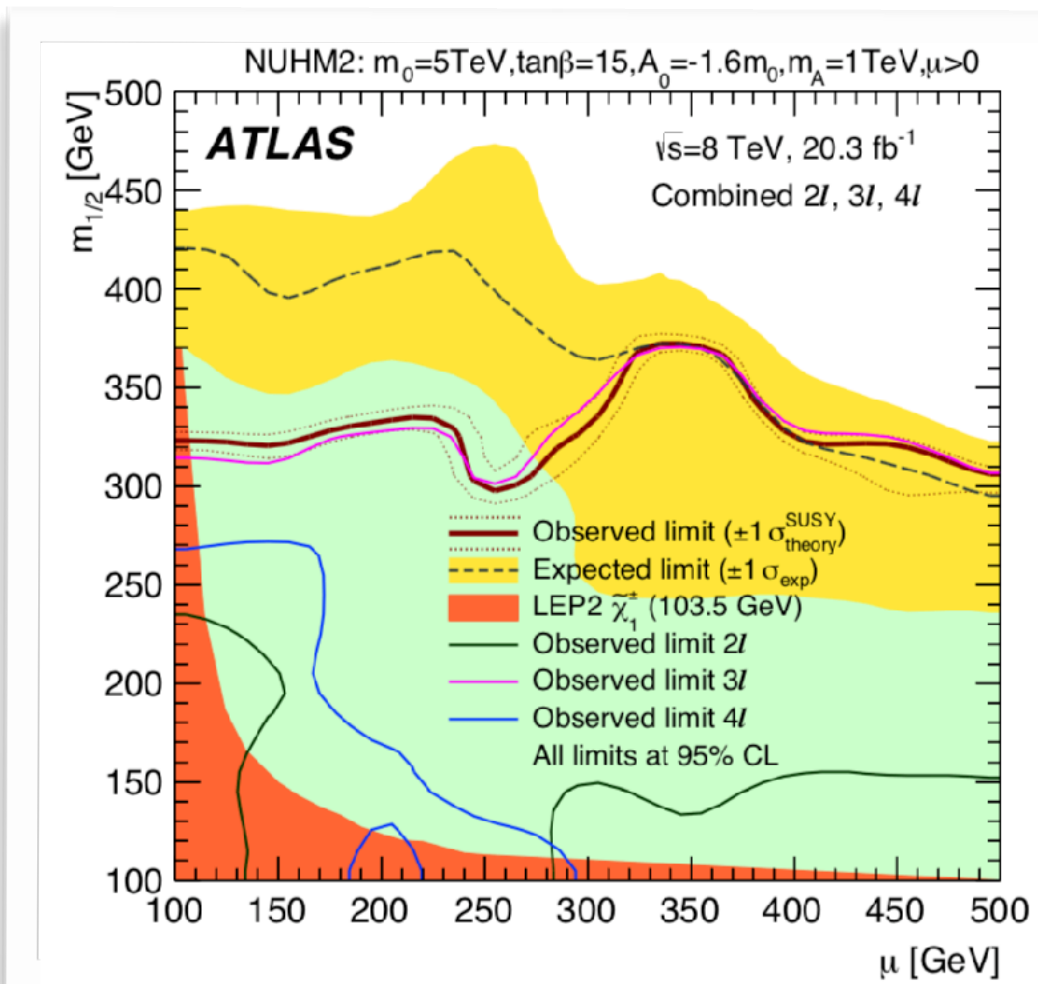
Some context

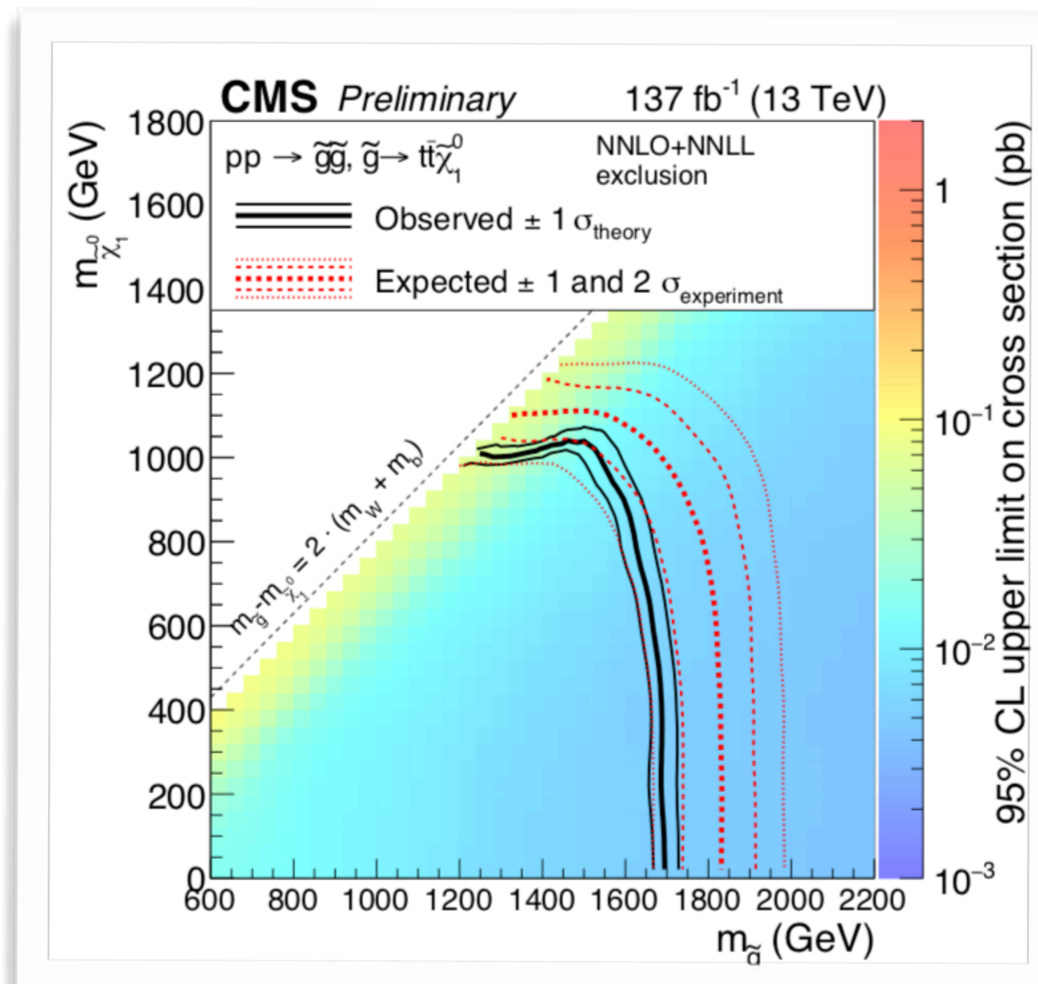
- Exploit the full potential of the LHC (for new physics)
  - Designing new analyses → probing new ideas Prospectives (based on MC simulations)
  - Recasting LHC analyses → studying new models The LHC legacy
- Data preservation in high-energy physics is mandatory
  - Going beyond raw data → analyses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

The Simplified Model Spectra (SMS) approach

✦ LHC ≡ discovery machine

- ✤ Many ATLAS and CMS searches for new physics
- ✤ Interpretation within popular frameworks and simplified models (SMS)





New physics results at the LHC

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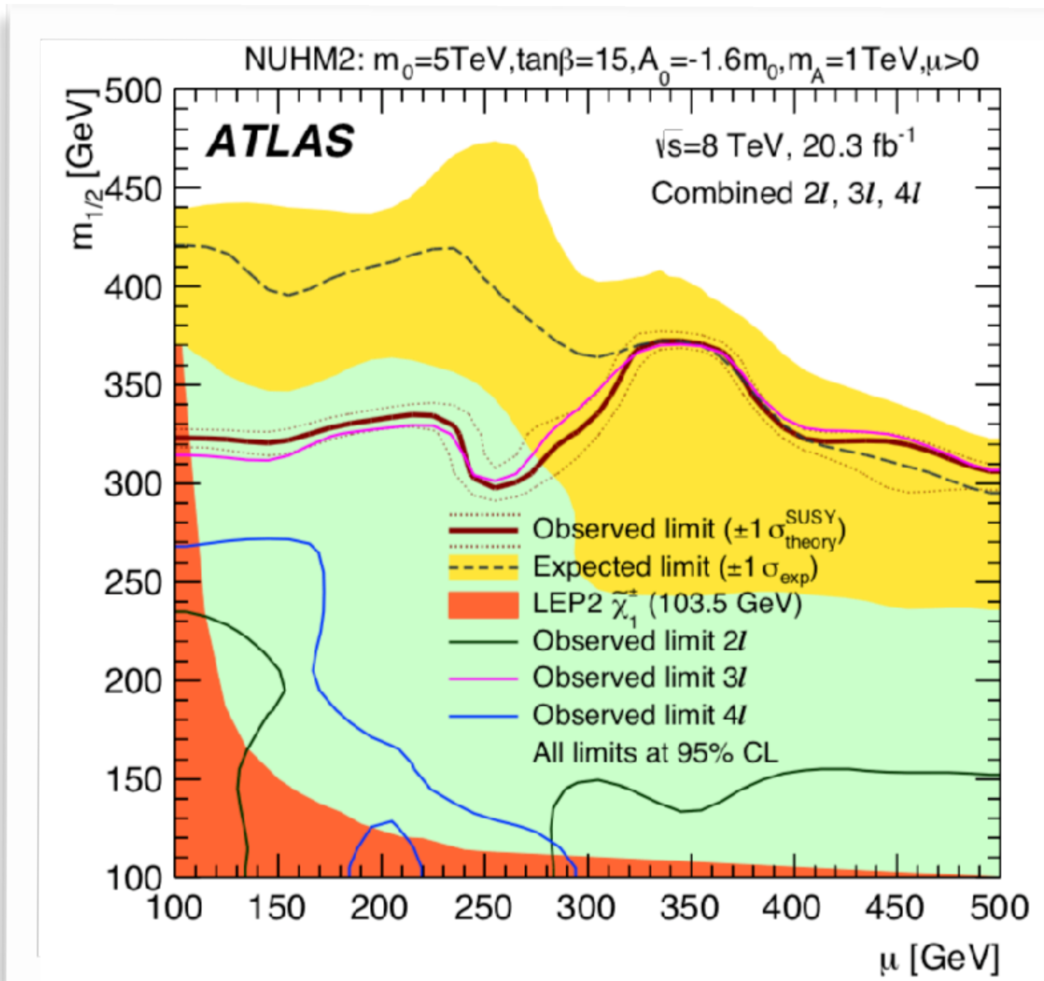

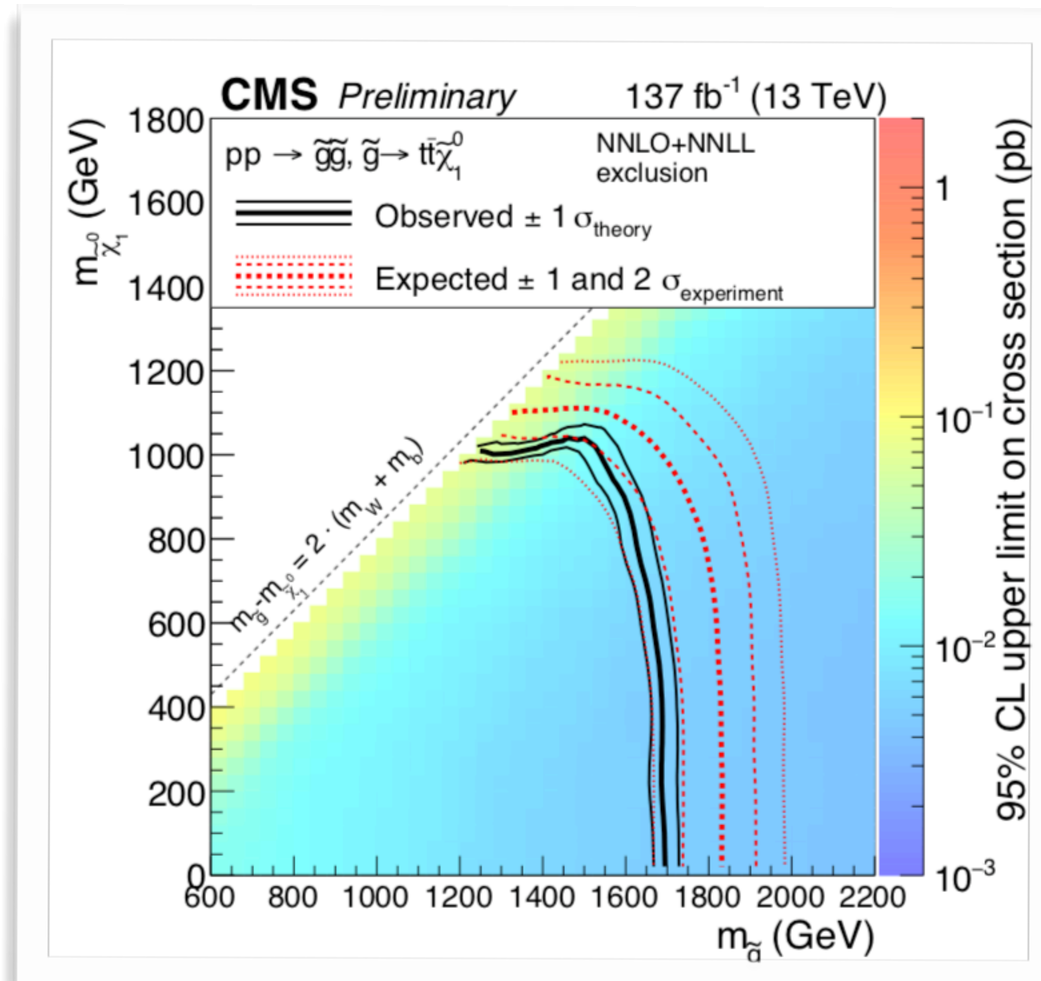

- ✦ Need for reinterpretations in all kinds of models

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

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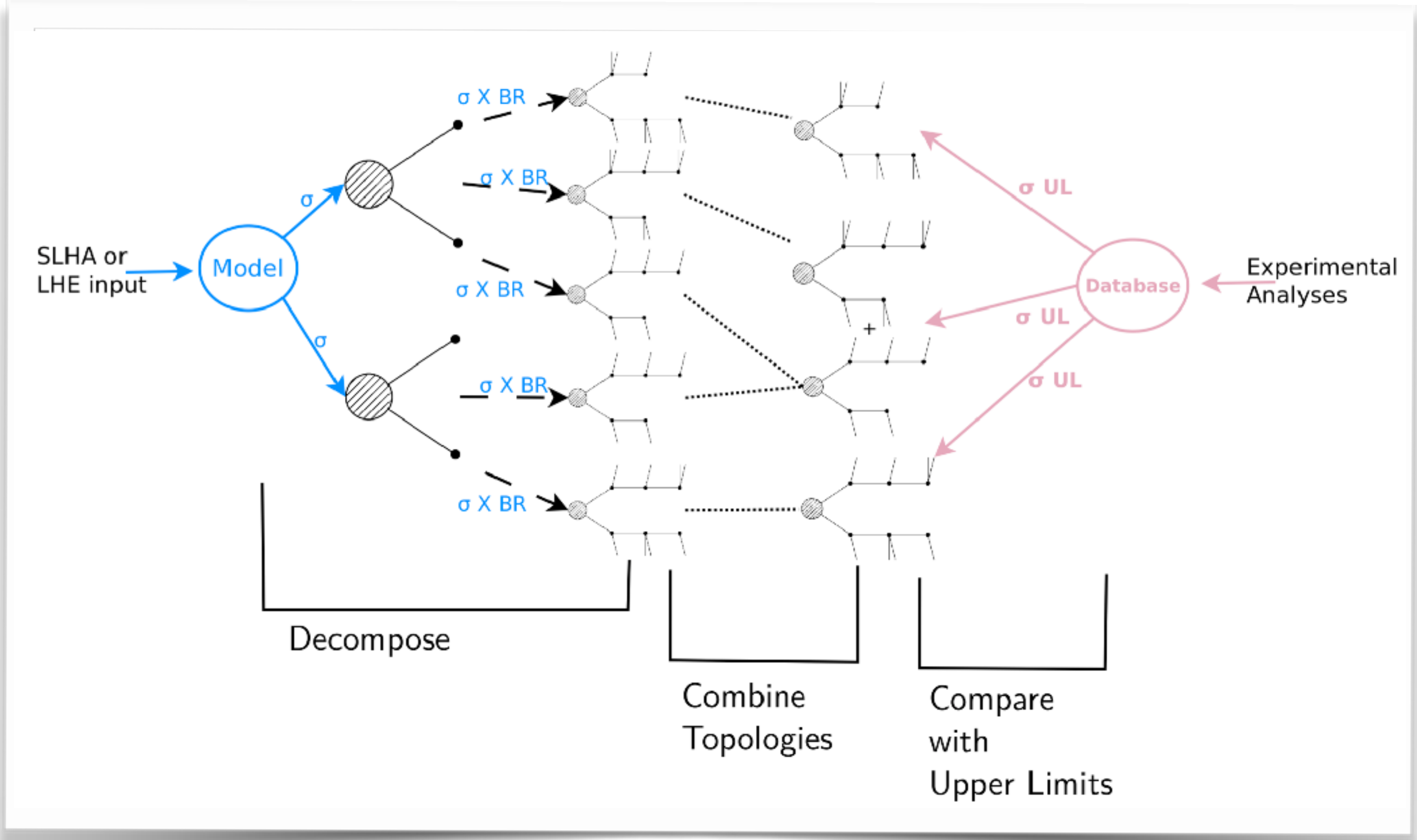
✦ Main features



- ✤ 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)]

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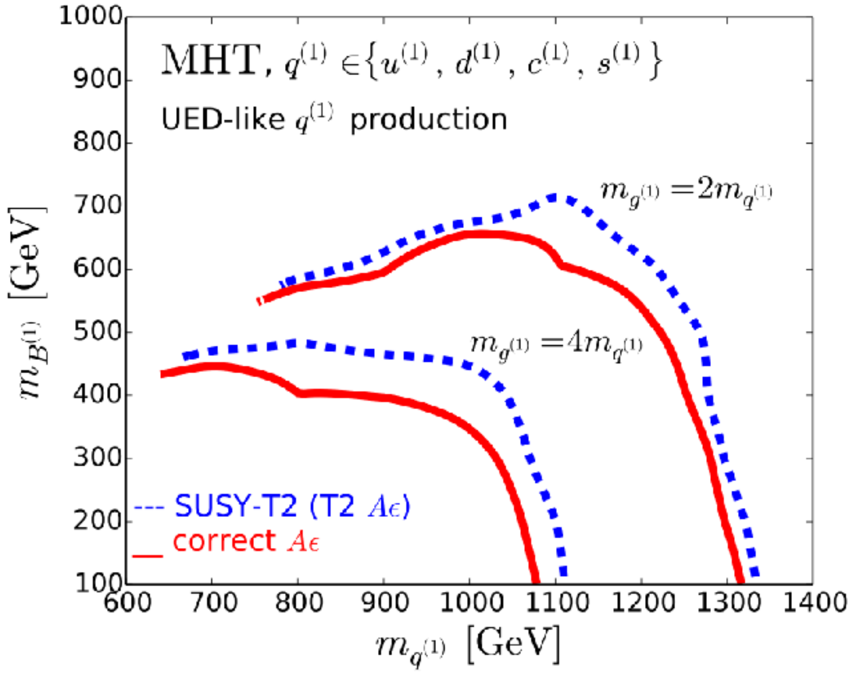
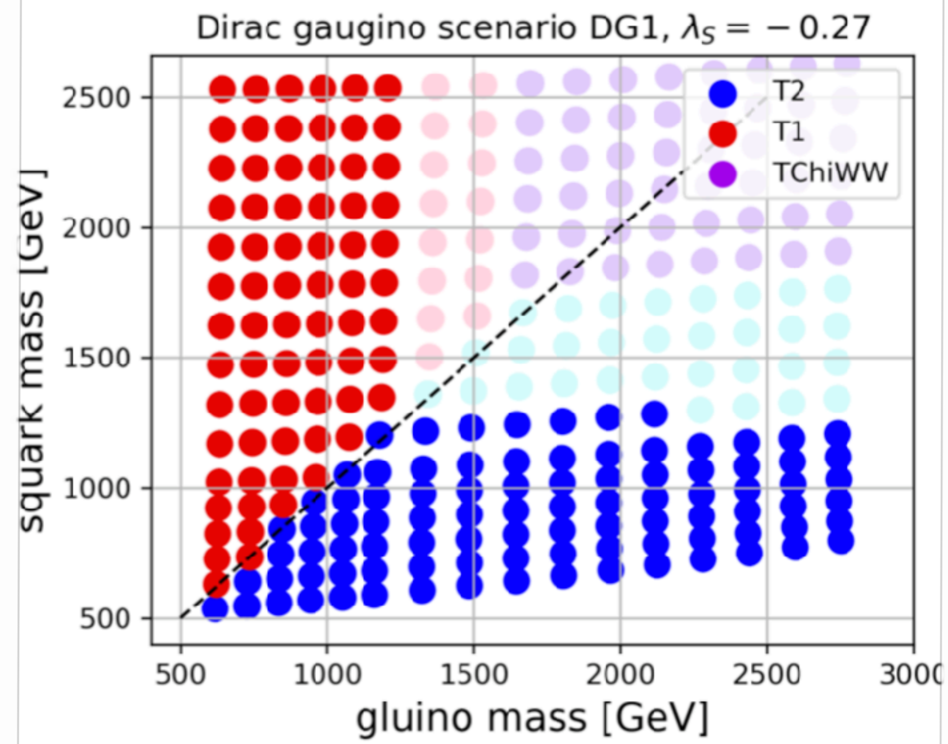
✦ Examples

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



Limitations (using SMODELS): SUSY *versus* UED

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



Dirac gauginos with SMODELS

The ‘fastsim’-based approach

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

Beyond the SMS approach

- ✦ Plethora of new physics realisations deserving to be studied
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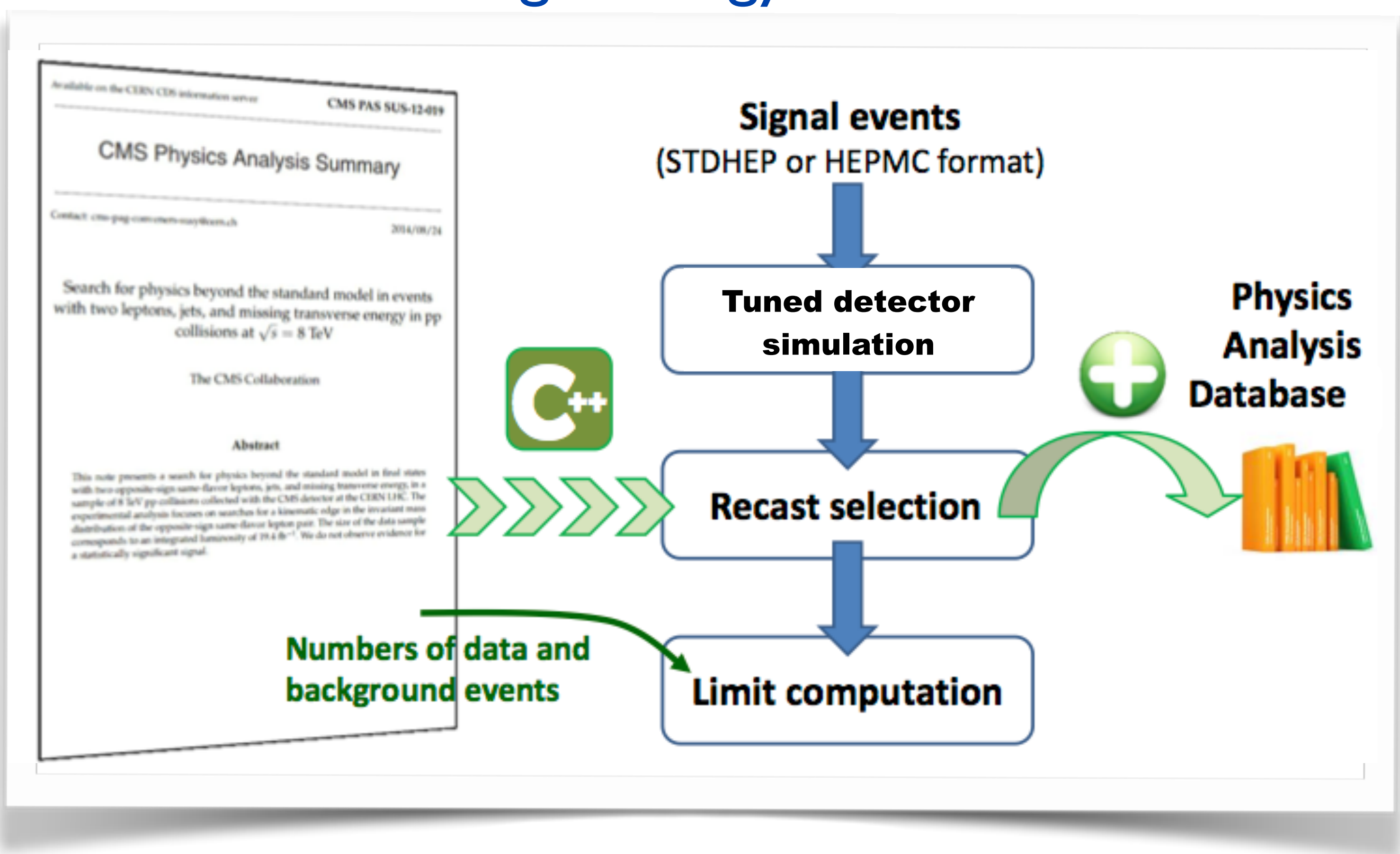
- ✦ Another recasting strategy



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

Detector modelling

✦ Detector simulation

See Eric's talk

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

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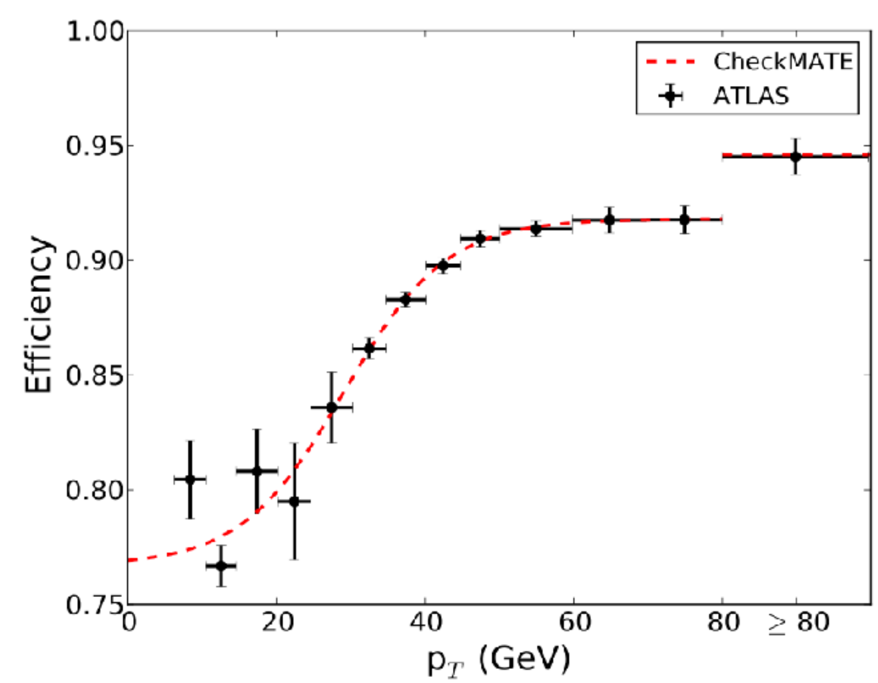
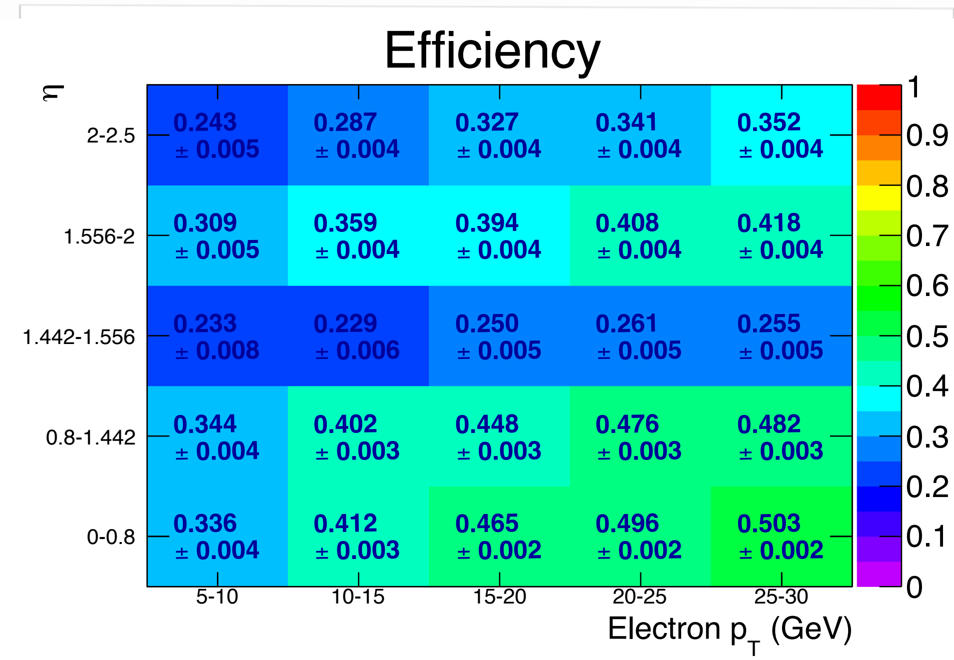
✦ Examples



Medium electron efficiency in CHECKMATE



Soft electron efficiency in MADANALYSIS 5 (SFS) and RIVET

Current existing public programmes

- ✦ 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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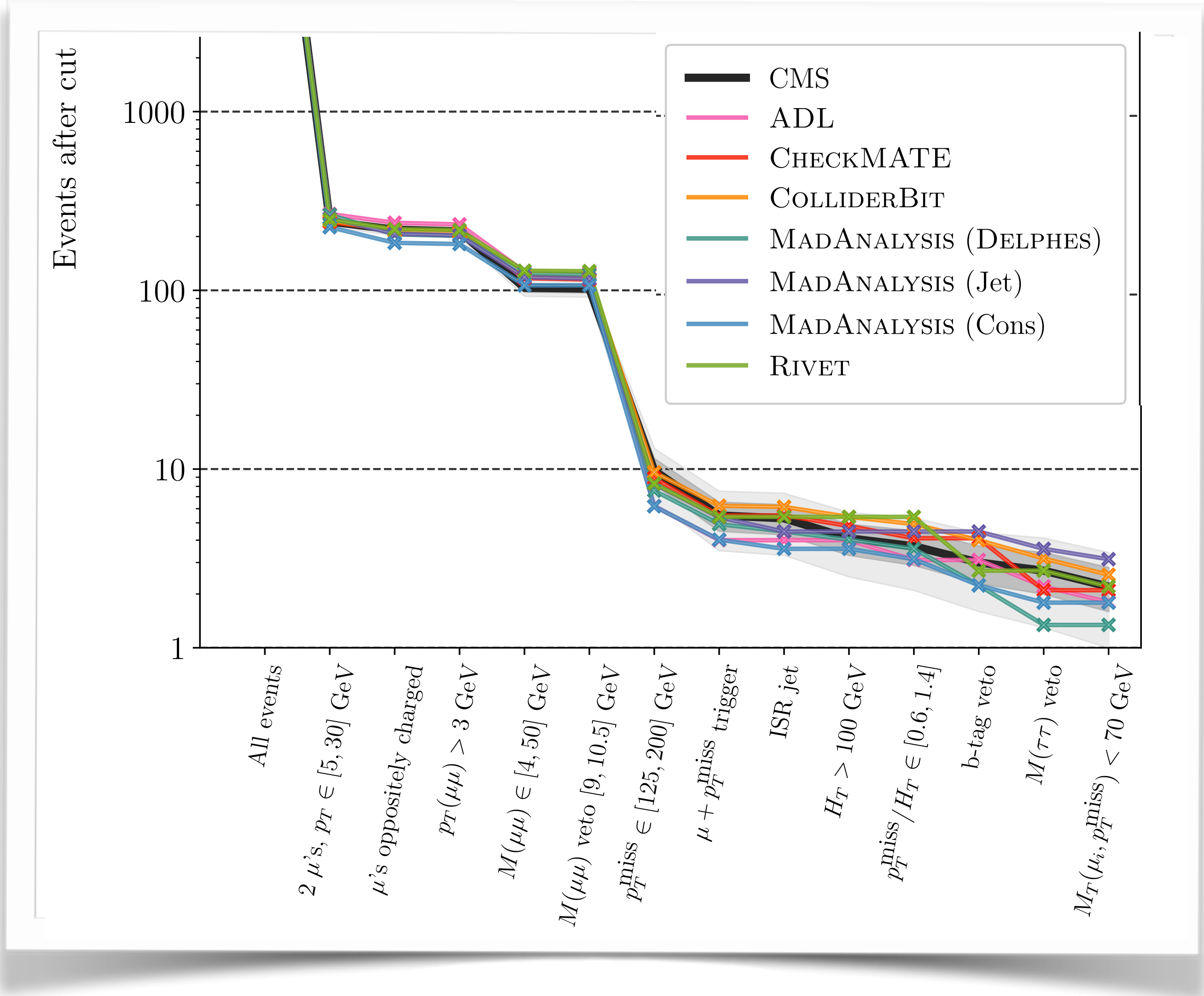
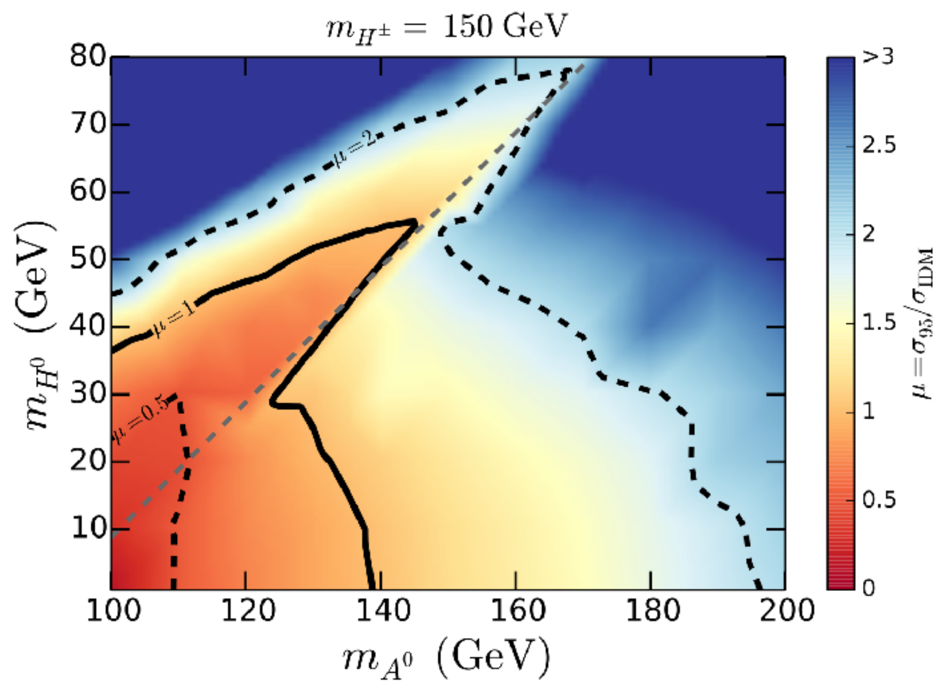


- ✦ Example: LH 2019
  - ✤ CMS-SUS-16-048
  - ✤ SUSY with soft leptons →sleptons/ewkinos
  - ✤ Reasonable agreement with CMS

Crucial to have different frameworks (transfer functions work better)

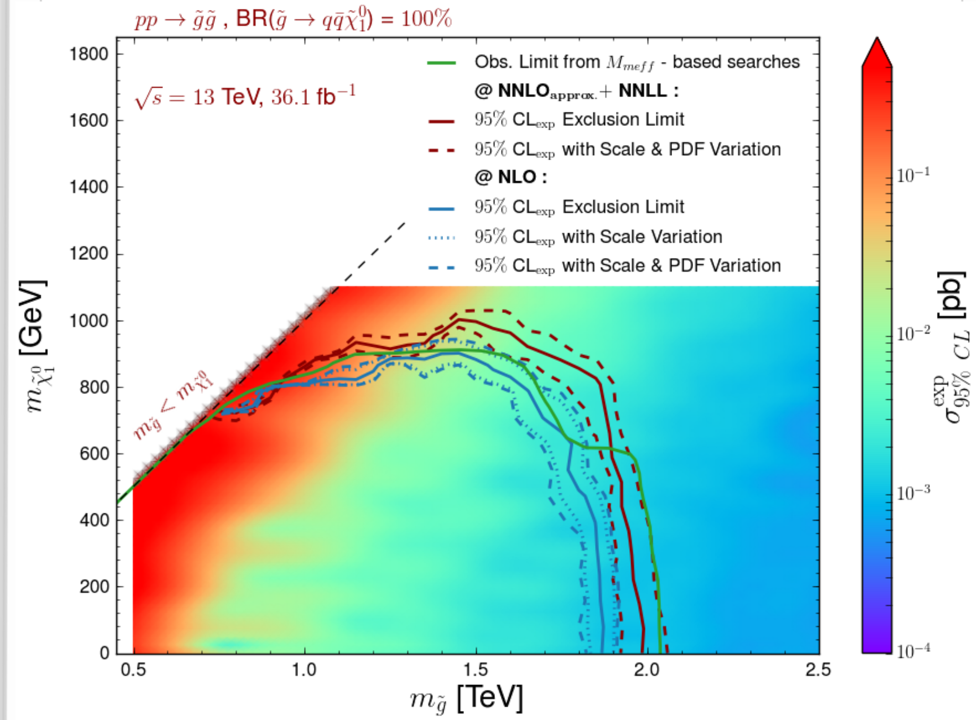
More examples

[Belanger *et al.*(PRD'15)]



The inert Higgs doublet model *vs.* SUSY searches in MADANALYSIS 5

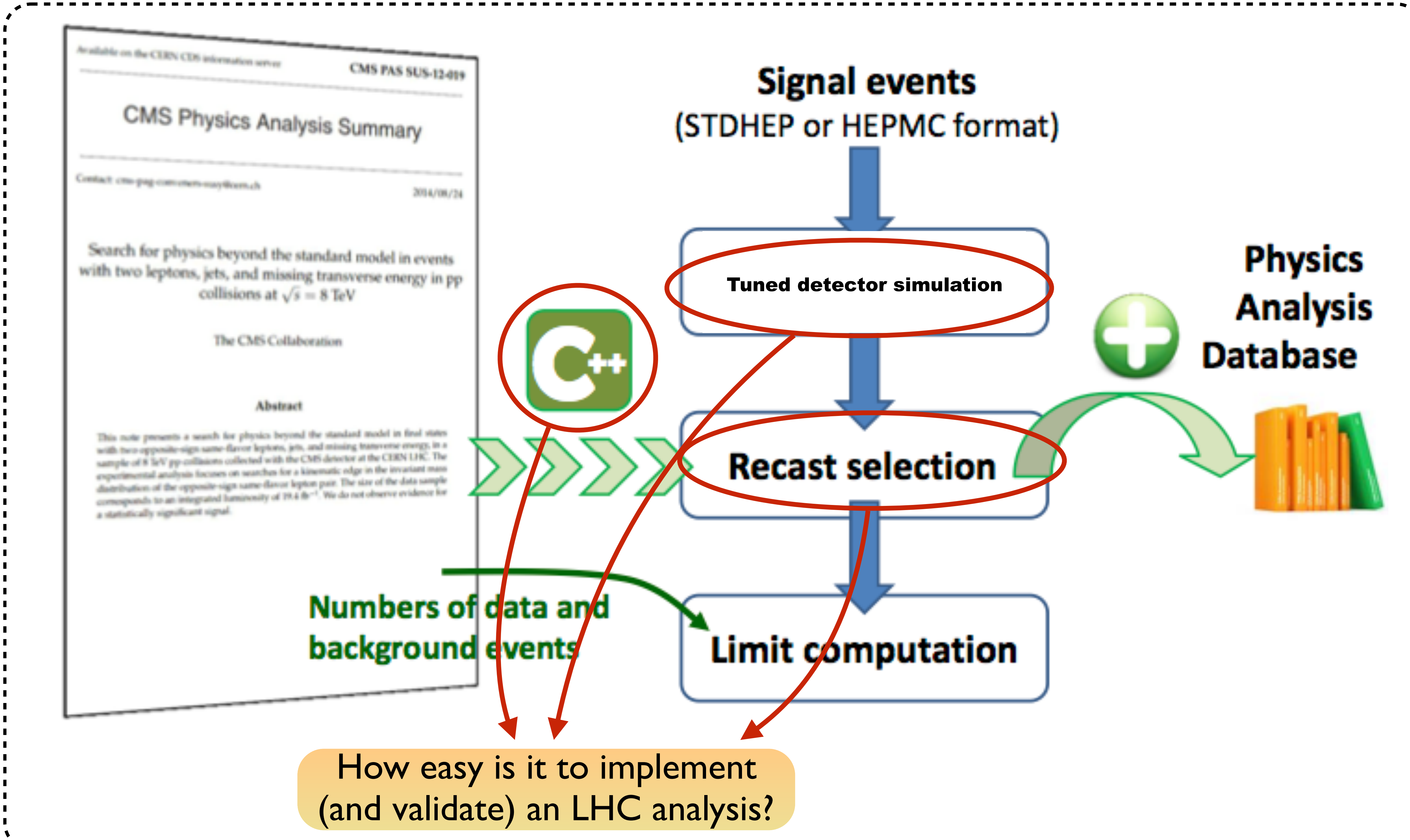
[Araz, BF & Frank (2019)]



ATLAS *vs.* MADANALYSIS 5 for gluinos

**LHC recasting
The challenges**

Reimplementing an analysis: the challenges



Implementing a new analysis

- ✦ Picking up an experimental publication
  - ✤ Reading
  - ✤ Understanding

✅ Relatively easy

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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

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Discussions with experimentalists

- ✦ Comparing theory tools and real life

CMS-SUS-17-001 in MadAnalysis 5

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

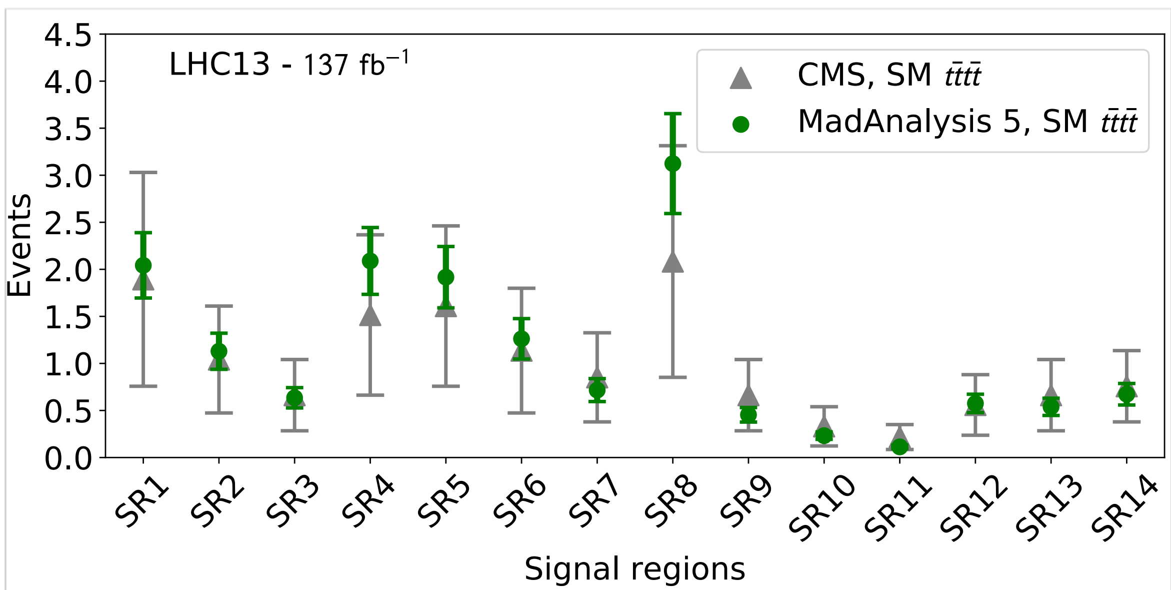
- CMS search for dark matter in the ttbar + MET channel
  - Dileptonic final state
  - Cutflows and Monte Carlo information for given benchmarks
- Validation at a very good level, cut by cut

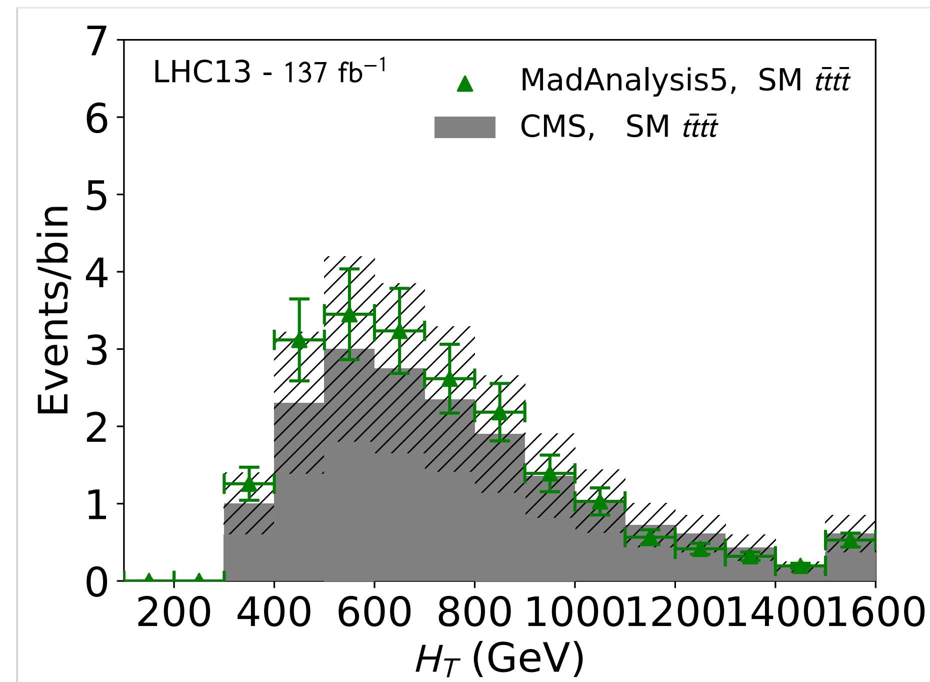
Cut	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1)$ GeV CMS	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (750, 1)$ GeV MA5	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300)$ GeV CMS	$(m_{\tilde{t}}, m_{\tilde{\chi}}) = (600, 300)$ GeV MA5
n(OS μ or e)$= 2$	-	-	-	-
$m_{\ell\ell} > 20$ GeV	0.99	0.99	0.99	0.97
$\lvert m_Z - m_{\ell\ell}\rvert > 15$ 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
$E_T^{\text{miss}} > 80$ GeV	0.94	0.95	0.89	0.88
$S > 5\ \text{GeV}^{1/2}$	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

CMS-TOP-18-003 in MADANALYSIS 5

[Darmé, BF & Maltoni (to appear)]

- ✦ CMS search for SM four-top production (in the multi-lepton channel)
  - ✤ Distributions and global selection efficiencies
- ✦ Validation as good as possible

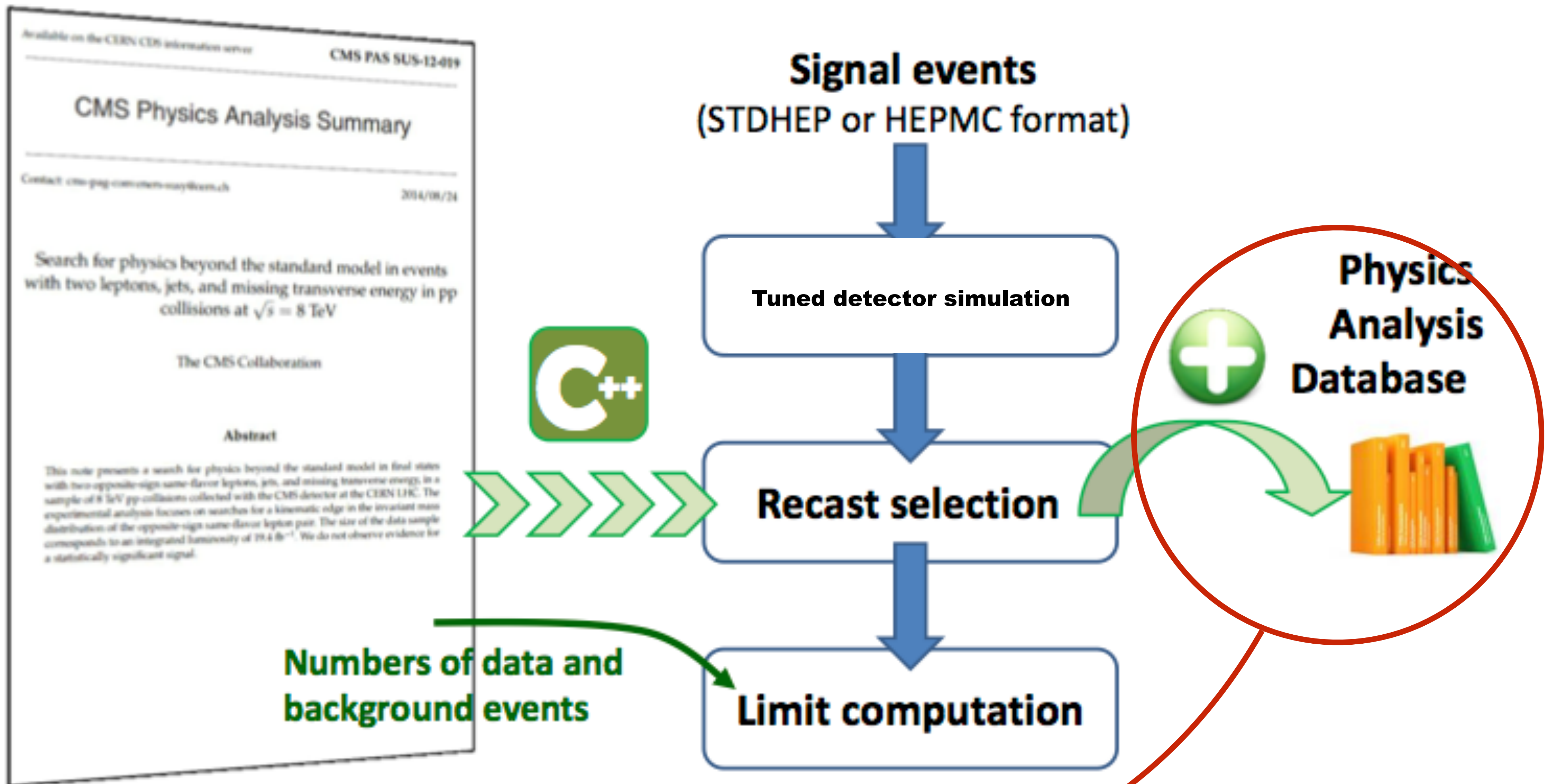




Preservation

The LHC legacy

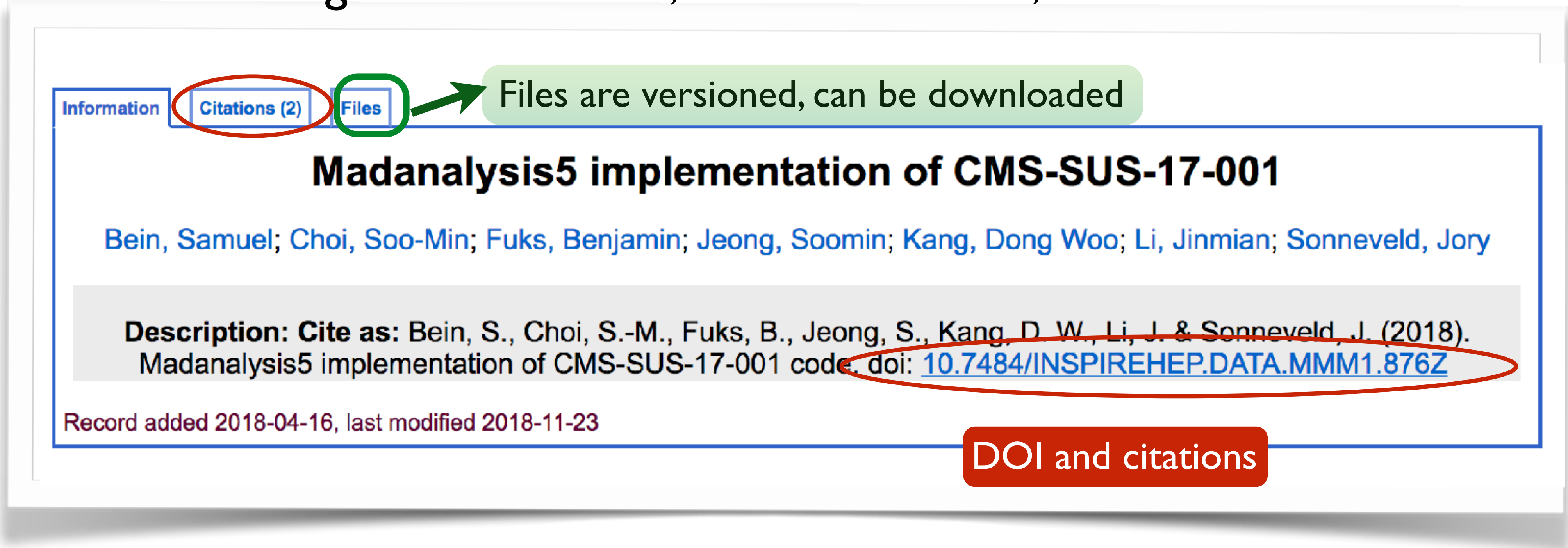
✦ Recasting strategy (as in MadAnalysis 5)



How to store recasted analyses?
Part of the LHC legacy

MADANALYSIS 5 analyses on INSPIRE

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



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.*)

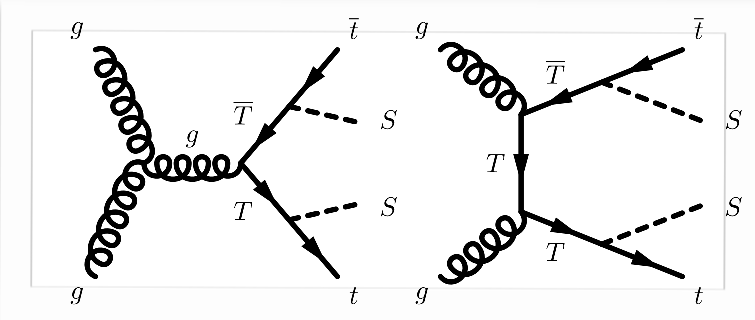
- ✦ Can be automatically installed within MADANALYSIS 5

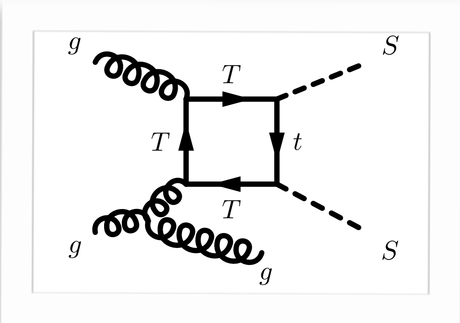
Some physics

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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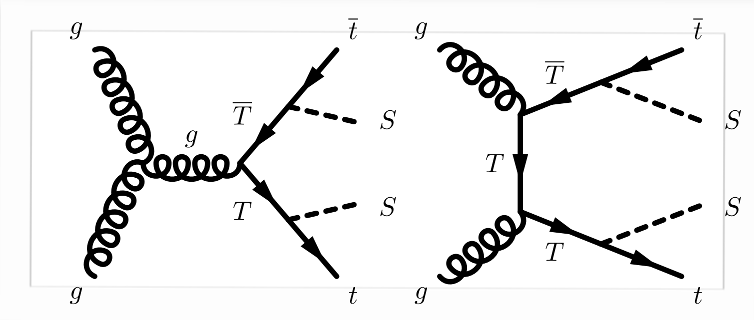

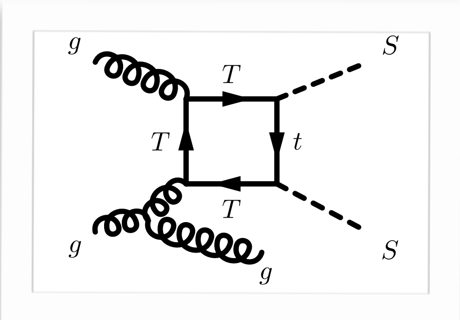

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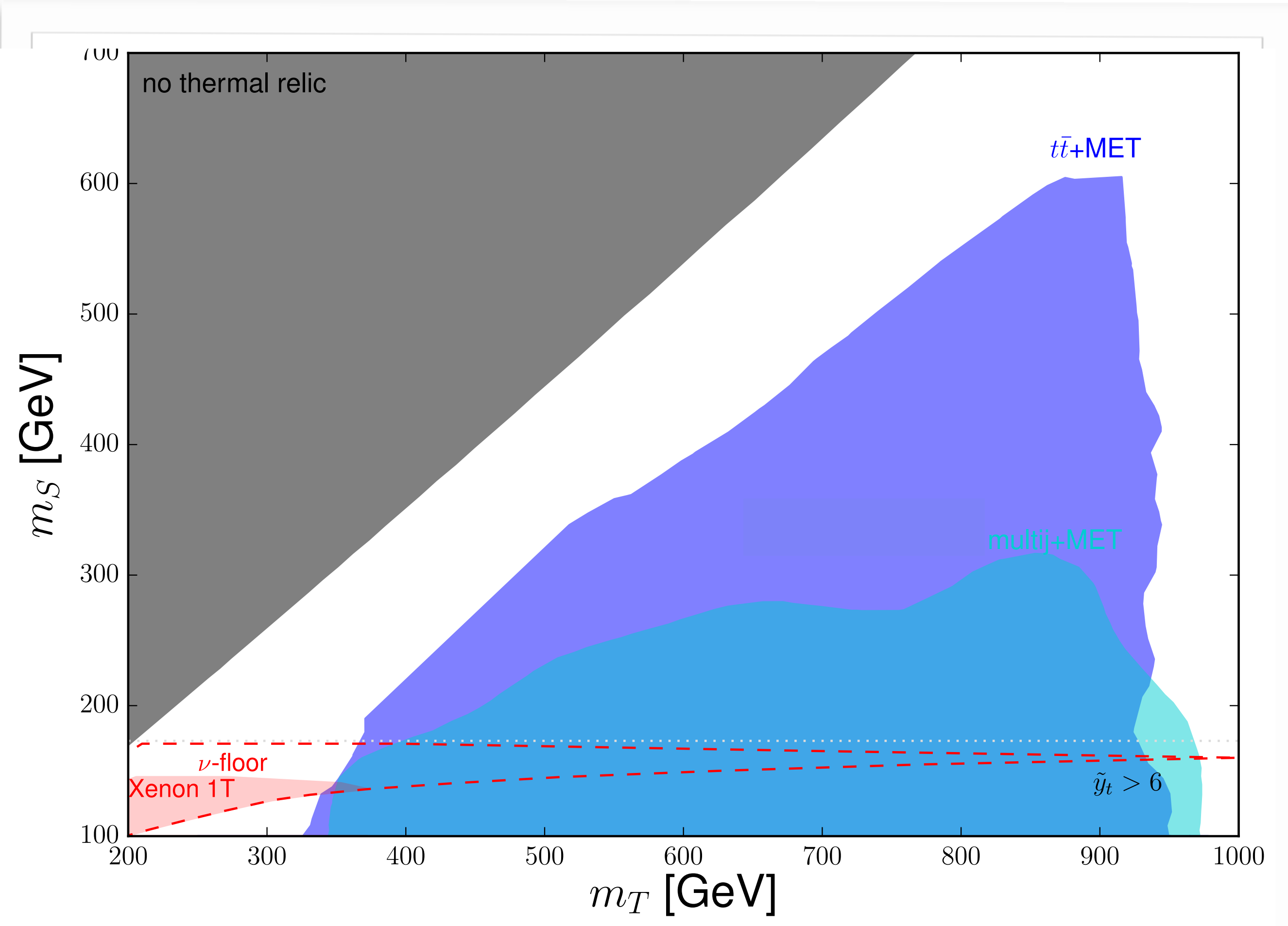


✤ General features

★ 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)

Top-philic *s*-channel dark matter

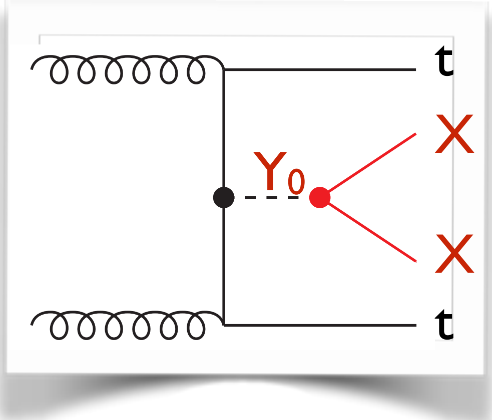
[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ 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)



Top-philic *s*-channel dark matter

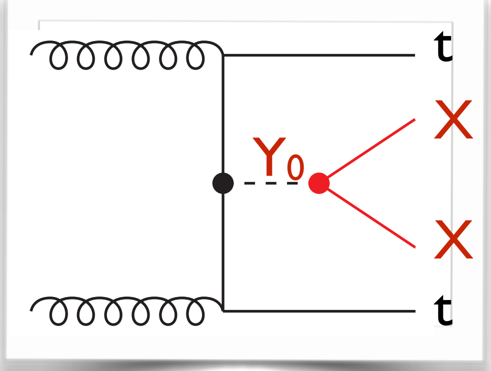
[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (JHEP'16)]

✦ A simplified model for top-philic dark matter

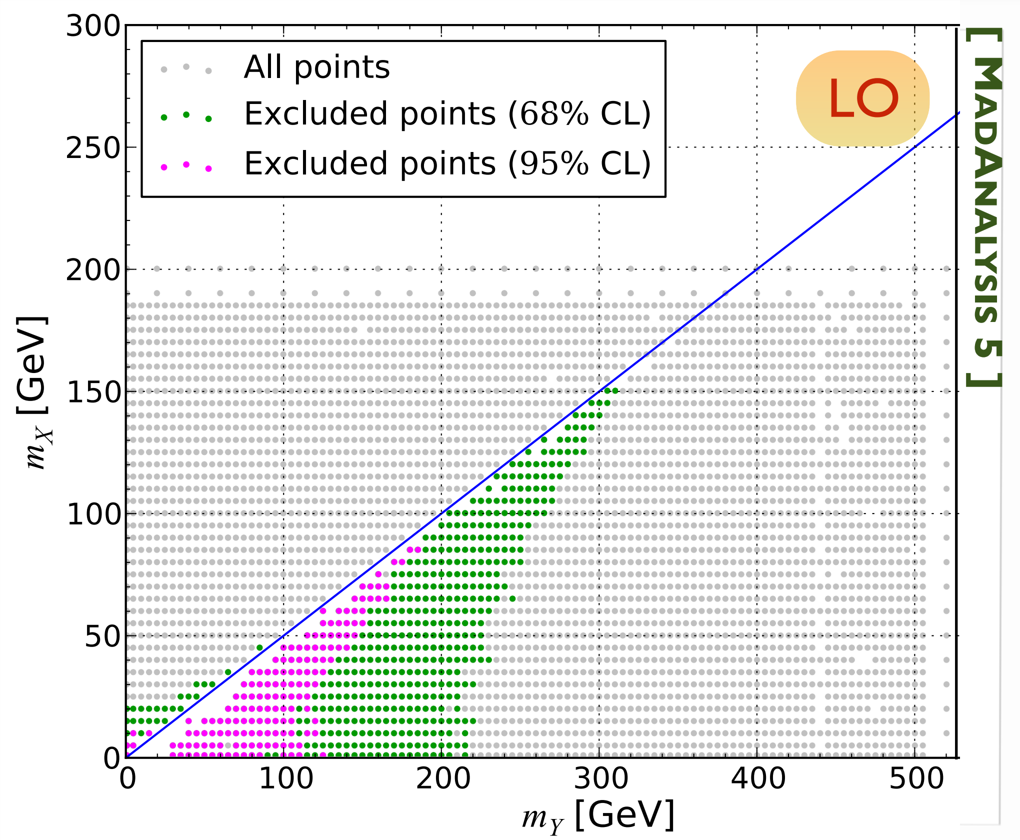
- ✤ A dark sector with a fermionic dark matter candidate X
- ✤ A (scalar) mediator Y_0 linking the dark sector and the top

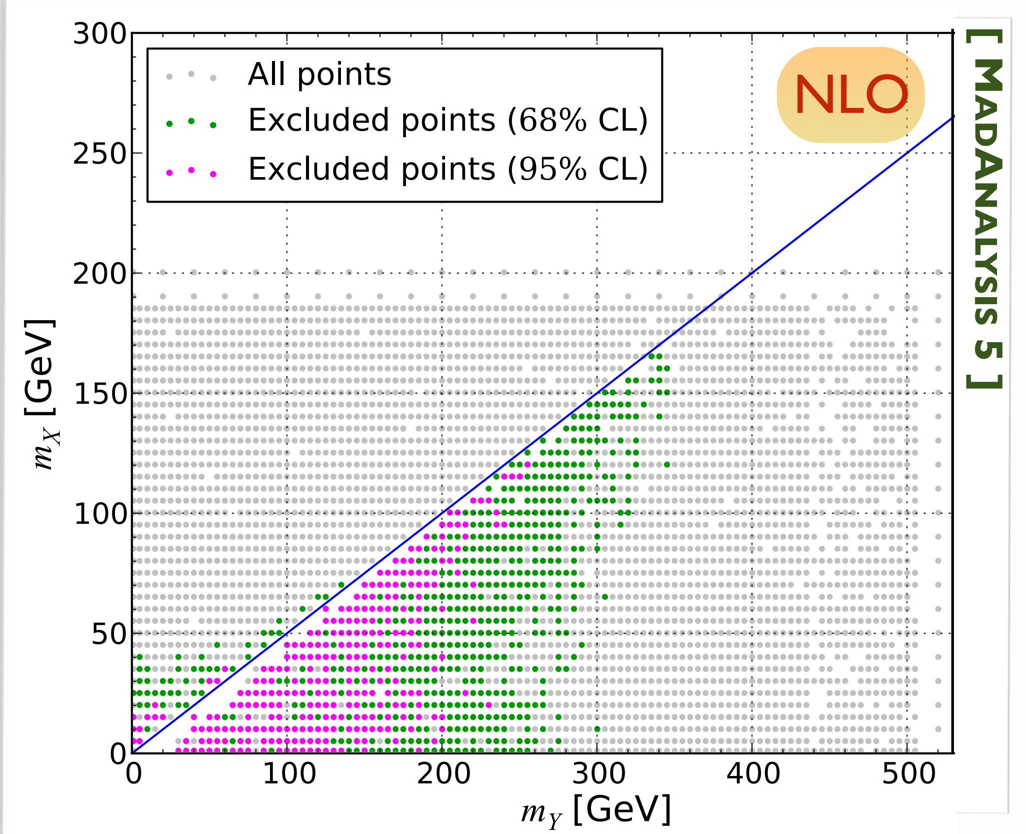
$$\mathcal{L}^{Y_0}_{t,X} = -\Big(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\Big) Y_0$$

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



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





- ✤ Including scale variations?

Top-philic s-channel dark matter @ NLO

[Arina, Backovic, Conte, BF, Guo, Heisig, Hespel, Krämer, Maltoni, Martini, Mawatari, Pellen & Vryonidou (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

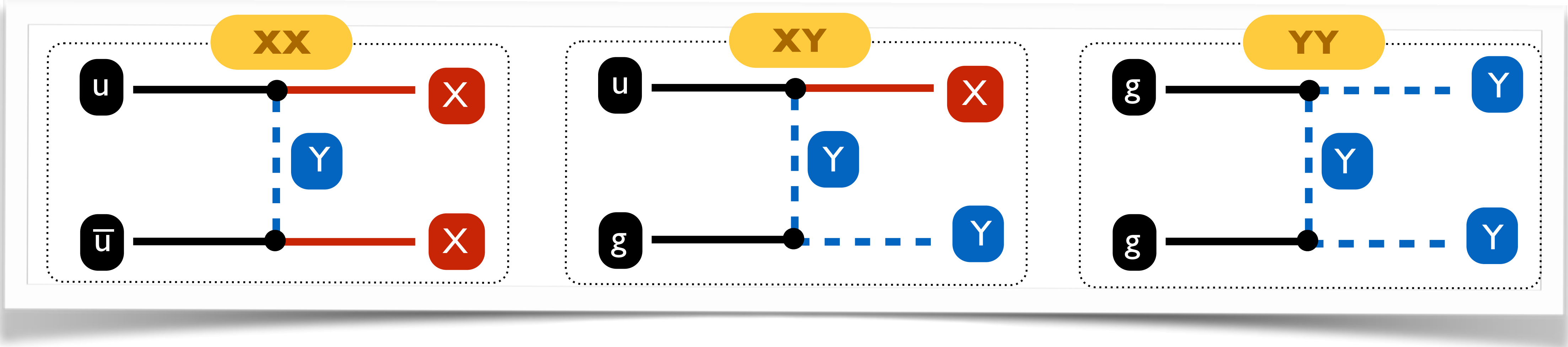
✤ The CLs number can increase / decrease at NLO

✤ The error band is reduced

t-channel dark matter (up-quark mediated)

[Arina, BF & Mantani (2020)]

✦ Three contributing classes of processes



- DM pair production
- DM/mediator associated production (+ mediator decays into DM+jet)
- Mediator pair production (+ mediator decays into DM+jet)

✦ Dark matter signal

- Each subprocess contributes to signal region population
  - Jets generated from ISR or in the mediator decays
- The signal is less naive than from considering XX production only

Recasting ATLAS SUSY 2016-27 (monojet; 36 ifb)

[Arina, BF & Mantani (2020)]

✦ CLs exclusion from the best region (m_Y = 1 TeV, m_X = 150 GeV; λ = 1)

Process	CL$_s$ [LO]	$E_T^{\rm miss}$ constraint	CL$_s$ [NLO]	$E_T^{\rm miss}$ constrtaint
Total	$75.6^{+10.1}_{-10.5}$ %	$\in [700, 800]$ GeV	$97.8^{+0.9}_{-1.4}$ %	≥ 700 GeV
XX	$0.7^{+0.6}_{-0.6}$ %	$\in [250, 300]$ GeV	$3.6^{+0.3}_{-0.6}$ %	≥ 900 GeV
XY	$62.7^{+12.3}_{-10.4}$ %	$\in [500, 600]$ GeV	$83.9^{+2.9}_{-4.3}$ %	$\in [700, 800]$ GeV
YY [total]	$24.0^{+3.1}_{-3.1}$ %	≥ 900 GeV	$58.1^{+2.2}_{-3.1}$ %	≥ 900 GeV
YY [QCD]	$10.7^{+4.4}_{-2.6}$ %	≥ 900 GeV	$17.0^{+2.1}_{-2.1}$ %	≥ 900 GeV
YY [t-channel]	$29.6^{+3.3}_{-2.6}$ %	≥ 900 GeV	$38.9^{+1.2}_{-1.8}$ %	≥ 900 GeV

[MadAnalysis 5]

- NLO simulations are crucial
  - Modification of the rates (larger yields) and shapes (different best region)
  - Better control of the theory errors
- Considering all signal components is crucial
  - One component alone is not sufficient to exclude the scenario

Impact of the uncertainties → future colliders

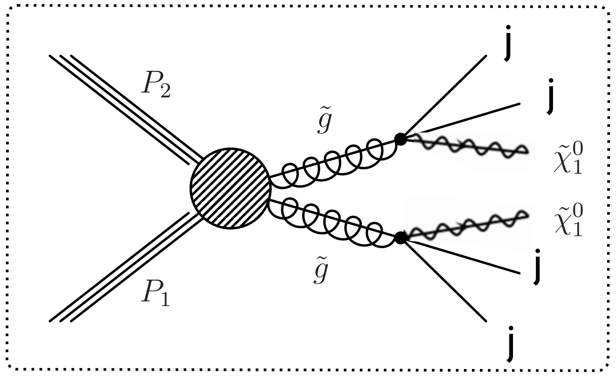
[Araz, Frank & BF (2019)]

✦ Constraining gluino pair production and decay @ LHC

✤ NLO impact on the shapes of the distributions

✤ Impact on the limits?

✤ Impact of the theory uncertainties?



Impact of the uncertainties → future colliders

[Araz, Frank & BF (2019)]

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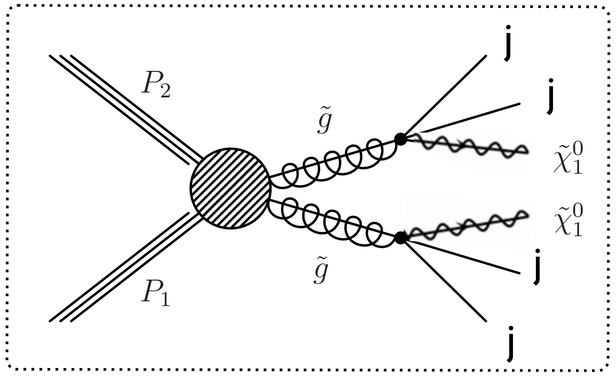
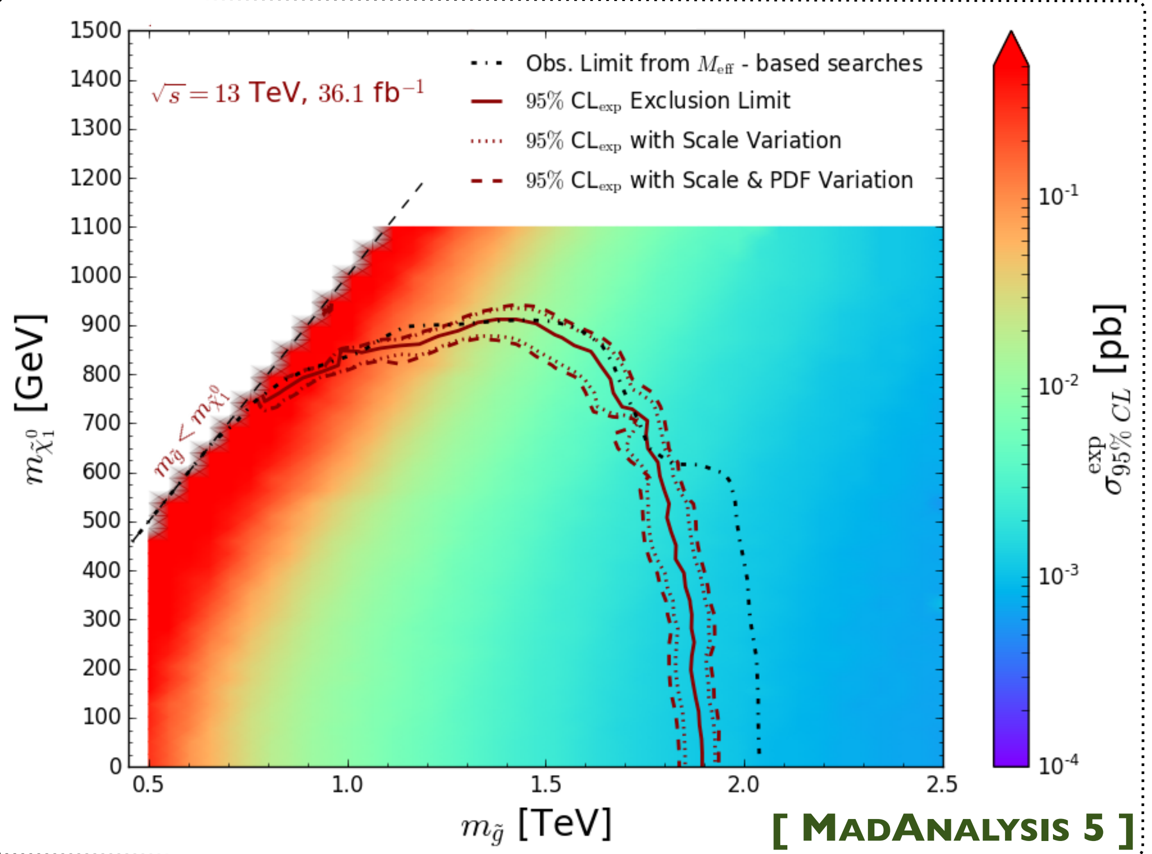
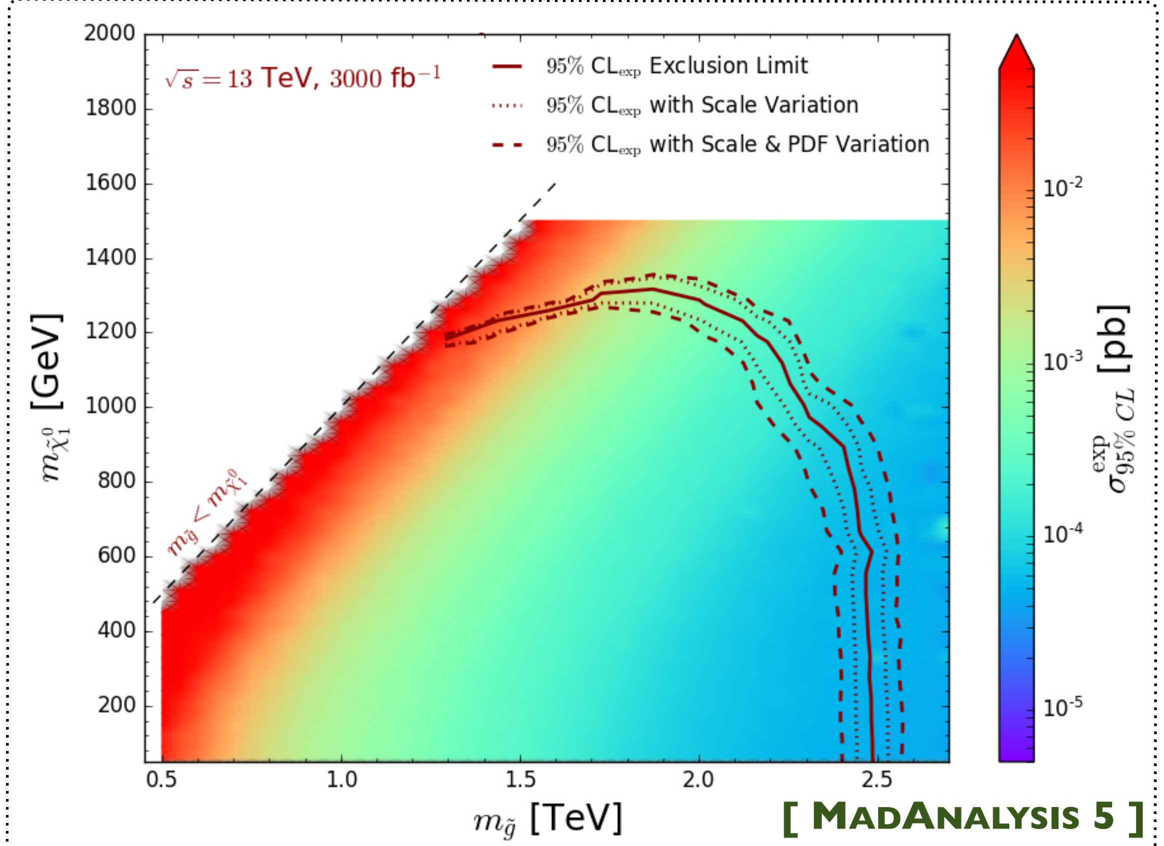


✦ Recasting ATLAS multijet + MET analysis (ATLAS SUSY 2016-07)

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





Goals of the workshop

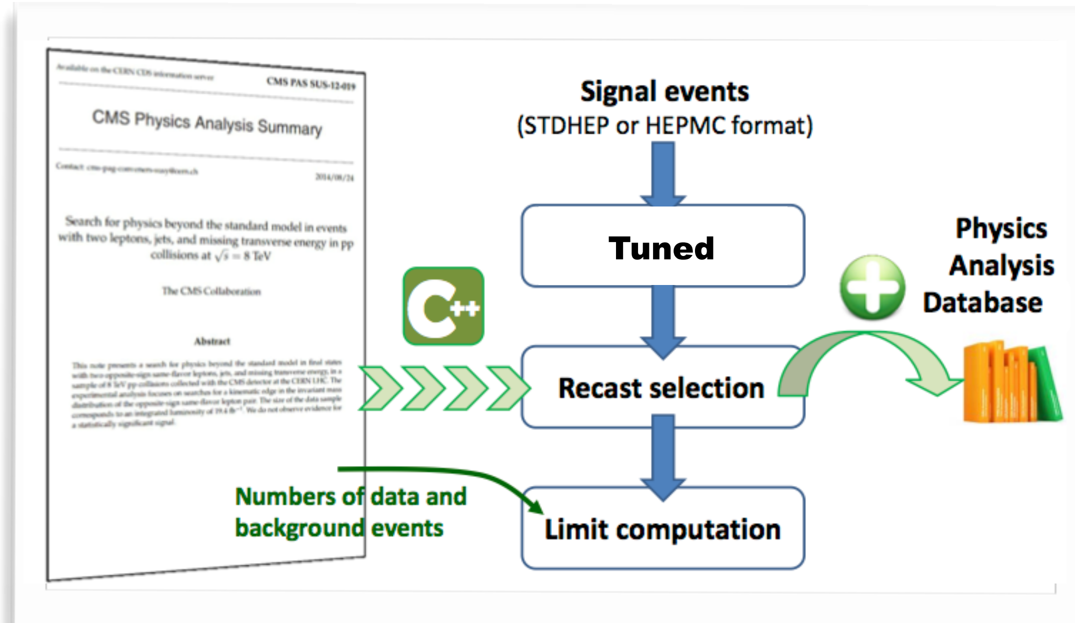
Summary

- ✦ 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)

Goals of the workshop

- ✦ A full recasting exercise
  - ✤ Reading
  - ✤ Reimplementation
  - ✤ Validation
  - ✤ Physics
  - ✤ Student presentation
  - ✤ Publication (proceedings)



Programme: tools & physics

	13 Feb 2020	14 Feb 2020	15 Feb 2020	16 Feb 2020	17 Feb 2020	18 Feb 2020	19 Feb 2020	20 Feb 2020
09:00-09:30		Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast	Breakfast
09:30 - 10:30		Di-Higgs for new physics	Experimental physics at the LHC	Machine learning in particle physics (1/2)	Introduction to composite models	Machine learning in particle physics (2/2)	The Standard Model and beyond (2/2)	Student talk preparation
10:30 - 10:45		Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break	Coffee break
10:45 - 12:15		MadAnalysis 5 for experts (1/2)	Analysis design (1/3)	Detector simulation Analysis validation (1/2)	Detector simulation Analysis validation (2/2)	Detector parameterisation and tests	Validation (2/4)	Student talk preparation
12:15 - 13:30		Lunch break	Lunch break	Lunch break	Lunch break	Lunch break	Lunch break	Lunch break
13:30 - 14:30	The problematics of recasting	MadAnalysis 5 for experts (2/2)	MC simulations	Free time	Jet physics	The Standard Model and beyond (1/2)	Neutrino physics at the LHC	**Student presentations**
14:30 - 15:30							Validation (3/4)	
15:30 - 16:00	Coffee break	Coffee break	Coffee break		Coffee break	Coffee break	Coffee break	Coffee break
16:00 - 18:30	Software installation & basic tutorials	Working group formation & analysis presentations	Analysis design (2/3)		Analysis design (3/3)	Validation (1/4)	Validation (4/4)	

- An international team of lecturers and tutors
  - Eric Conte, Thomas Flacke, Taejeong Kim, Pyungwon Ko, Richard Ruiz, Jeonghyeon Song, Hwidong Yoo
  - Jack Araz, Robin Ducrocq, Thomas Flacke, Si Hyun Jeon, Richard Ruiz, Dipan Sengupta,

More information: https://indico.cern.ch/e/ma5_2020

The recasting exercice

- ✦ Pick your three favourite analyses
  → send your choices to fuks@lpthe.jussieu.fr
  - ✤ ATLAS-EXOT-2018-30: W' search (single lepton + MET)
  - ✤ ATLAS-SUSY-2017-04: displaced leptons
  - ✤ ATLAS SUSY-2018-04: stau pair
  - ✤ ATLAS SUSY-2018-06: electroweakinos (multi-leptons + missing energy)
  - ✤ CMS EXO-17-030: tri-jet resonance pair production (RPV gluinos)
  - ✤ CMS EXO-19-002: multi-leptons + missing energy (neutrino models)
  - ✤ CMS HIG-18-011: exotic Higgs to pseudo-scalars into 2μ+2b