Top LHC France 2023

Testing BSM theories against cross section measurements

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[SciPost Phys. Core 6, 014 (2023)]

Probing a leptophobic top-colour model with cross section measurements and precise signal and background predictions: A case study

17 May 2023

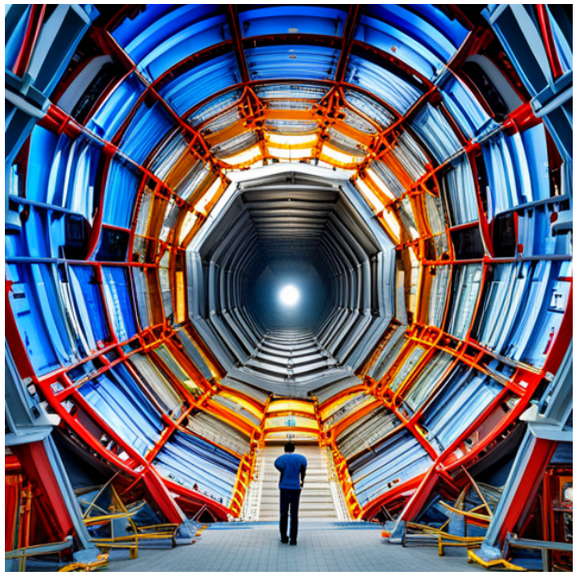
Plan of the presentation

- **Introduction**
  - Motivation
  - Rivet
  - Contur
- **Calculations of signal and background**
  - Signal
  - Background
- **Sensitivity**
  - 1st Approach
  - 2nd Approach
  - Measurements vs searches
- **Summary & Conclusions**

Part I

Introduction

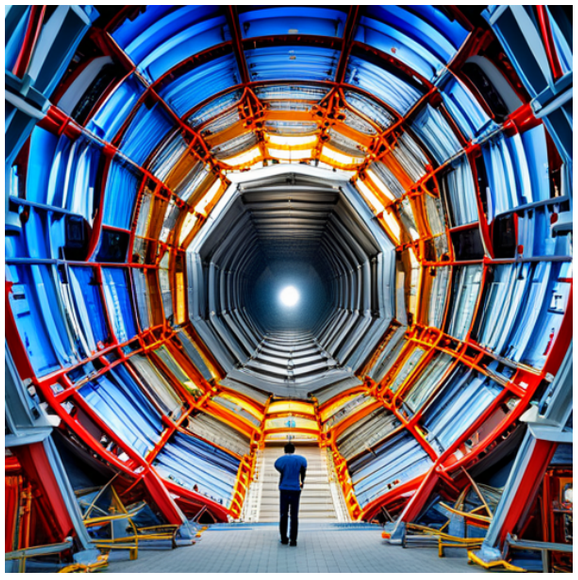
Motivation



dream.ai

- **LHC**: test the **SM** & search for new physics (**NP**).

Motivation



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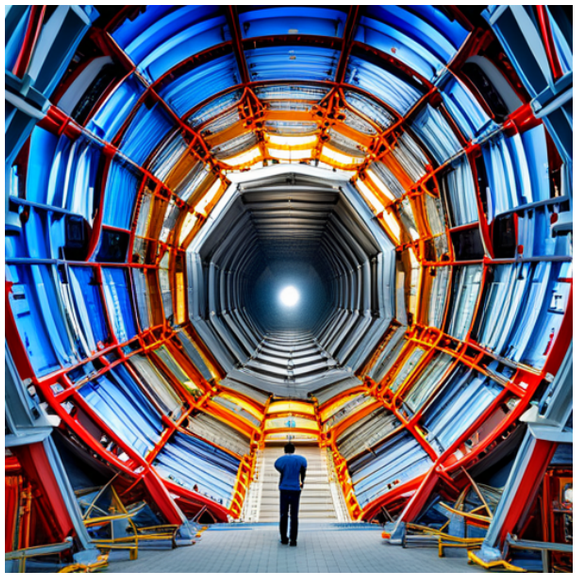

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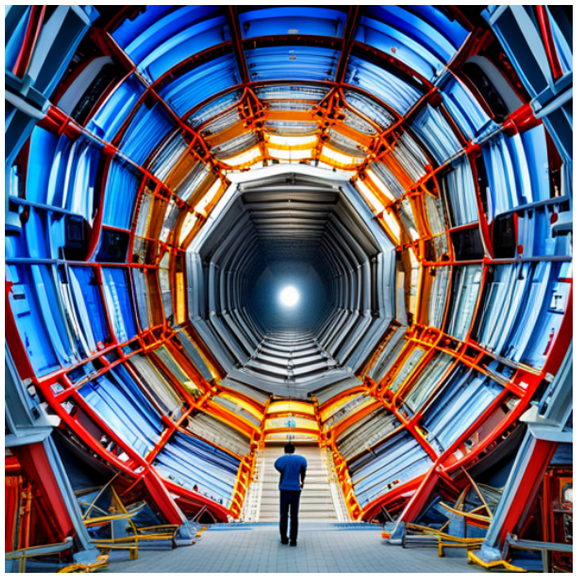

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- **Precision calculation**: **SM** background & **NP** signals.

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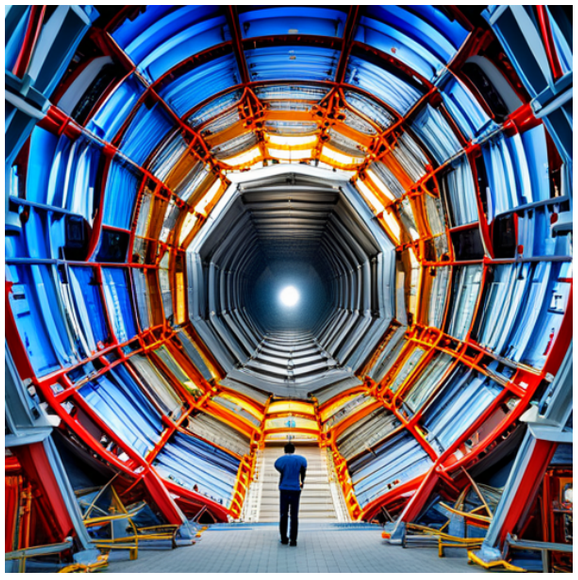

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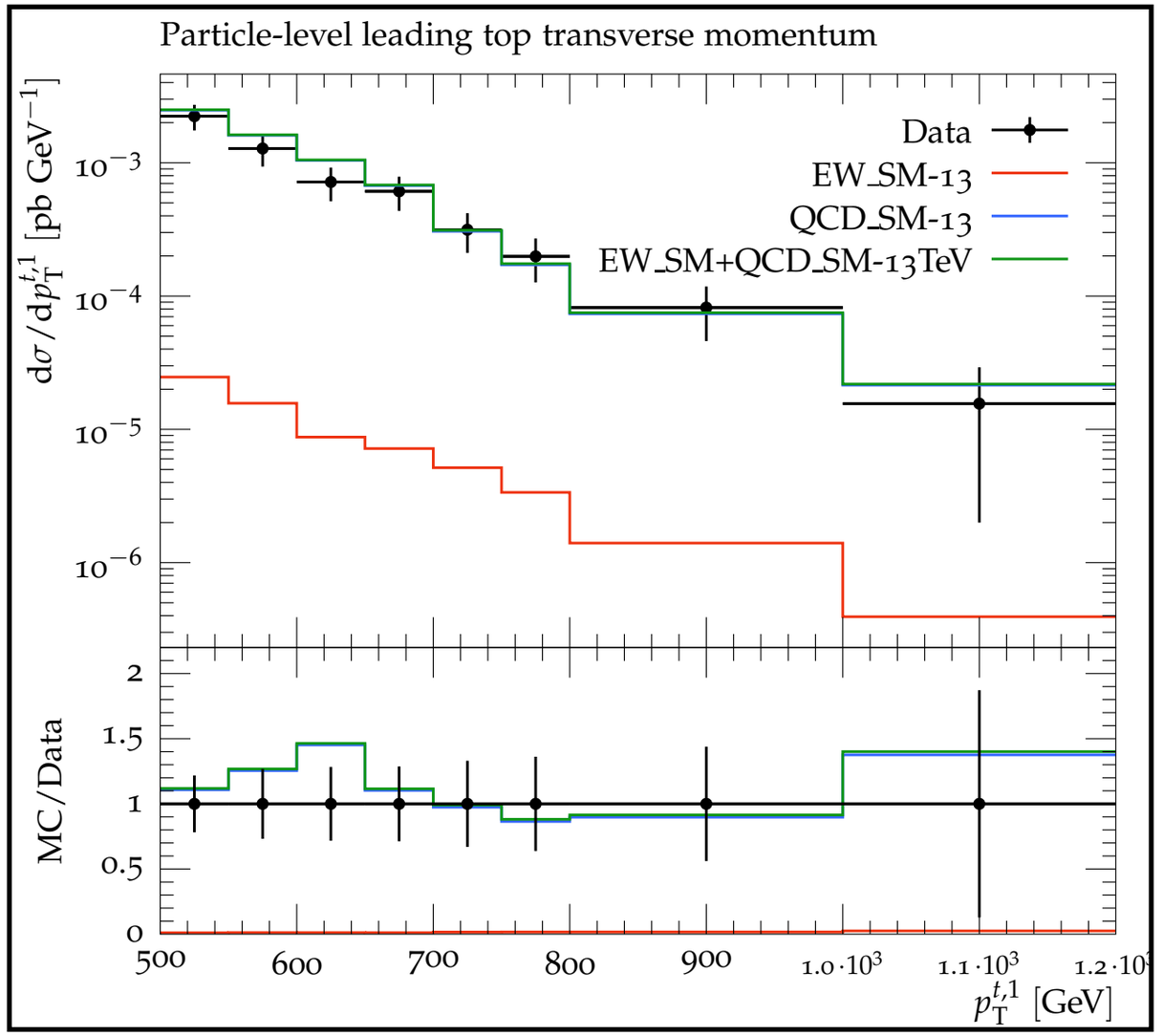
Rivet

- **R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory
  - Preservation of particle-collider analyses logic
  - Tuning of non perturbative parameters
  - Validation and improvement of **MCEG** codes
  - Analysis reinterpretation via **MC** simulations



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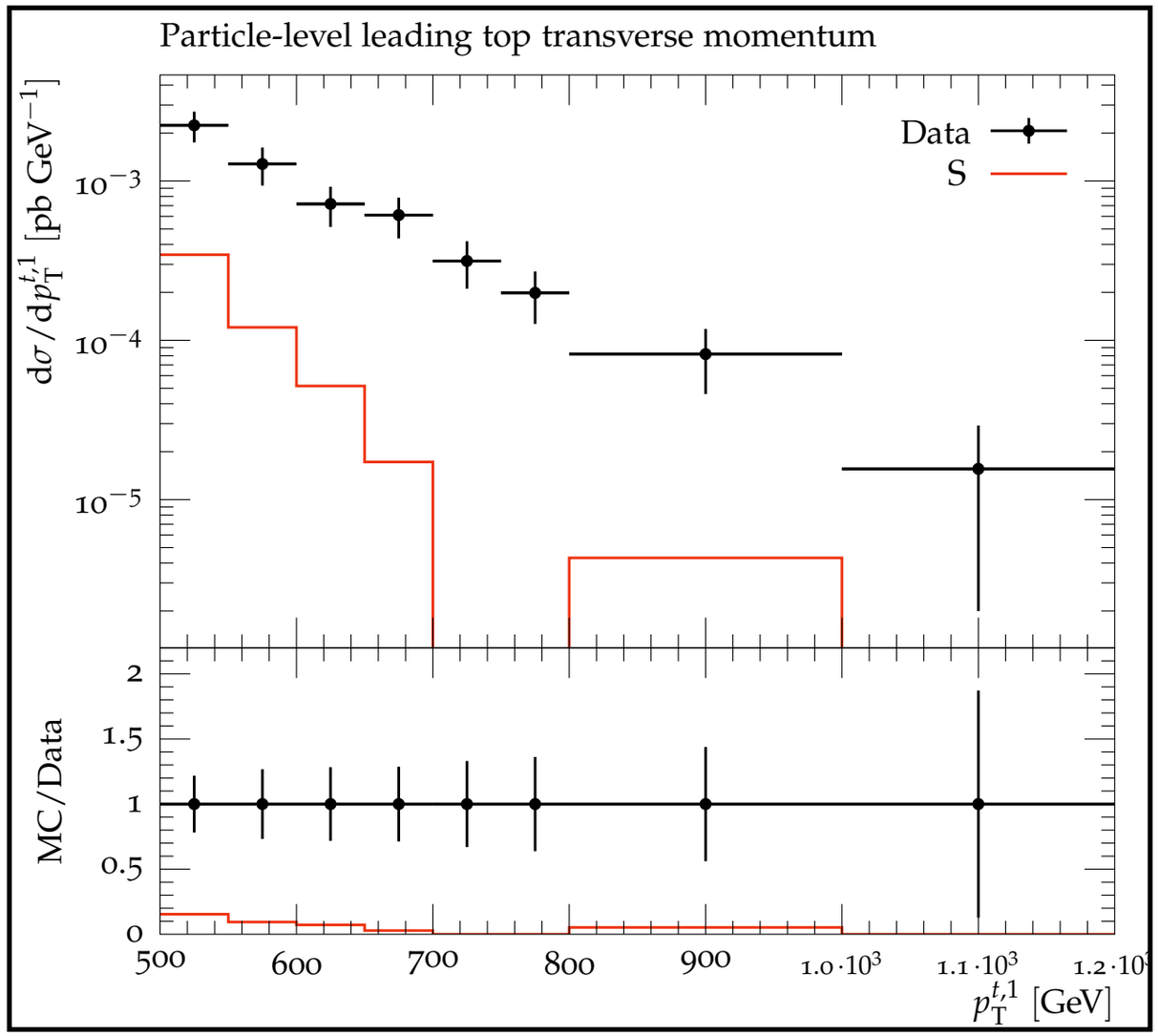

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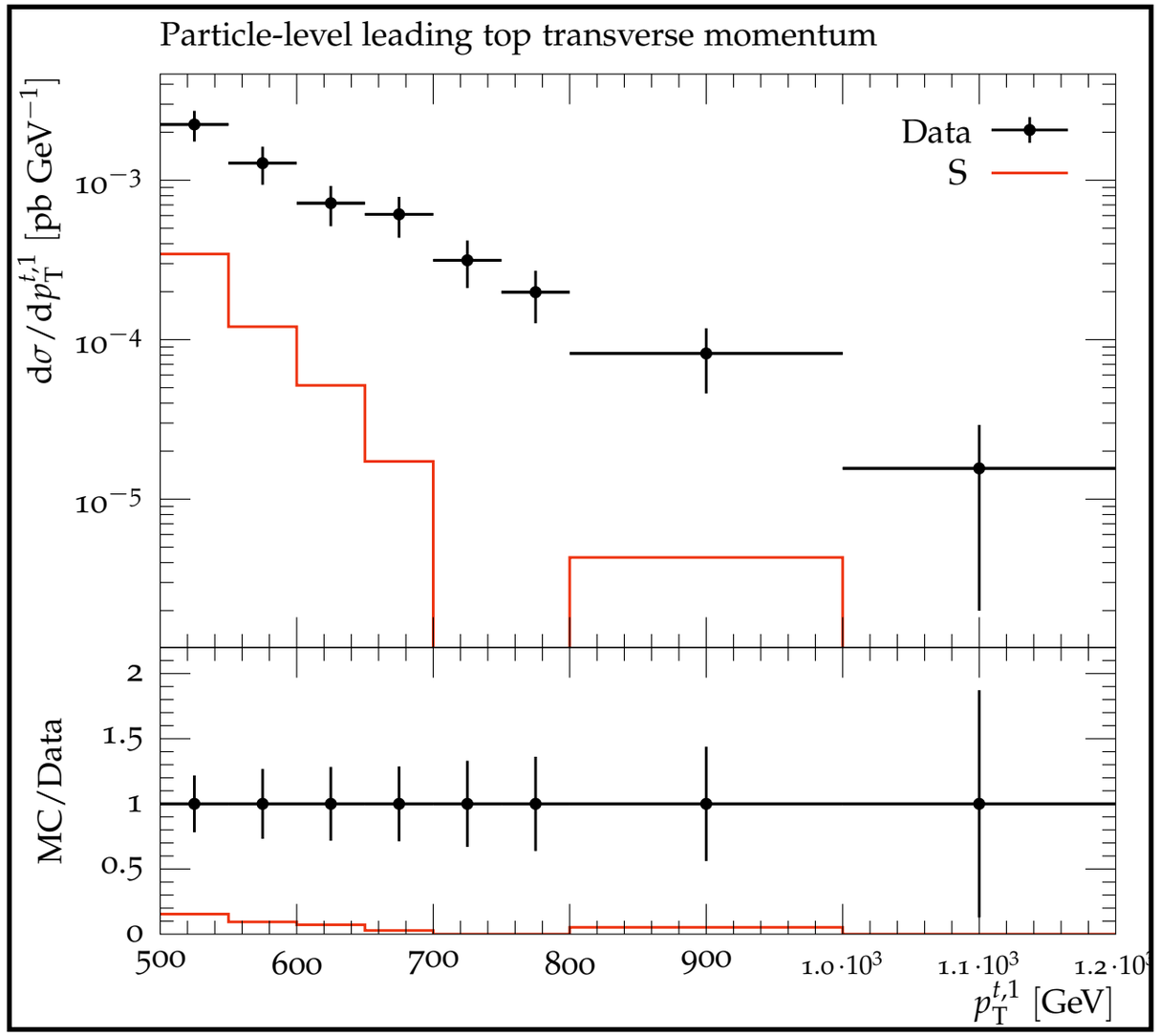
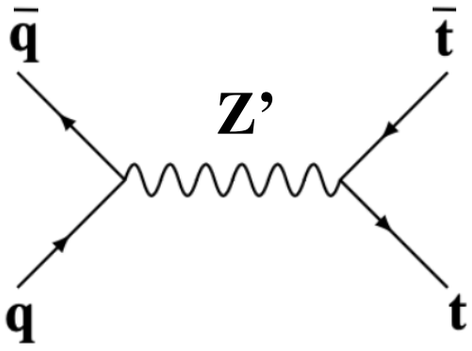
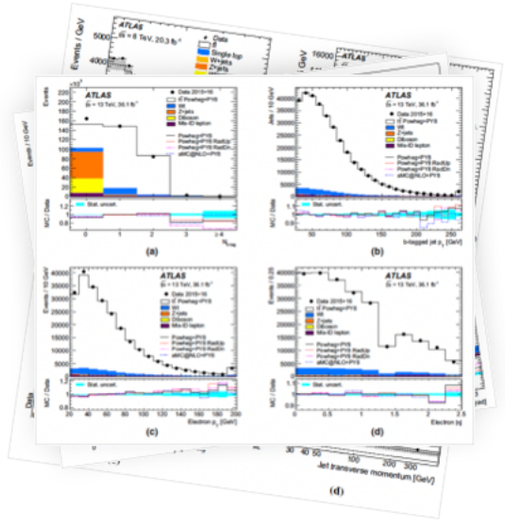


Contur uses bank of **LHC** results preserved in **Rivet** to rapidly check if new models are already ruled out

Contur





- At what significance do existing **measurements** exclude the **BSM** idea?
- **Two approaches** can be used in order to calculate the exclusion limits.

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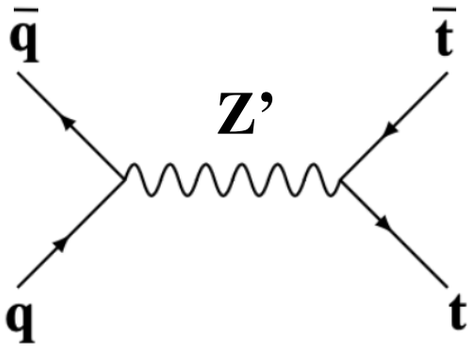
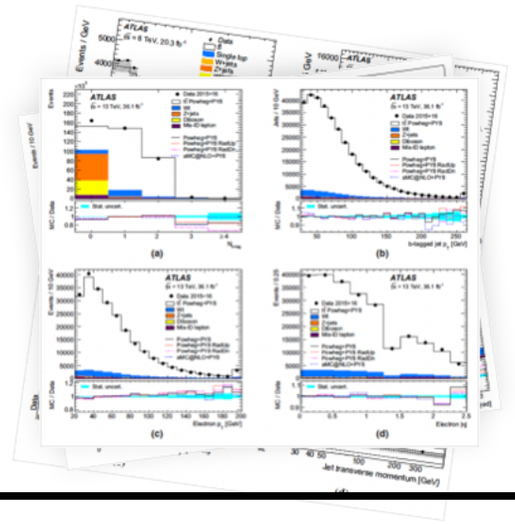
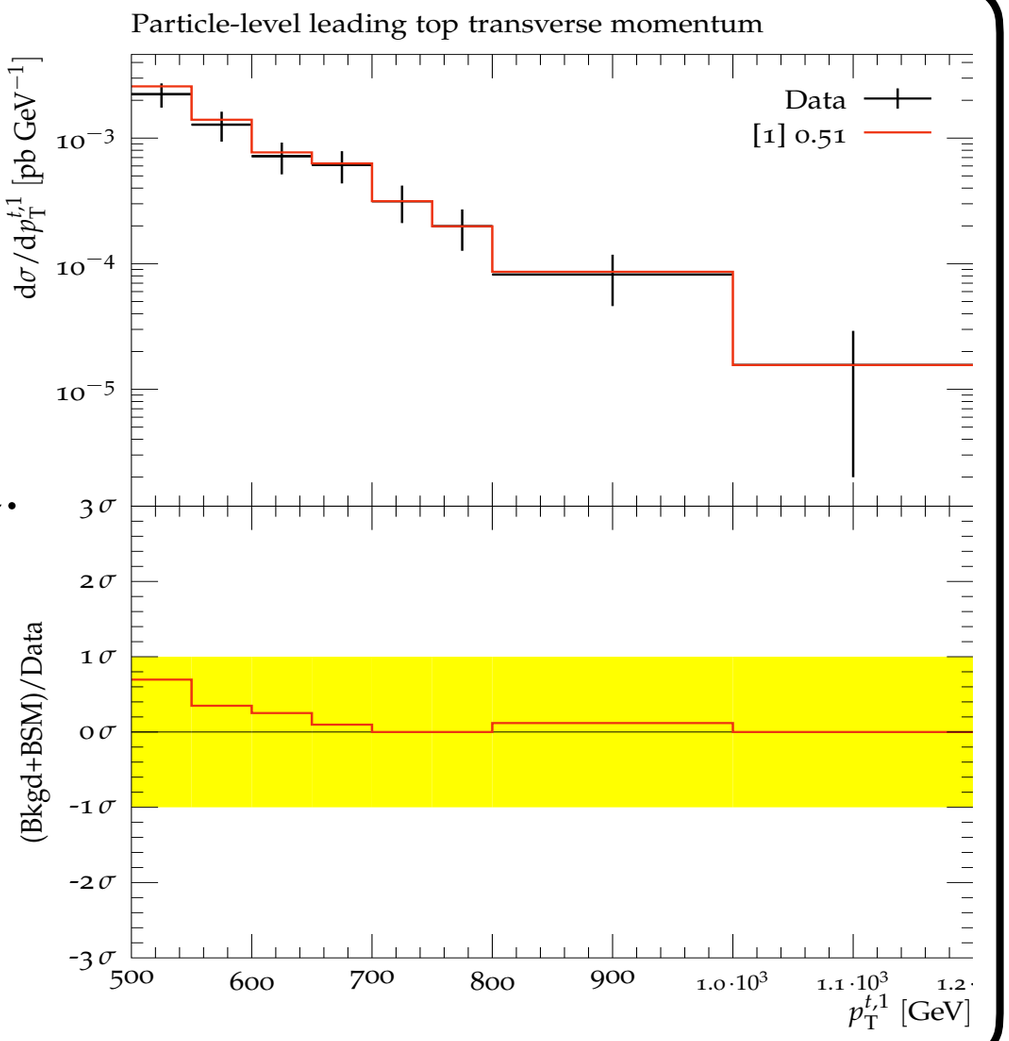




- At what significance do existing **measurements** exclude the **BSM** idea?
- **Two approaches** can be used in order to calculate the exclusion limits.

1st Approach (default):

- **Condition:**
  - Striking signals.
  - Data & **SM** agree.
- **Method**:
  - Assume background = data.
  - Add signal on top of background.
  - Uncertainties on the data define the room left for **BSM**.



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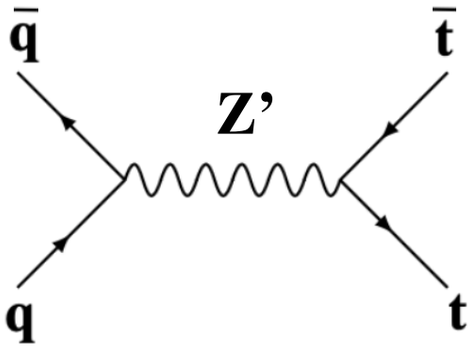

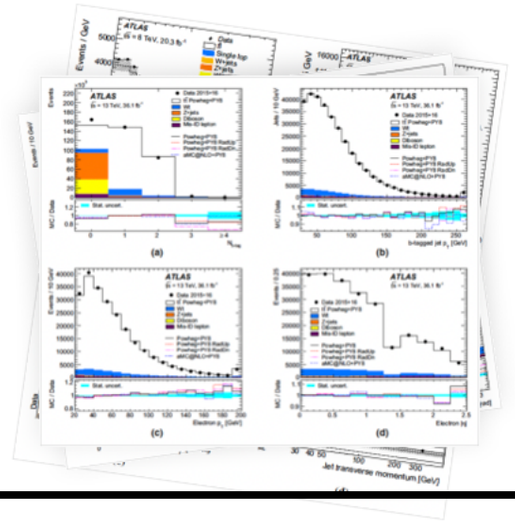

- At what significance do existing **measurements** exclude the **BSM** idea?
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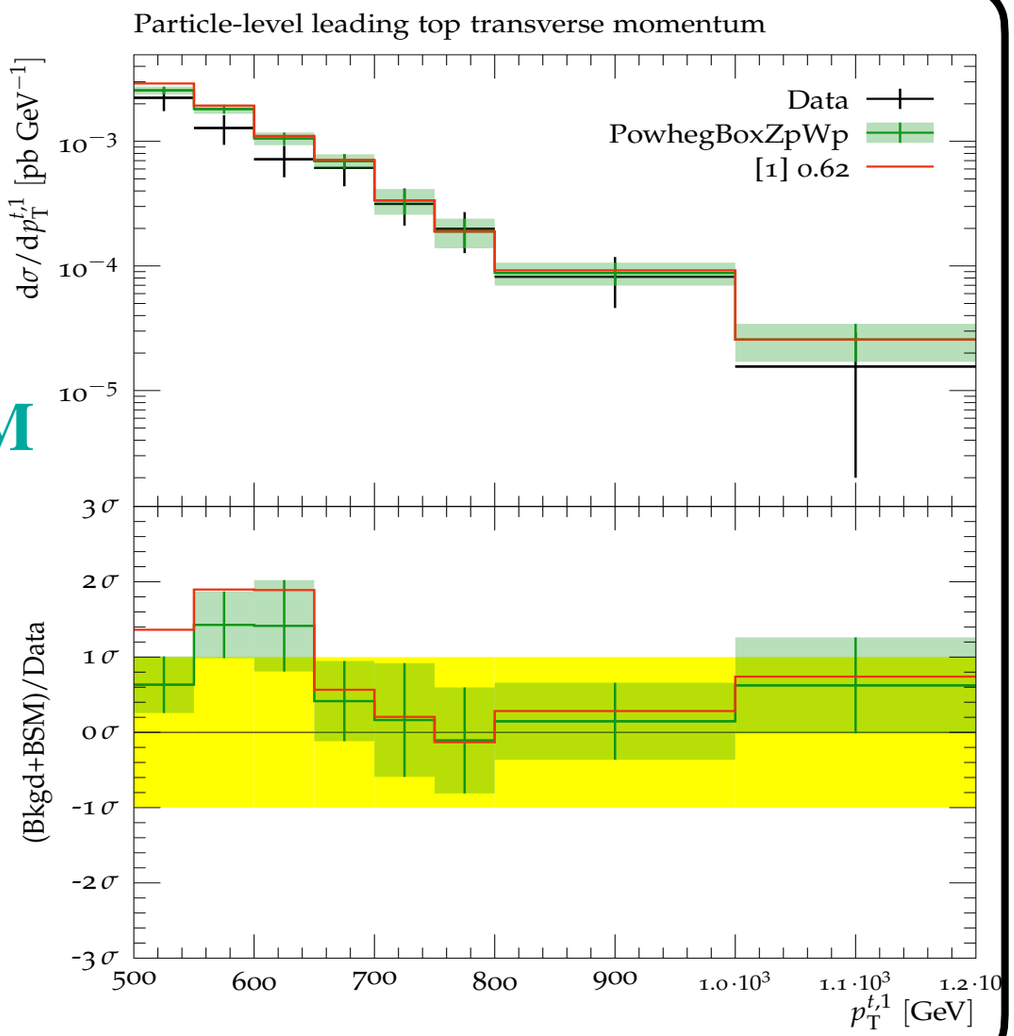
2nd Approach:

- **Condition:**
  - **SM** predictions.
- **Method**:
  - Assume background = **SM**
  - Add signal on top of background.
  - Check for consistency with the data within uncertainties.



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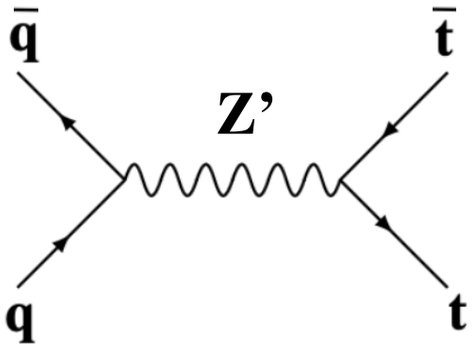

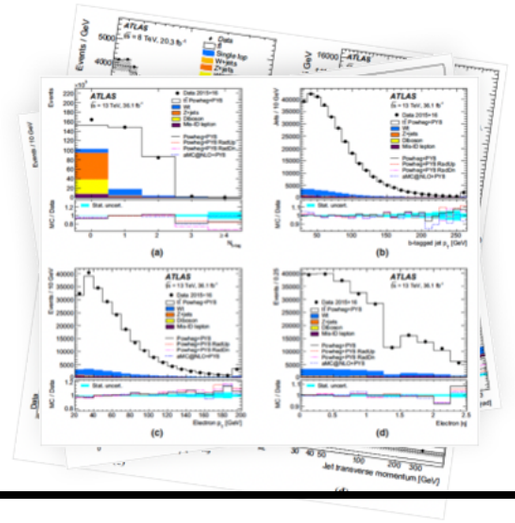

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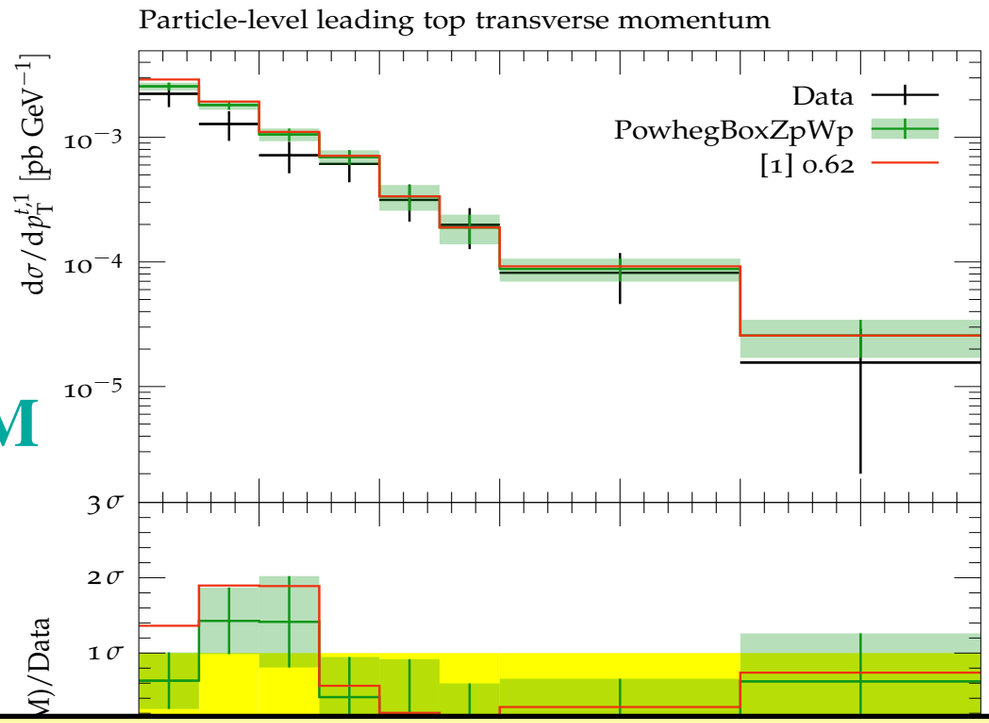

Contur provides the book-keeping and steering machinery to repeat this process over a grid of parameter values.

Contur: before vs now

Before this project

- **Contur** was only used in **default mode**.
- **2nd Approach** necessitate **SM** theoretical predictions.
- **LO** signals.

For this project

- **14 NLO SM** predictions using multiple **POWHEG BOX** packages including **PBZpWp**.
- **NLO** signal using **PBZpWp**.
- Interfaced the different tools.
- Tested a leptophobic **top**-colour model against the **LHC measurement**.

Part II

Calculations of signal and background

Signal

The Leptophobic Top-colour model (TC) [arXiv:1112.4928]:

- New strong dynamics with $\mathbf{SU(3)_2}$ symmetry coupling preferentially to the third generation while the original $\mathbf{SU(3)_1}$ gauge group couples only to the 1st and 2nd generation; breaking $\mathbf{SU(3)_1 x SU(3)_2 \rightarrow SU(3)_C}$

- To block the formation of a bottom quark condensate an additional $\mathbf{U(1)_2}$ symmetry with associated **Z'** is introduced; $\mathbf{U(1)_1 x U(1)_2 \rightarrow U(1)_Y}$

- **Z'** couples only to 1st and 3rd generation

- Input parameters:
  - The mass of **Z'**: $\mathbf{M_{Z'}}$
  - The Ratio of the two **U(1)** coupling constants: $\mathbf{\cot \theta_H}$

Signal

- $\Gamma_{Z'} = \frac{\alpha \cot^2 \theta_H M_{Z'}}{8 \cos^2 \theta_W} \left[\sqrt{1 - \frac{4M_t^2}{M_{Z'}^2}} \left(2 + \frac{4M_t^2}{M_{Z'}^2} \right) + 4 \right]$
- Input parameters ($\mathbf{M_{Z'}}$, $\mathbf{\cot \theta_H}$) ⟷ ($\mathbf{M_{Z'}}$, $\mathbf{\Gamma_{Z'}/M_{Z'}}$)
- **LO:**
  - $2 \rightarrow 2$ processes, with **Z'** either in **s-channel** or as an external outgoing leg
  - **Herwig** for event generation, decay of the **top**, and showering
- **NLO:**
  - **$pp \rightarrow Z' \rightarrow t\bar{t}$**
  - Events using **PBZpWp** with stable on-shell **top** quark
  - **Pythia** 8.2 to decay the **top** quark and to shower the events
  - **PDF**: LUXqed NNPDF (324900)

Background

The partonic **top-quark** pair production cross section at **NLO**:

$$\sigma_{ab}(\mu_r) = \sigma_{1;1}(\alpha_S\alpha) + \sigma_{2;0}(\alpha_S^2) + \sigma_{0;2}(\alpha^2) + \sigma_{3;0}(\alpha_S^3)$$
$$+\sigma_{2;1}(\alpha_S^2\alpha) + \sigma_{1;2}(\alpha_S\alpha^2) + \sigma_{0;3}(\alpha^3)$$

- $\sigma_{2;0}$: **SM QCD**
- $\sigma_{3;0}$: **NLO QCD** corrections to the **SM QCD**
- $\sigma_{2;1}$: **EW** corrections to the **SM QCD**
- $\sigma_{1;1}$: Interference between **QCD** & **EW top** quark pair production
- $\sigma_{0;2}$: **EW top** quark pair production
- $\sigma_{1;2}$: **NLO QCD** corrections to **EW top** quark pair production
- $\sigma_{0;3}$: **EW** corrections to **EW top** quark pair production

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- $\sigma_{2;0}$: **SM QCD**
- $\sigma_{3;0}$: **NLO QCD** corrections to the **SM QCD**

hvq

[arXiv:0707.3088]

- $\sigma_{2;1}$: **EW** corrections to the **SM QCD**
- $\sigma_{1;1}$: Interference between **QCD** & **EW top** quark pair production
- $\sigma_{0;2}$: **EW top** quark pair production
- $\sigma_{1;2}$: **NLO QCD** corrections to **EW top** quark pair production
- $\sigma_{0;3}$: **EW** corrections to **EW top** quark pair production

PBZpWp

[arXiv:2012.14855]

Background

- Event sample of **QCD** corrections to **top** pair production up to **NNLO**:
  - **ttJ_MiNNLO** [arXiv:2012.14267]
  - $\sigma_{4;0}$
  - Only 13 TeV

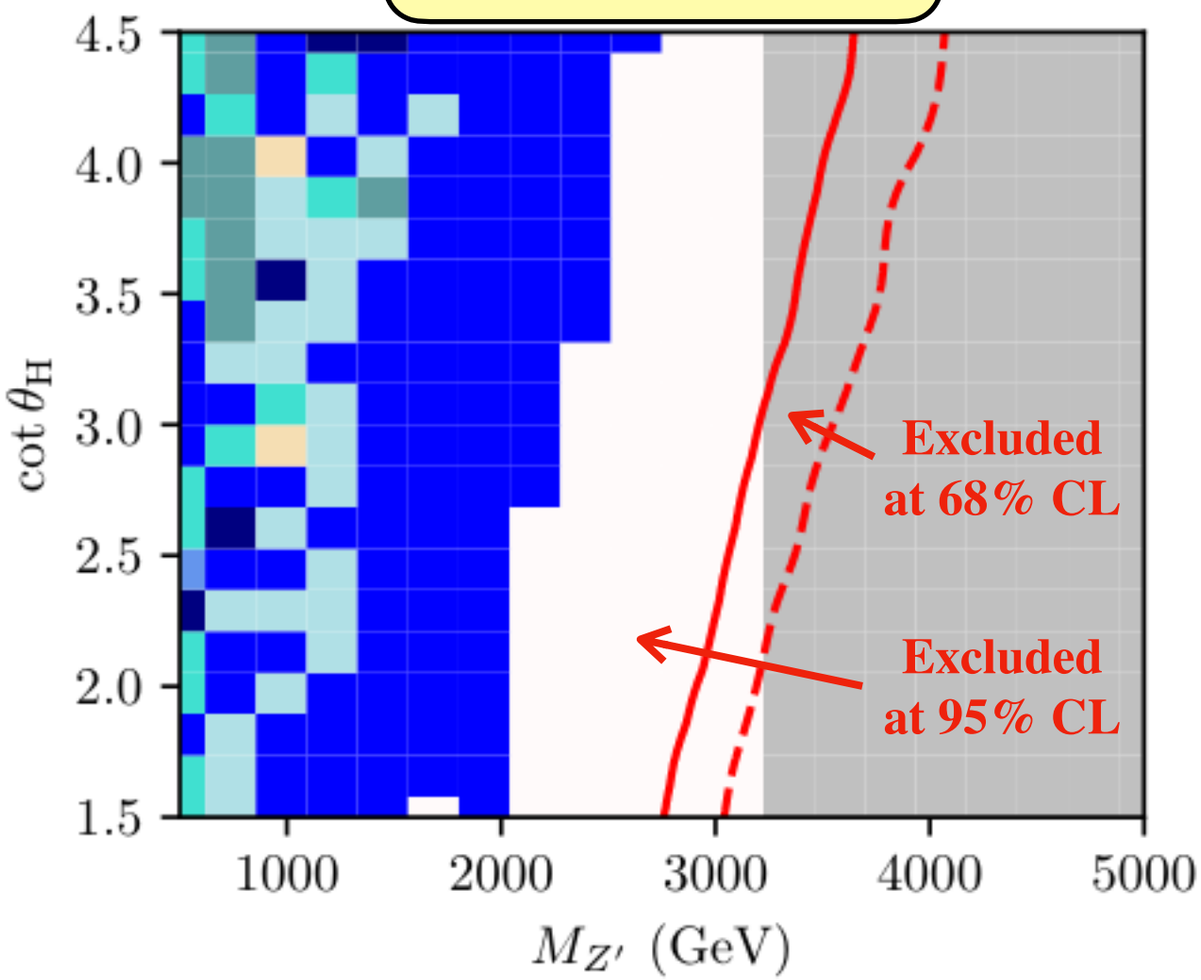
- **ATLAS** inclusive jet and dijet cross section measurement [arXiv:1711.02692]:
  - **dijet** [arXiv:1012.3380]
  - $\sigma_{3;0}$

Part III

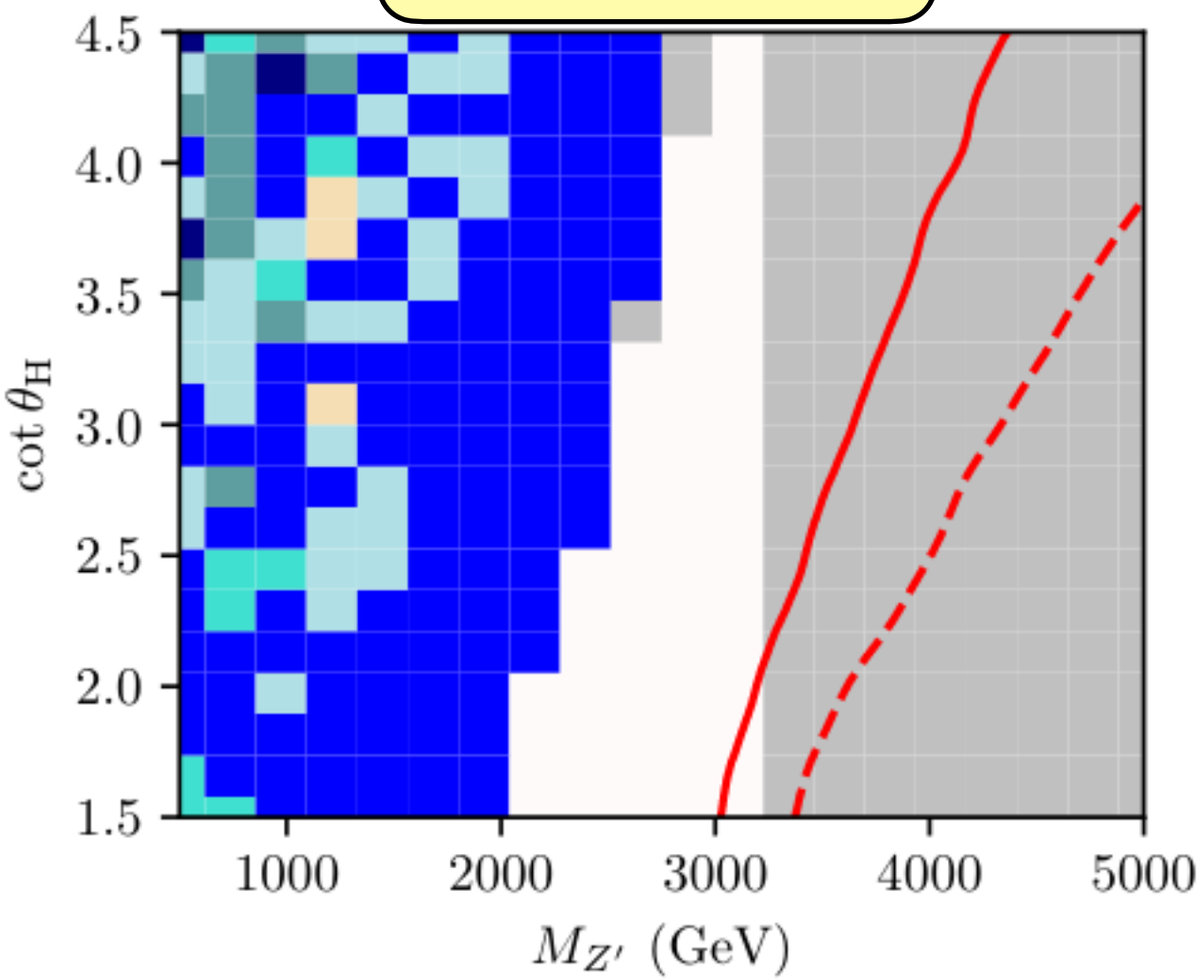
Sensitivity

1st Approach

Signal: NLO

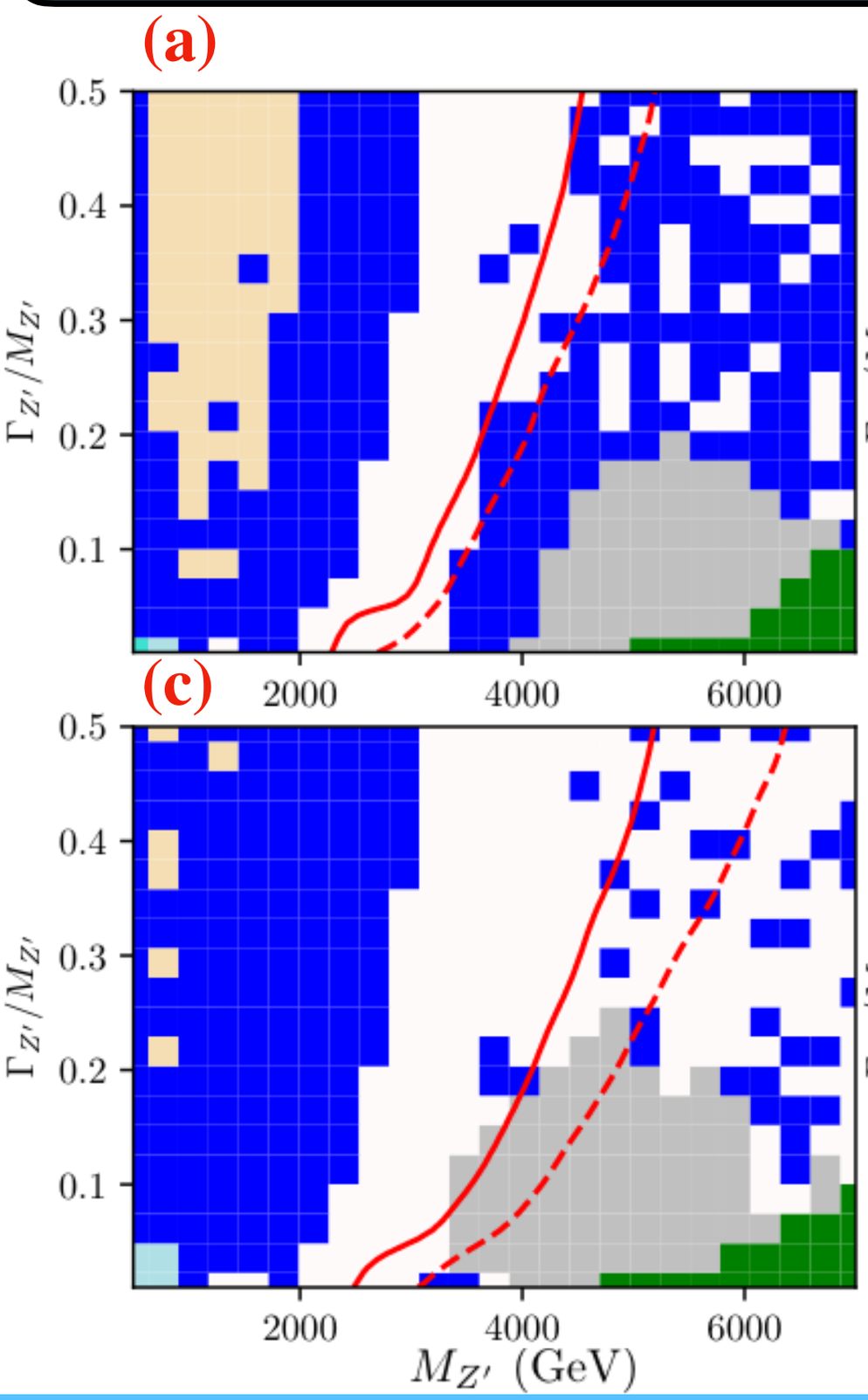


Signal: LO



CMS $\ell+E_T^{\text{miss}}$+jet
ATLAS $\mu+E_T^{\text{miss}}$+jet
ATLAS Hadronic $t\bar{t}$
ATLAS $\ell+E_T^{\text{miss}}$+jet
ATLAS jets
ATLAS $\ell_1\ell_2+E_T^{\text{miss}}$
ATLAS $e+E_T^{\text{miss}}$+jet
CMS Hadronic $t\bar{t}$
ATLAS $\ell_1\ell_2+E_T^{\text{miss}}$+jet

2nd Approach



(a): Background = data only for measurements where we have predictions

(b): Background = NLO SM predictions

(c): Background = NNLO SM predictions (only for 13TeV tt case, NLO othrwise)

(d): expected limit

- ATLAS Hadronic $t\bar{t}$
- ATLAS ℓ+E_T^{miss}+jet
- ATLAS $\mu\mu$+jet
- CMS Hadronic $t\bar{t}$
- ATLAS jets
- ATLAS ee+jet
- ATLAS E_T^{miss}+jet
- CMS ℓ+E_T^{miss}+jet
- ATLAS $\ell_1\ell_2$+E_T^{miss}+jet

Measurements vs searches

Excluded $M_{Z'}$ [Tev]				
$\Gamma_{Z'}/M_{Z'}$ [%]	Data as bgd.	NLO as bgd.	NNLO as bgd.	CMS [1810.05905]
1	2.29	2.35	2.50	3.80
10	3.17	3.22	3.55	5.25
30	4.01	4.04	4.53	6.65
50	4.54	4.61	5.19	-

- Our limits are weaker than the direct searches:
  - No measurements using the full Run 2 luminosity were yet available in **Rivet**
  - Binning in **measurements** vs binning in **searches**

Part IV

Summary & Conclusions

Summary & Conclusions

- An analysis using **Contur** different modes
- We validated the **Contur** previous approach (Data = **SM**)
- First use of higher order results for both signal and background
- This analysis illustrated both **strengths** and **weakness** of a **Contur** like approach:
  - In this study we studied a model with a single, clear signature for which several searches already exist
  - In this case **Contur** exclusions are not found to be competitive
  - Derive exclusions limits in a previously unexplored regions of the parameter space
  - Wide range of **BSM** models can be rapidly checked
  - Even more interesting for models with a greater number of free parameters and more complex phenomenology

Backup slides

Measurements vs searches

Contur Category	$\mathcal{L}$ [fb^{-1}]	Rivet/Inspire ID	Highest SM Order	Rivet description
ATLAS 8 LMETJET	20.3	ATLAS_2015_I1397637 [44]	NLO	Boosted $t\bar{t}$ differential cross-section
ATLAS 8 LMETJET	20.3	ATLAS_2015_I1404878 [45]	NLO	$t\bar{t}$ (to l+jets) differential cross sections at 8 TeV
CMS 8 LMETJET	19.7	CMS_2017_I1518399 [46]	NLO	Differential $t\bar{t}$ cross-section as a function of the leading jet mass for boosted top quarks at 8 TeV
ATLAS 13 LMETJET	3.2	ATLAS_2017_I1614149 [50]	NNLO	Resolved and boosted $t\bar{t}$ l+jets cross sections at 13 TeV
ATLAS 13 LMETJET	3.2	ATLAS_2018_I1656578 [51]	NNLO	Differential $t\bar{t}$ l+jets cross-sections at 13 TeV
ATLAS 13 LMETJET	36	ATLAS_2019_I1750330 [49]	NNLO	Semileptonic $t\bar{t}$ at 13 TeV
CMS 13 LMETJET	2.3	CMS_2016_I1491950 [54]	NNLO	Differential $t\bar{t}$ cross sections using the lepton+jets final state in pp collisions at 13 TeV
CMS 13 LMETJET	35.9	CMS_2018_I1662081 [52]	NNLO	Differential $t\bar{t}$ cross sections as a function of kinematic event variables in pp collisions at 13 TeV
CMS 13 LMETJET	35.8	CMS_2018_I1663958 [43]	NNLO	$t\bar{t}$ lepton+jets 13 TeV
ATLAS 13 L1L2METJET	36.1	ATLAS_2019_I1759875 [48]	NNLO	Dileptonic $t\bar{t}$ at 13 TeV
ATLAS 13 TTHAD	36.1	ATLAS_2018_I1646686 [53]	NNLO	All-hadronic boosted $t\bar{t}$ at 13 TeV
CMS 13 TTHAD	35.9	CMS_2019_I1764472 [47]	NNLO	Differential $t\bar{t}$ cross section as a function of the jet mass and top quark mass in boosted hadronic top quark decays
ATLAS 13 JETS	3.2	ATLAS_2018_I1634970 [55]	NLO	ATLAS inclusive jet and dijet cross section measurement at 13 TeV

Category	$\mathcal{L}$ [fb^{-1}]	decay channels
CMS 13	35.9	Leptonic and hadronic decays of the top
ATLAS 13	139	Fully hadronic decay channel only
ATLAS 13	36.1	Fully hadronic decay mode
ATLAS 13	36.1	Semileptonic decay mode