Search for Dark Matter in Missing-Energy Final States with an Energetic Jet or Top Quarks with the ATLAS Detector

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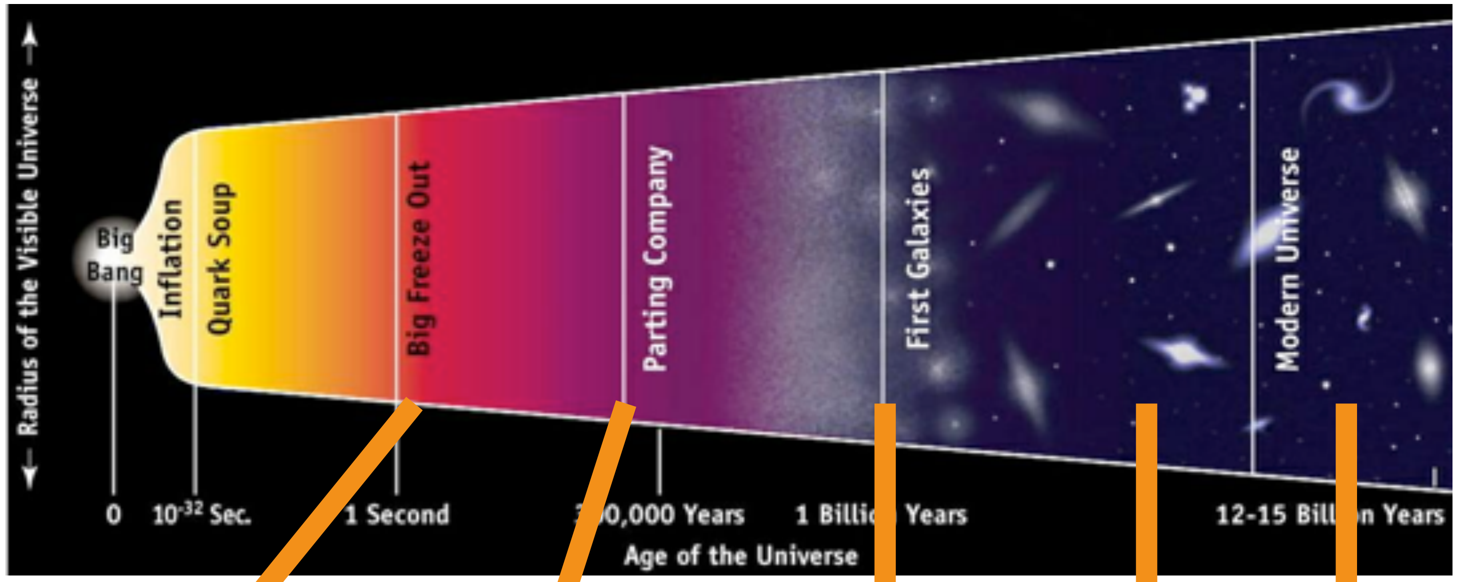
Why Dark Matter?

http://scienceblogs.com/startswithabang/files/2012/10/bigbang.jpeg



big-bang nucleosynthesis

cosmic microwave background

large-scale structure formation

galaxy clusters

galaxy rotation curves

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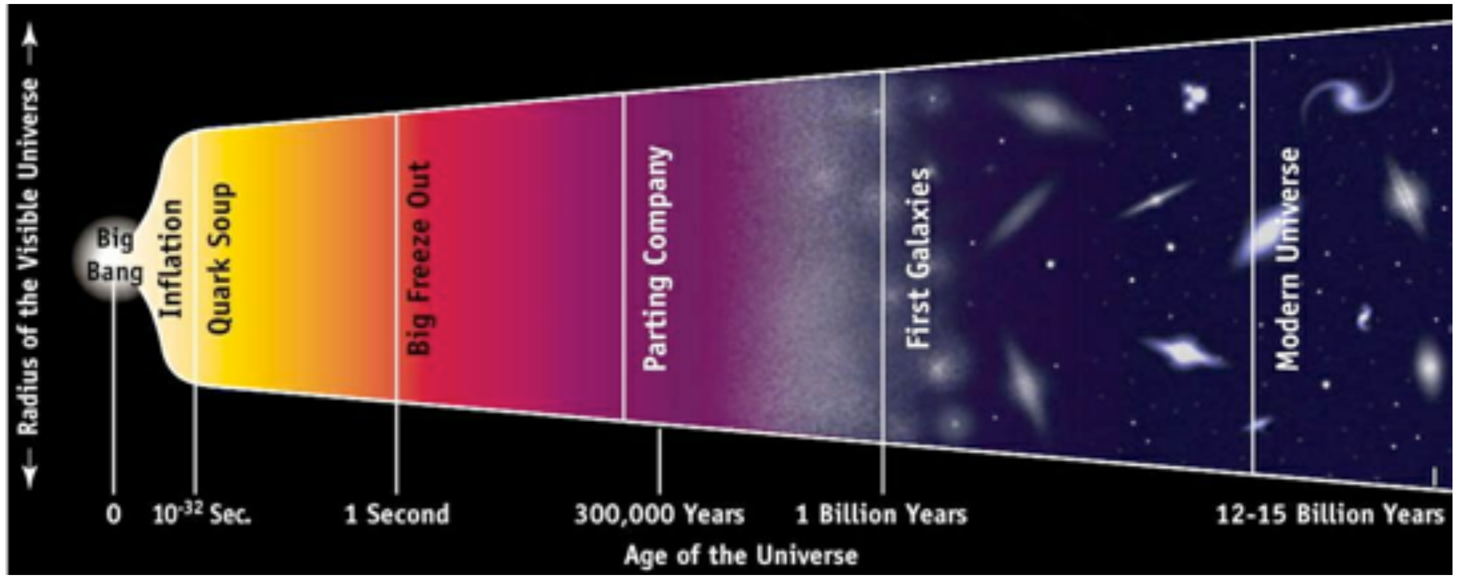

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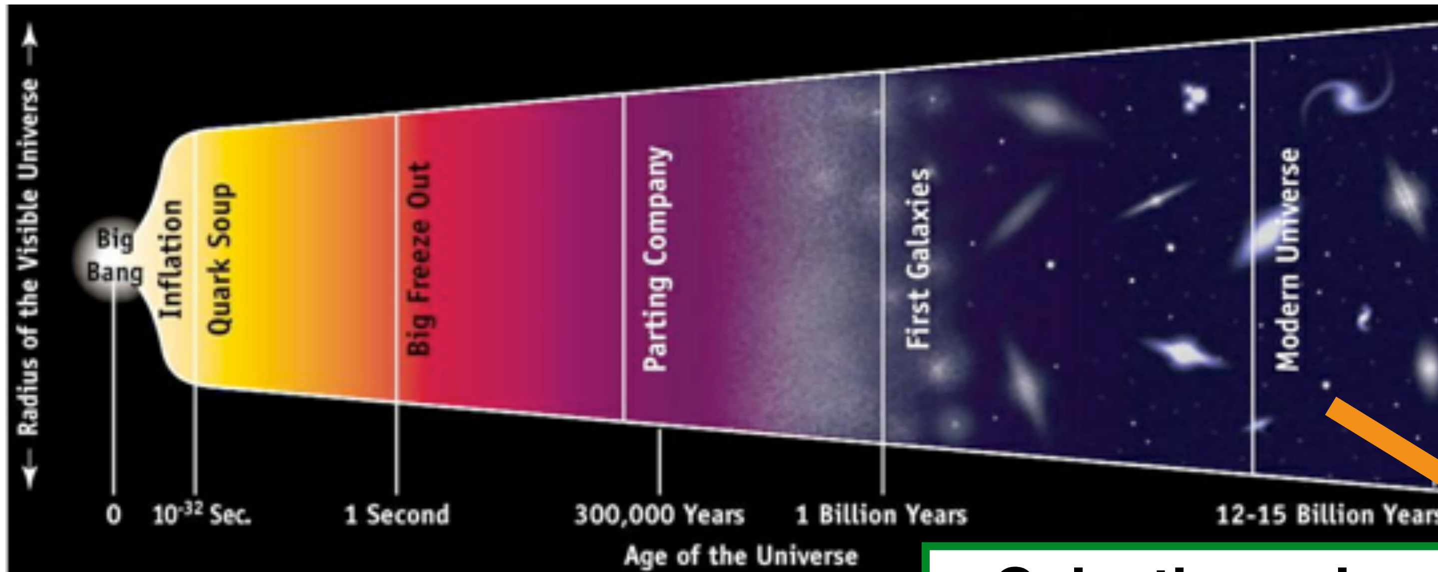
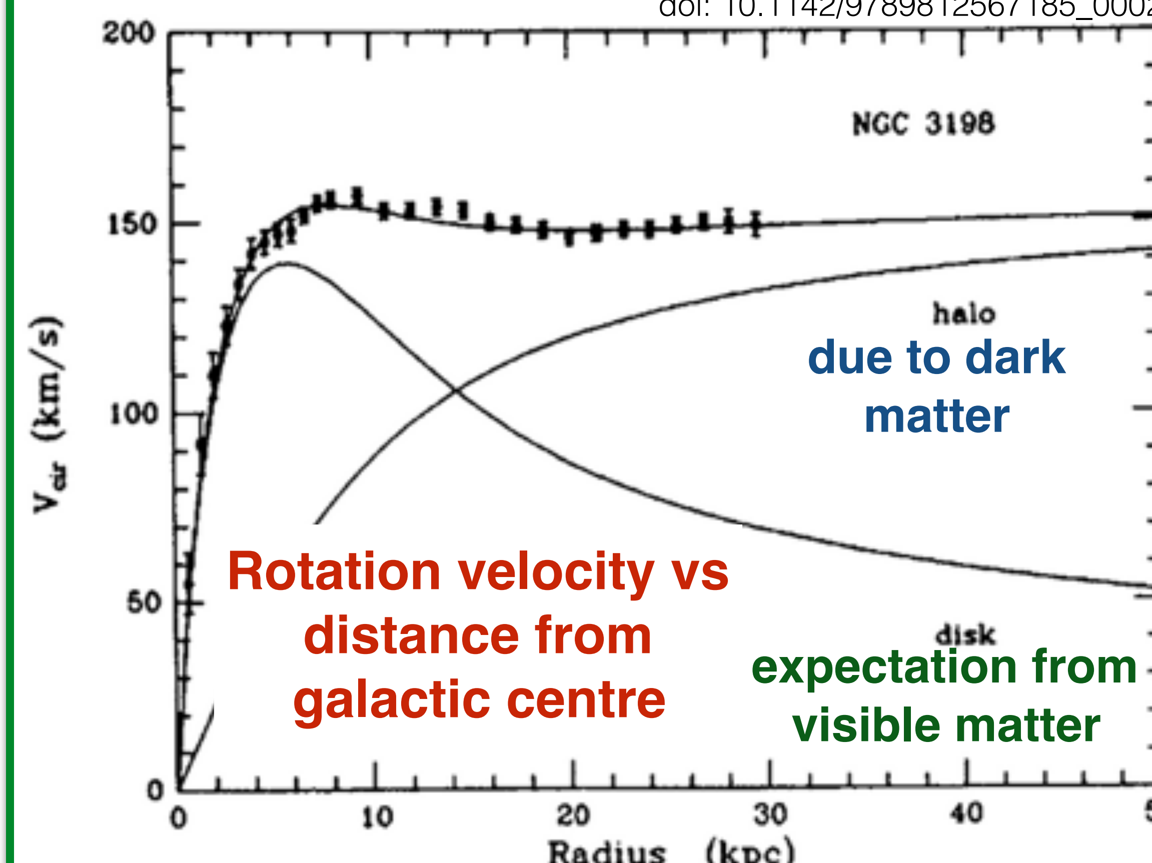


Galactic scales:
rotation velocities of stars in galaxies does not follow expectation

doi: 10.1142/9789812567185_0002



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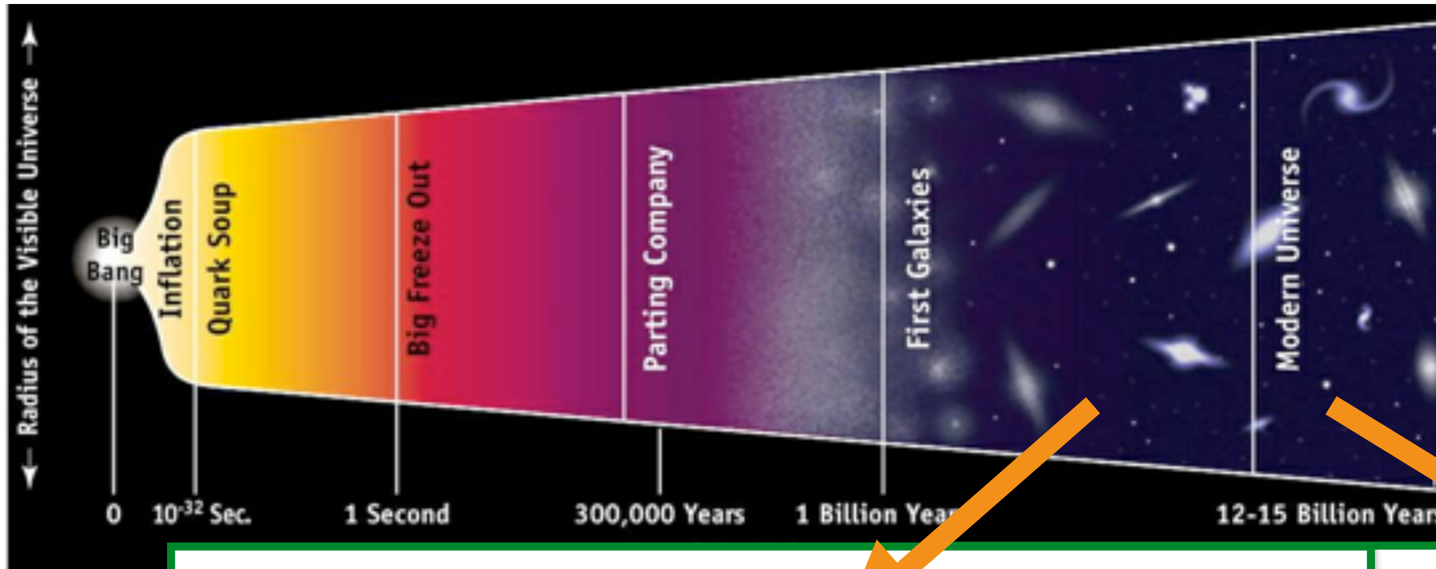

Cluster scales:
gravitational lensing shows displacement of visible matter (red) and gravitational centre (blue)

Chandra X-Ray Observatory: 1E 0657-56

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ectation

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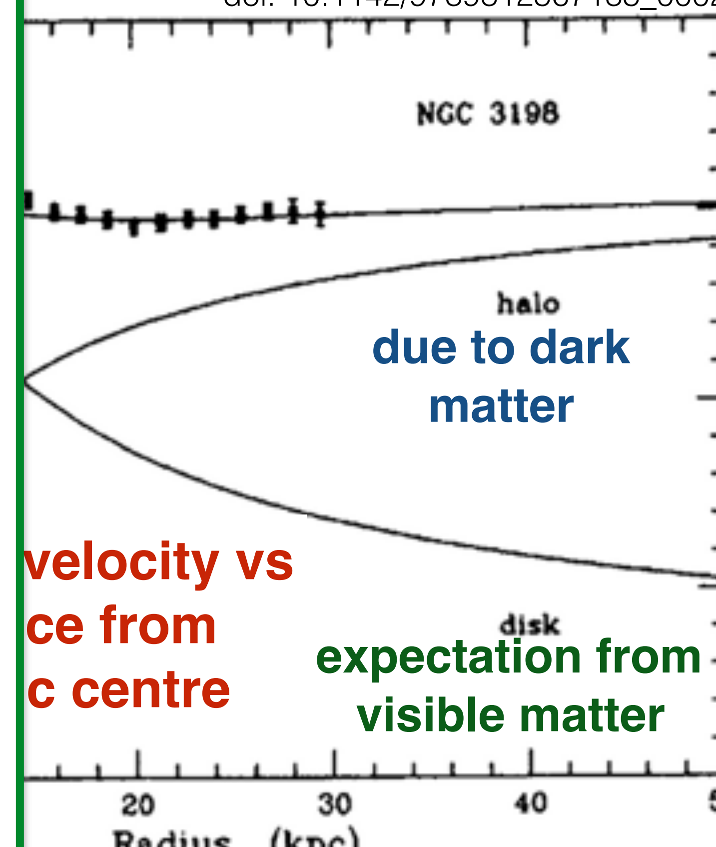

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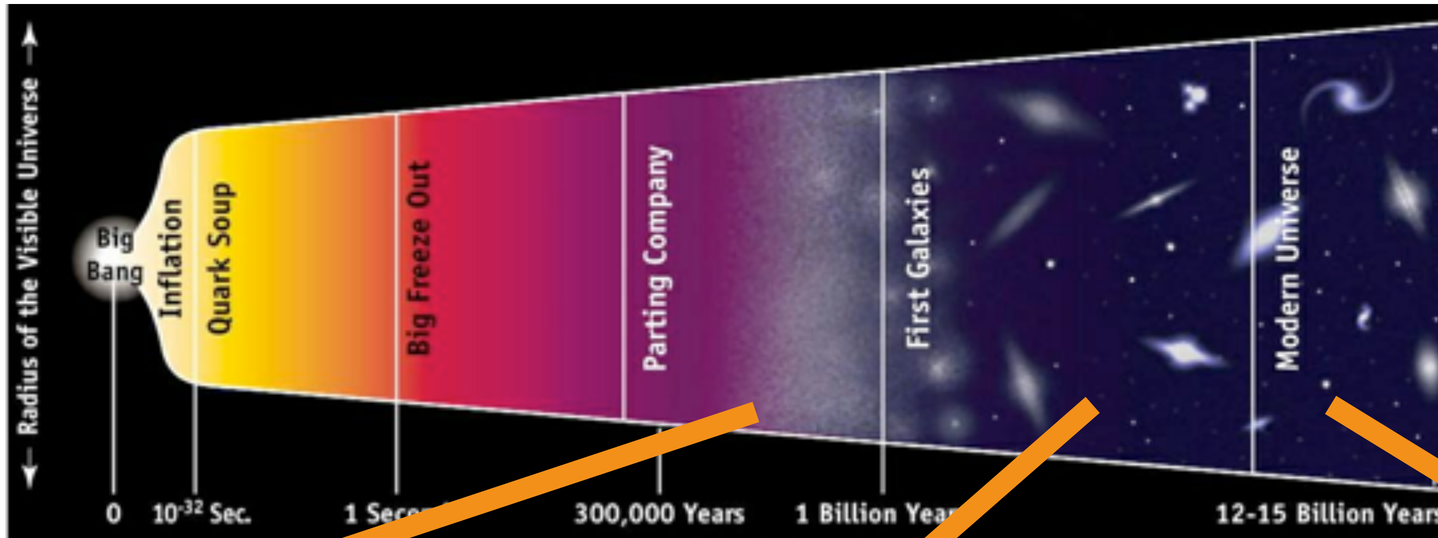
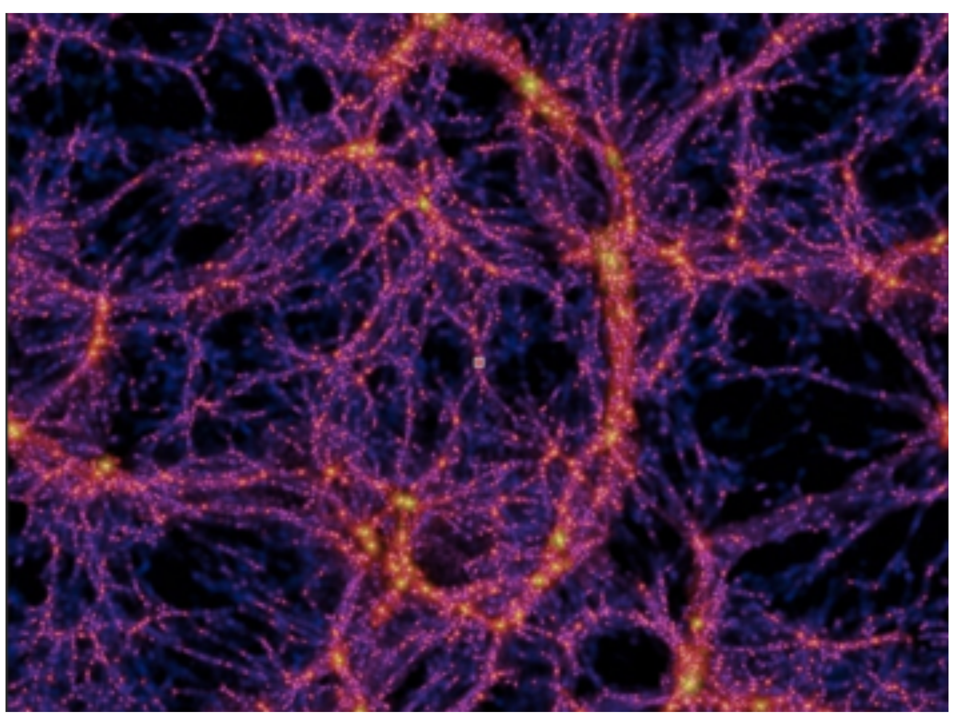


Cosmological scales:
Large-scale structure formation only successfully described with dark matter component



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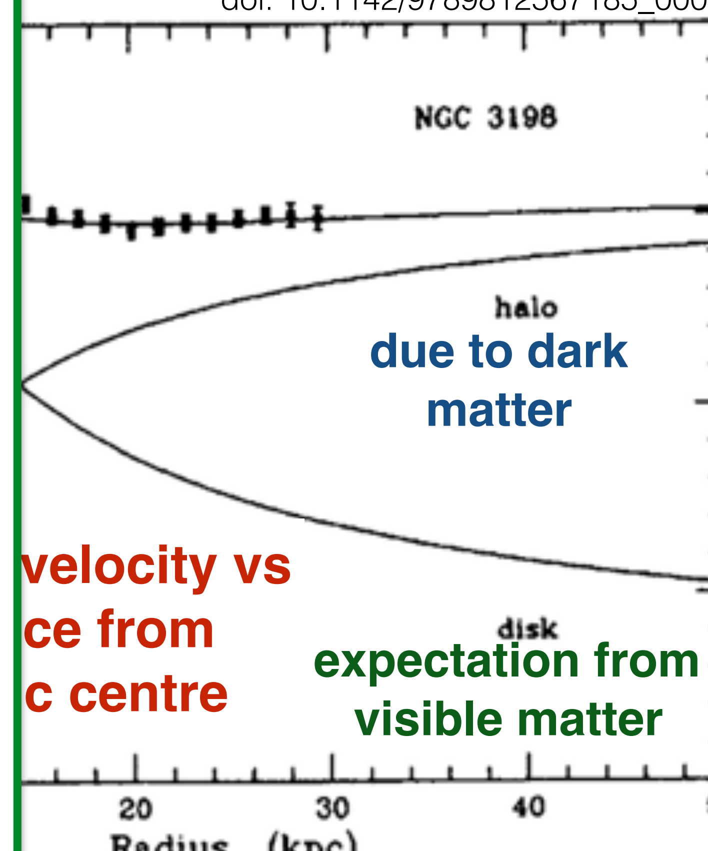

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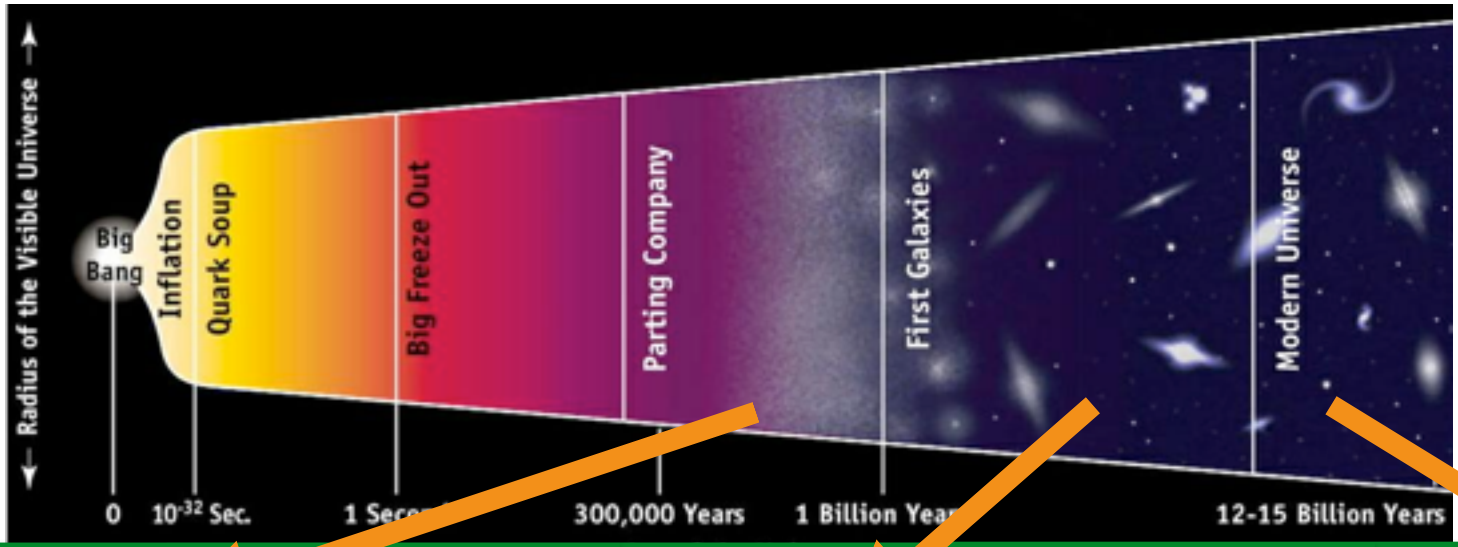

Cosmological scales:
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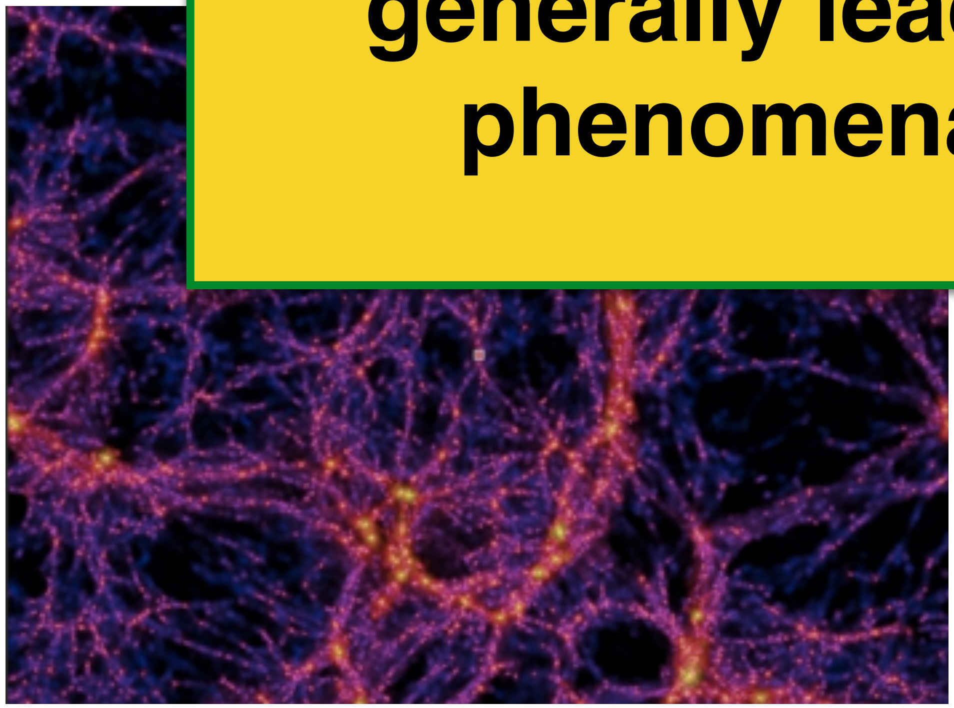

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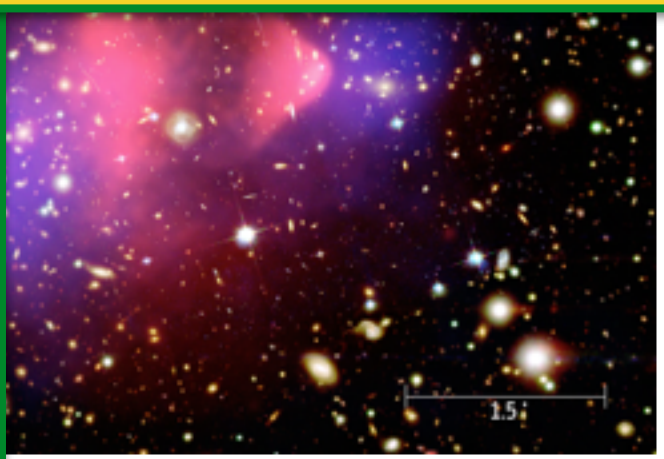

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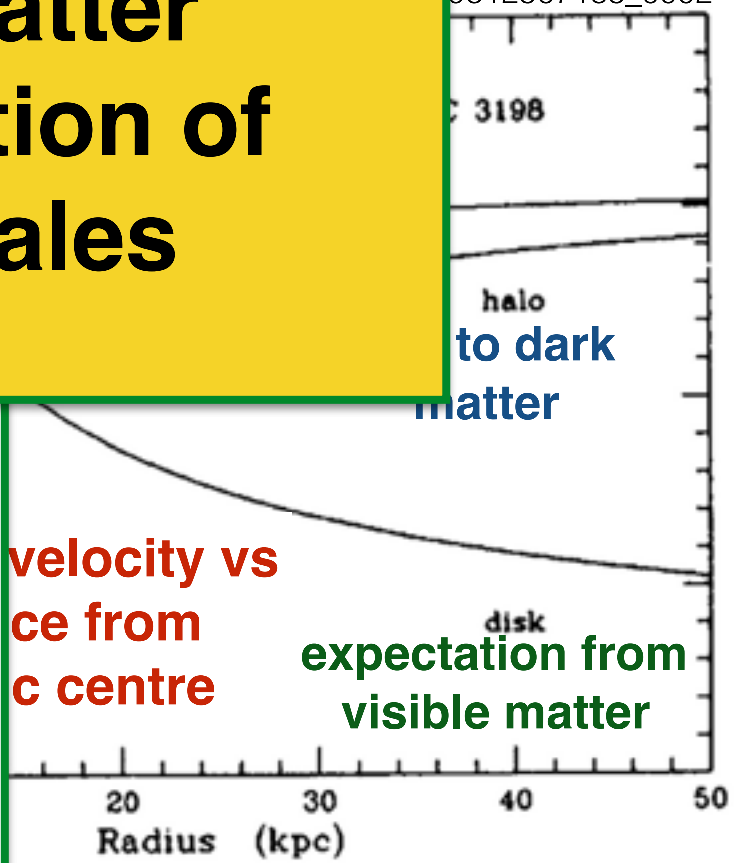
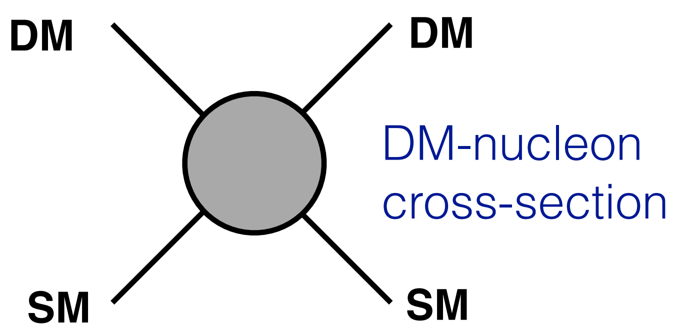


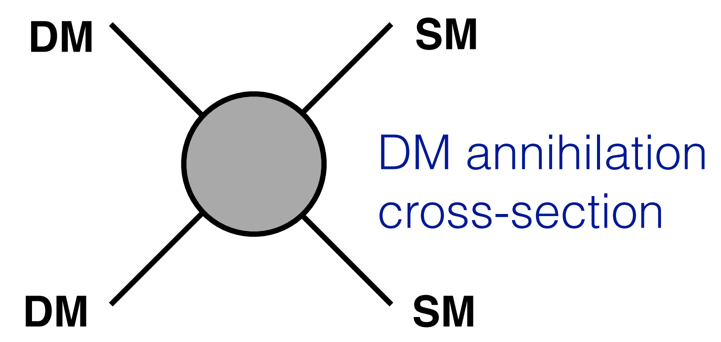
Assumption of particle dark matter generally leads to good description of phenomena on all different scales

Looking for dark matter…

Direct detection (DD): recoil from DM-nucleus scattering



Indirect detection (ID): DM-DM annihilation products



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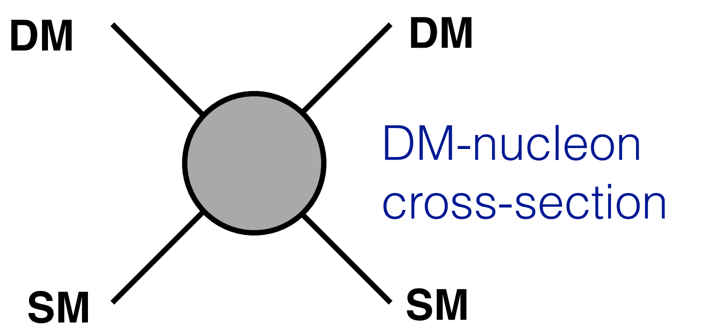

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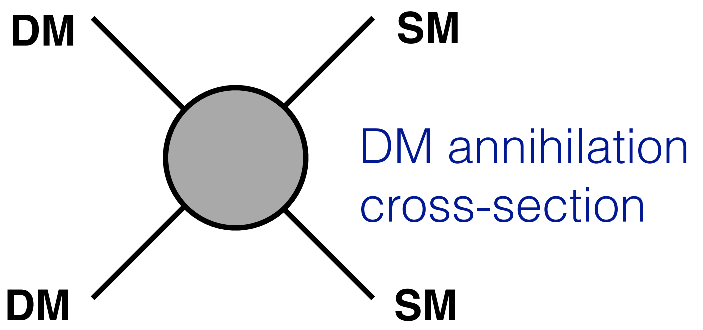
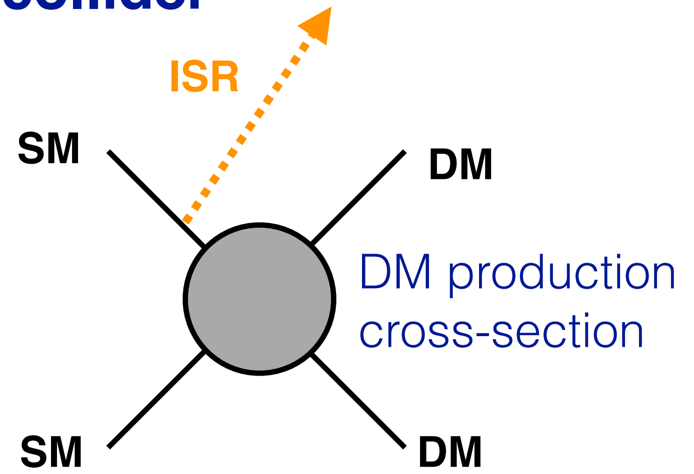


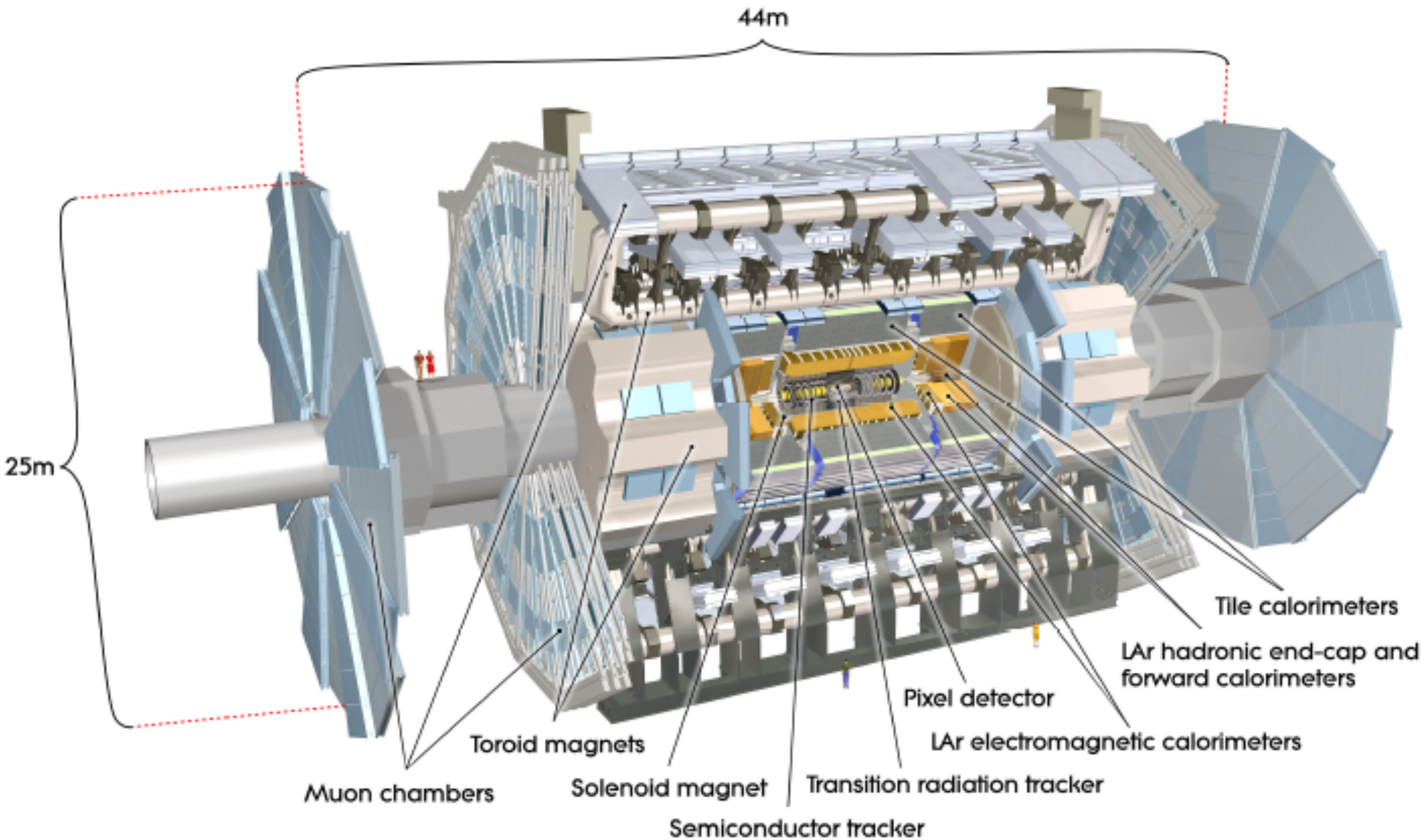
… at a collider

- No DM interaction with the detector → **missing E_T signatures**
  - Initial-state radiation (ISR) (can be **jets,** photons, W, Z, …)
  - Associated DM production with heavy quarks
  - Direct coupling to DM (e.g. mono-Higgs)

3. DM production at a collider



The ATLAS Detector



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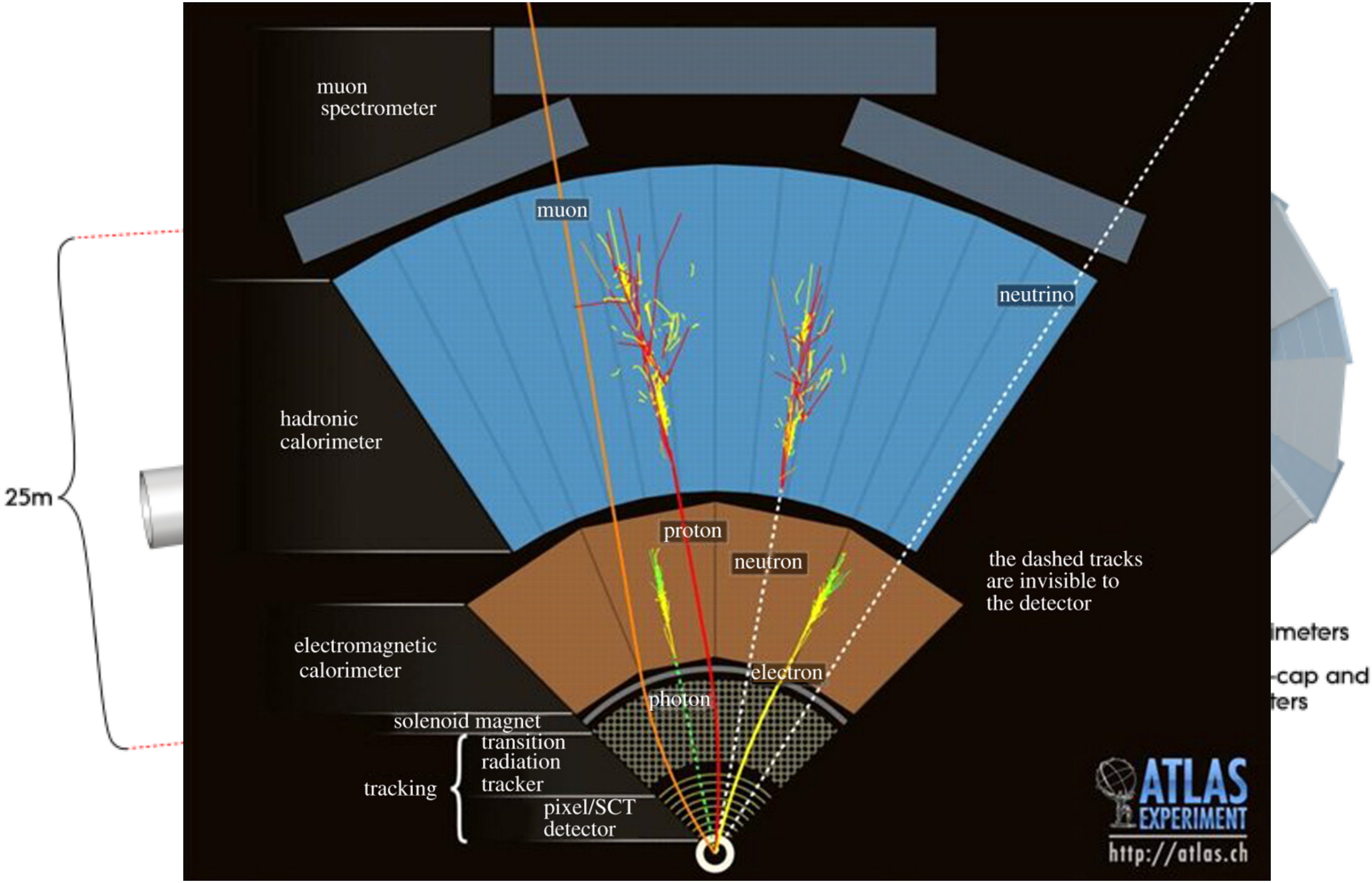
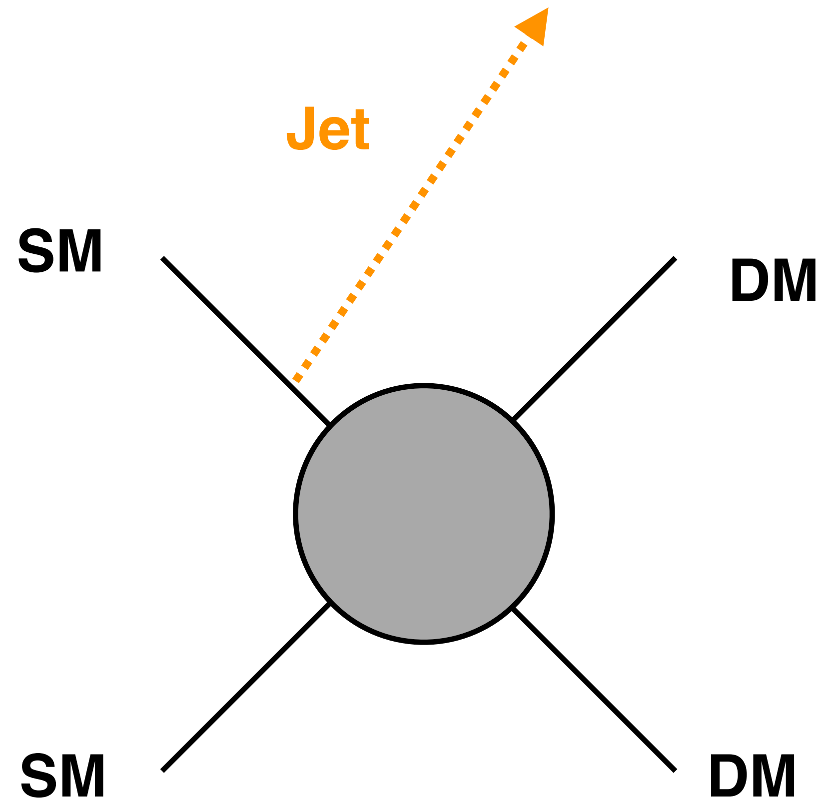


Monojet Analysis



Eur. Phys. J. C 75, no. 7, 299 (2015)

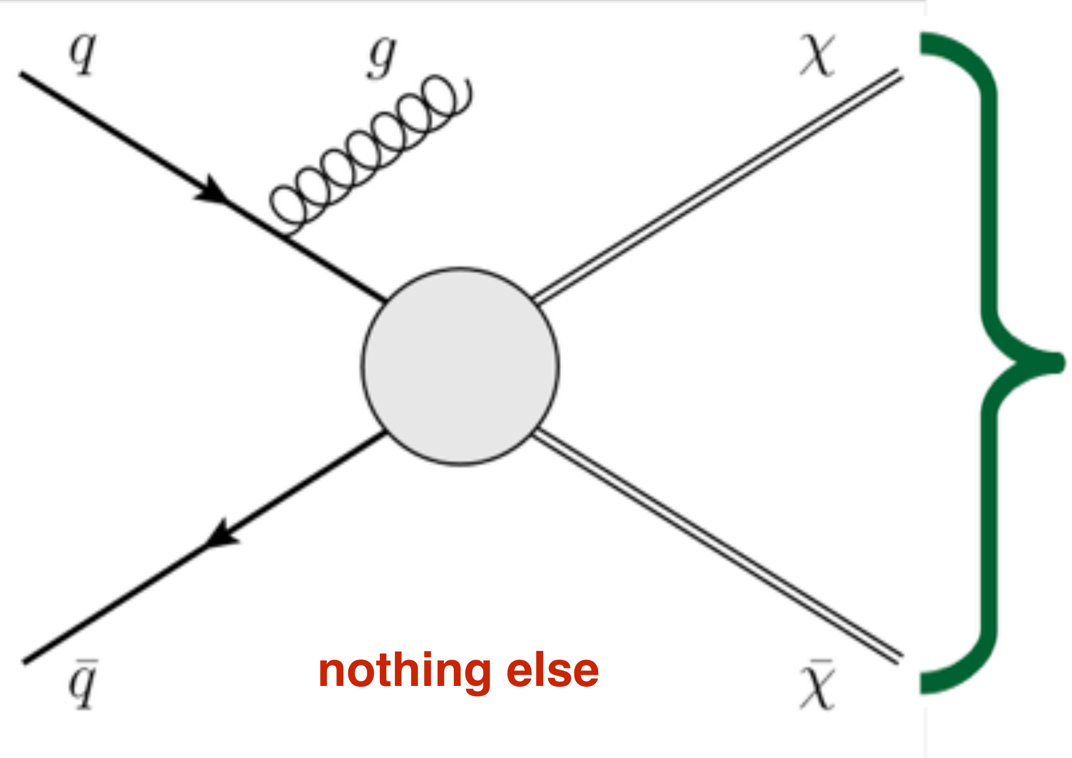
Analysis Overview

Monojet is generally the most sensitive ISR channel (highest cross section)

- Selection based on large E_T^{miss}, high-p_T jet(s) from initial state radiation and veto on other objects, such as leptons

leading jet p_T > 120 GeV

high-p_T jet(s)



nothing else

large E_T^{miss}

lower E_T^{miss} thresholds between 150 and 700 GeV define signal regions

veto on leptons and isolated tracks

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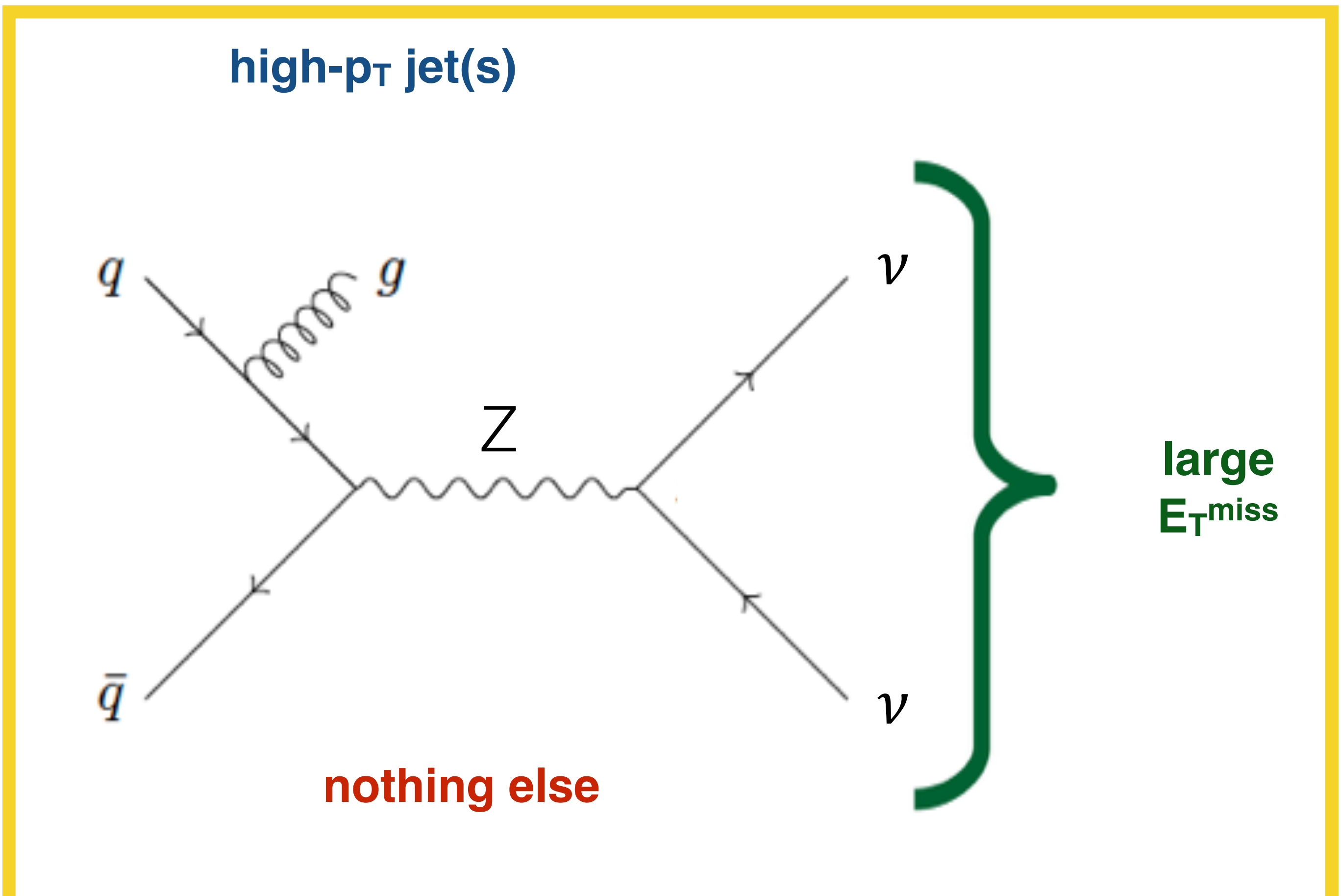
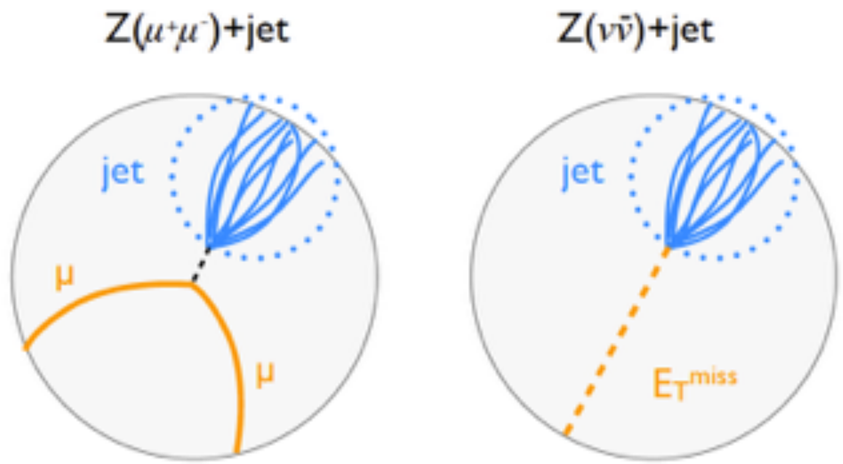


lower E_T^{miss} thresholds between 150 and 700 GeV define signal regions

veto on leptons and isolated tracks

Challenge: estimate irreducible background from Z($\rightarrow \nu\nu$) + jets

Background Estimate



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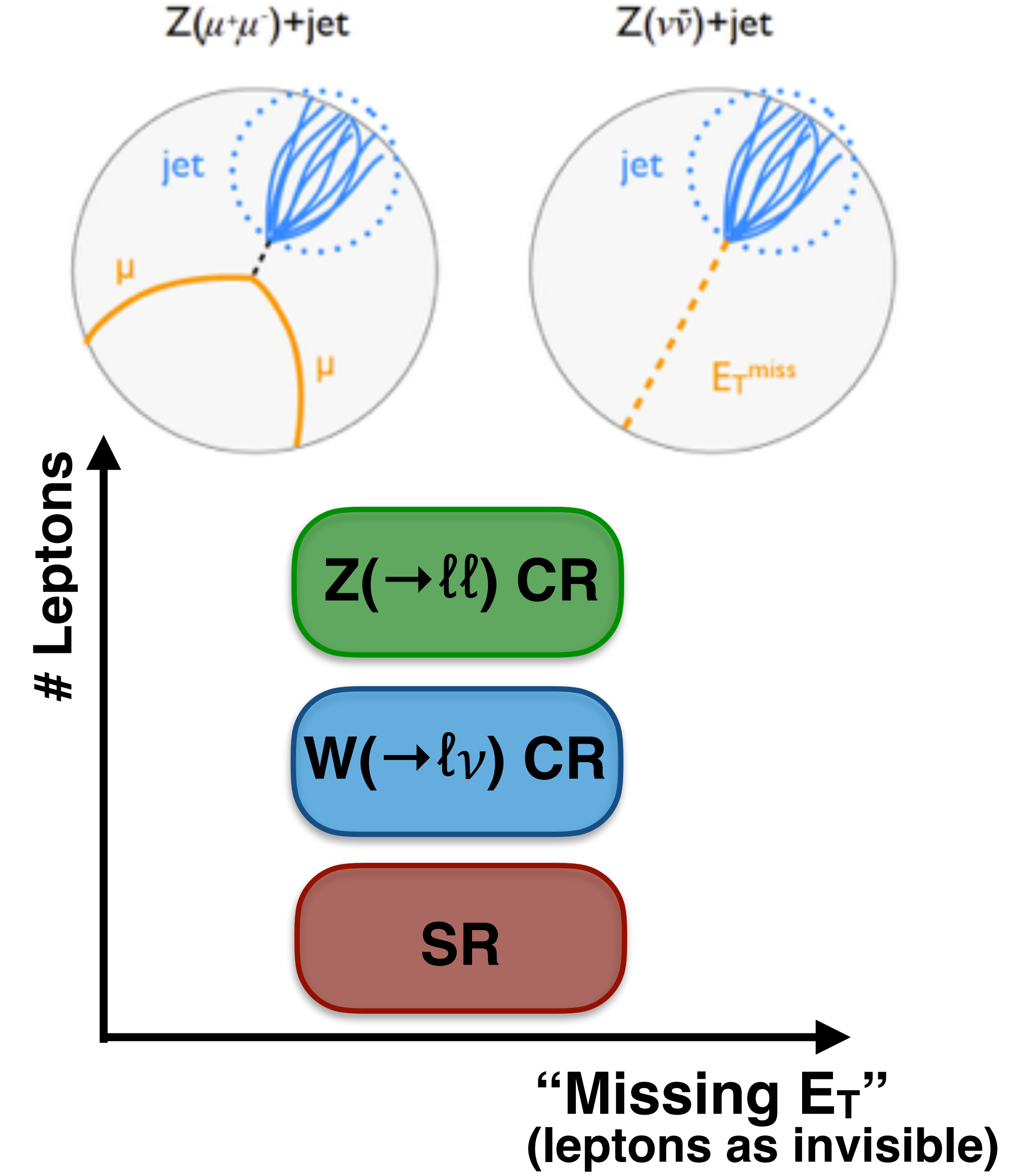

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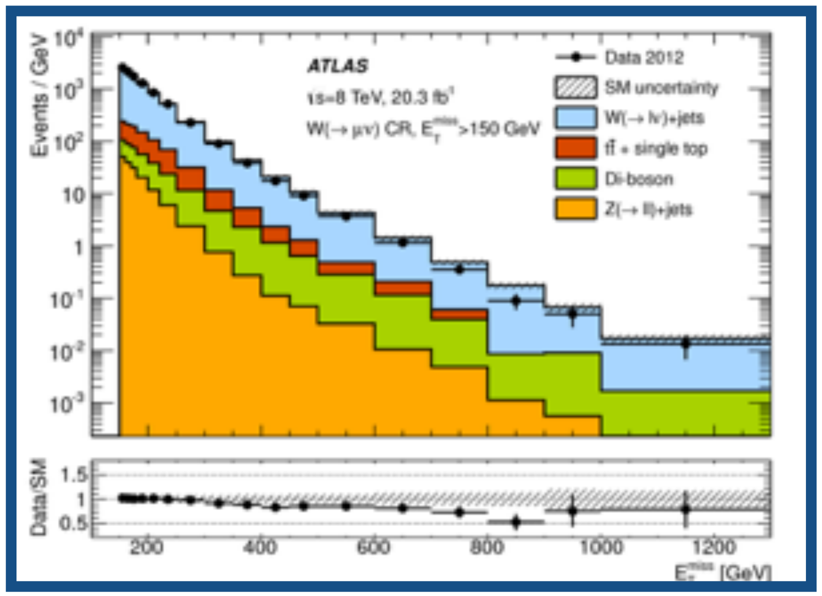

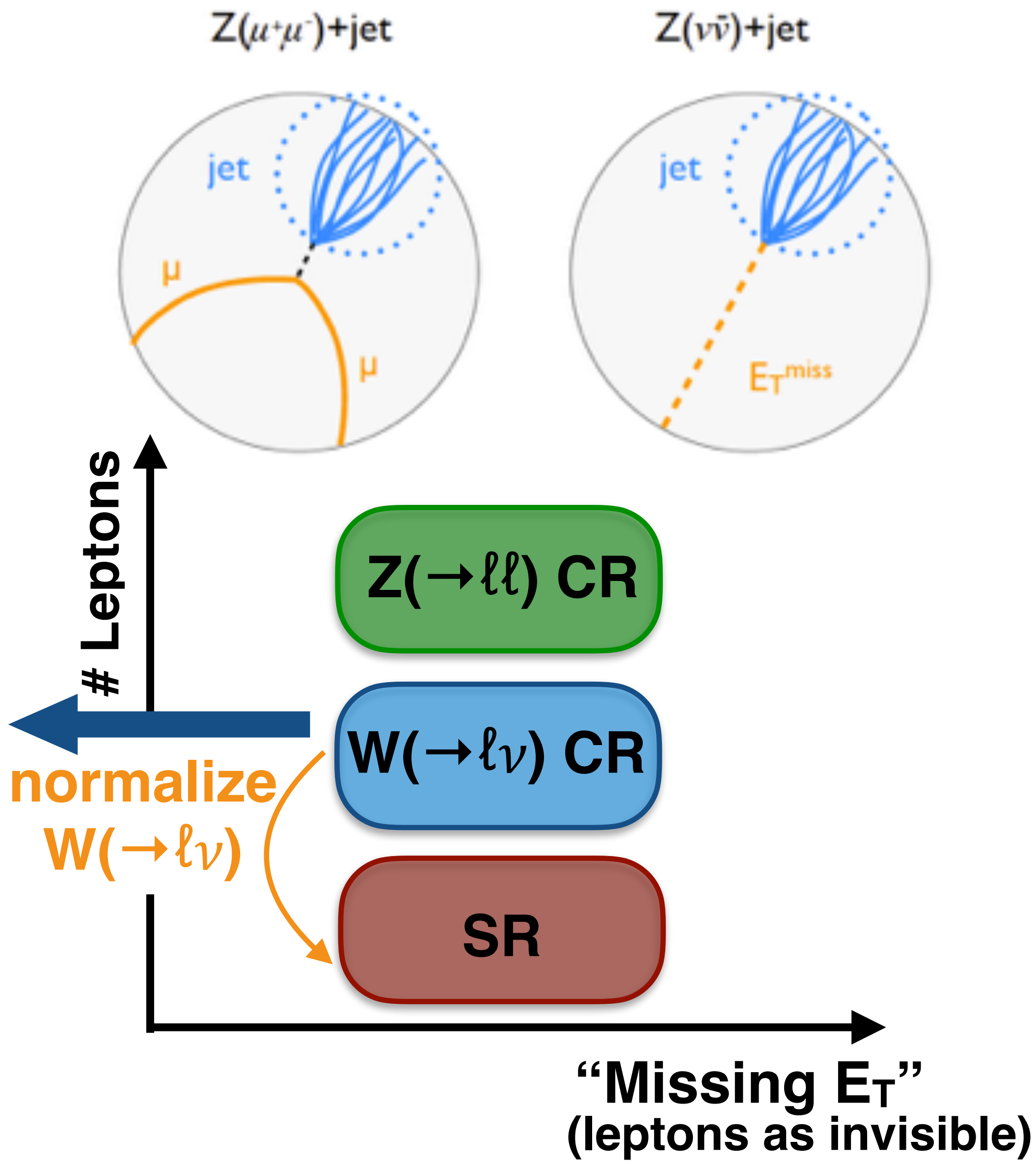

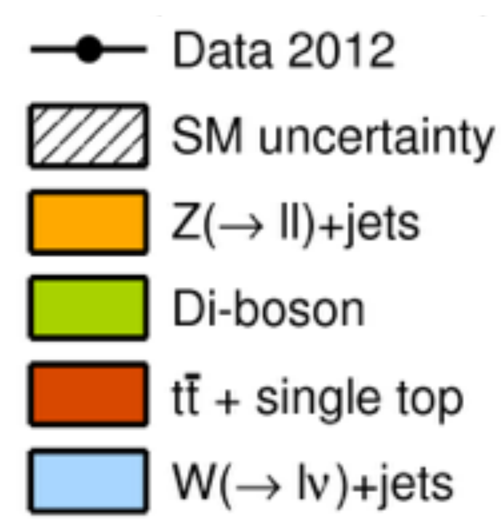

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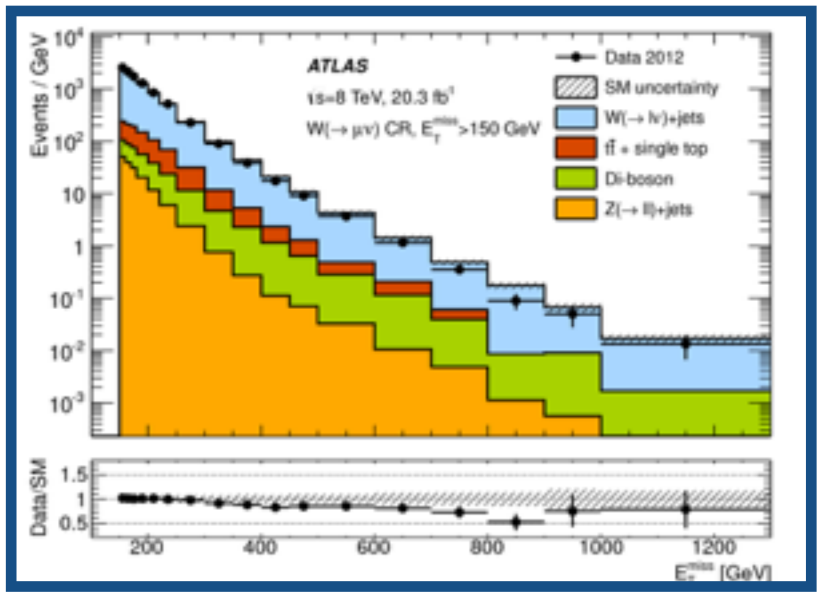

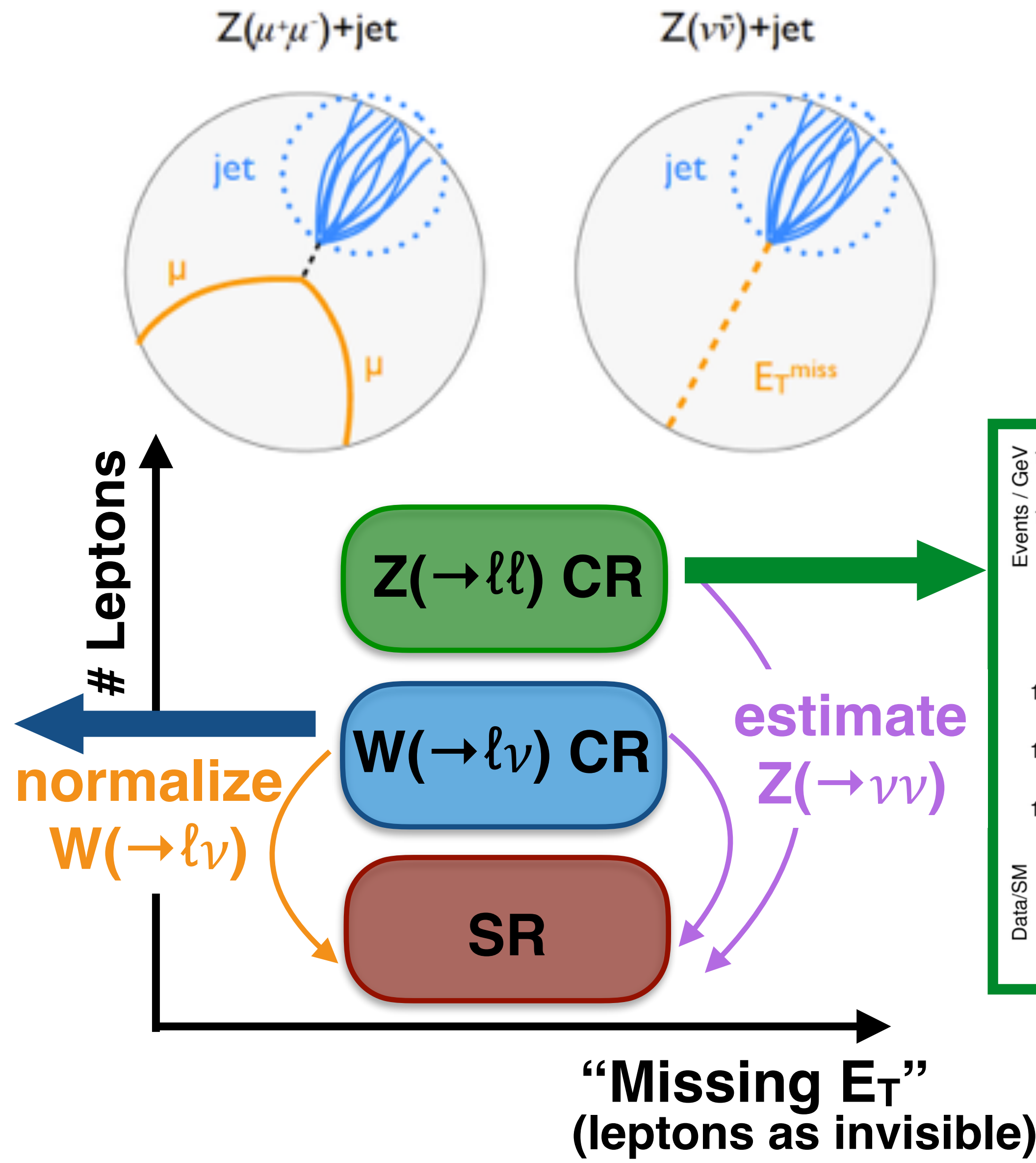

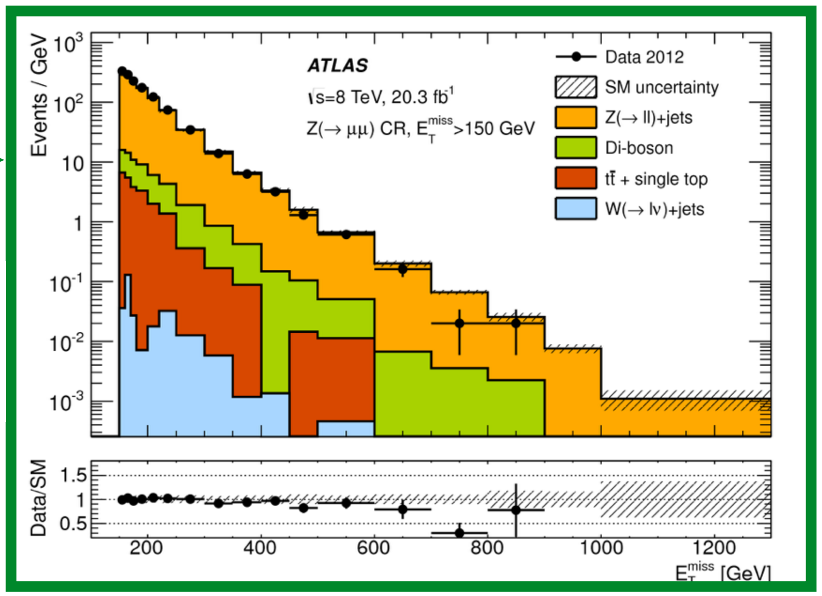

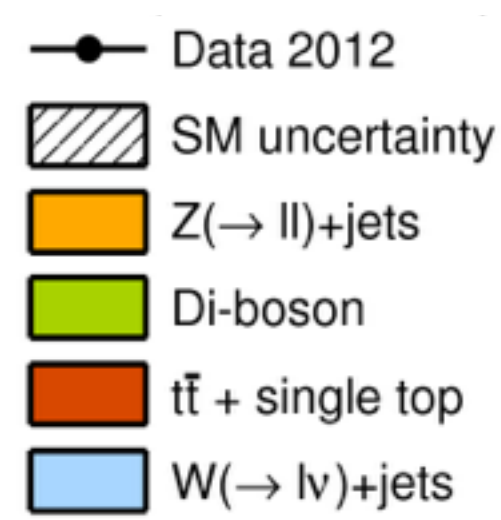

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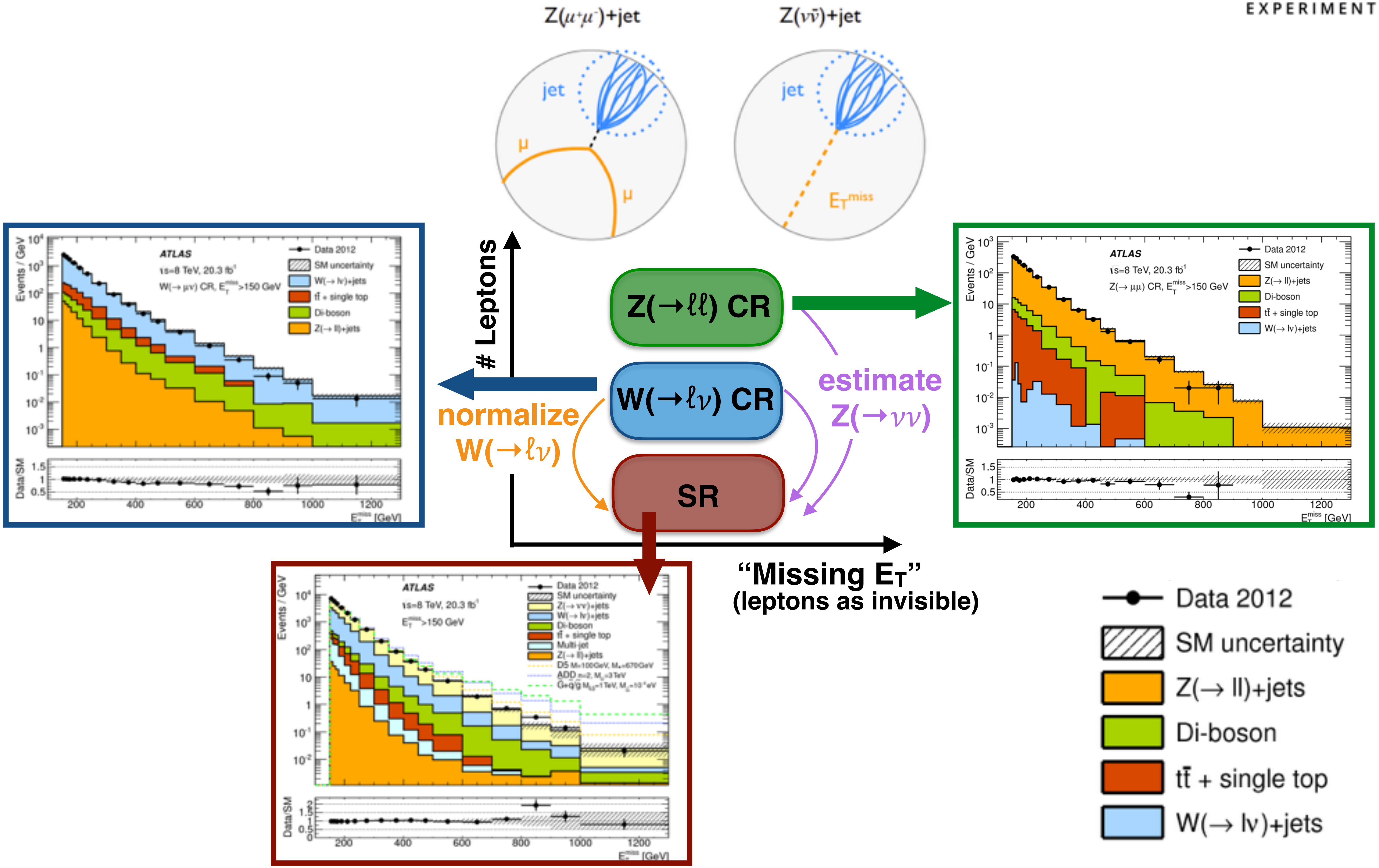
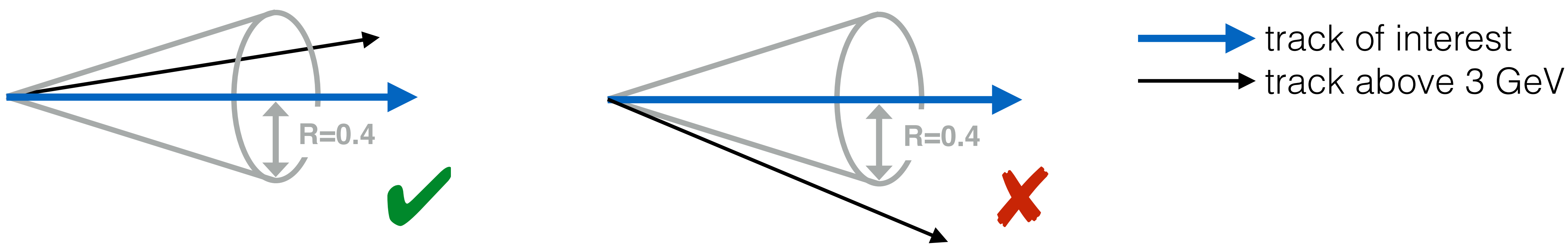


Improvements

Veto on isolated tracks

- Reduces backgrounds with missed leptons and hadronically decaying taus
- Performance: efficiency ~ 97% for DM signal and $Z(\rightarrow \nu\nu)$,
  50 - 70% for other backgrounds, systematic effect on background estimate < 1%



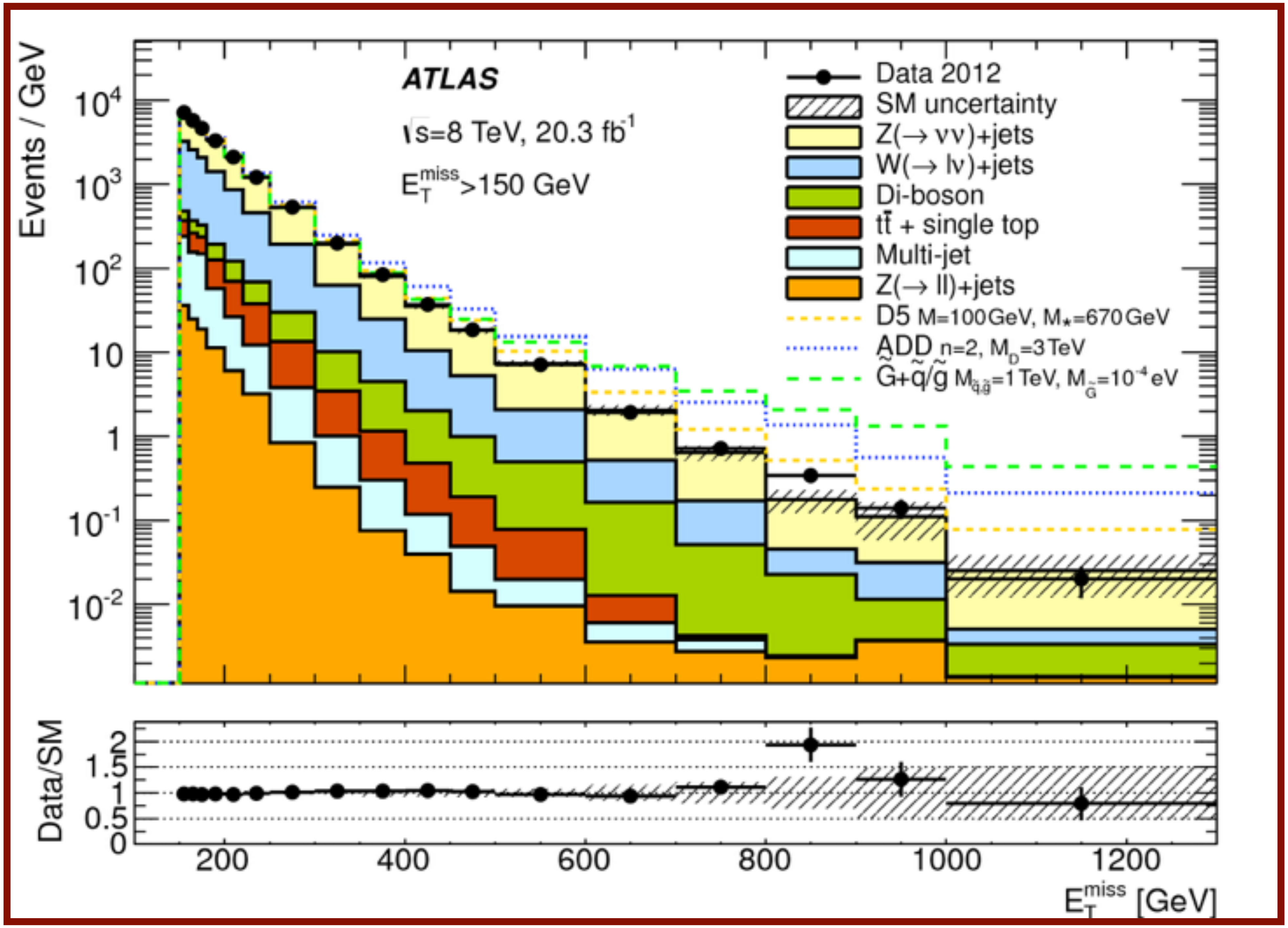
First dedicated optimisation of sensitivity to DM signals

- signal events prefer higher event scale, therefore number of jets is higher than in backgrounds
- As a consequence, leading jet p_T and E_T^{miss} are less balanced

→ **inclusive number of jets & asymmetric jet p_T/E_T^{miss} cuts**

Results

largest deviation: 1.7 σ in highest-E_T^{miss} signal region



Interpretation

EFT validity:

G. Busoni, A. De Simone, JG, E. Morgante, A. Riotto

JCAP 1406:060, 2014

Simplified Model Study:

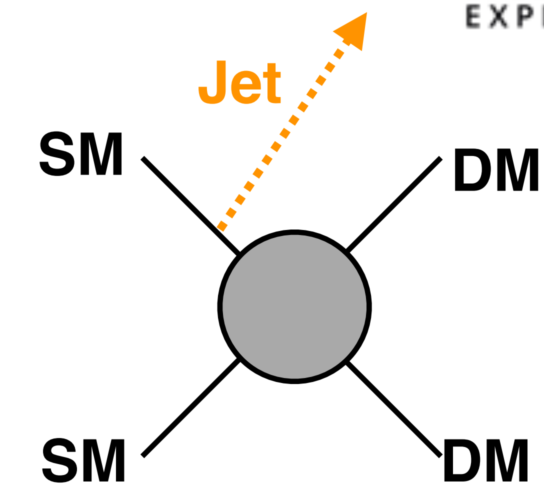
A.J. Brennan, M.F. McDonald, JG, T.D. Jacques

JHEP05(2016)112

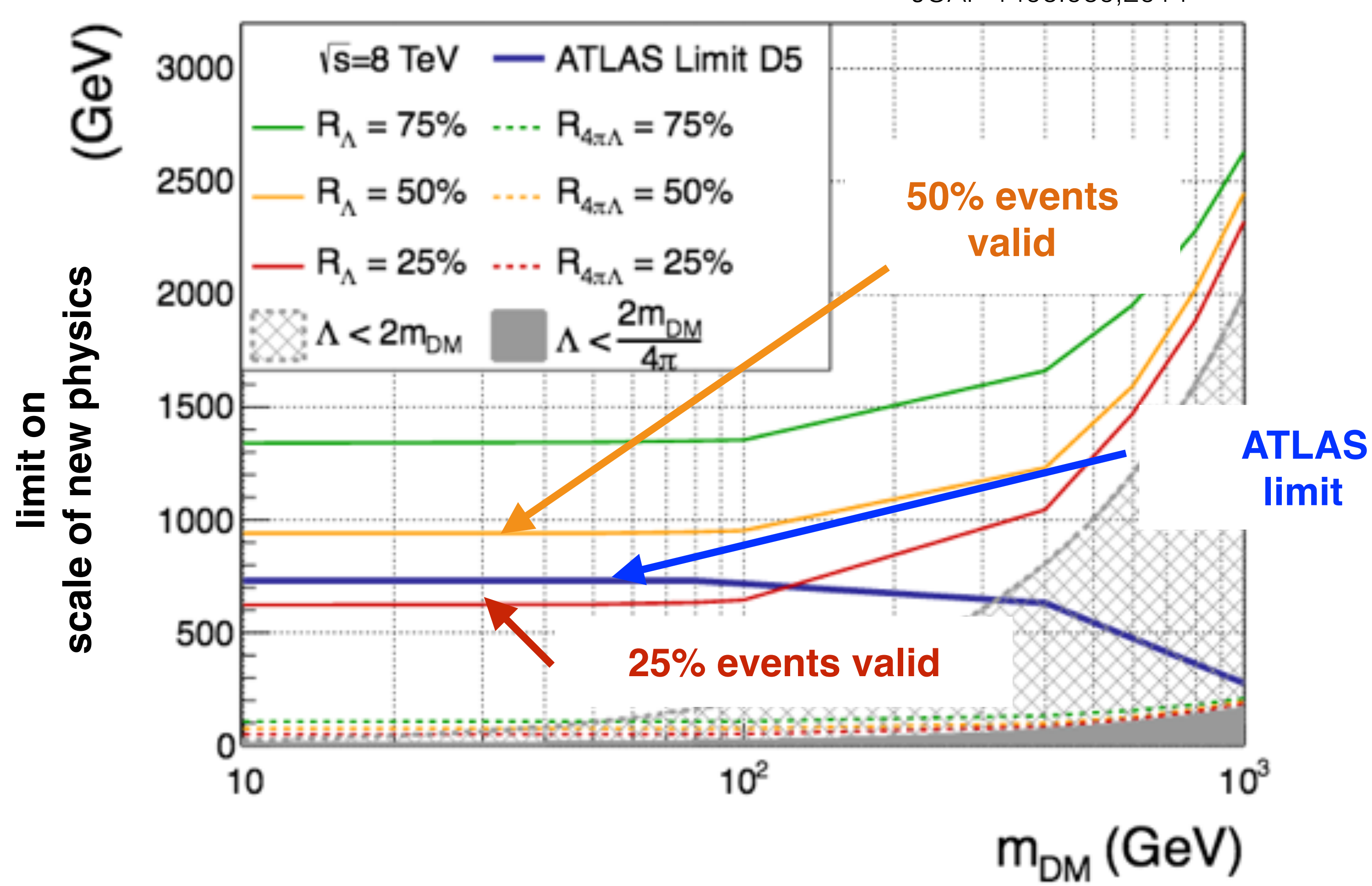
DM Effective Field Theory

LHC results were interpreted in effective field theory (EFT) models

- "Ignore" parts of model that should not affect observations → as general as possible
- Justified only, if energy scale well below new physics ($Q_{trans} \ll m_{Med}$)



JCAP 1406:060,2014



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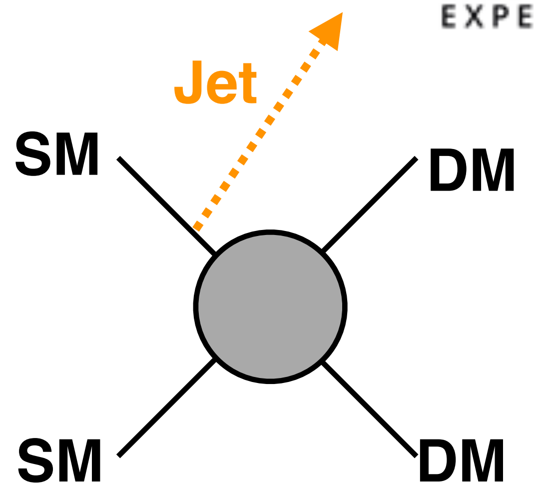
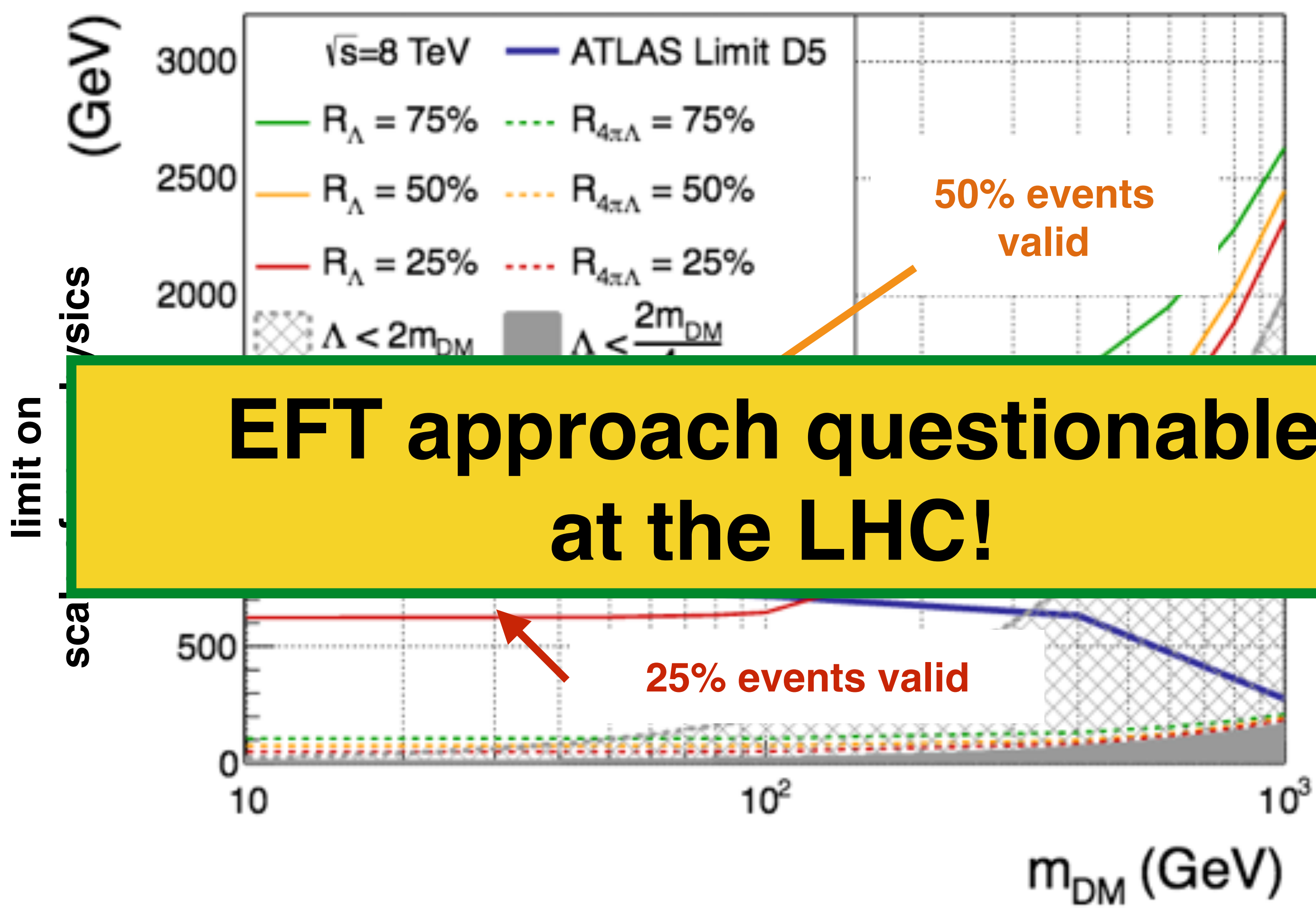


JCAP 1406:060,2014



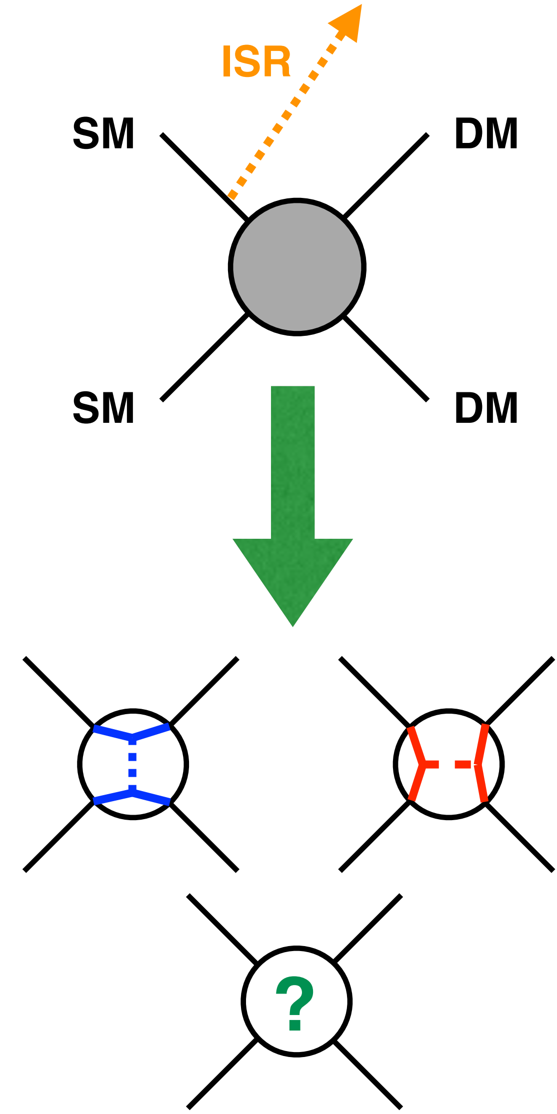
EFT approach questionable at the LHC!

JCAP 1406:060, 2014

Simplified Models

Need to move to simplified models

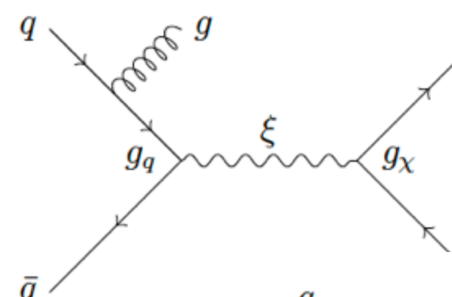
- Construct simple model with DM, a mediator and one interaction: more complete, but less general → more parameters

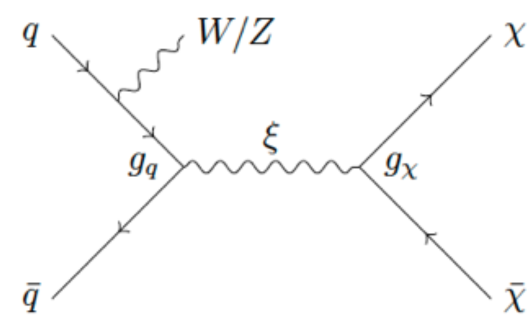


Reinterpretation of monojet, mono-Z(→ℓℓ) and mono-W/Z(→qq) analyses performed within 3 simplified models

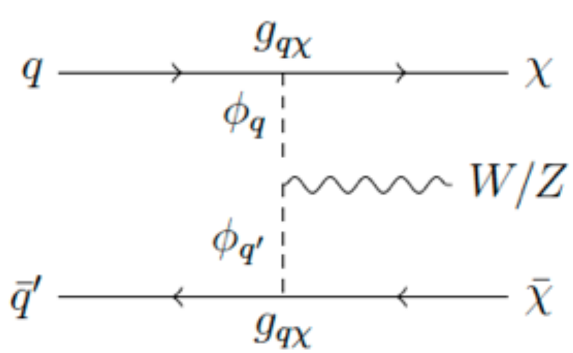
$$\mathcal{L}_{sV} \supset \xi_\mu \left[\sum_q g_q \bar{q}\gamma^\mu q + g_\chi \bar{\chi}\gamma^\mu \chi \right]$$

$$\mathcal{L}_{sA} \supset \xi_\mu \left[\sum_q g_q \bar{q}\gamma^\mu \gamma_5 q + g_\chi \bar{\chi}\gamma^\mu \gamma_5 \chi \right]$$





$$\mathcal{L}_{tS} \supset \sum_i g_{q\chi} \bar{Q}_i P_R \phi_i \chi + \text{h.c.}$$



Conclusions: searches could profit from dedicated optimisation for simplified models, especially in low E_T^{miss} region

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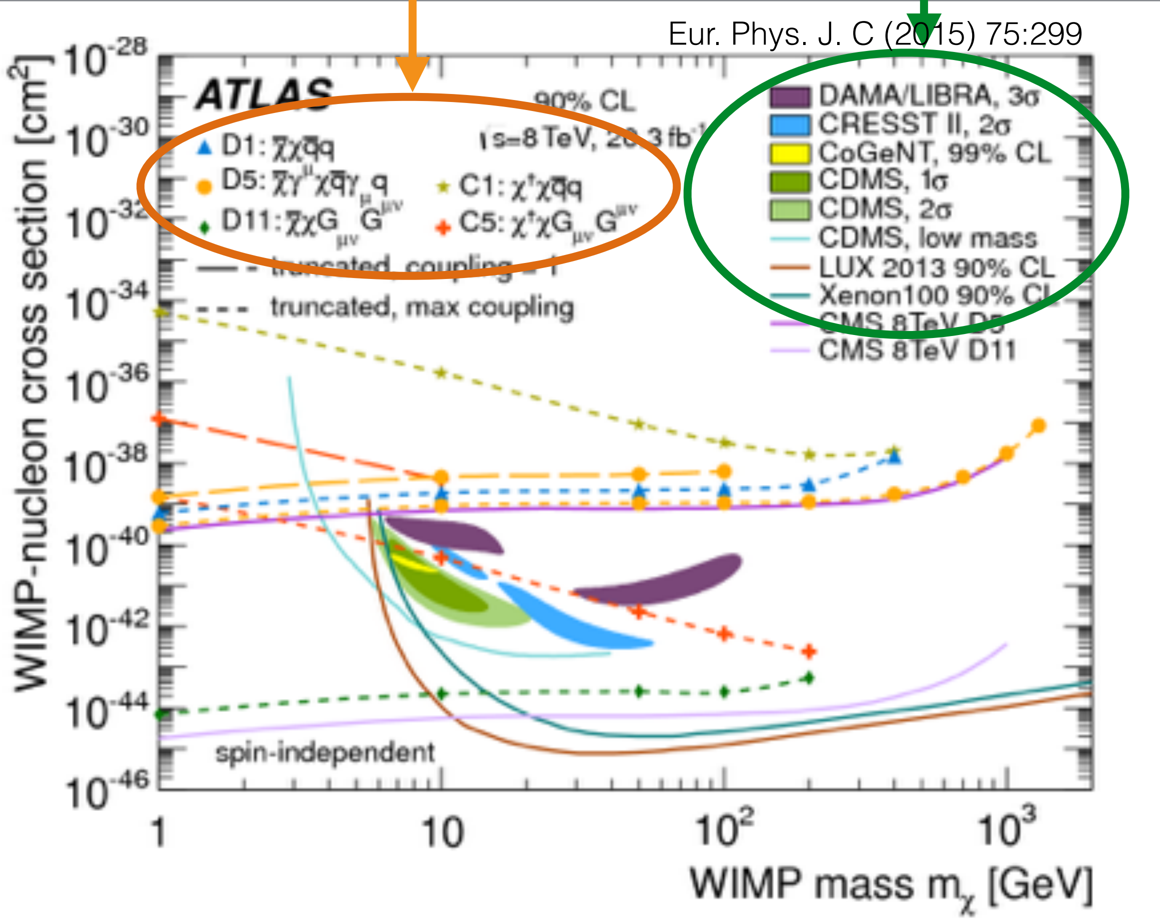
How to do comparisons?

collider limits direct detection results



"Famous" plot, criticised a lot because EFT mostly not valid

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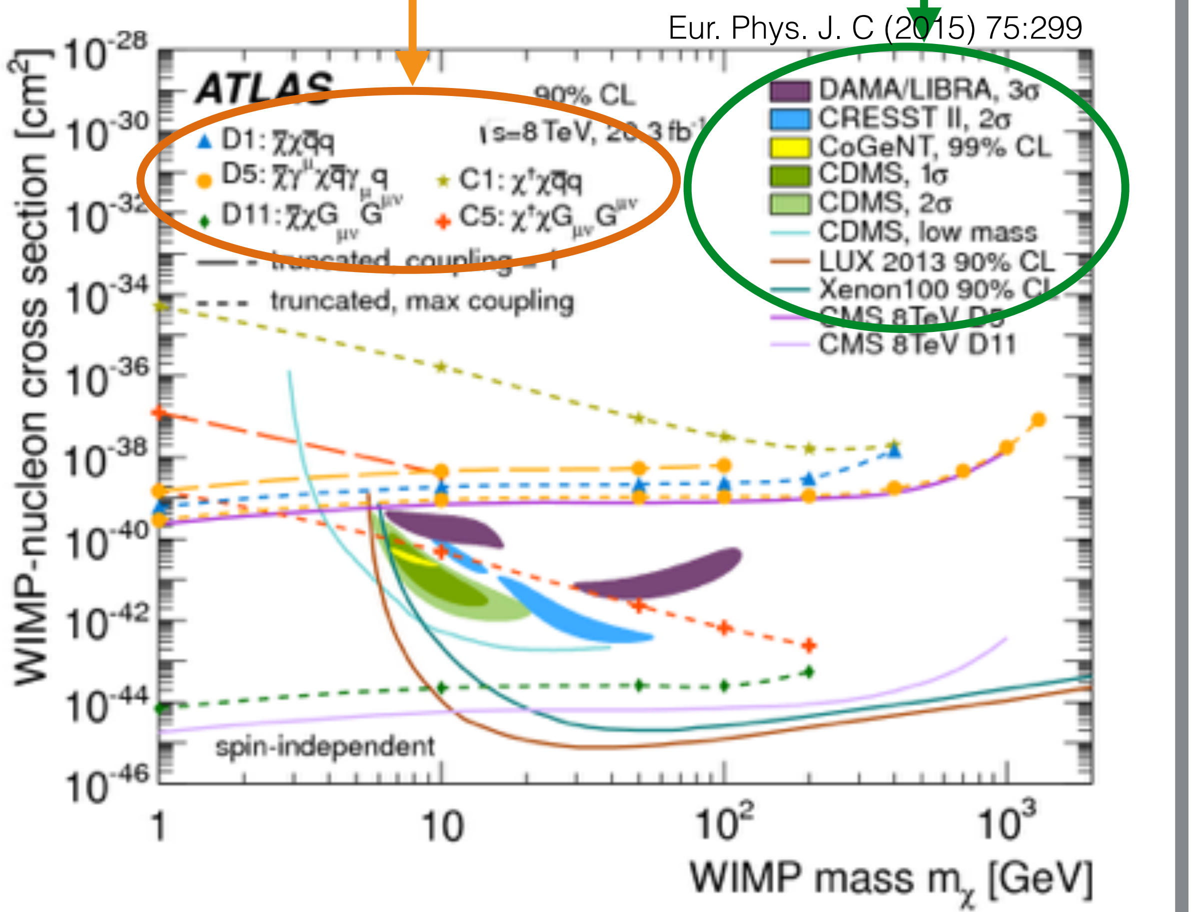
collider limits

direct detection results



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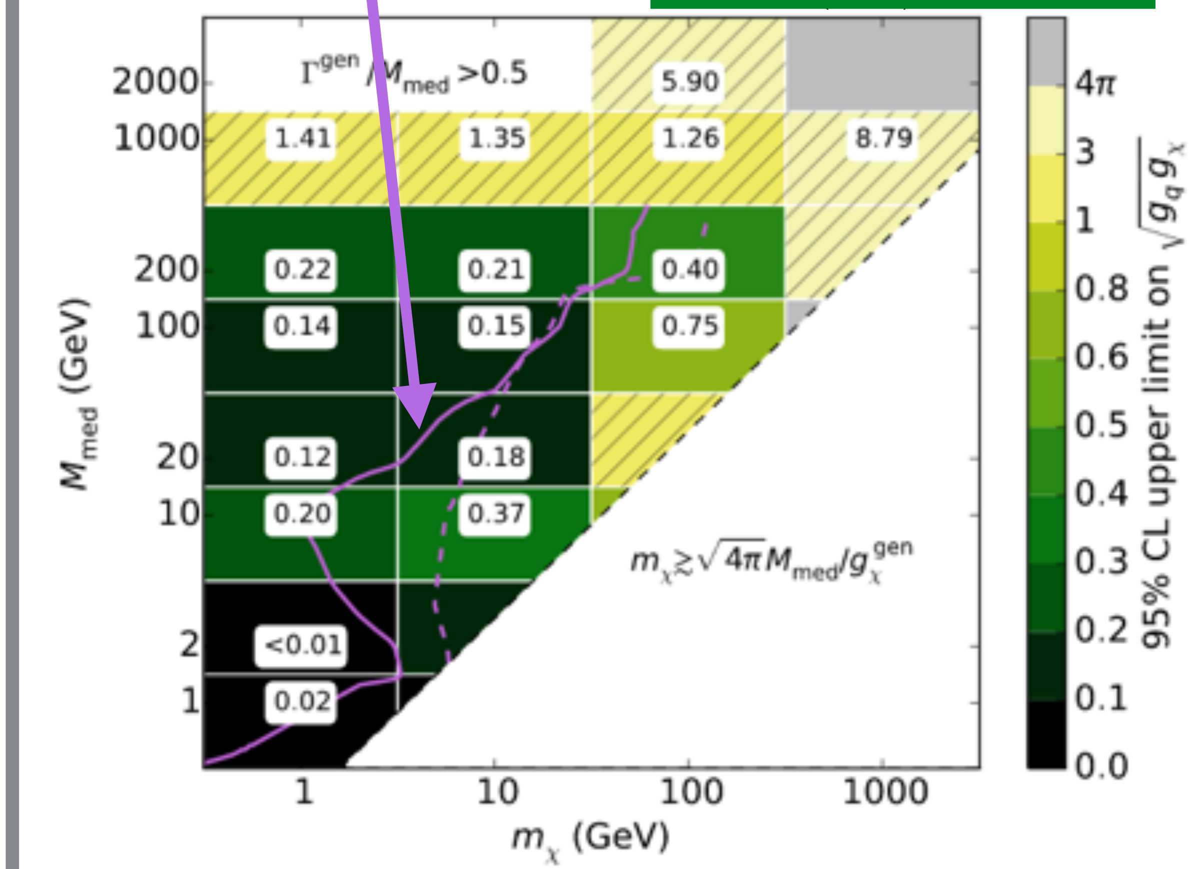
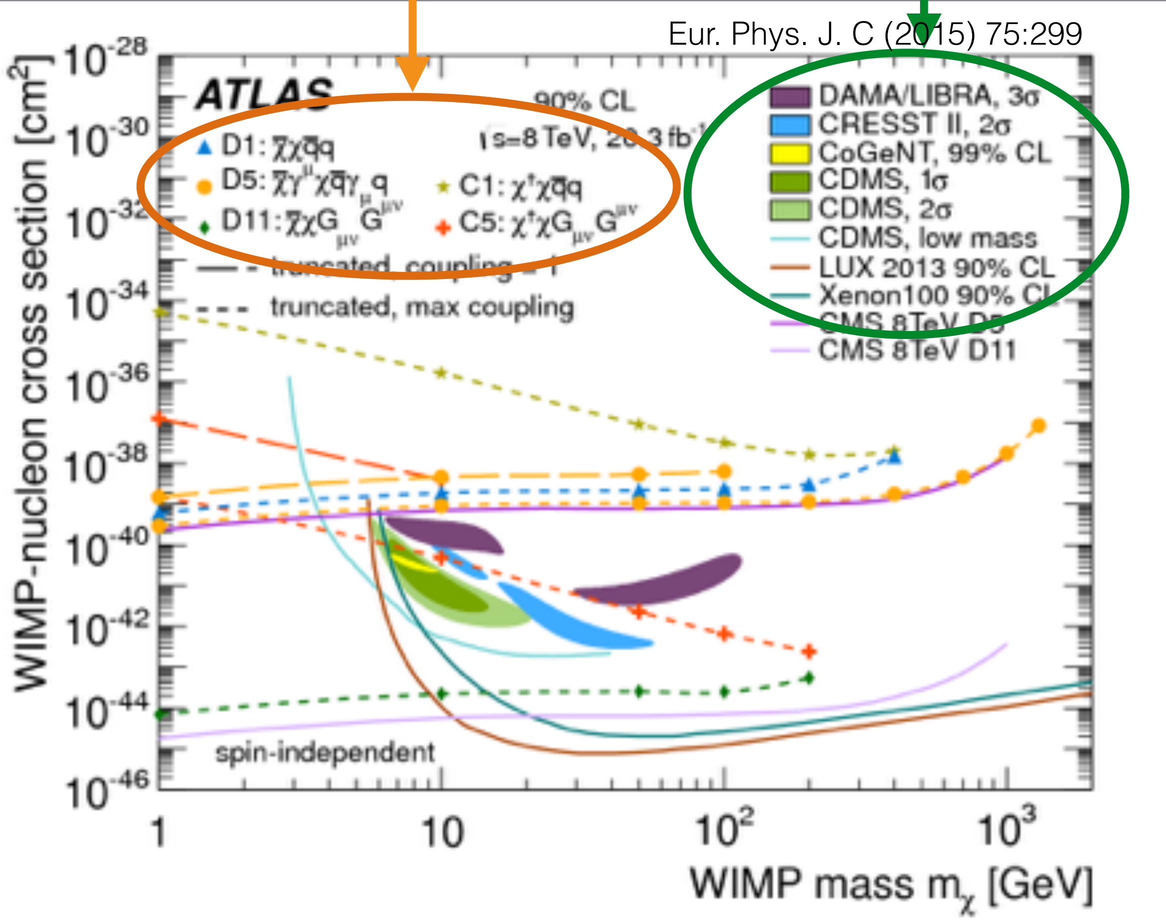


"fairer" comparison possible with Simplified Models possible, but more parameters

How to do comparisons?

collider limits   direct detection results



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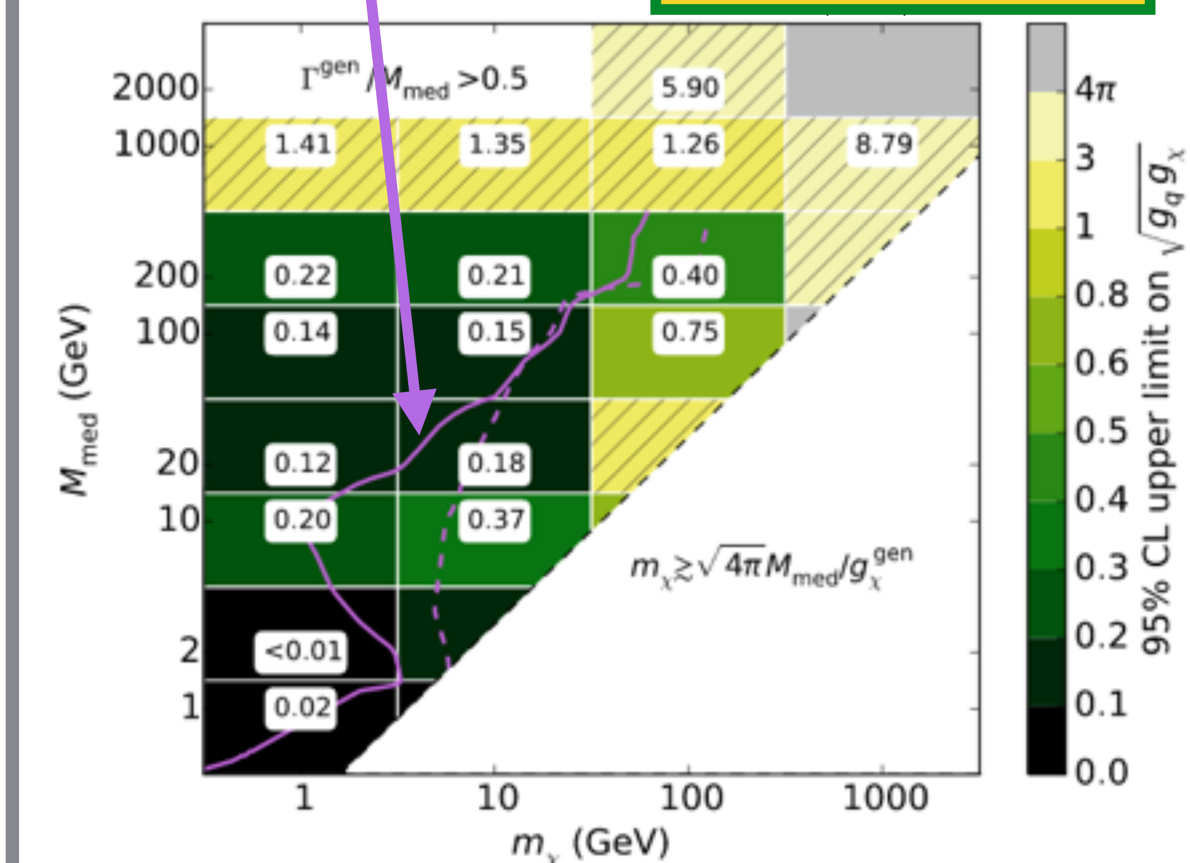
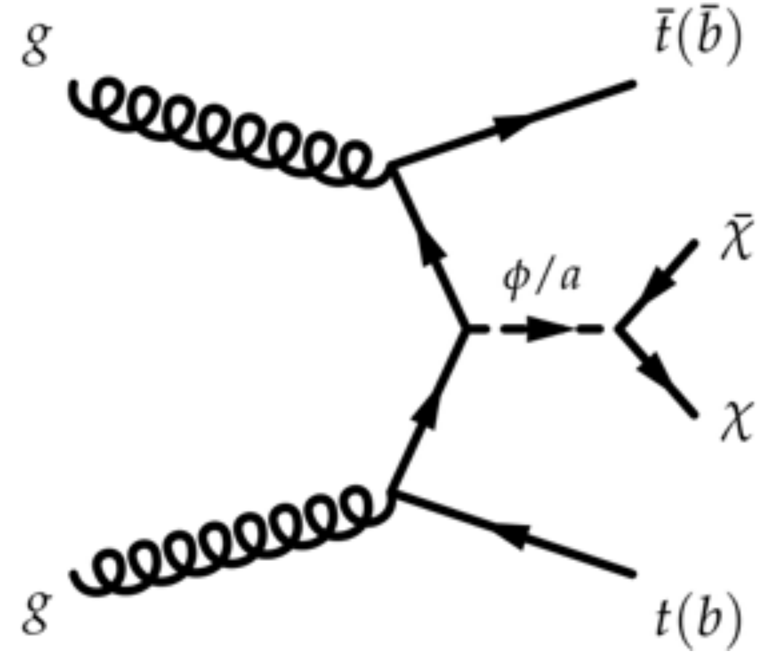


"fairer" comparison possible with Simplified Models possible, but more parameters

Lots of progress in DM@LHC community: simplified models well established → comparisons have less question marks now

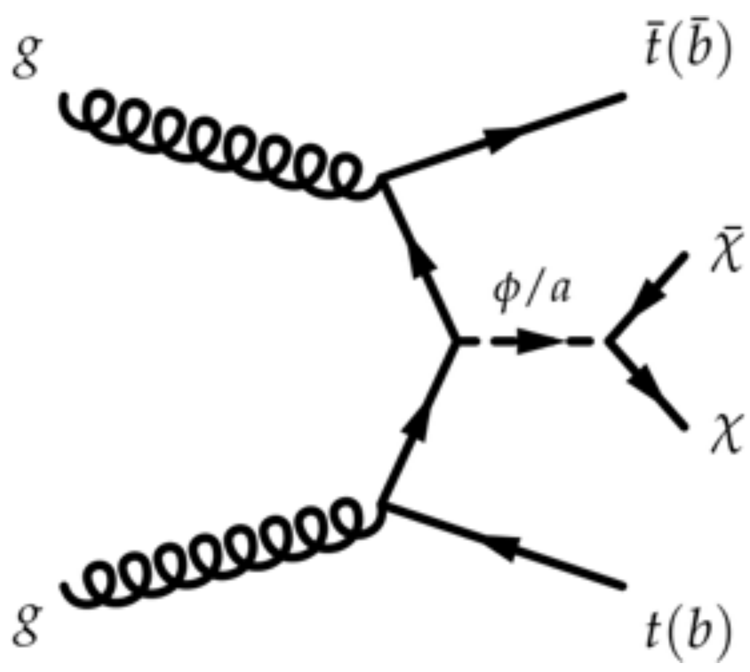
Dark Matter + top quarks



ATLAS-CONF-2016-050

Motivation

Theoretical motivation: Yukawa-like couplings between spin-0 mediator and SM quarks: stronger couplings to heavier quarks



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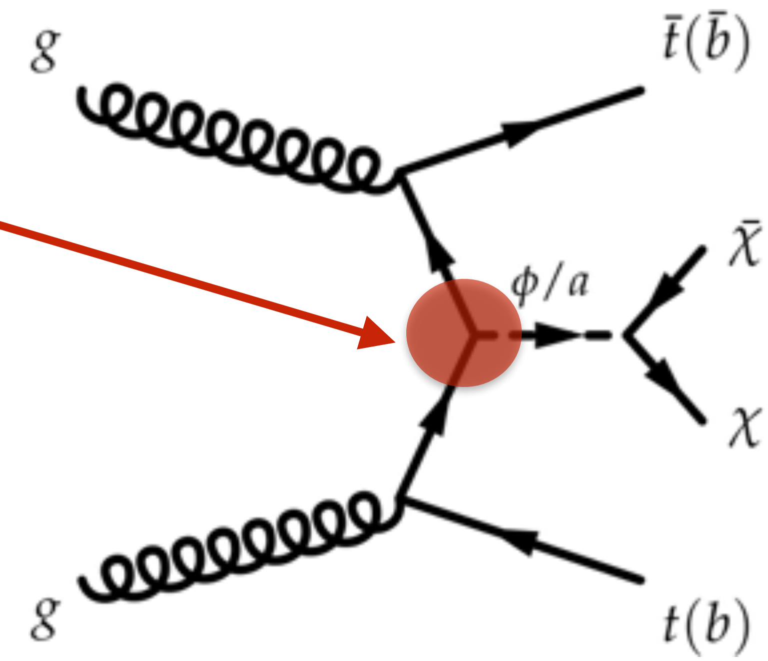

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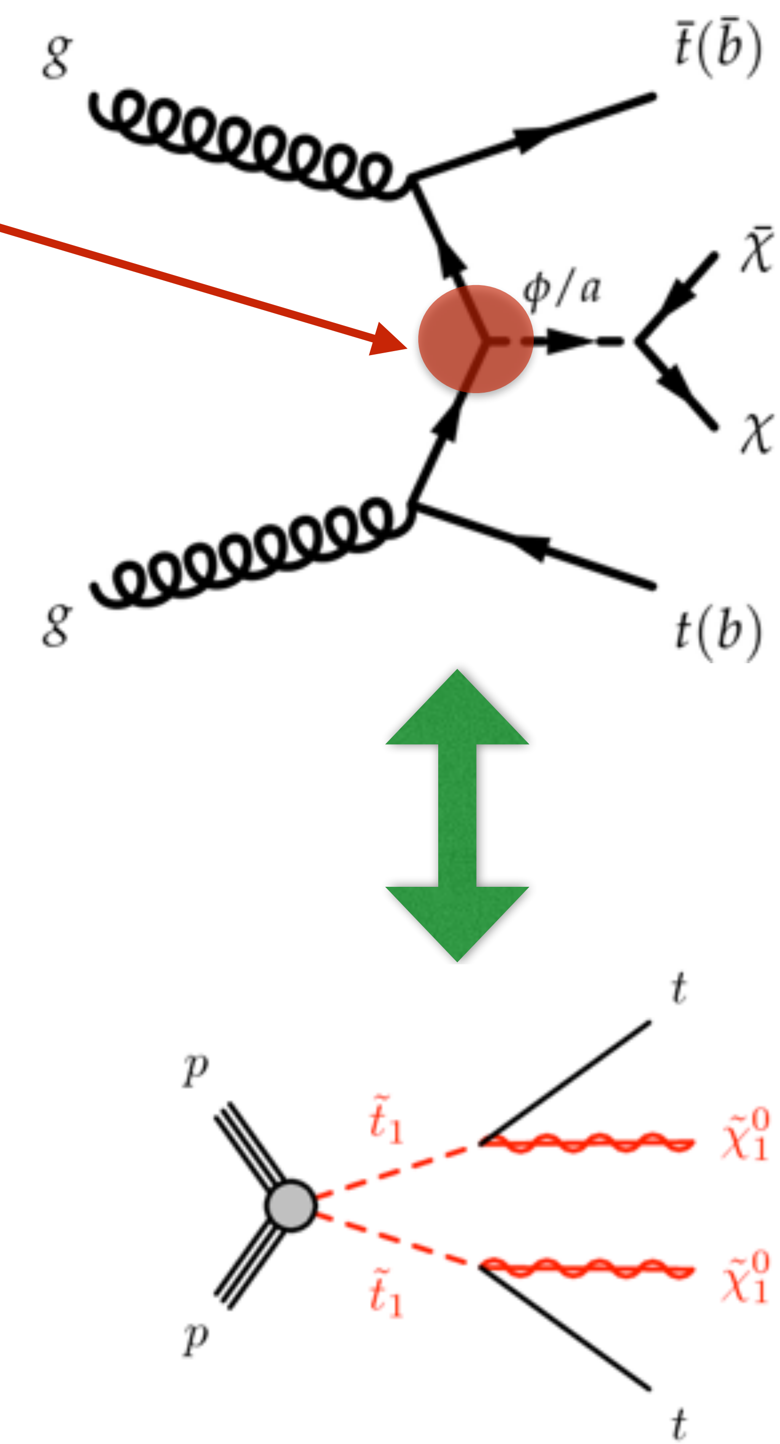

- Searches for stops and DM+tt share the same final state: tt + E_T^{miss} → analyses performed together
  - ATLAS stop 0L, 1L and 2L results all had DM interpretation (*)
    - I worked on 1L channel → presented in the following

(*) Also result on DM + bb was released for ICHEP

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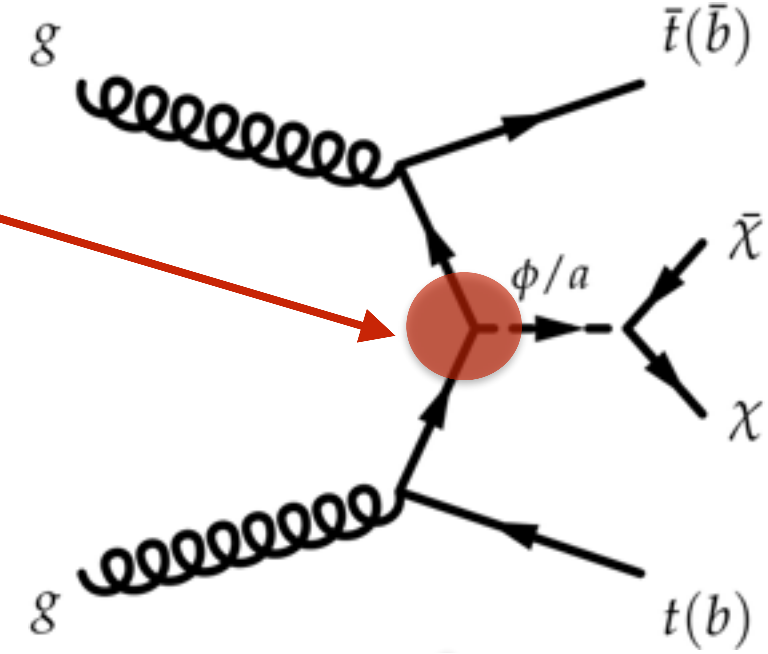

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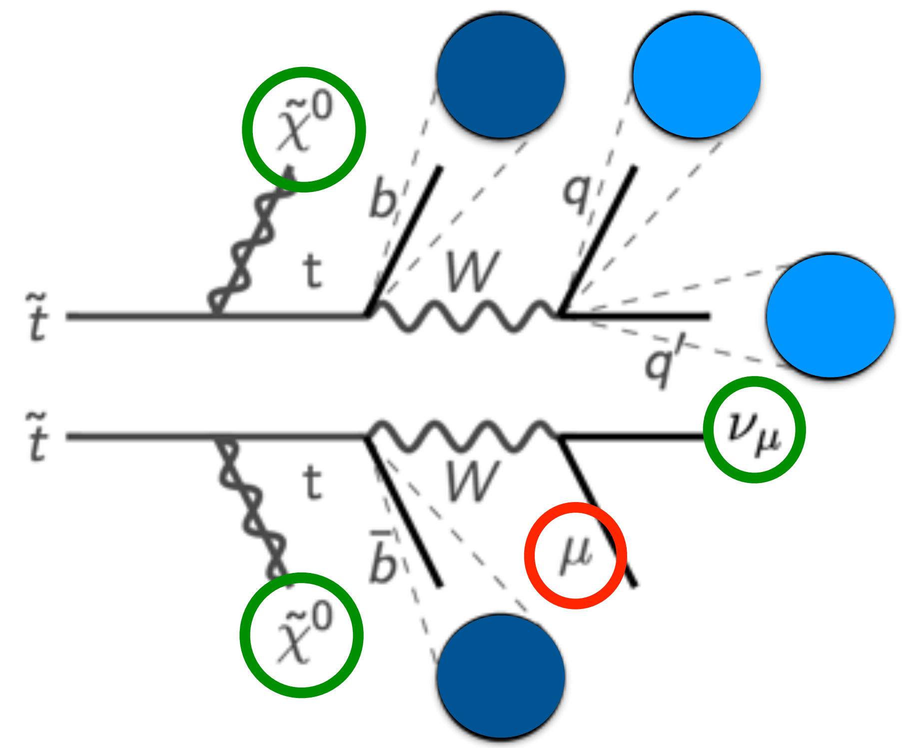


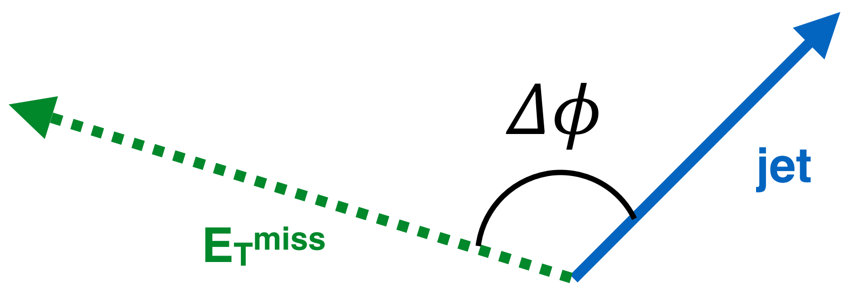
4 jets (thereof 2 b-jets), E_T^{miss}, 1 lepton (e or μ)

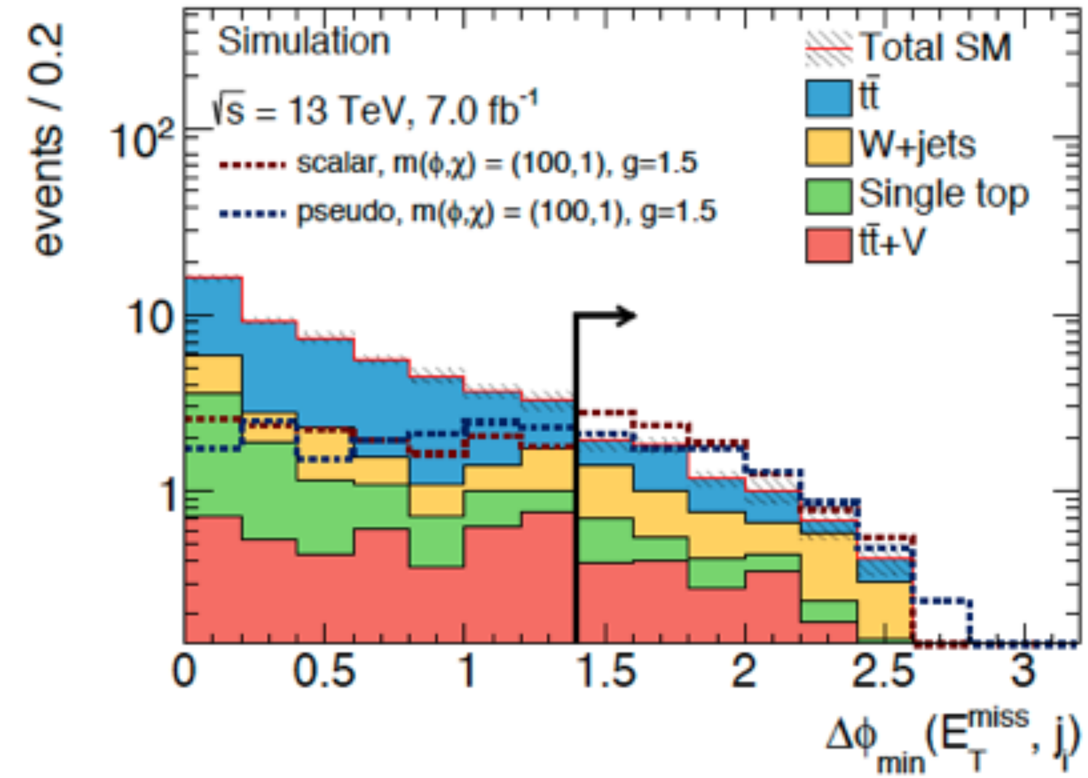
(*) Also result on DM + bb was released for ICHEP

Discriminating Variables

- Especially useful for DM regions, selects specific event topologies:

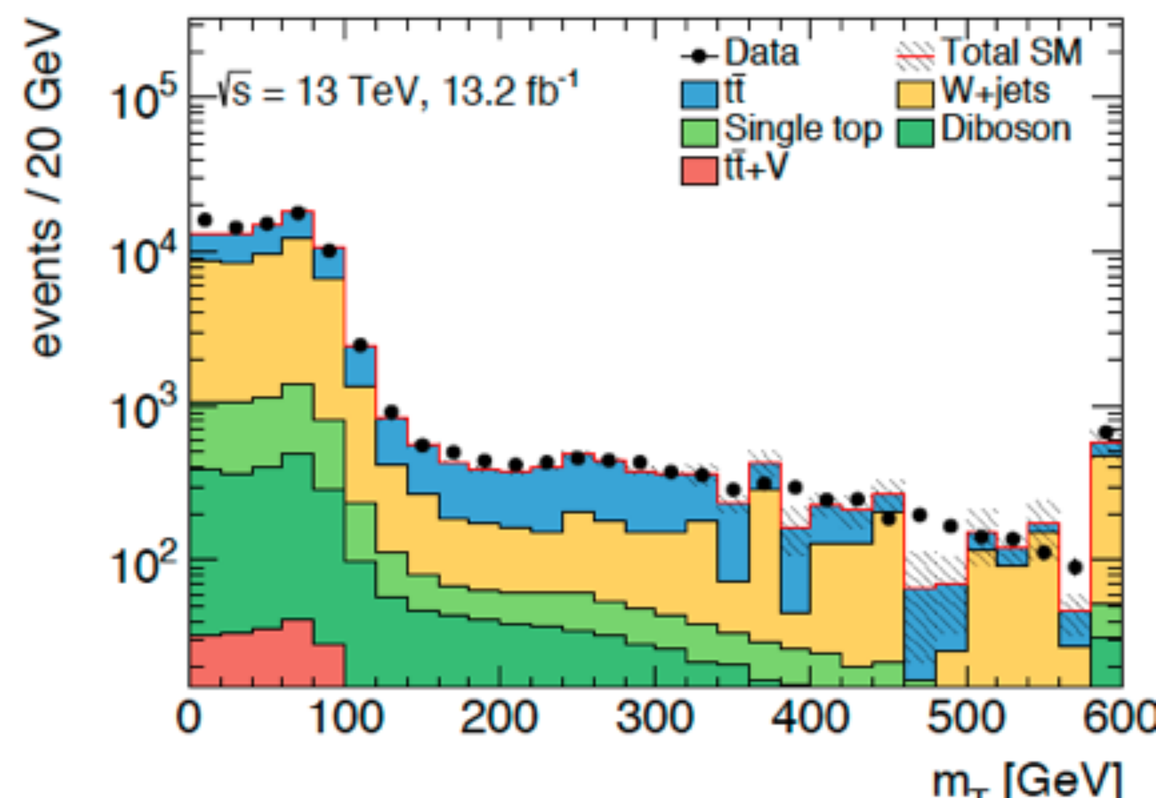
  $\Delta\phi_{min}(E_T^{miss}, \text{jets})$





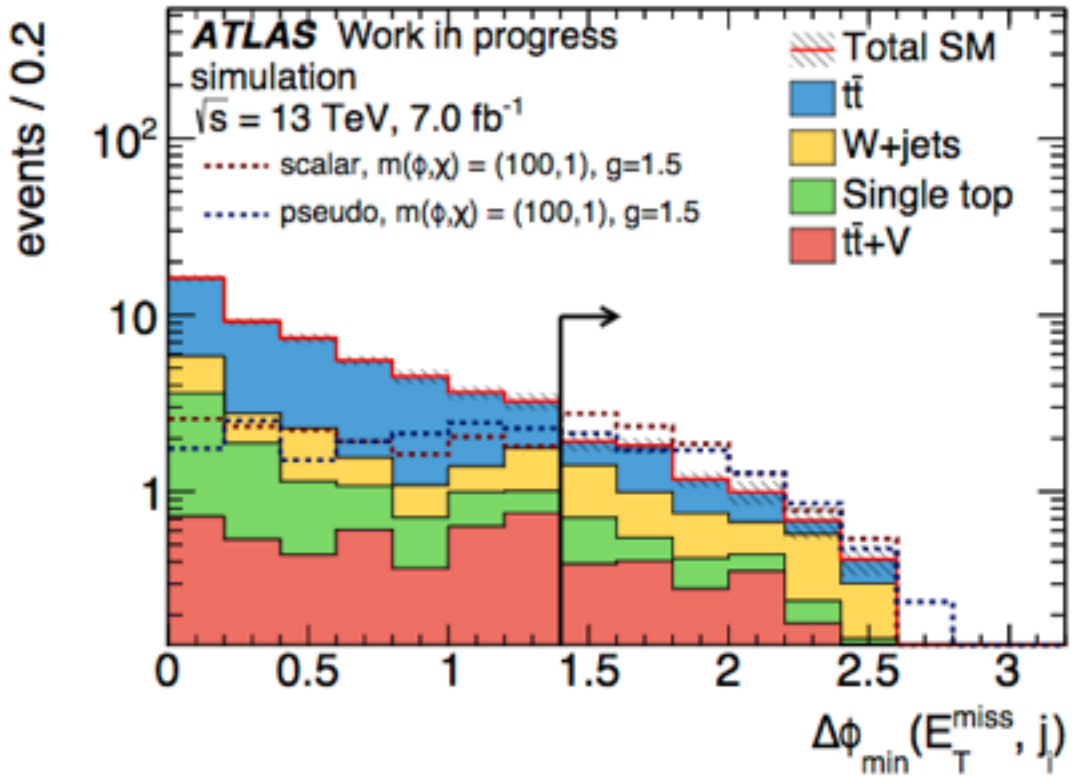
- Transverse mass m_T, reconstructs mass of leptonically decaying W boson:

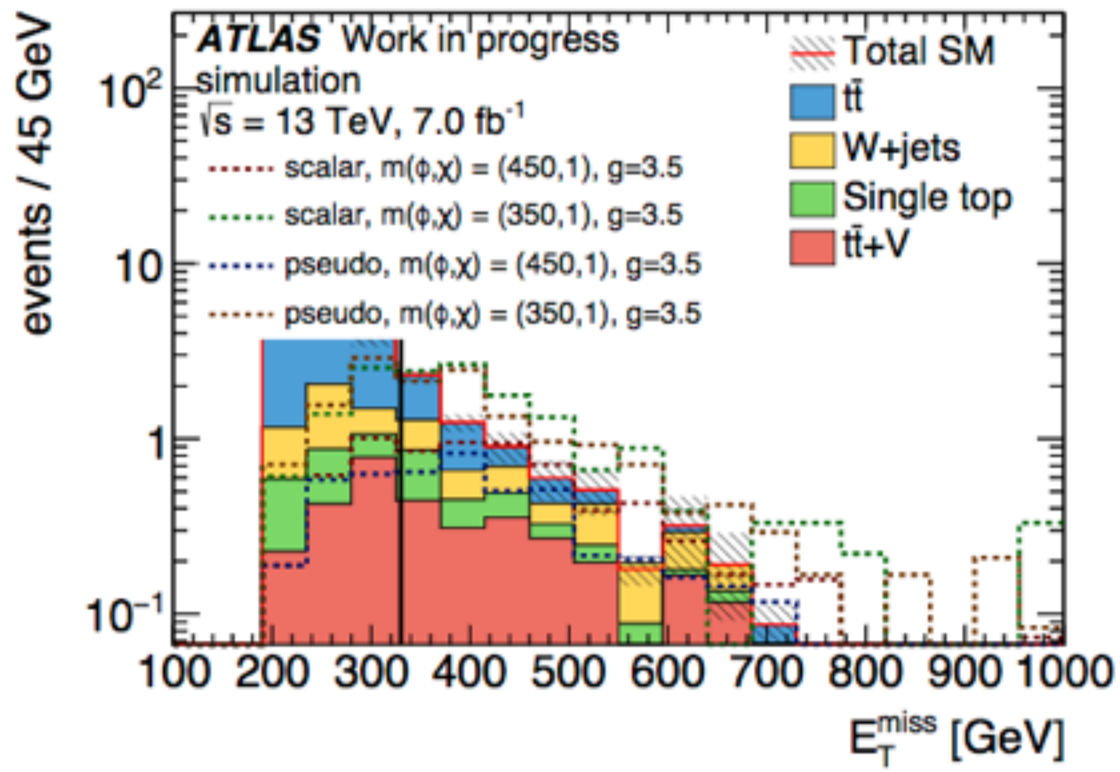
$$m_{\mathrm{T}i}^2 = \left(\sqrt{p_{\mathrm{T}i}^2 + m_{p_i}^2} + \sqrt{q_{\mathrm{T}i}^2 + m_{q_i}^2}\right)^2 - (\vec{p}_{\mathrm{T}i} + \vec{q}_{\mathrm{T}i})^2$$



DM Signal Regions

DM_low	***DM_high***
Natural coupling (g~1), low-mass mediator (M_{med} = 100 GeV)	Maximal coupling (g~3.5), high-mass mediator (M_{med} = 350 GeV)

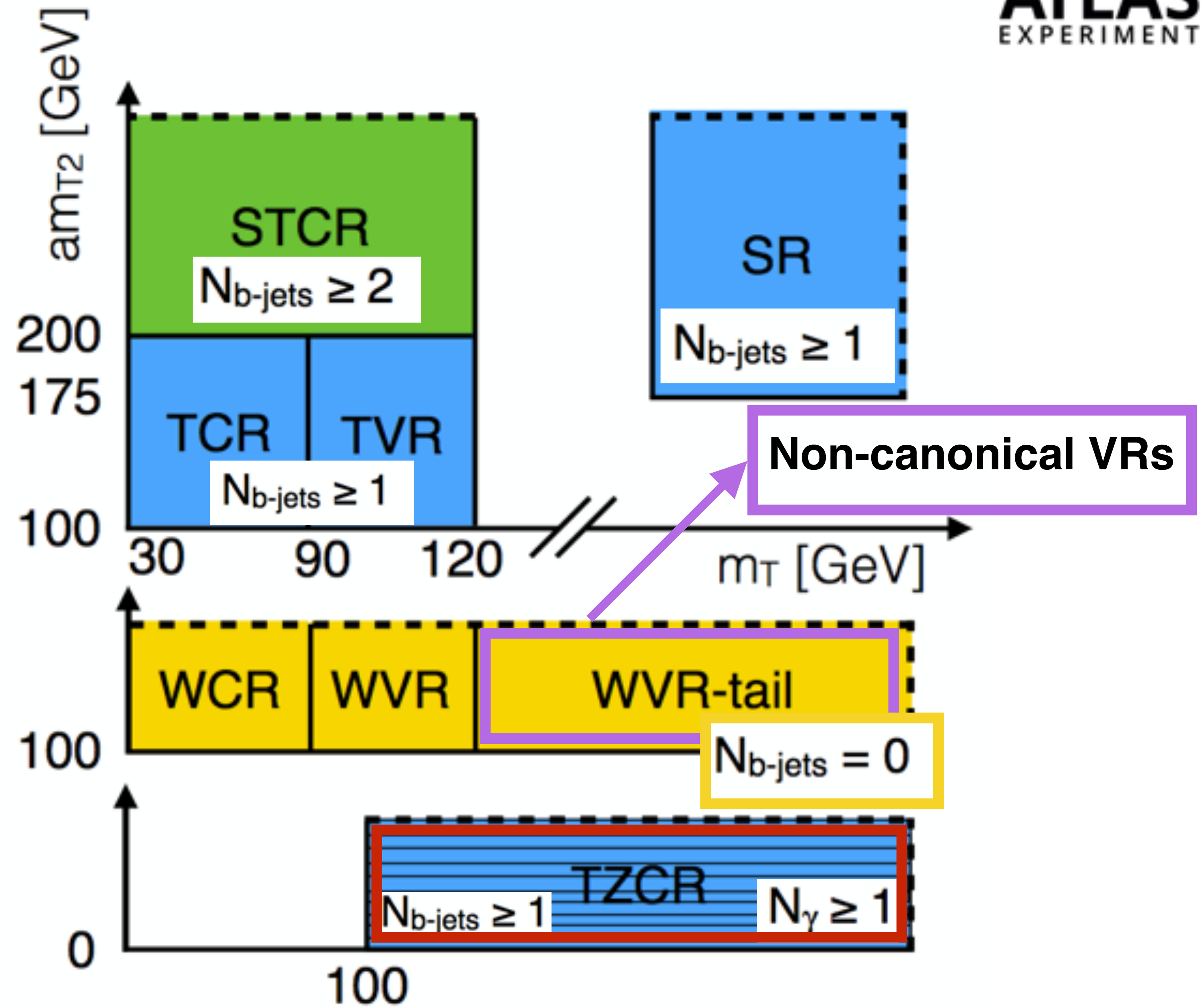




DM_low	DM_high
most important variables: E_T^{miss}, $\Delta\phi_{min}$	**most important variables:** E_T^{miss}, $\Delta\phi_{min}$ and m_T
largest backgrounds: ttbar (2L, 1L1τ) (33%), W+jets (31%), tt+Z (23%)	**largest backgrounds:** ttbar (2L, 1L1τ) (31%), tt+Z (30%)

Background Estimation

- construct background-enriched control region (CR)
- extrapolate over few key variables, constrain MC normalisation in signal region (SR)
- check extrapolation in validation region (VR)



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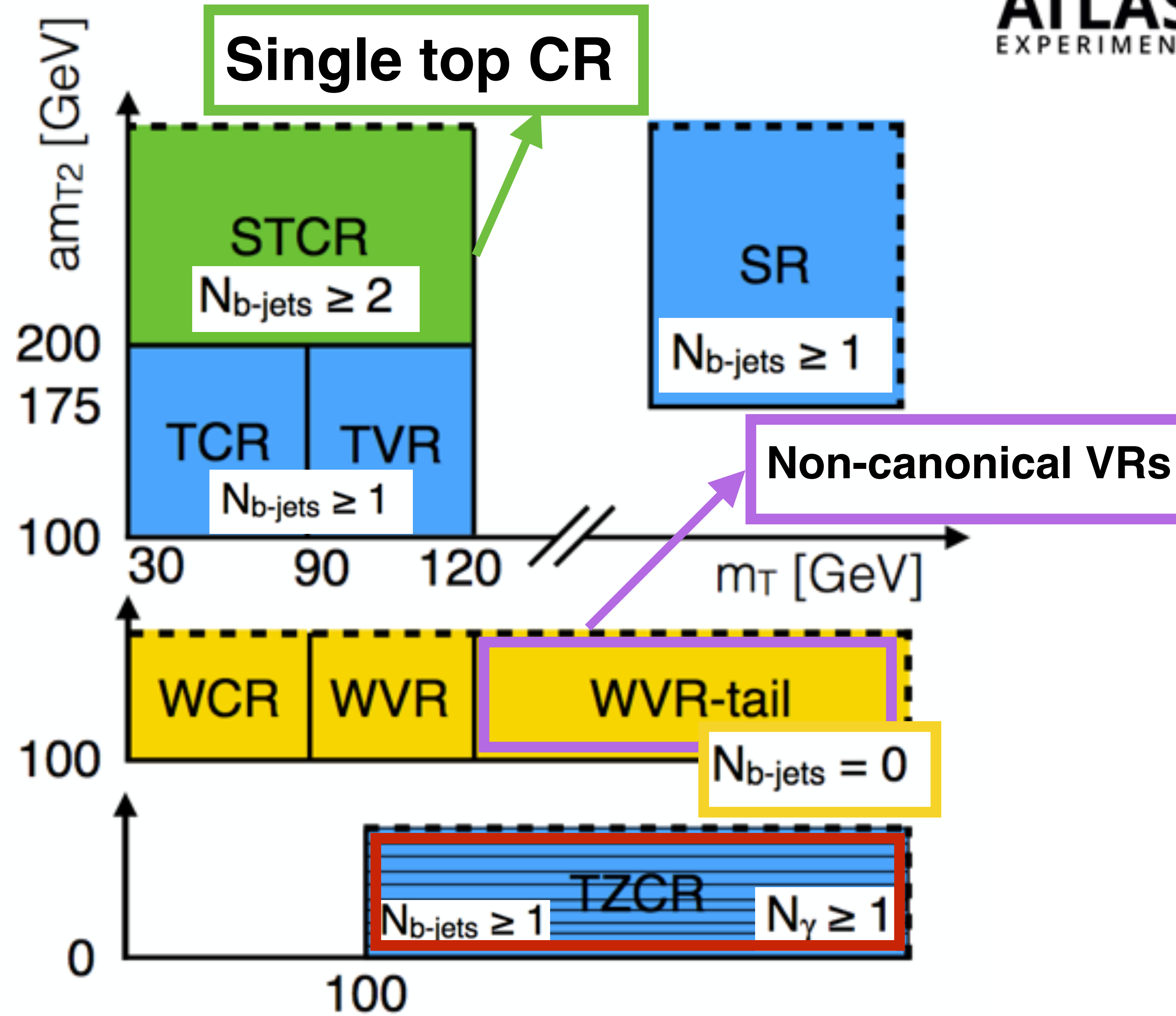

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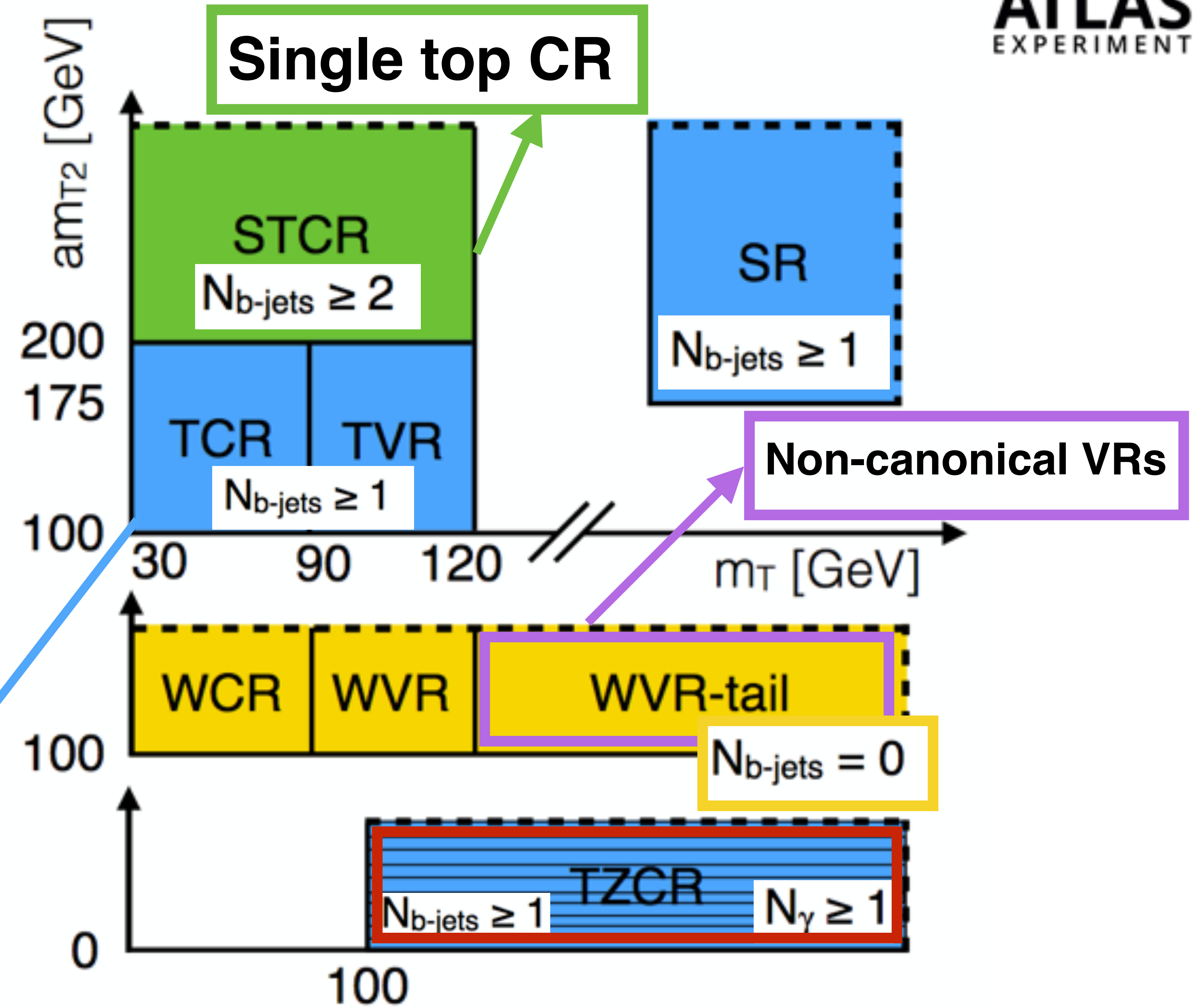

ttbar CRs/VRs

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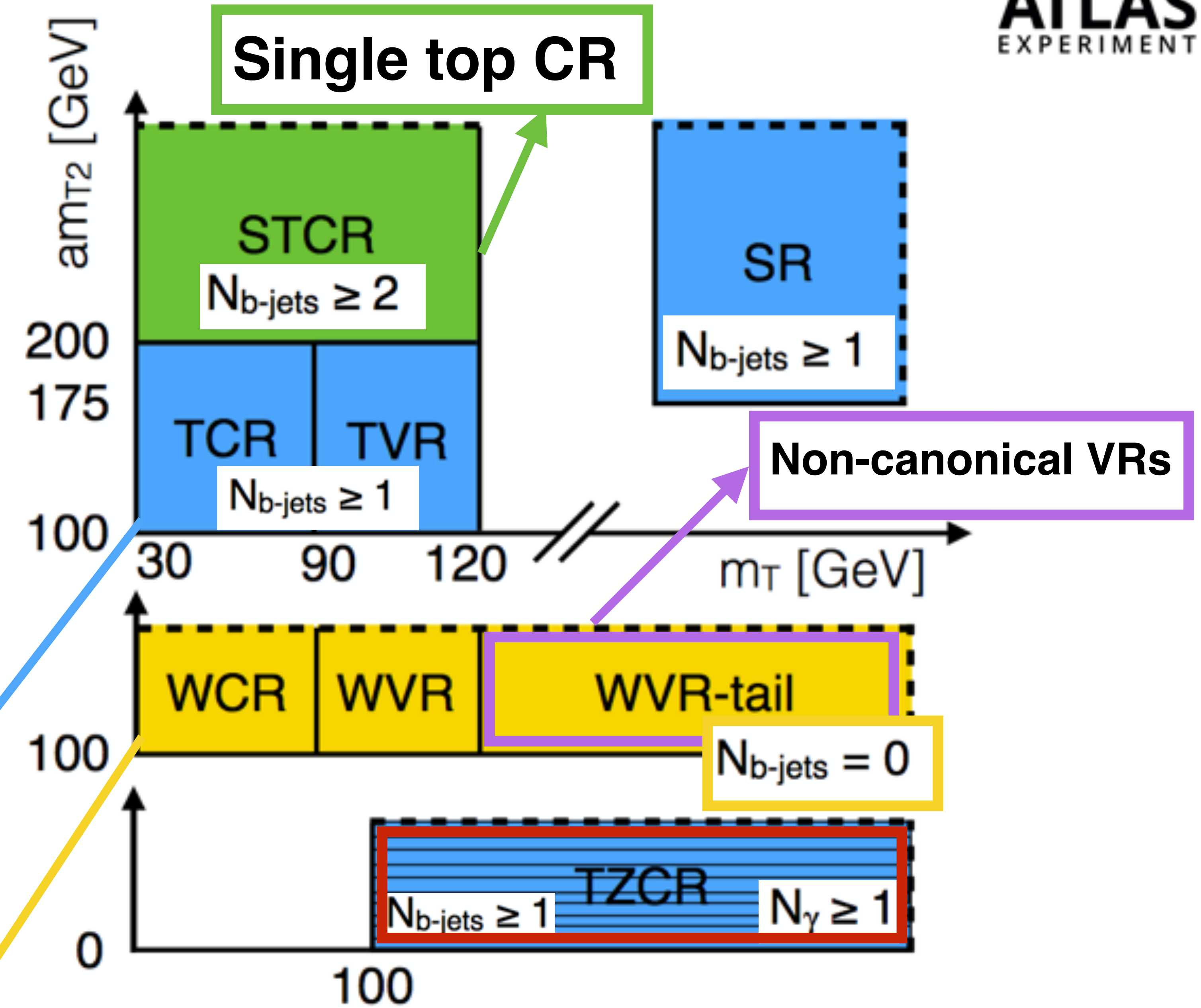

ttbar CRs/VRs

W+jets CRs/VRs

Background Estimation

- construct background-enriched control region (CR)
- extrapolate over few key variables, constrain MC normalisation in signal region (SR)
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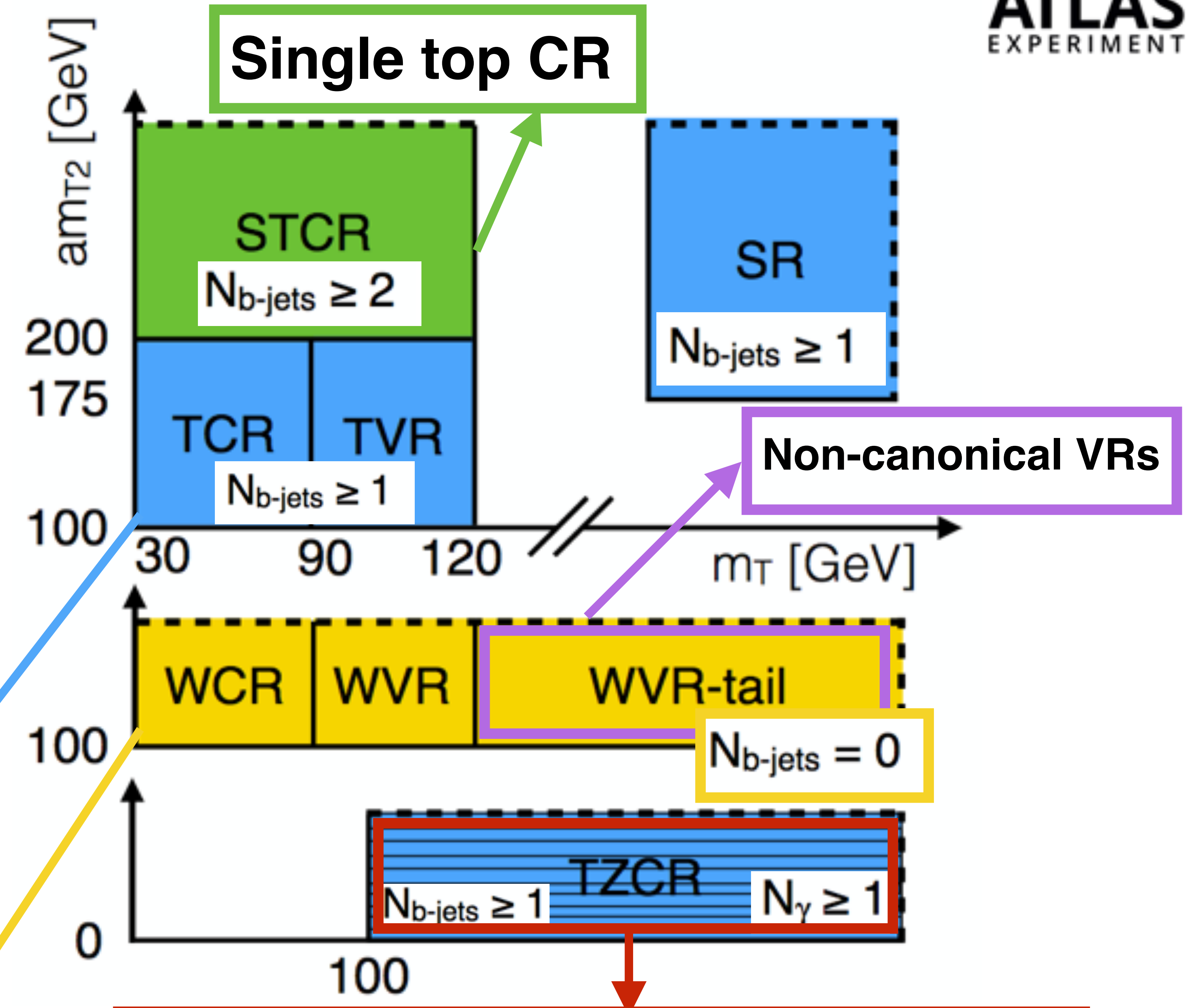

ttbar CRs/VRs

W+jets CRs/VRs

tt+γ CR for tt+Z: require photon, treat as invisible for E_T^{miss}, m_T, $H_T^{miss}{}_{sig}$

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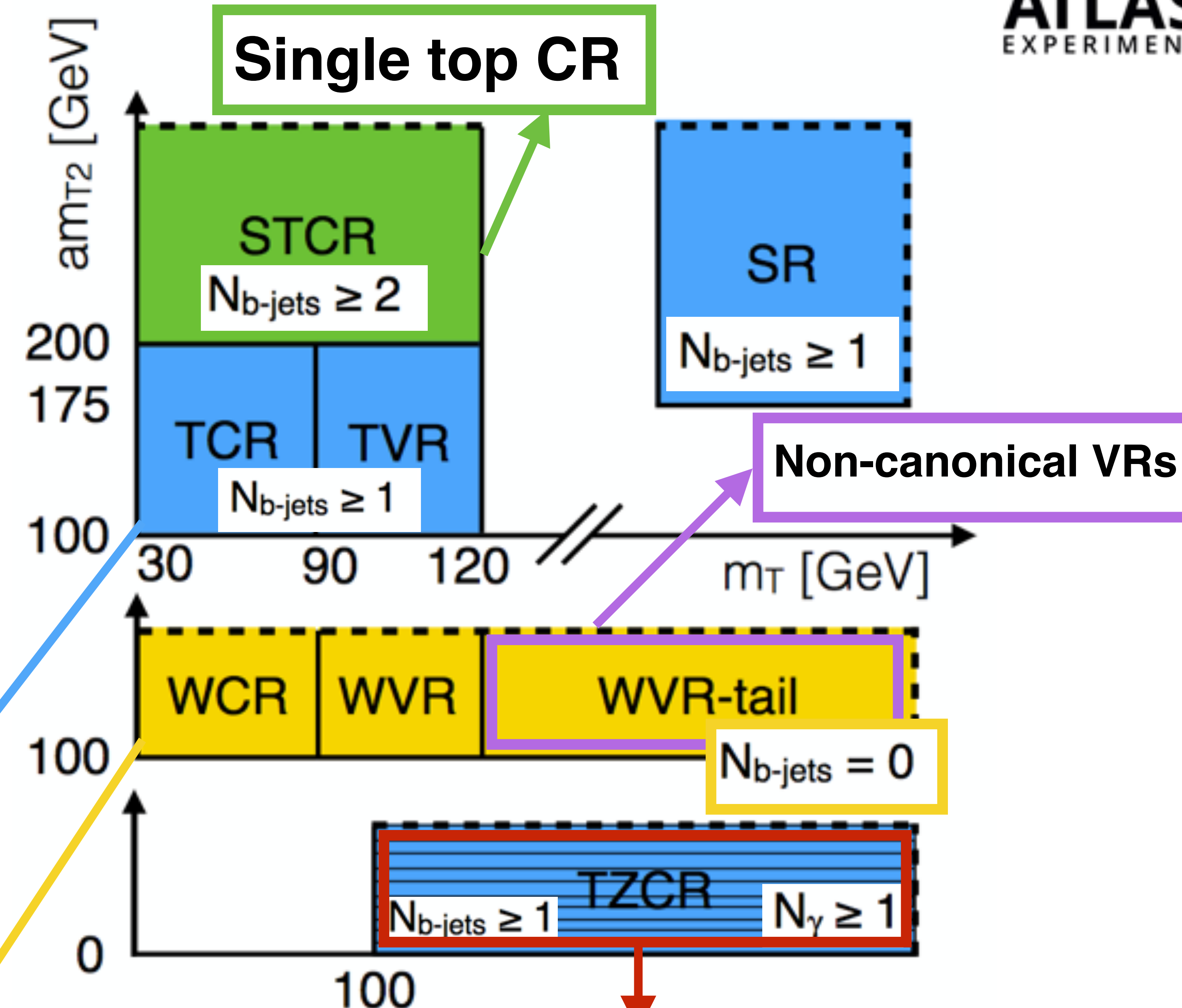


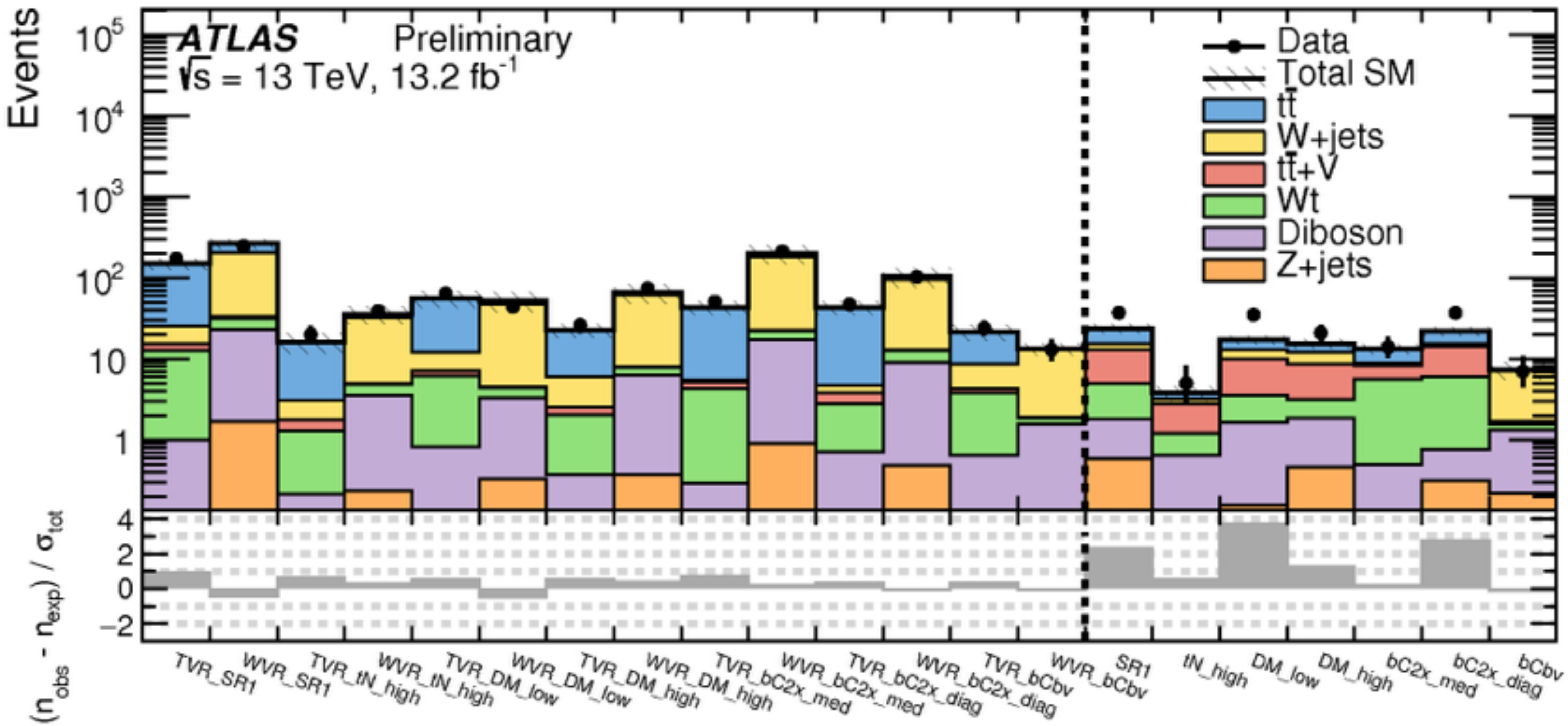
ttbar CRs/VRs

W+jets CRs/VRs

tt+γ CR for tt+Z: require photon, treat as invisible for E_T^{miss}, m_T, $H_T^{miss}{}_{sig}$

Use simultaneous fit of all CRs to obtain final results

Results



Reasonable agreement with prediction in validation regions

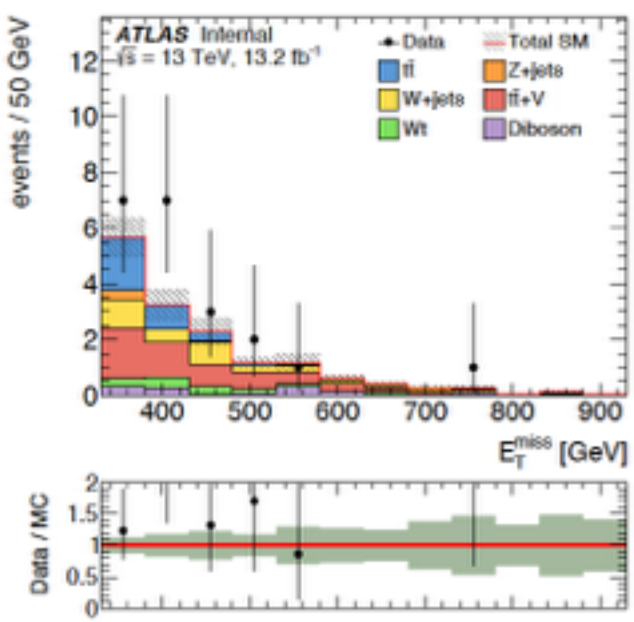
Excess in 3 signal regions (regions are not orthogonal)

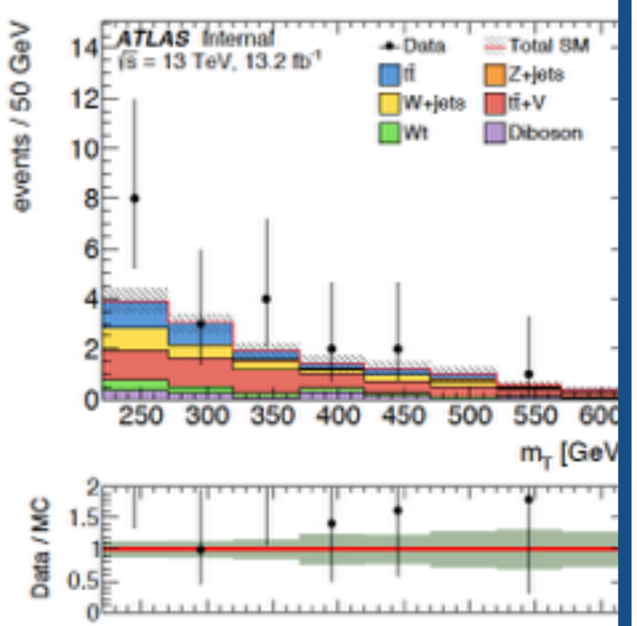
- Largest in *DM_low*: 3.3 σ

Distributions in DM SRs

DM_high

$m_T > 220$ GeV
$E_T^{miss} > 330$ GeV
$\Delta\phi_{min}(E_T^{miss}, \text{jets}) > 0.8$

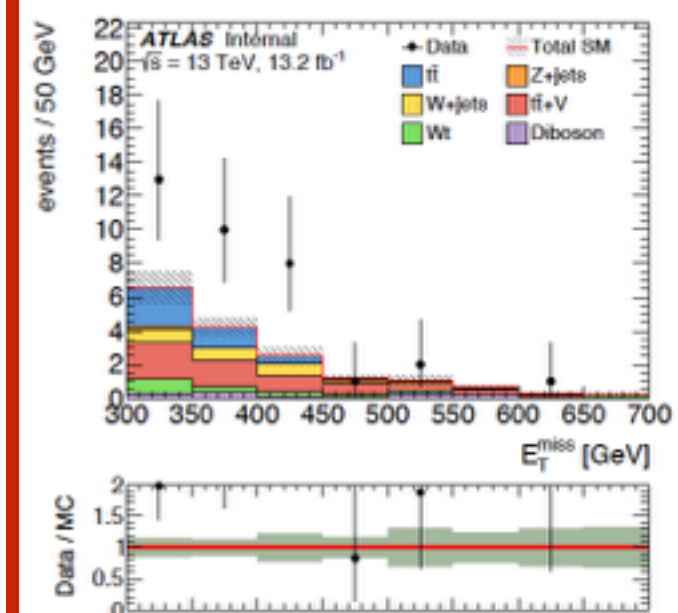


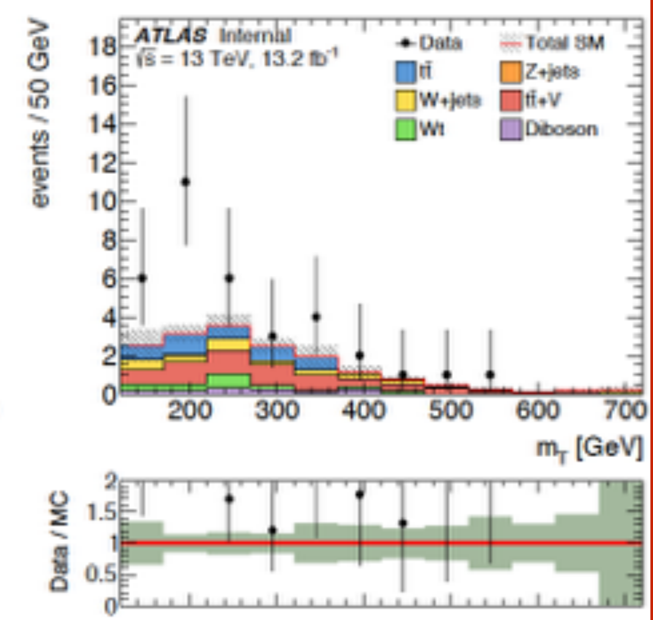


No striking features observed

DM_low

$m_T > 120$ GeV
$E_T^{miss} > 300$ GeV
$\Delta\phi_{min}(E_T^{miss}, \text{jets}) > 1.4$





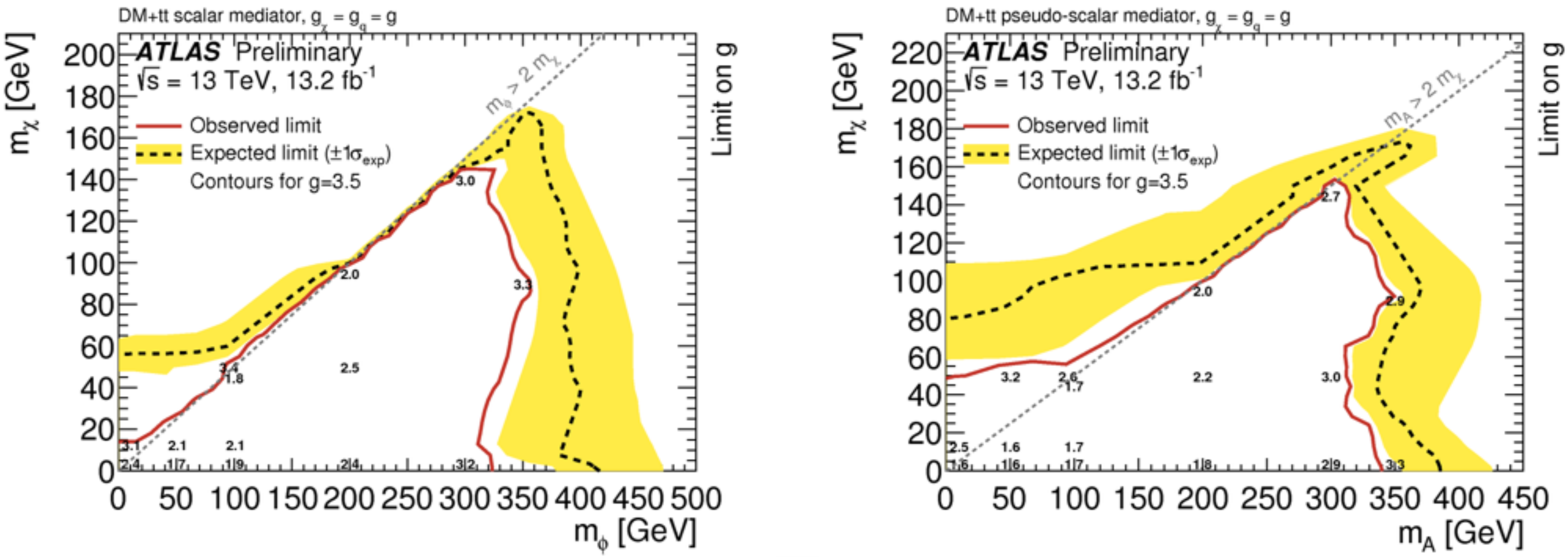
Excess tends to small m_T, small E_T^{miss}

Interpretation

Use simplified model of DM pair production

Present limits for $g = g_\chi = g_q = 3.5$ → maximal coupling that still (kind of) makes sense

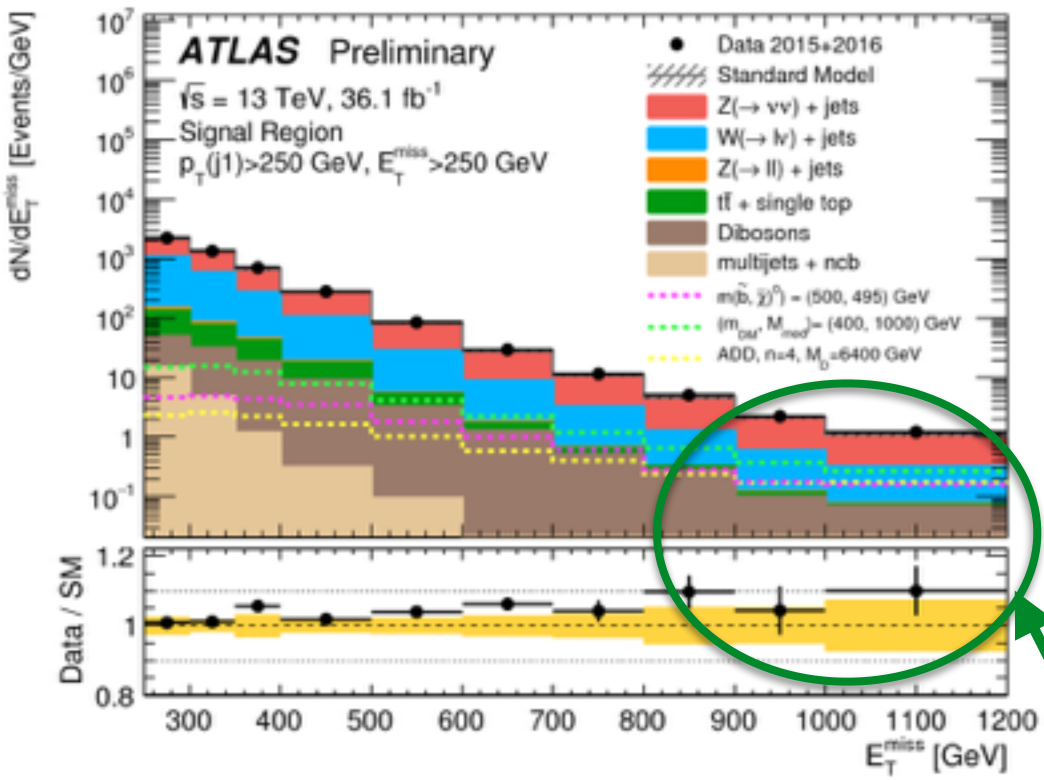
- Exclusion contour for g=1 not meaningful (yet)
- On-shell/off-shell features visible in m_χ - M_{med} plane

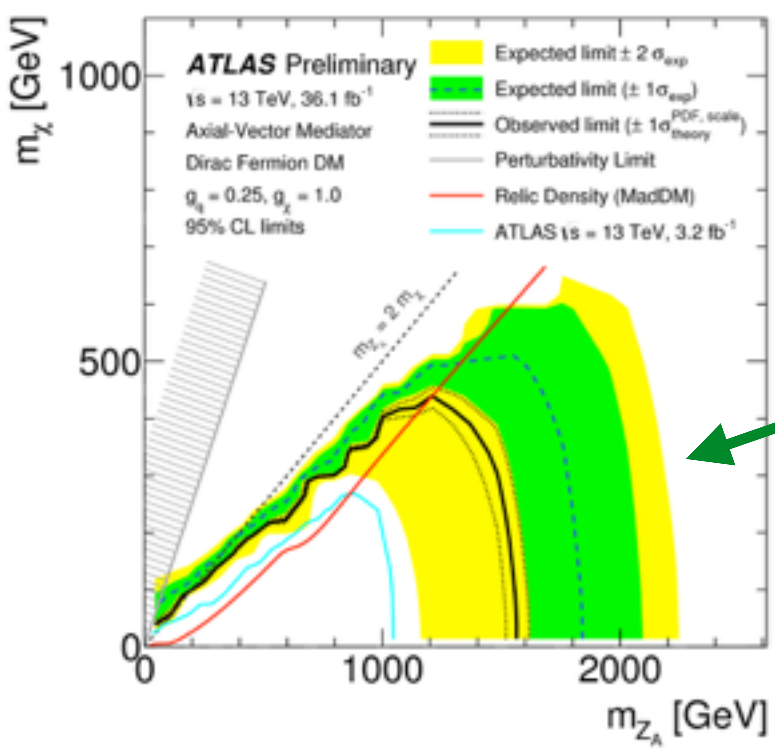


Updated Results

Monojet

ATLAS-CONF-2017-060



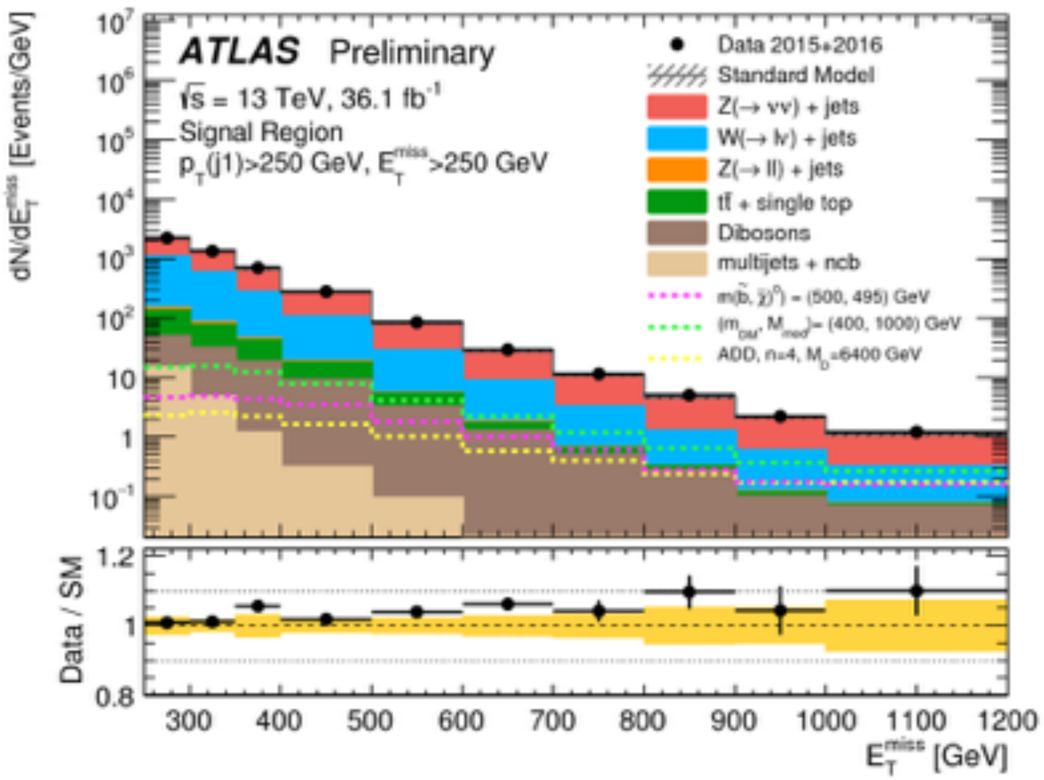


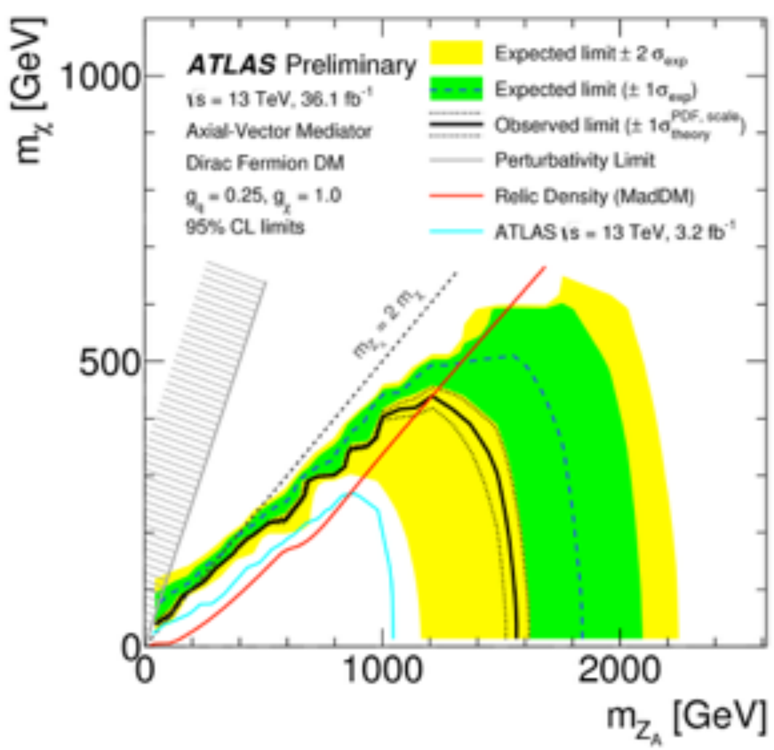
improved statistics in E_T^{miss} tail

interpretation: simplified model

Monojet

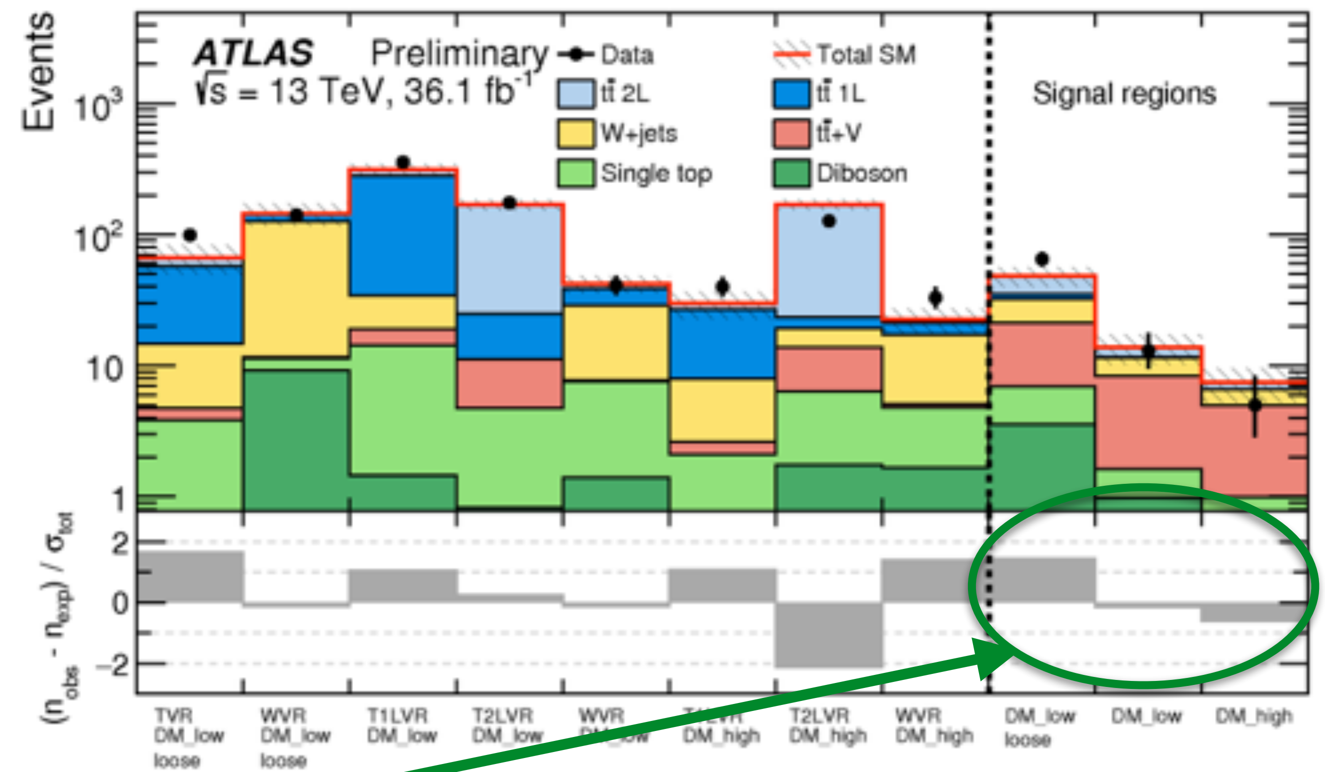
ATLAS-CONF-2017-060

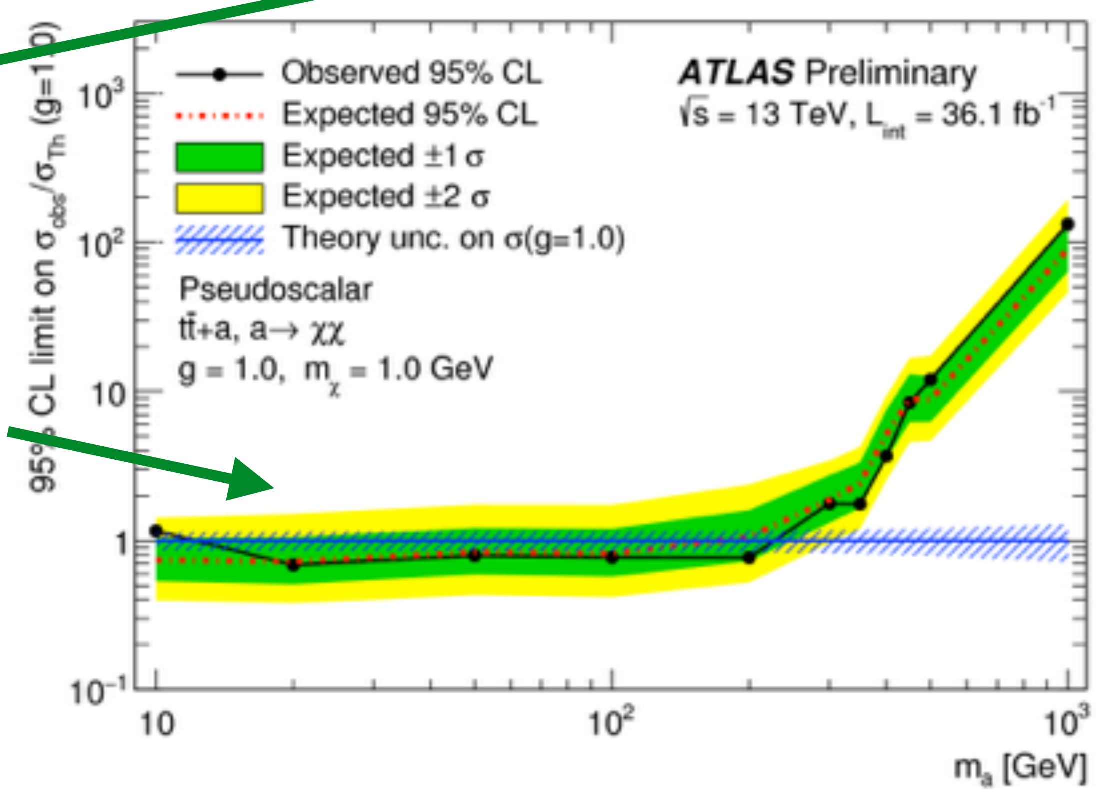




DM + tops

ATLAS-CONF-2017-037





Excess not confirmed

sensitivy to natural coupling (g=1)

Conclusions

ATLAS EXPERIMENT

Effective field theories of dark matter production not suited for interpreting LHC results
→ simplified models necessary

Monojet search improved by dark matter optimisation and track veto

Dark matter + tops analysis sensitive to (pseudo-) scalar mediators

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Interesting times ahead!

more data to come, better statistics allows to improve analyses further

test theory ideas beyond "simple" WIMP picture:
complex dark sectors → more complex and challenging signatures

Conclusions

Effective field theories of dark matter production not suited for interpreting LHC results → simplified models necessary

Monojet search improved by dark matter optimisation and track veto

Dark matter + tops analysis sensitive to (pseudo-) scalar mediators

Interesting times ahead!

more data to come, better statistics allows to improve analyses further

test theory ideas beyond "simple" WIMP picture:
complex dark sectors → more complex and challenging signatures

LHC is an important and interesting place to look for dark matter:
Not one experiment, not one search strategy, not even one discipline of physics alone can hope to pin down properties of dark matter, which makes it both challenging and interesting

THANK YOU!

BACKUP

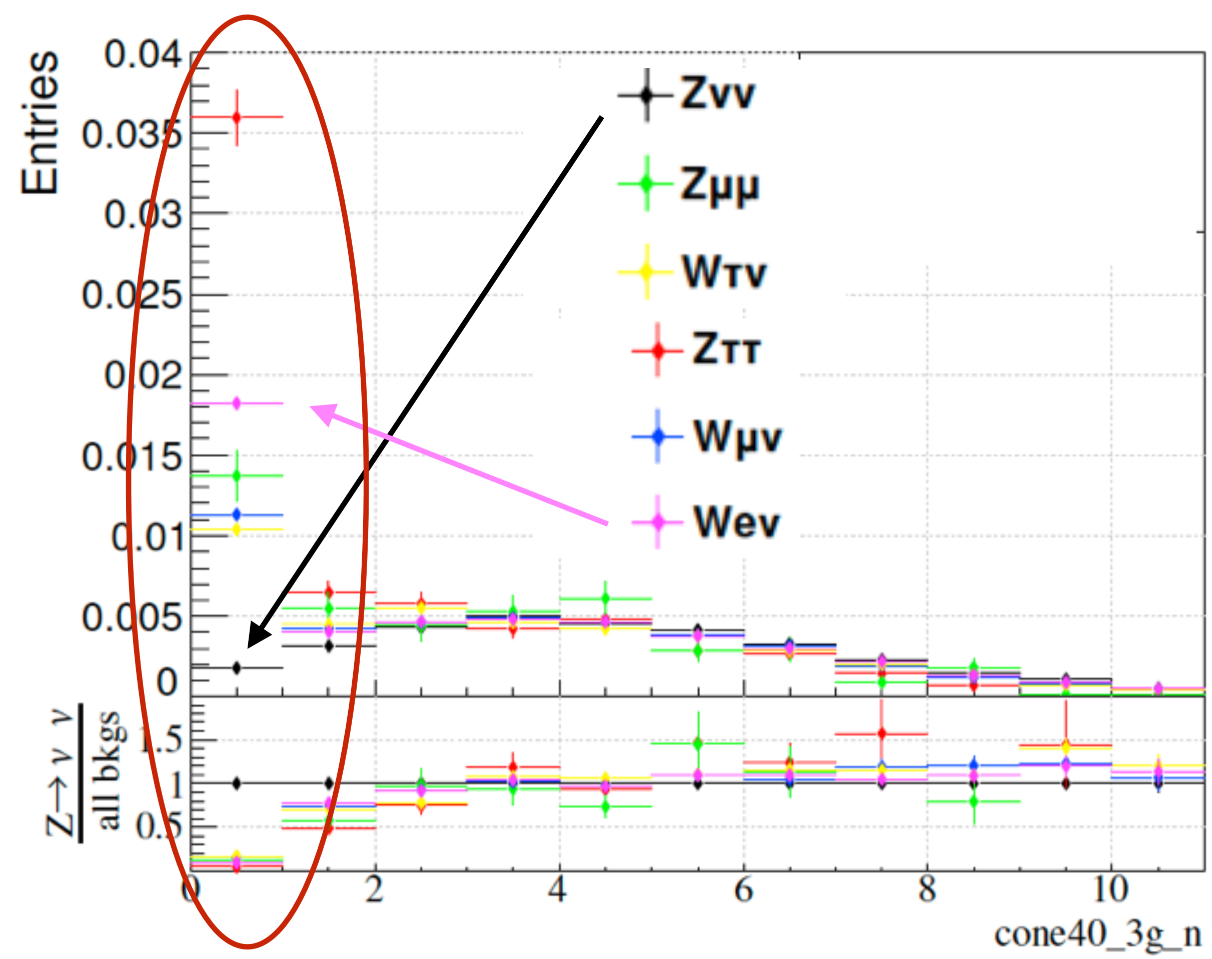
Veto on Isolated Tracks

ATLAS EXPERIMENT

Reduces backgrounds containing missed leptons and hadronically decaying tau leptons

- **Definition:** veto events containing a track with no other tracks above 3 GeV in its vicinity (cone of 0.4)
- **Performance:** efficiency ~ 97% for dark matter signal and Z($\rightarrow \nu\nu$), 50 - 70% for other backgrounds

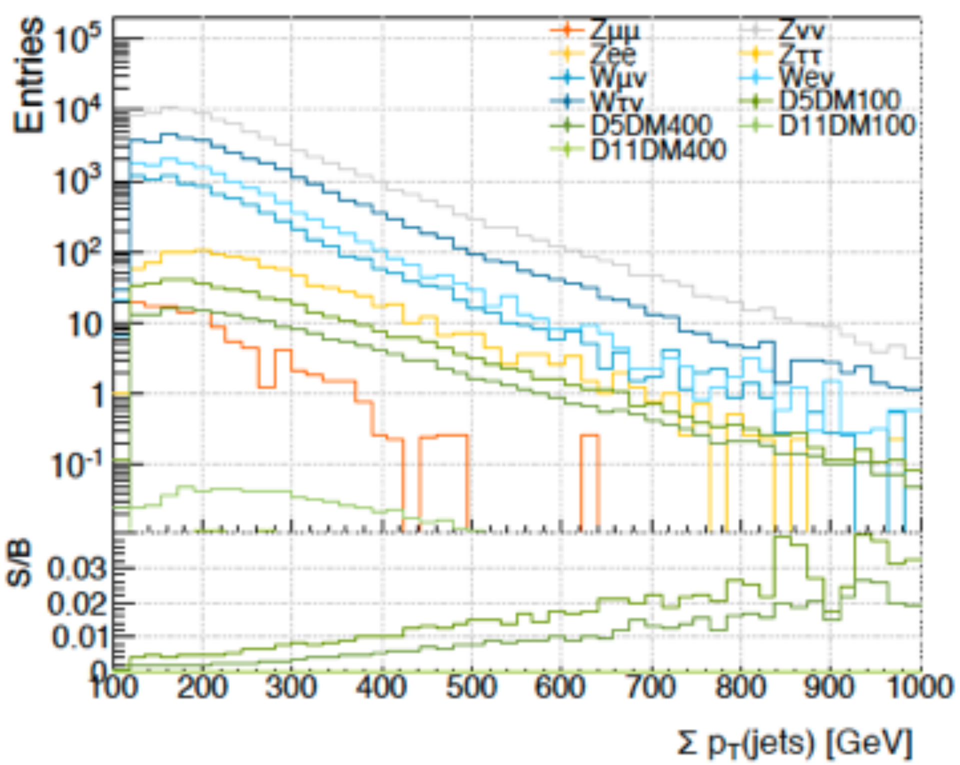
  → improvement of "S/(S+B)" ~ 7-10%
- **Validation:** efficiency independent of event properties like E_T^{miss}, jet p_T, #vertices
  MC modelling excellent for leptons and non-leptonic part of event as well as in low-E_T^{miss} region
  - systematic effect on background estimate < 1%

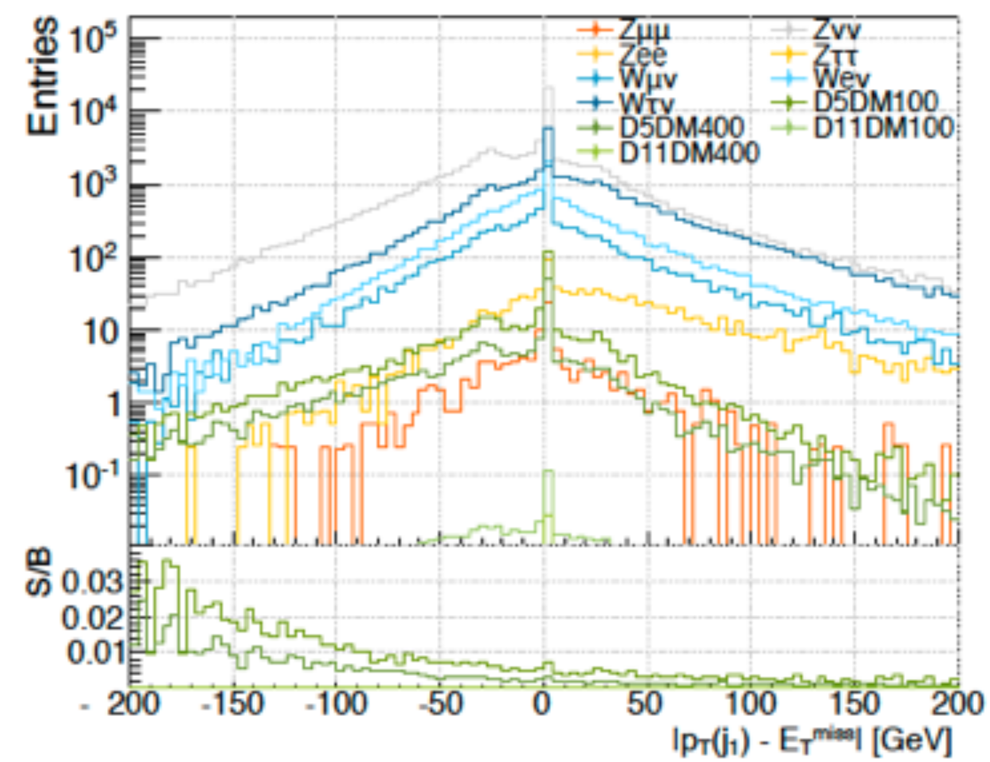


Optimisation for DM Signals

First dedicated optimisation of sensitivity to DM signals

- Signal benchmarks leading to different E_T^{miss} spectra were considered ("D5", "D11")
- Optimisation revealed: signal events prefer higher event scale, therefore sum of jet p_T's and number of jets is higher than in backgrounds
- As a consequence, leading jet p_T and E_T^{miss} are less balanced

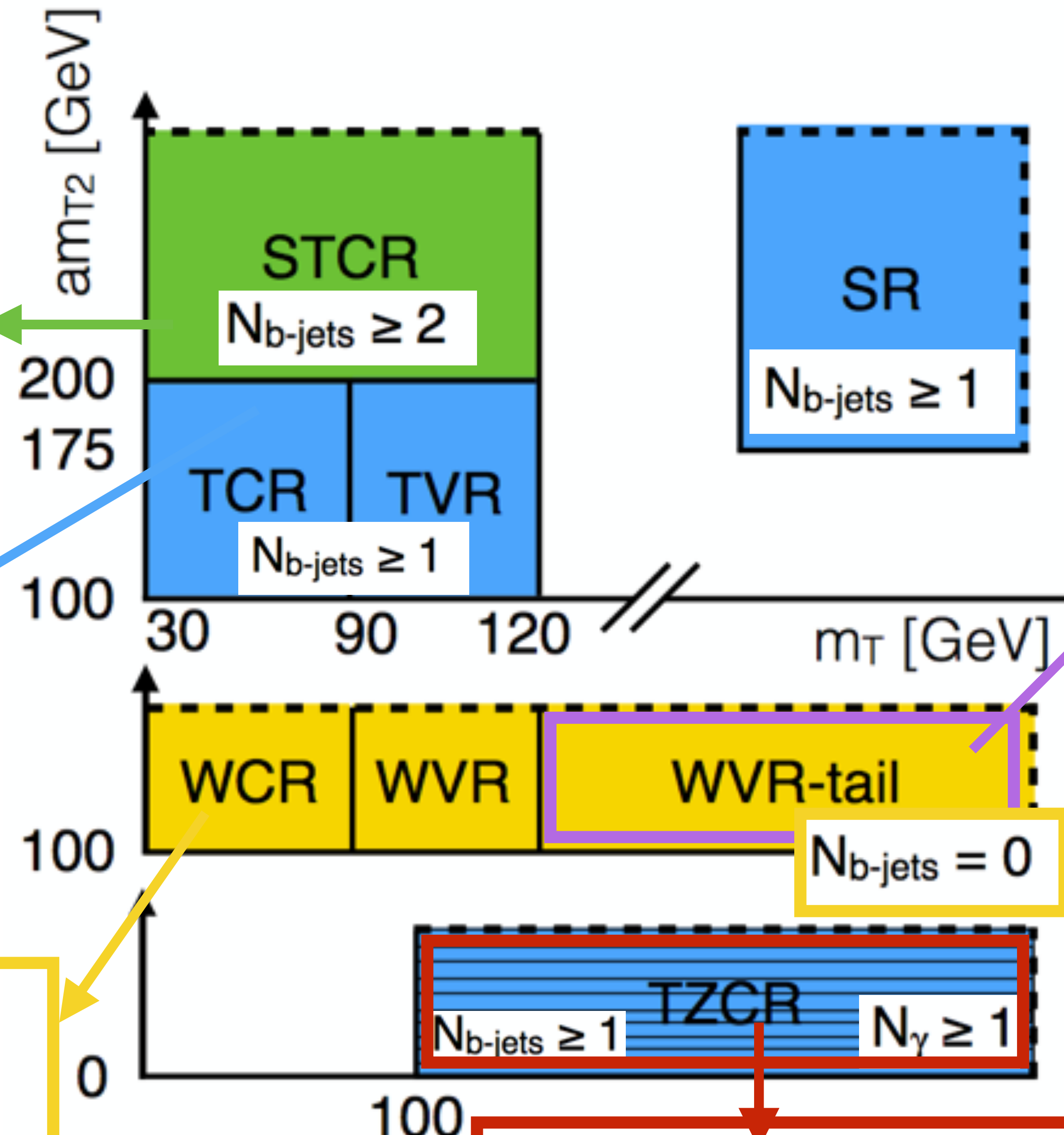




inclusive number of jets & asymmetric jet p_T/E_T^{miss} cuts

Background Estimation

Single top CR for each SR:
≥2 b-jets, high am_{T2} and lower cut on $\Delta R(b_1,b_2)$



ttbar CRs/VRs for each SR:
lower m_T window

Non-canonical VRs:
check m_T and am_{T2} tails,
low am_{T2} region,
1L1τ selection, …

W+jets CRs/VRs for each SR:
same as TCR/TVR,
but b-jet veto

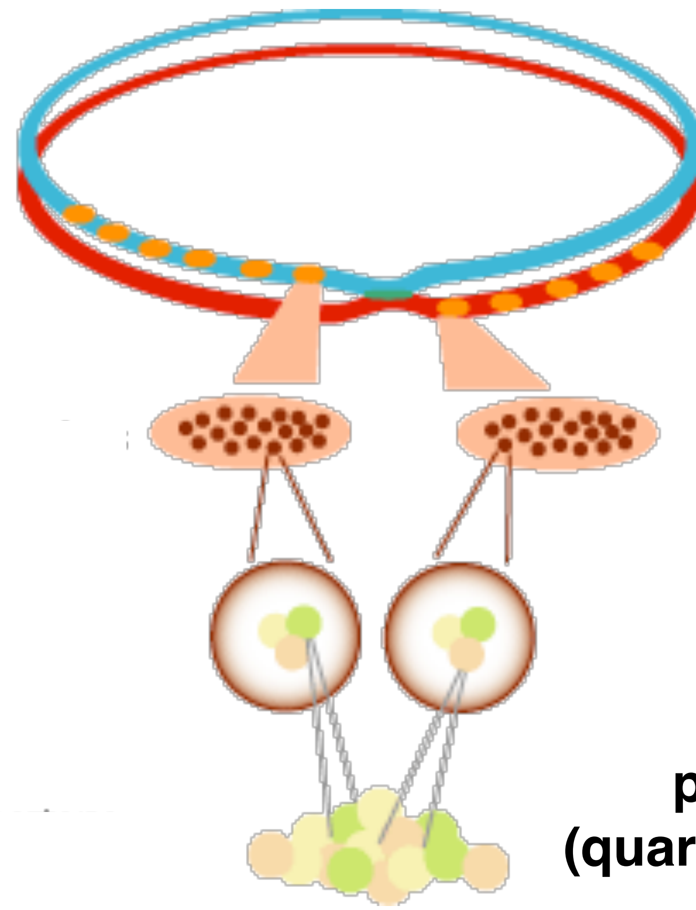
tt+γ CR for tt+Z: require photon,
treat as invisible for E_T^{miss}, m_T, $H_T^{miss}{}_{sig}$

Use simultaneous fit of all CRs to obtain final results

The LHC

Currently the world's most powerful particle accelerator

- Can collide protons at centre-of-mass energies of up to 14 TeV → "discovery machine"
- Data from collision energies of 8 TeV (2012) and 13 TeV (2015/2016) were analysed



Monojet Selection

	Selection criteria									
Pre-selection	Primary vertex $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV Jet quality requirements At least one jet with $p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 4.5$ Lepton and isolated track vetoes									
Monojet selection	Leading jet $p_{\mathrm{T}} > 120$ GeV and $\lvert\eta\rvert < 2.0$ Leading jet $p_{\mathrm{T}}/E_{\mathrm{T}}^{\mathrm{miss}} > 0.5$ $\Delta\phi(\mathrm{jet}, \vec{p}_{\mathrm{T}}^{\mathrm{\,miss}}) > 1.0$									
Signal regions		SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	> 200	> 250	> 300	> 350	> 400	> 500	> 600	> 700

Monojets: EW background estimate

$$N_{\mathrm{SR}}^{W(\to\mu\nu)} = \frac{(N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{data}} - N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{non-}W/Z})}{N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{MC}}} \times N_{\mathrm{SR}}^{\mathrm{MC}(W(\to\mu\nu))} \times \xi_{\ell} \times \xi_{\mathrm{trg}} \times \xi_{\ell}^{\mathrm{veto}}$$

Monojets: EW background estimate

$$N_{\mathrm{SR}}^{W(\to\mu\nu)} = \frac{(N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{data}} - N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{non}-W/Z})}{N_{W(\to\mu\nu),\mathrm{CR}}^{\mathrm{MC}}} \times N_{\mathrm{SR}}^{\mathrm{MC}(W(\to\mu\nu))} \times \xi_{\ell} \times \xi_{\mathrm{trg}} \times \xi_{\ell}^{\mathrm{veto}}$$

$$N_{\mathrm{signal}}^{Z(\to\nu\bar{\nu})} = \frac{(N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{data}} - N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{non}-W/Z})}{N_{W(\to\mu\nu),\mathrm{control}}^{\mathrm{MC}}} \times N_{\mathrm{signal}}^{\mathrm{MC}(Z(\to\nu\bar{\nu}))} \times \xi_{\ell} \times \xi_{\mathrm{trg}}$$

Monojets: Results

ATLAS EXPERIMENT

Signal Region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Observed events	364378	123228	44715	18020	7988	3813	1028	318	126
SM expectation	372100 ± 9900	126000 ± 2900	45300 ± 1100	18000 ± 500	8300 ± 300	4000 ± 160	1030 ± 60	310 ± 30	97 ± 14
$Z(\to \nu\bar{\nu})$	217800 ± 3900	80000 ± 1700	30000 ± 800	12800 ± 410	6000 ± 240	3000 ± 150	740 ± 60	240 ± 30	71 ± 13
$W(\to \tau\nu)$	79300 ± 3300	24000 ± 1200	7700 ± 500	2800 ± 200	1200 ± 110	540 ± 60	130 ± 20	34 ± 8	11 ± 3
$W(\to e\nu)$	23500 ± 1700	7100 ± 560	2400 ± 200	880 ± 80	370 ± 40	170 ± 20	43 ± 7	9 ± 3	3 ± 1
$W(\to \mu\nu)$	28300 ± 1600	8200 ± 500	2500 ± 200	850 ± 80	330 ± 40	140 ± 20	35 ± 6	10 ± 2	2 ± 1
$Z/\gamma^*(\to \mu^+\mu^-)$	530 ± 220	97 ± 42	19 ± 8	7 ± 3	4 ± 2	3 ± 1	2 ± 1	1 ± 1	1 ± 1
$Z/\gamma^*(\to \tau^+\tau^-)$	780 ± 320	190 ± 80	45 ± 19	14 ± 6	5 ± 2	2 ± 1	0 ± 0	0 ± 0	0 ± 0
$t\bar{t}$, single top	6900 ± 1400	2300 ± 500	700 ± 160	200 ± 70	80 ± 40	30 ± 20	7 ± 7	1 ± 1	0 ± 0
Dibosons	8000 ± 1700	3500 ± 800	1500 ± 400	690 ± 200	350 ± 120	183 ± 70	65 ± 35	23 ± 16	8 ± 7
Multijets	6500 ± 6500	800 ± 800	200 ± 200	44 ± 44	15 ± 15	6 ± 6	1 ± 1	0 ± 0	0 ± 0

2:7% for SR1 and 6.2% for SR7 to 14% for SR9

Monojets: Systematic Uncertainties

	Background	
Experimental	Jet energy scale and resolution	0.2-3%
	E_T^{miss} reconstruction	0.2-1%
	Lepton properties	1.4-2%
	Trigger efficiency	0.1% (SR1)
Theoretical	W/Z modelling	1-3%
	Top modelling	0.7-4%
	Diboson modelling	0.7-3%
Other	Multijet estimate	2% (SR1), 0.7% (SR2)
	Multijet and γ+jets in $W(\rightarrow e\nu)$ CR	1% (SR9)

	Signal	
Acceptance × Efficiency	Jet energy scale and resolution, E_T^{miss} reconstruction	1-10%
	Beam energy	3%
	Luminosity	2.8%
	PDF choice	5-29%
	Renormalisation/factorisation scales	3%
	Parton matching scale	5%
Cross-section	Beam energy	2-9%
	Renormalisation/factorisation scales	2-17% (D1, D5, D9), 40-46% (C5, D11)
	PDF choice	19-70% (D1, D11, C5), 5-36% (D5, D9) increasing with DM mass

Monojets: Systematic Uncertainties

Exemplarily for one estimate: Z($\rightarrow \nu\nu$) from W($\rightarrow \mu\nu$)

- combination reduces uncertainties, considers correlations

	Znunu (Wmunu)								
Lower bound on E_T^{miss} (GeV)	150	200	250	300	350	400	500	600	700
dataStat	0.295	0.499	0.817	1.26	1.871	2.673	4.999	9.214	16.074
mcStat	0.215	0.3	0.409	0.483	0.676	0.941	1.668	3.263	5.341
JER	0.341	0.062	0.285	0.68	0.894	0.632	0.37	0.226	1.033
JESGlobal	1.482	1.917	2.003	1.67	2.284	1.398	2.017	4.959	4.899
MET	0.825	0.831	0.526	0.607	0.532	0.765	1.871	2.155	2.9
Top	1.625	2.1	2.442	3.077	4.609	4.767	6.721	7.895	4.423
VV	1.452	2.122	2.871	3.61	4.576	5.43	7.114	9.174	9.931
other CR bgd	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
lepton	0.515	0.564	0.63	0.589	0.572	0.554	1.058	0.846	2.275
trigger SF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NCB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
theory	1.273	1.276	1.281	1.299	2.17	2.166	3.152	5.079	6.053

EFT Validity Measure

Use ratio of cross section with validity condition imposed over total cross section to quantify validity

$$R_{\Lambda}^{\text{tot}} \equiv \frac{\sigma|_{Q_{\text{tr}}<\Lambda}}{\sigma} = \frac{\int_{p_{\text{T}}^{\text{min}}}^{p_{\text{T}}^{\text{max}}} \text{d}p_{\text{T}} \int_{\eta_{min}}^{\eta_{max}} \text{d}\eta \left. \frac{\text{d}^2\sigma}{\text{d}p_{\text{T}}\text{d}\eta} \right|_{Q_{\text{tr}}<\Lambda}}{\int_{p_{\text{T}}^{\text{min}}}^{p_{\text{T}}^{\text{max}}} \text{d}p_{\text{T}} \int_{\eta_{min}}^{\eta_{max}} \text{d}\eta \frac{\text{d}^2\sigma}{\text{d}p_{\text{T}}\text{d}\eta}}$$

SiMs: Minimal Width

Early SiMs interpretations used fixed width for mediator

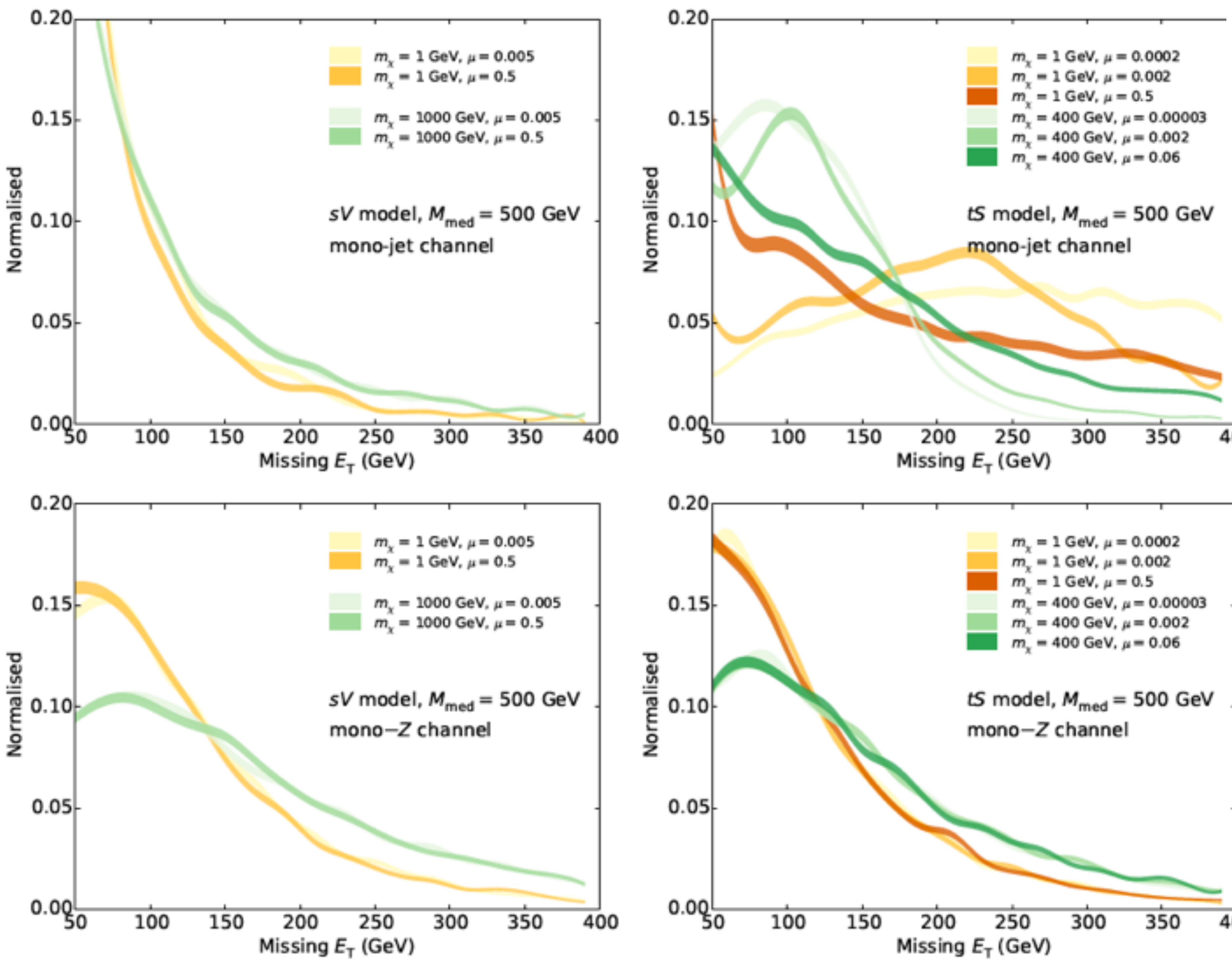
- e.g. $M_{med}/3$ → very large width and $M_{med}/8\pi$ → minimal width

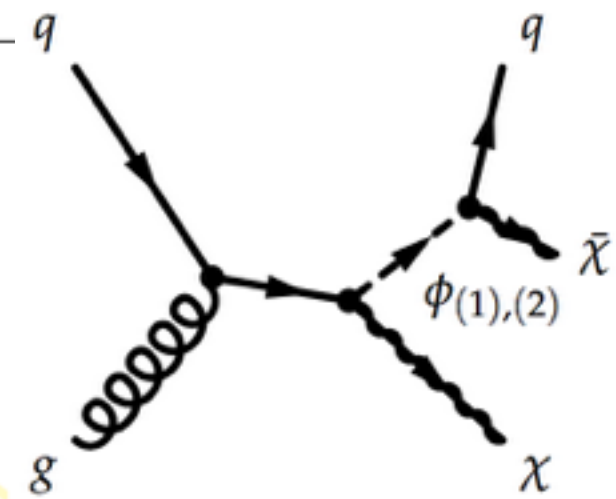
In principle, the width is fixed by masses, couplings and decay channels

- Calculate it for each point:

$$\Gamma_{sV} = \frac{g_\chi^2 M}{12\pi}\left(1+\frac{2m_\chi^2}{M^2}\right)\left(1-\frac{4m_\chi^2}{M^2}\right)^{\frac{1}{2}}\Theta(M-2m_\chi)$$
$$+\sum_q \frac{g_q^2 M}{4\pi}\left(1+\frac{2m_q^2}{M^2}\right)\left(1-\frac{4m_q^2}{M^2}\right)^{\frac{1}{2}}\Theta(M-2m_q)$$

SiMs: Width Effects





SiMs: Approximations

Assume that kinematics is not altered by coupling changes

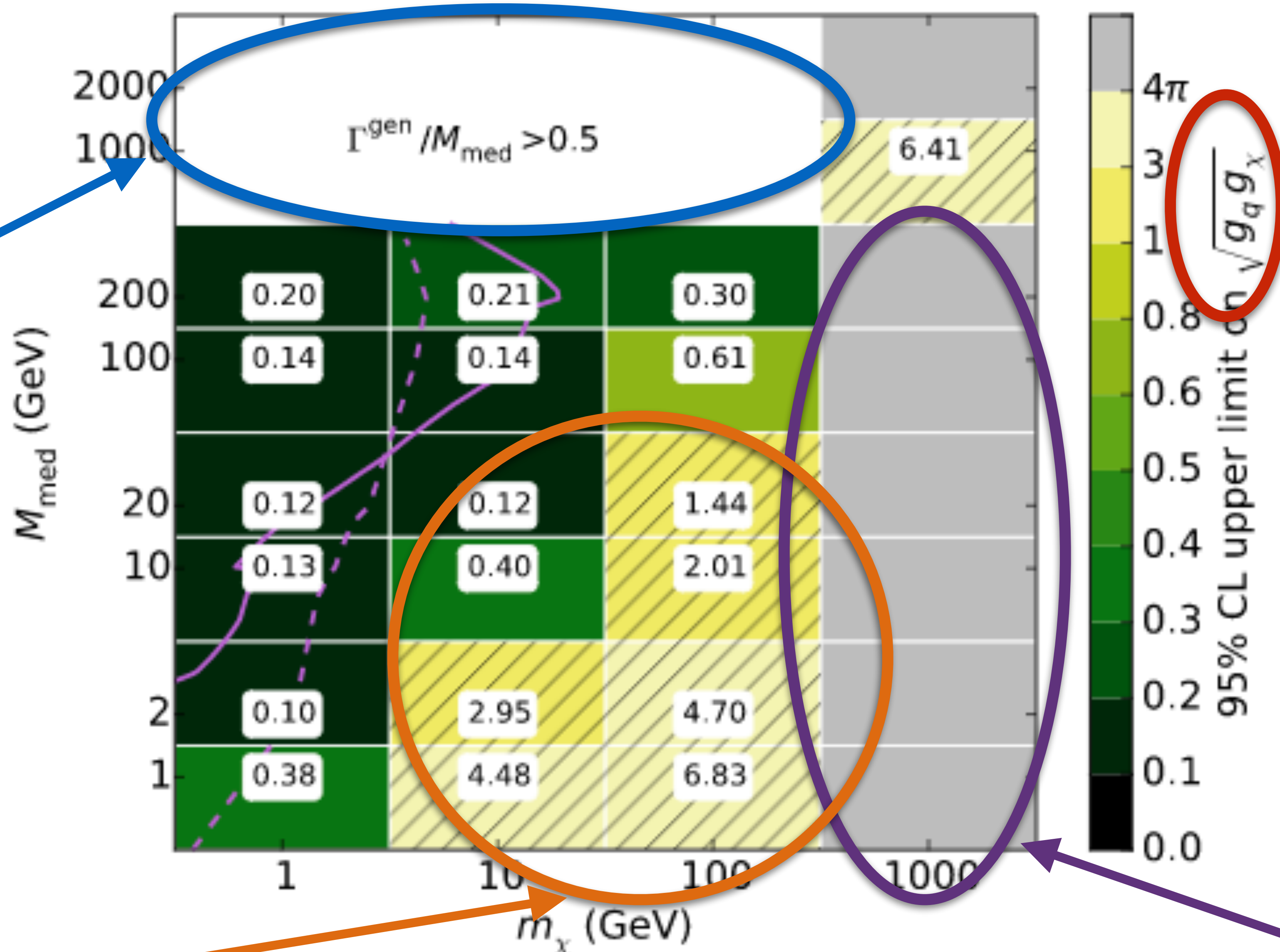
- Simplifies limit calculation -
  stick to regime in which this is valid ($\Gamma/M_{med} < 0.5$)

$$\sigma \propto \begin{cases} g_q^2 g_\chi^2/\Gamma & \text{if } M_{\text{med}} \geq 2m_{\text{DM}} \\ g_q^2 g_\chi^2 & \text{if } M_{\text{med}} < 2m_{\text{DM}} \end{cases}$$

Generator assumes Breit-Wigner propagator

- Not accurate for large widths
- Not accurate for $m_{DM} >> M_{med}$
- We apply a rescaling procedure to correct for it

SiMs: Results



$\Gamma/M_{med} < 0.5$ is not fulfilled at generation

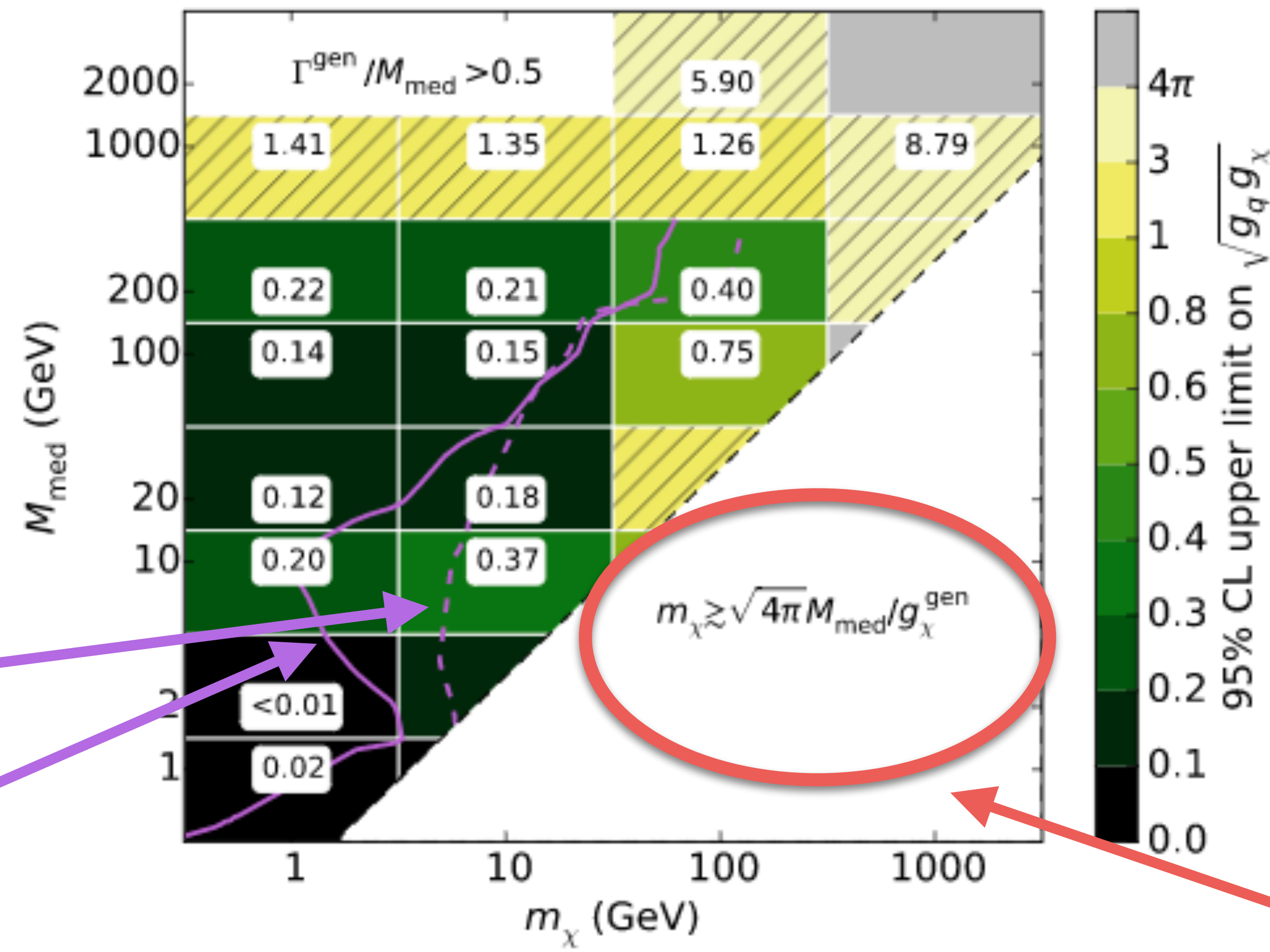
place limits on couplings

limits beyond perturbativity - meaningless

$\Gamma/M_{med} < 0.5$ is not fulfilled with limits on couplings

(a) sV model, $g_\chi/g_q = 1$, mono-jet channel.

SiMs: Results



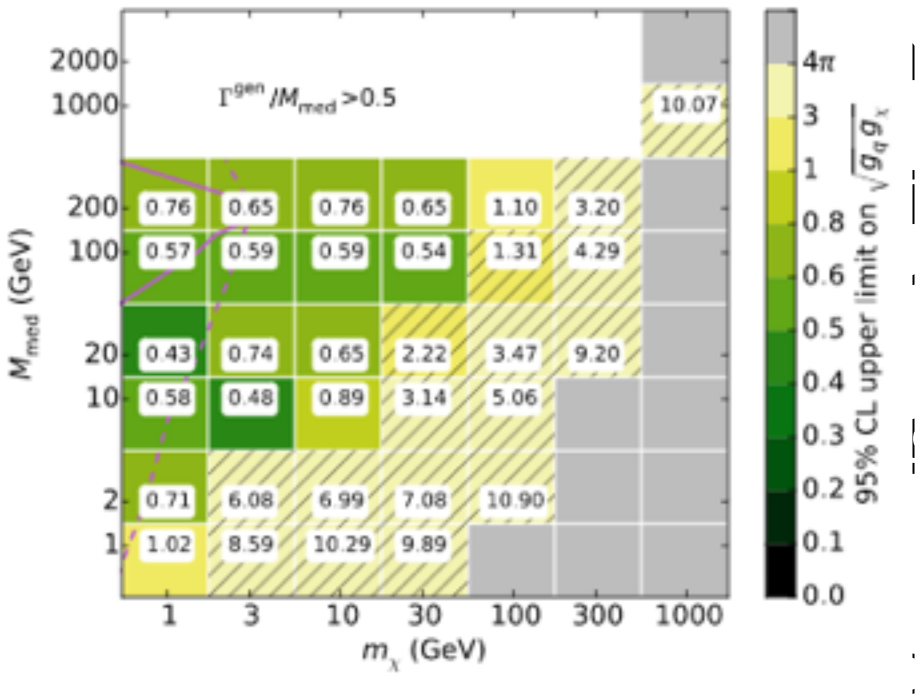
(d) sA model, $g_\chi/g_q = 1$, mono-jet channel.

dotted region: not enough stats

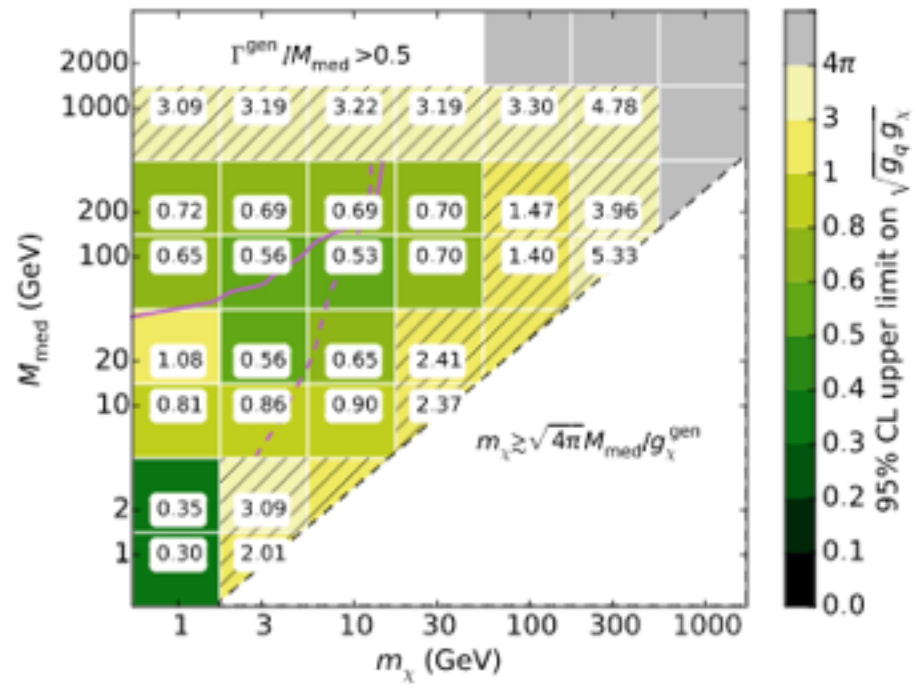
dashed line: direct detection
solid line: relic density

violates perturbative unitarity

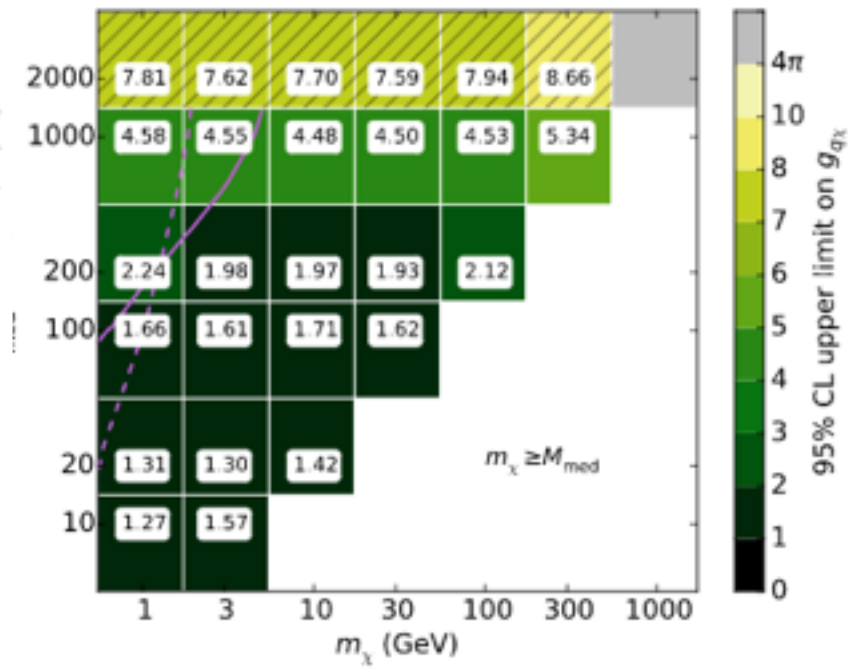
SiMs: Model Comparison



(b) sV model, $g_\chi/g_q = 1$, mono-Z channel.

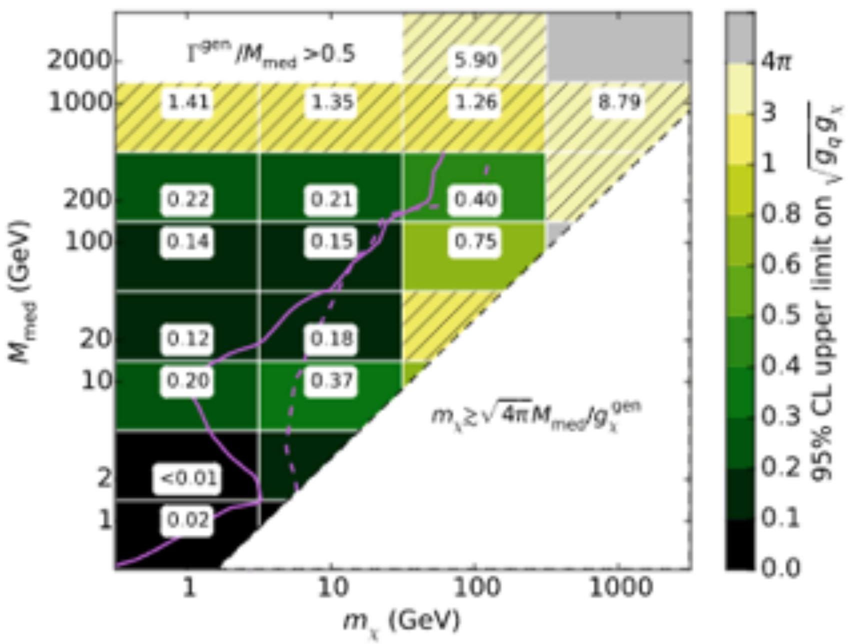


(e) sA model, $g_\chi/g_q = 1$, mono-Z channel.

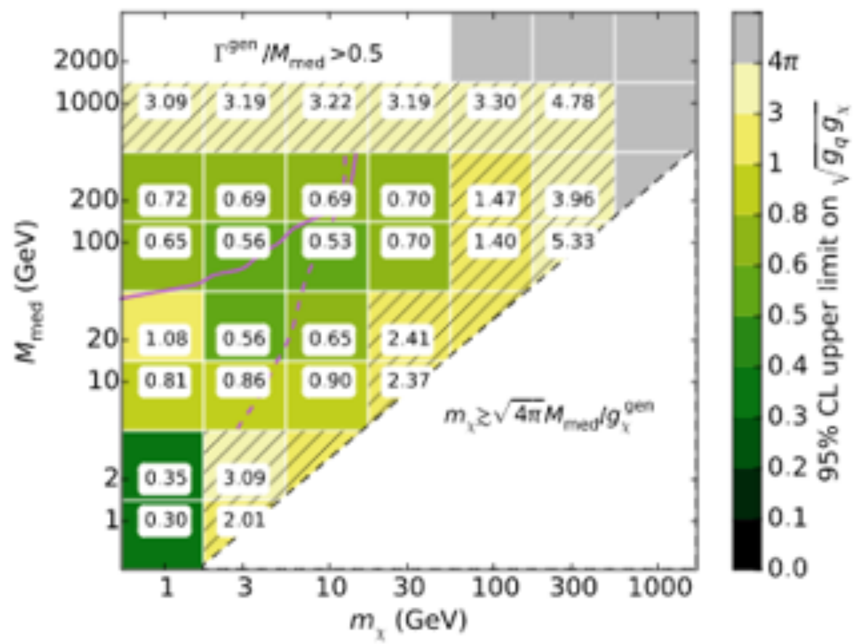


(a) tS model, mono-Z channel.

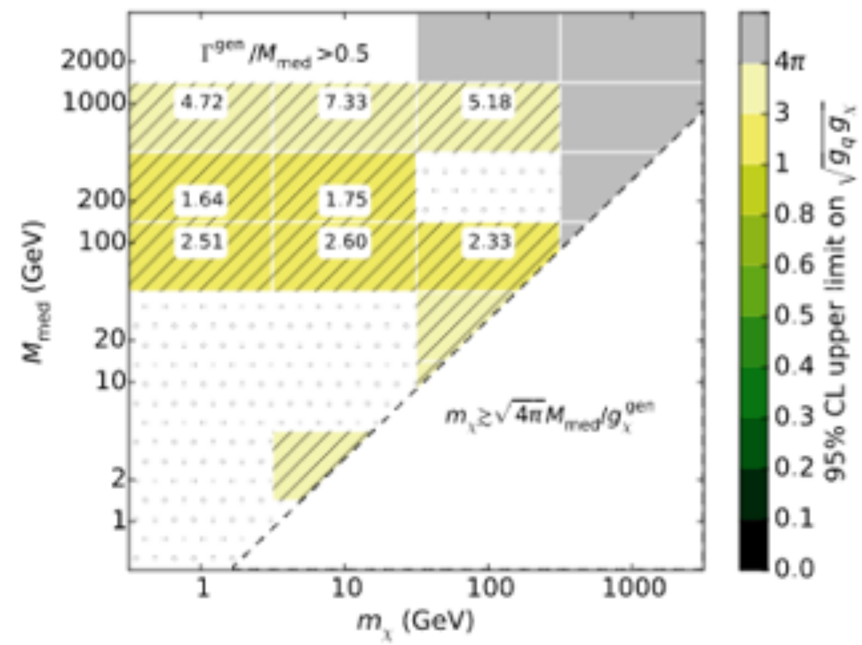
SiMs: Channel Comparison



(d) sA model, $g_\chi/g_q = 1$, mono-jet channel.



(e) sA model, $g_\chi/g_q = 1$, mono-Z channel.



(f) sA model, $g_\chi/g_q = 1$, mono-W/Z channel.

Stop 1L: Object definitions

Overlap removal

Object 1 Object 2	e μ	e j	μ j	ℓ j	γ j	γ e	τ e
$\Delta R <$	0.01	0.2	0.2	$\min\left(0.4, 0.04 + \frac{10}{p_T^\ell/\text{GeV}}\right)$	0.2	0.1	0.1
Condition	calo-tagged μ	j not b-tagged	j not b-tagged and $\left(n^j_{\text{track}} < 3 \text{ or } \frac{p_T^\mu}{p_T^j} > 0.7\right)$	–	–	–	–
Precedence	e	e	μ	j	γ	e	e

Jets

Baseline	
p_T	> 20 GeV
Signal	
p_T	> 25 GeV
$\lvert\eta\rvert$	< 2.5
JVT	0.59 for $\lvert\eta\rvert < 2.4$ and $p_T < 60$ GeV
b-jets	
p_T	> 20 GeV
$\lvert\eta\rvert$	< 2.5
JVT	0.59 for $\lvert\eta\rvert < 2.4$ and $p_T < 60$ GeV
MV2c10	> 0.6459 ($\varepsilon_b = 76.97\%$)

Electrons

Baseline	
ID	VeryLooseLH
E_T	> 7 GeV
$\lvert\eta^{\text{cluster}}\rvert$	< 2.47
Signal	
ID	LooseAndBLayerLH
E_T	> 25 GeV
Isolation	LooseTrackOnly
d_0 significance	< 5
$z_0 \sin(\theta)$	< 0.5 mm

Muons

Baseline	
ID	Loose
p_T	> 6 GeV
$\lvert\eta\rvert$	< 2.7
Signal	
ID	Loose
p_T	>25 GeV
Isolation	LooseTrackOnly
d_0 significance	< 3
$z_0 \sin(\theta)$	< 0.5 mm

large-R Jets

- reclustered from signal jets
- radius parameter optimised to R=1.2 (1.0) for tN_high (bCbv)
- “trimming”: drop small-R jets with $p_T < 5\%$ of large-R jet p_T

Stop 1L: Trigger

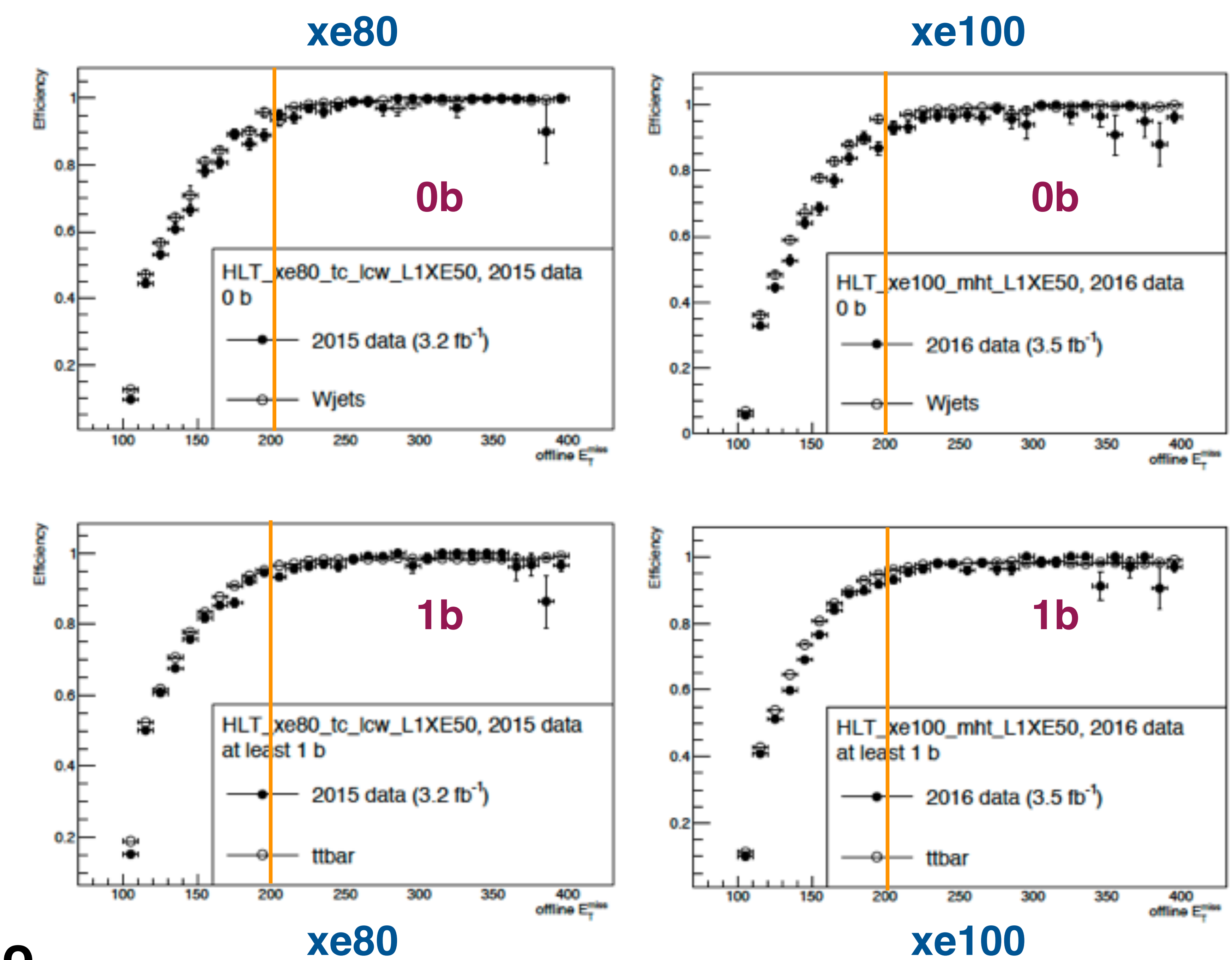
Choice between single-lepton and E_T^{miss} triggers

- went for E_T^{miss}: no significant gain in efficiency when including lepton triggers

lowest value of E_T^{miss}: 200 GeV (in CRs)

- triggers not fully efficient

sufficiently good MC modelling of turn-on, also in 0b/1b selections

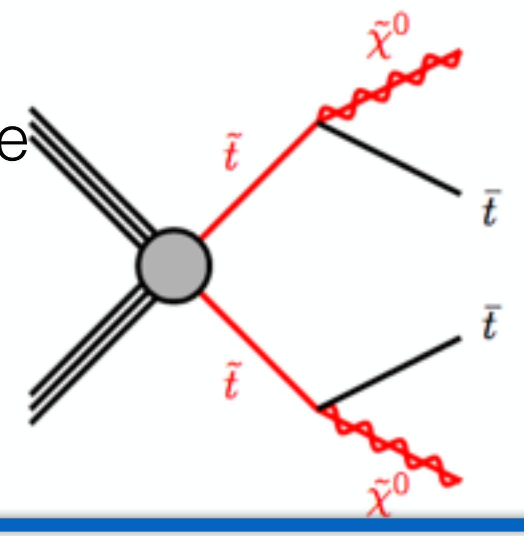


xe80_tc_lcw for 2015 data and xe100_mht for 2016 data

Stop 1L: Signal Region Overview

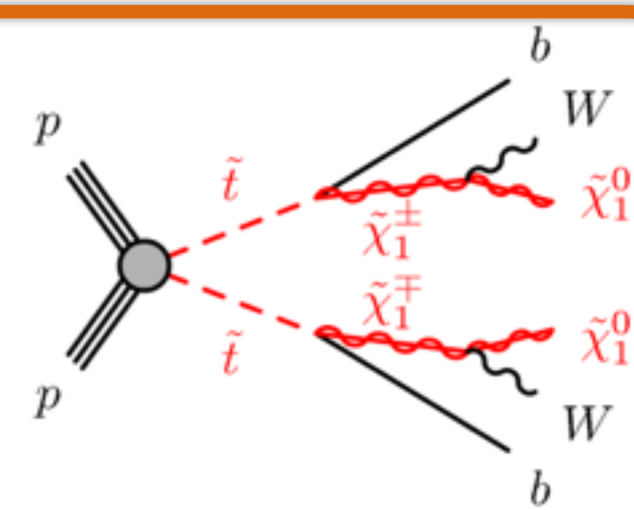
stop → top + Neutralino (tN):

- object p_Ts dependent on mass splitting → look at intermediate ("tN_med") and large ("tN_high") mass splitting, also keep Moriond "SR1" to check excess
- make use of top reconstruction techniques: resolved or within large-R jets



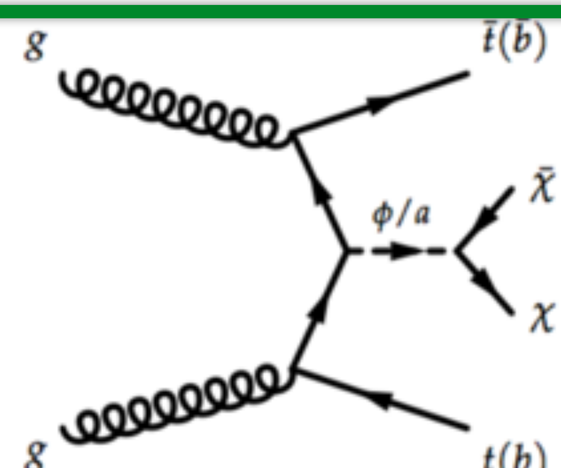
stop → b + Chargino (bC)

- m($\chi^{\pm}$) = 2 m(χ^0) theoretically motivated, resulting in high-p_T (b-)jets ("bC2x_diag", "bC2x_med")
- include also region with small mass-splitting between stop and Chargino → soft b-jets are not reconstructed, use b-veto ("bCbv")



DM+tt

- DM production associated with tops well motivated for Yukawa-like couplings of (pseudo-)scalar mediator (low m_{Med}: "DM_low", high m_{Med}: "DM_high")
- final state similar to tt+Z(inv)



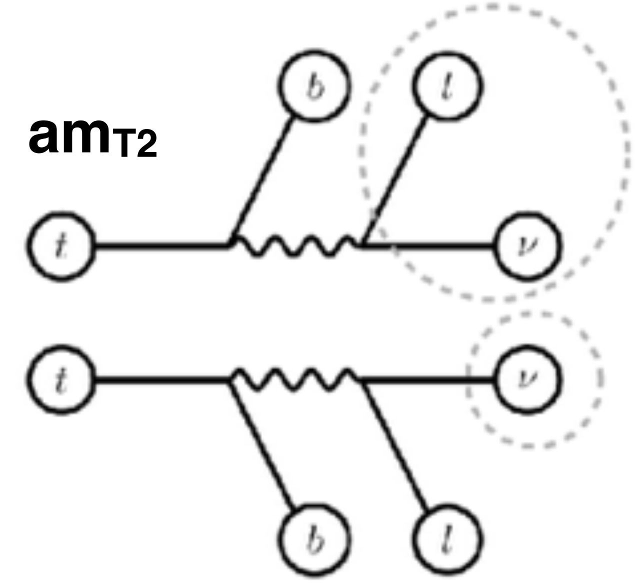
Stop 1L: Discriminating Variables

"stransverse mass" m_{T2}: $$m_{T2} \equiv \min_{\vec{q}_{Ta}+\vec{q}_{Tb}=\vec{p}_{T}^{miss}} \{\max(m_{Ta}, m_{Tb})\},$$

- not used directly, but its modified versions that try to account for missing objects in the decay chains:

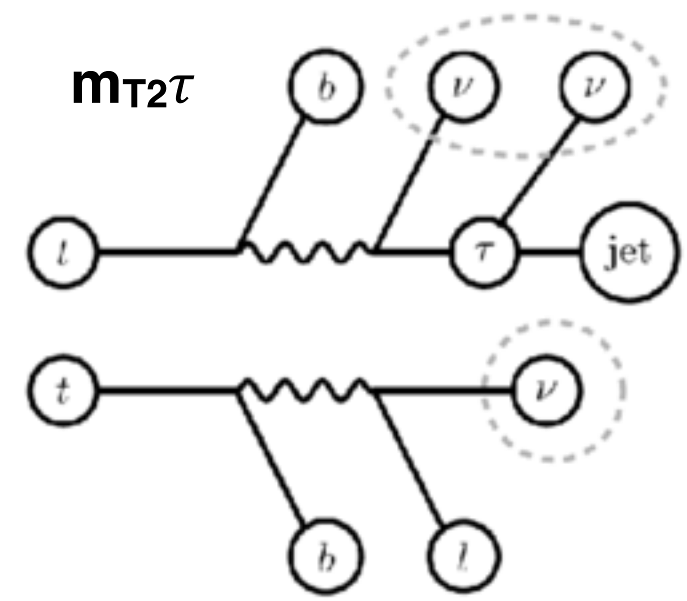
am_{T2}: targeting ttbar (2L) background, where one lepton is undetected

am_{T2}

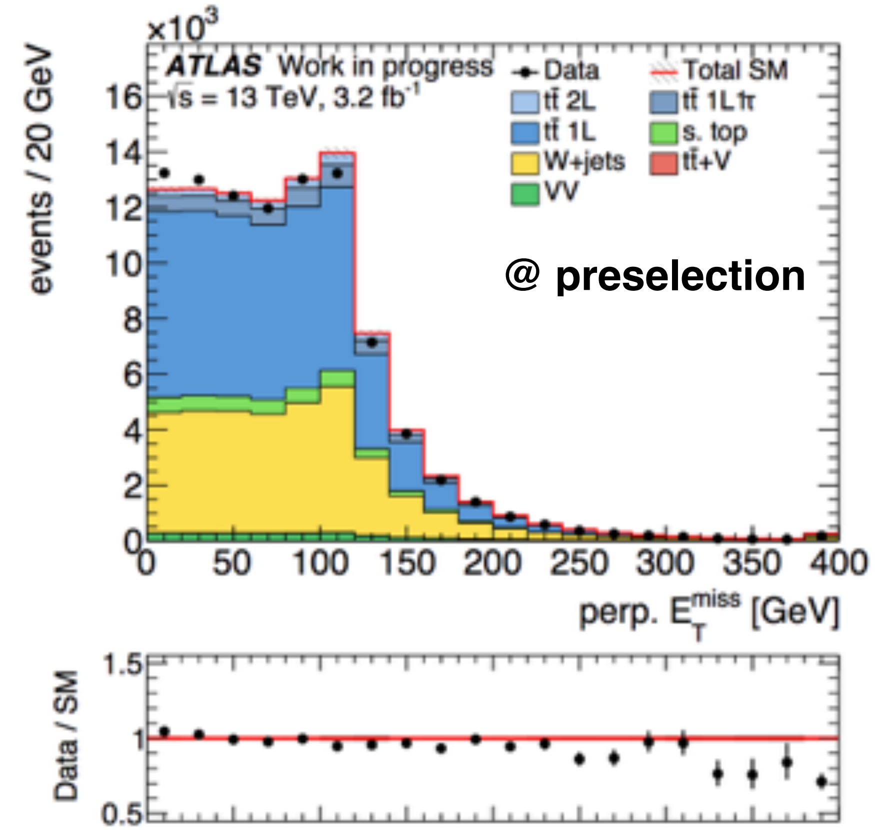


$m_{T2}\tau$: reject ttbar (1L1τ) backgrounds, use reconstructed hadronic τ candidates in calculation

$m_{T2}\tau$

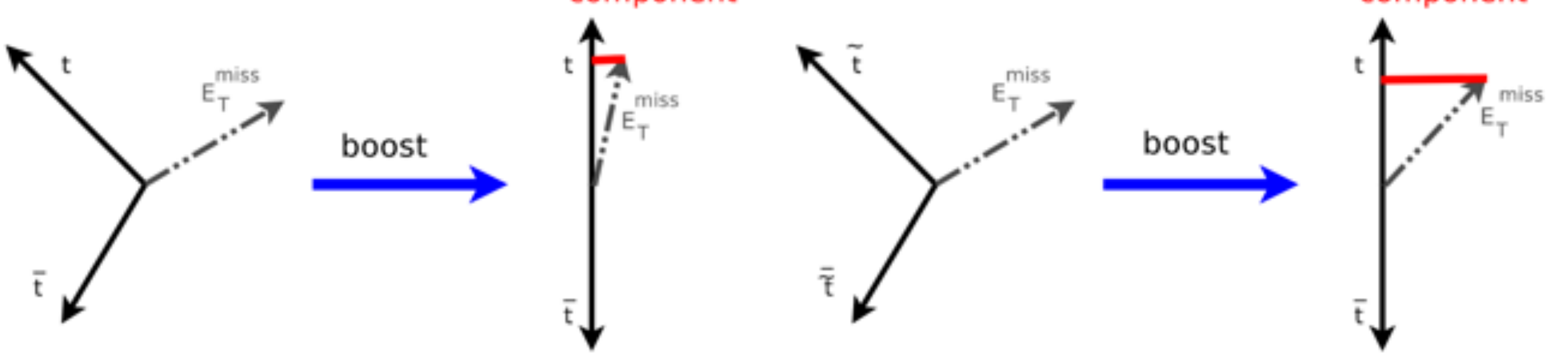


Stop 1L: Discriminating Variables



Reconstruction of hadronic and leptonic top candidates via χ^2 procedure

- E_T^{miss} perpendicular to leptonic top was found to perform well



(a) SM $t\bar{t}$ decay (b) $\tilde{t}\tilde{t}^*$ decay

- Significance of missing hadronic transverse energy H_T, $H_T^{miss}{}_{sig}$ (with scale M=100 GeV), protects from multijet background:

$$H_{\mathrm{T,sig}}^{\mathrm{miss}} = \frac{|\vec{H}_{\mathrm{T}}^{\mathrm{miss}}| - M}{\sigma_{|\vec{H}_{\mathrm{T}}^{\mathrm{miss}}|}}$$

DM: SR and CR overview

Common event selection for DM	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons
Jets	at least four signal jets, and $|\Delta\phi(\mathrm{jet}_i, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})| > 0.4$ for $i \in \{1, 2\}$
Hadronic τ veto	veto events with a hadronic τ decay and $m_{\mathrm{T2}}^{\tau} < 80\,\mathrm{GeV}$

Variable	DM_low	TCR / WCR	STCR
$\geq$4 jets with $p_{\mathrm{T}} >$ [GeV]	(60 60 40 25)	(60 60 40 25)	(60 60 40 25)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 300	> 200 / > 230	> 200
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 14	> 8	> 8
m_{T} [GeV]	> 120	[30,90]	[30,120]
am_{T2} [GeV]	> 140	$[100, 200]$ / > 100	> 200
$\min(\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}_i))$ $(i \in \{1-4\})$	> 1.4	> 1.4	> 1.4
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \ell)$	> 0.8	> 0.8	–
$\Delta R(b_1, b_2)$	–	–	> 1.8
Number of b-tags	≥ 1	≥ 1 / $= 0$	≥ 2

Variable	DM_high	TCR / WCR	STCR
$\geq$4 jets with $p_{\mathrm{T}} >$ [GeV]	(50 50 50 25)	(50 50 50 25)	(50 50 50 25)
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 330	> 300 / > 330	> 250
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 9.5	> 9.5	> 5
m_{T} [GeV]	> 220	[30,90]	[30,120]
am_{T2} [GeV]	> 170	$[100, 200]$ / > 100	> 200
$\min(\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}_i))$ $(i \in \{1-4\})$	> 0.8	> 0.8	> 0.8
$\Delta R(b_1, b_2)$	–	–	> 1.2
Number of b-tags	≥ 1	≥ 1 / $= 0$	≥ 2

Results

ATLAS EXPERIMENT

Signal region	SR1	tN_high	bC2x_diag	bC2x_med	bCbv	DM_low	DM_high
Observed	37	5	37	14	7	35	21
Total background	24 ± 3	3.8 ± 0.8	22 ± 3	13 ± 2	7.4 ± 1.8	17 ± 2	15 ± 2
$t\bar{t}$	8.4 ± 1.9	0.60 ± 0.27	6.5 ± 1.5	4.3 ± 1.0	0.26 ± 0.18	4.2 ± 1.3	3.3 ± 0.8
W+jets	2.5 ± 1.1	0.15 ± 0.38	1.2 ± 0.5	0.63 ± 0.29	5.4 ± 1.8	3.1 ± 1.5	3.4 ± 1.4
Single top	3.1 ± 1.5	0.57 ± 0.44	5.3 ± 1.8	5.1 ± 1.6	0.24 ± 0.23	1.9 ± 0.9	1.3 ± 0.8
$t\bar{t} + V$	7.9 ± 1.6	1.6 ± 0.4	8.3 ± 1.7	2.7 ± 0.7	0.12 ± 0.03	6.4 ± 1.4	5.5 ± 1.1
Diboson	1.2 ± 0.4	0.61 ± 0.26	0.45 ± 0.17	0.42 ± 0.20	1.1 ± 0.4	1.5 ± 0.6	1.4 ± 0.5
Z+jets	0.59 ± 0.54	0.03 ± 0.03	0.32 ± 0.29	0.08 ± 0.08	0.22 ± 0.20	0.16 ± 0.14	0.47 ± 0.44
$t\bar{t}$ NF	1.03 ± 0.07	1.06 ± 0.15	0.89 ± 0.10	0.95 ± 0.12	0.73 ± 0.22	0.90 ± 0.17	1.01 ± 0.13
W+jets NF	0.76 ± 0.08	0.78 ± 0.08	0.87 ± 0.07	0.85 ± 0.06	0.97 ± 0.12	0.94 ± 0.13	0.91 ± 0.07
Single top NF	1.07 ± 0.30	1.30 ± 0.45	1.26 ± 0.31	0.97 ± 0.28	–	1.36 ± 0.36	1.02 ± 0.32
$t\bar{t} + W/Z$ NF	1.43 ± 0.21	1.39 ± 0.22	1.40 ± 0.21	1.30 ± 0.23	–	1.47 ± 0.22	1.42 ± 0.21
p_0 (σ)	0.012 (2.2)	0.26 (0.6)	0.004 (2.6)	0.40 (0.3)	0.50 (0)	0.0004 (3.3)	0.09 (1.3)
$N^{\text{limit}}_{\text{non-SM}}$ exp. (95% CL)	$12.9^{+5.5}_{-3.8}$	$5.5^{+2.8}_{-1.1}$	$12.4^{+5.4}_{-3.7}$	$9.0^{+4.2}_{-2.7}$	$7.3^{+3.5}_{-2.2}$	$11.5^{+5.0}_{-3.4}$	$9.9^{+4.6}_{-2.9}$
$N^{\text{limit}}_{\text{non-SM}}$ obs. (95% CL)	26.0	7.2	27.5	9.9	7.2	28.3	15.6

Stop 1L: Systematics

Experimental Systematic Uncertainties	
JES	4-15%
JER	0-9%
b-tagging	0-6%
E_T^{miss} TST	0-3%
leptons	small
photons	small
luminosity	small
Theoretical Systematic Uncertainties	
ttbar	17-32%
Wt	14-68%
Wjets	40%
Dibosons	20-30%
SUSY	13-23%
DM	5% (only acc)

Example: Theory Systematics

ATLAS EXPERIMENT

Listed for ttbar sample

source	SR1	tN_med	tN_high	bC2x_diag	bC2x_med	bCbv	DM_high	DM_low
	Uncertainties on TF to SR [%]							
Hard Scatter	15.1 ± 2.2	21.0 ± 2.6	17.1 ± 4.9	12.1 ± 1.9	9.5 ± 1.7	22.6 ± 1.4	15.4 ± 2.6	14.6 ± 2.3
Radiation	9.1 ± 1.1	12.4 ± 1.3	10.2 ± 2.3	8.8 ± 0.9	11.2 ± 0.9	21.7 ± 1.4	6.3 ± 1.2	13.4 ± 1.1
Had / Frag	7.7 ± 1.1	8.0 ± 1.3	7.4 ± 2.3	7.5 ± 0.9	7.7 ± 0.8	5.1 ± 1.3	6.9 ± 1.2	7.8 ± 1.1
Total	19	26	21	17	17	32	18	21
	Uncertainties on TF to WCR [%]							
Hard Scatter	21.5 ± 1.2	21.5 ± 1.2	21.5 ± 1.2	26.2 ± 1.3	35.2 ± 1.5	21.5 ± 1.1	21.5 ± 1.4	22.1 ± 1.3
Radiation	20.5 ± 1.2	20.5 ± 1.2	20.5 ± 1.2	24.1 ± 1.2	18.9 ± 1.3	20.5 ± 1.1	20.6 ± 1.3	21.0 ± 1.3
Had / Frag	6.3 ± 1.1	6.3 ± 1.1	6.3 ± 1.1	7.2 ± 1.1	7.1 ± 1.2	3.4 ± 1.0	6.3 ± 1.3	6.6 ± 1.2
Total	36	40	37	40	44	44	35	38
	Uncertainties on TF to STCR [%]							
Hard Scatter	5.5 ± 1.3	5.5 ± 1.3	6.5 ± 2.0	5.9 ± 1.5	5.2 ± 1.2	-	6.7 ± 1.8	5.5 ± 1.2
Radiation	3.9 ± 0.7	3.9 ± 0.7	5.0 ± 1.0	3.9 ± 0.8	3.7 ± 0.6	-	4.5 ± 0.9	3.7 ± 0.6
Had / Frag	6.3 ± 0.7	6.3 ± 0.7	6.3 ± 1.0	6.4 ± 0.8	5.8 ± 0.6	-	6.3 ± 0.9	6.3 ± 0.6
Total	9	9	10	10	9	-	10	9

Background-only Fit Result

ATLAS EXPERIMENT

Four free fit parameters yield normalisation of four major backgrounds

- Systematics treated as nuisance parameters (Gaussian smearing)

13.2^{-1}fb	mu_ttbar	mu_wjet	mu_wt	mu_ttZ
SR1	1.03 ± 0.07	0.76 ± 0.08	1.07 ± 0.30	1.43 ± 0.21
tN_high	1.06 ± 0.15	0.78 ± 0.08	1.30 ± 0.45	1.39 ± 0.22
bC2x_med	0.95 ± 0.12	0.85 ± 0.06	0.97 ± 0.28	1.30 ± 0.23
bC2x_diag	0.89 ± 0.10	0.87 ± 0.07	1.26 ± 0.31	1.40 ± 0.21
bCbv	0.73 ± 0.22	0.97 ± 0.12	–	–
DM_low	0.90 ± 0.17	0.94 ± 0.13	1.36 ± 0.36	1.47 ± 0.22
DM_high	1.01 ± 0.13	0.91 ± 0.07	1.02 ± 0.32	1.42 ± 0.21

What could have gone wrong?
(especially in DM_low)

Objects
- ID and quality criteria not adequate
- Detector effects that are not in MC

Background estimate
- MC modelling
- Fit
- backgrounds missing
- mismodelling of crucial variables

Run conditions, pile-up
- PRW

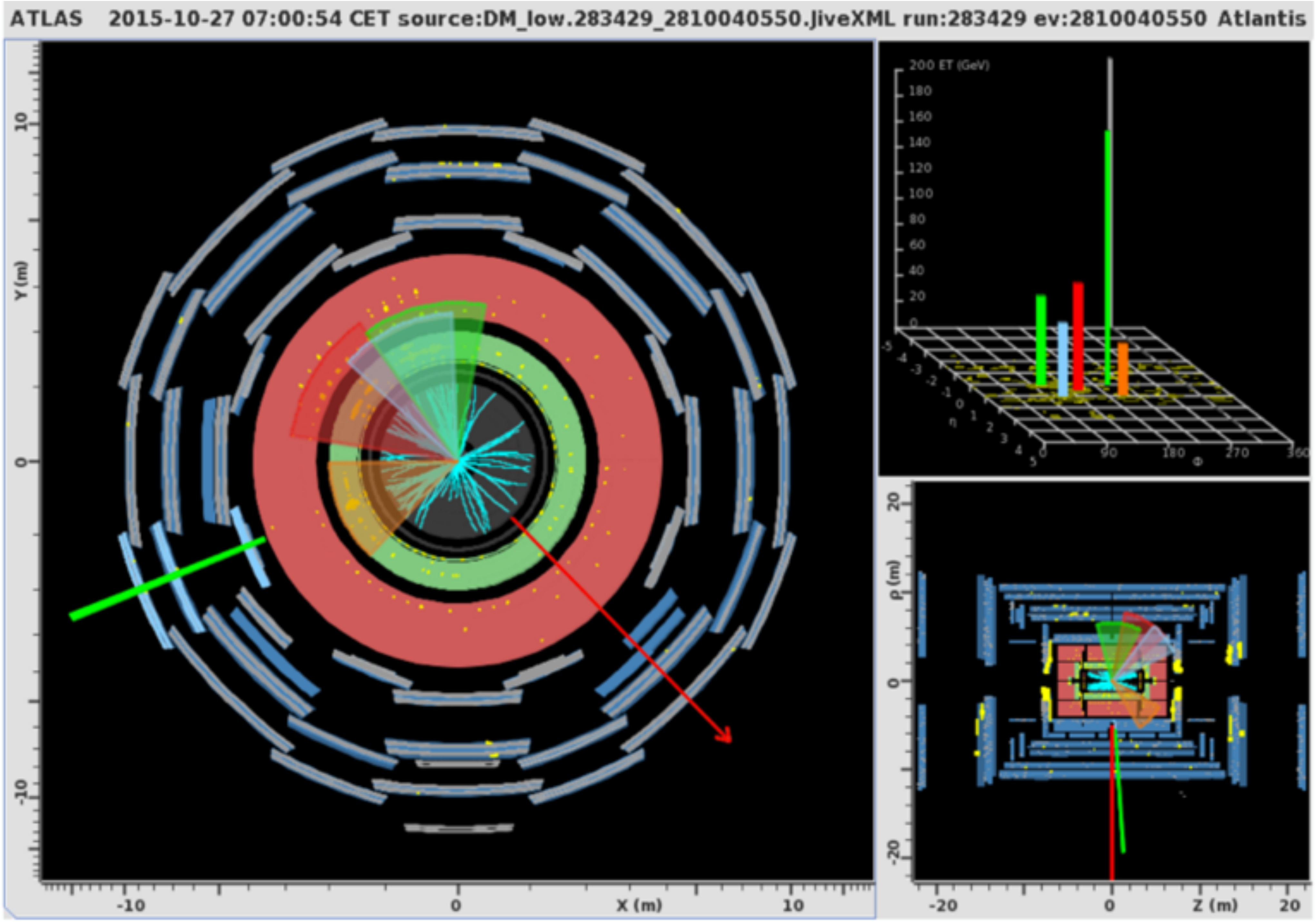
understand the excess
- kinematic distributions
- Event displays
- printouts of SR events

ATLAS EXPERIMENT

understand the excess

Event display

Enforced event topology clearly visible - no other problems spotted



understand the excess

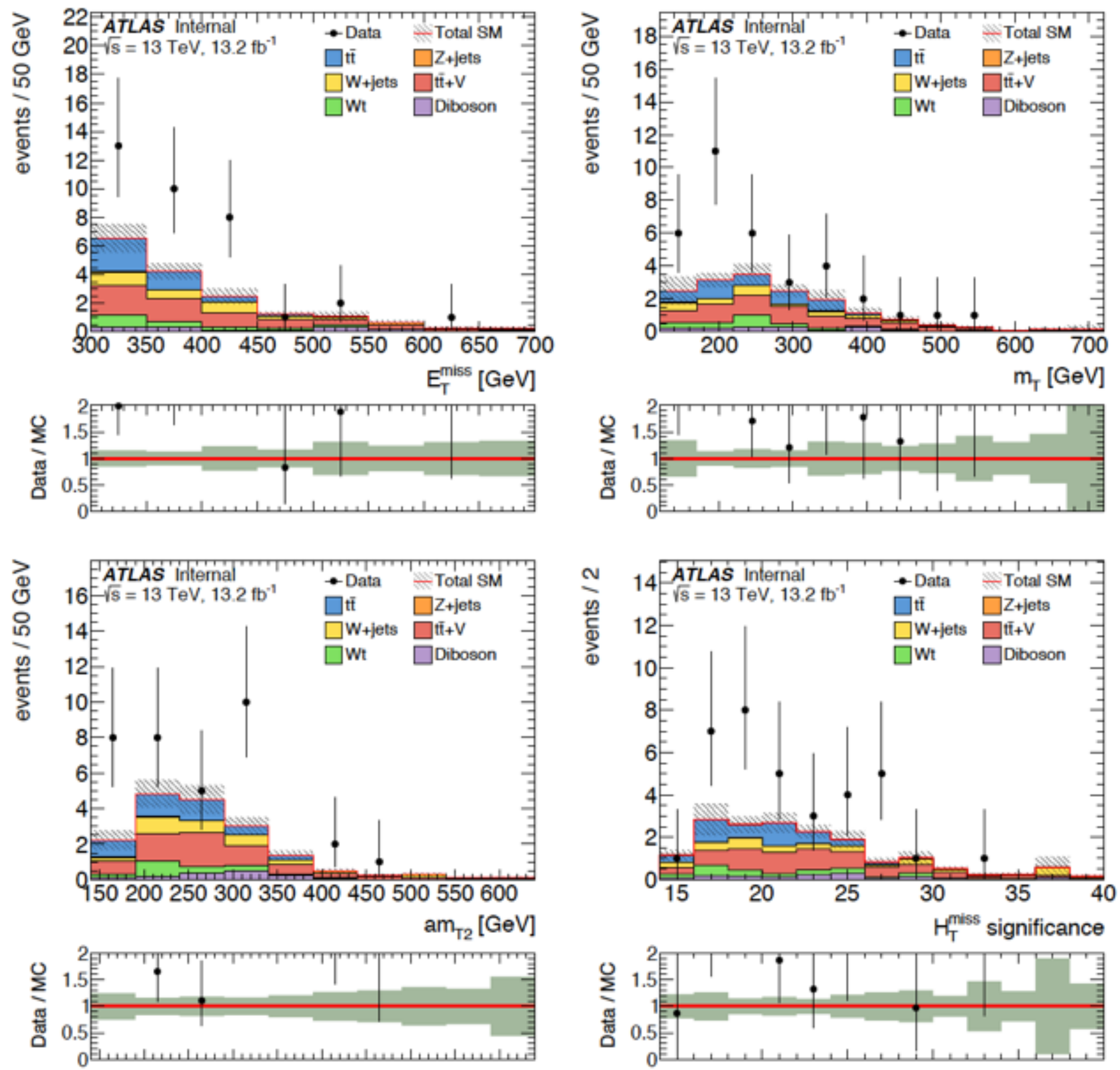
Characteristics

ATLAS EXPERIMENT

Excess tends to small E_T^{miss} and m_T

No clear trend with am_{T2} and H_T^{miss} significance

same picture holds for other "suspicious SRs"



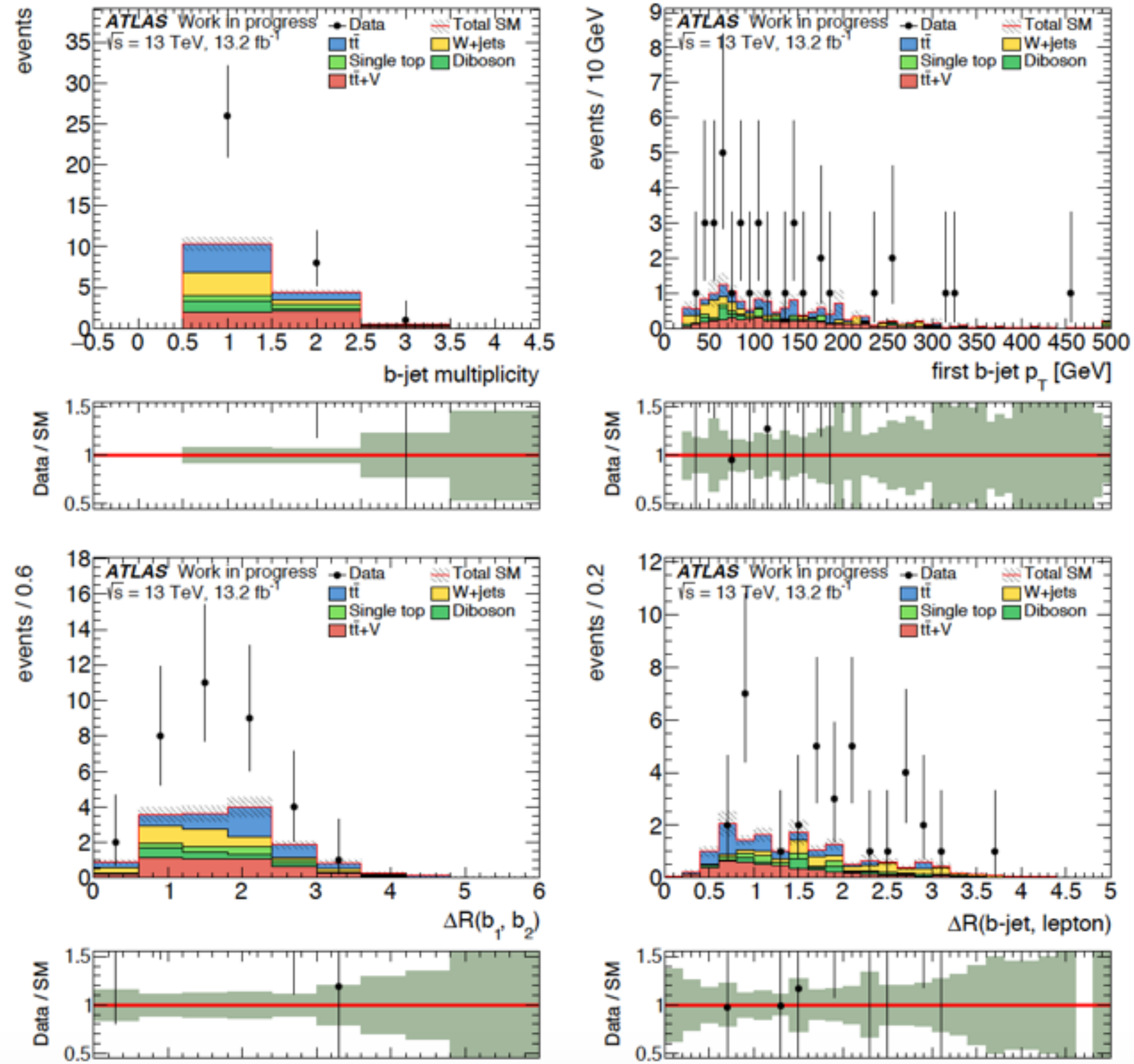
understand the excess

b-jets

Striking: excess seems to be favouring 1-b-jet bin

- not the case for other “suspicious SRs"

b-jet p_T and angular distributions look unproblematic



understand the excess

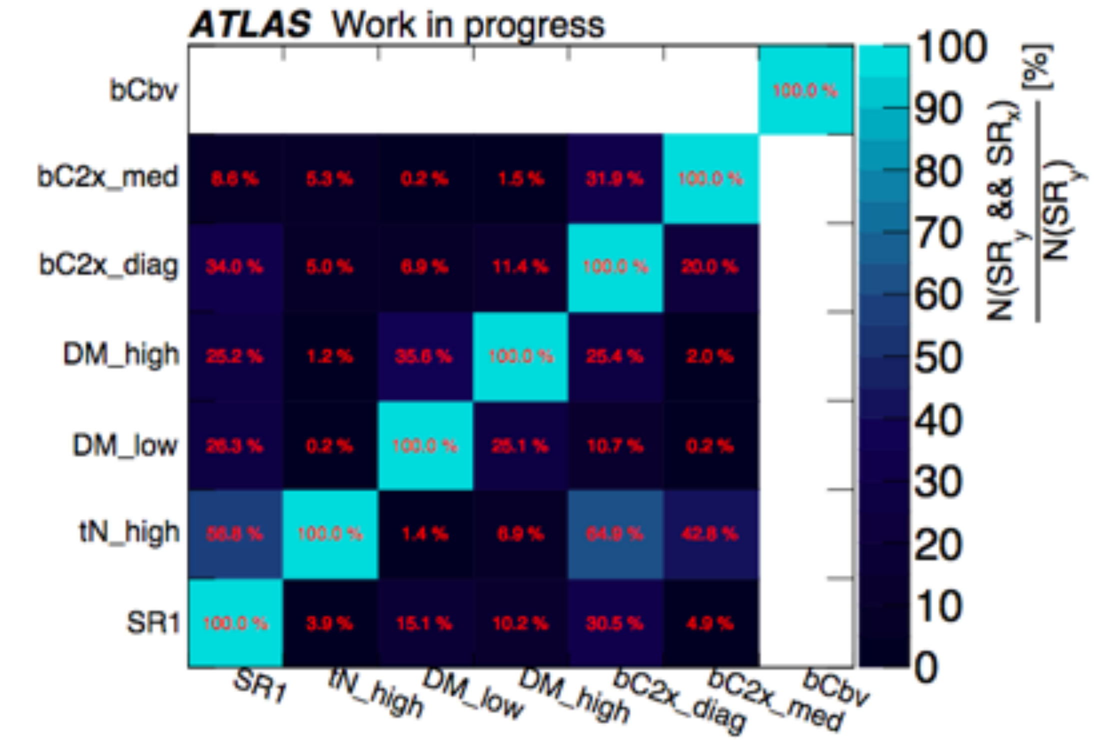
SR overlaps

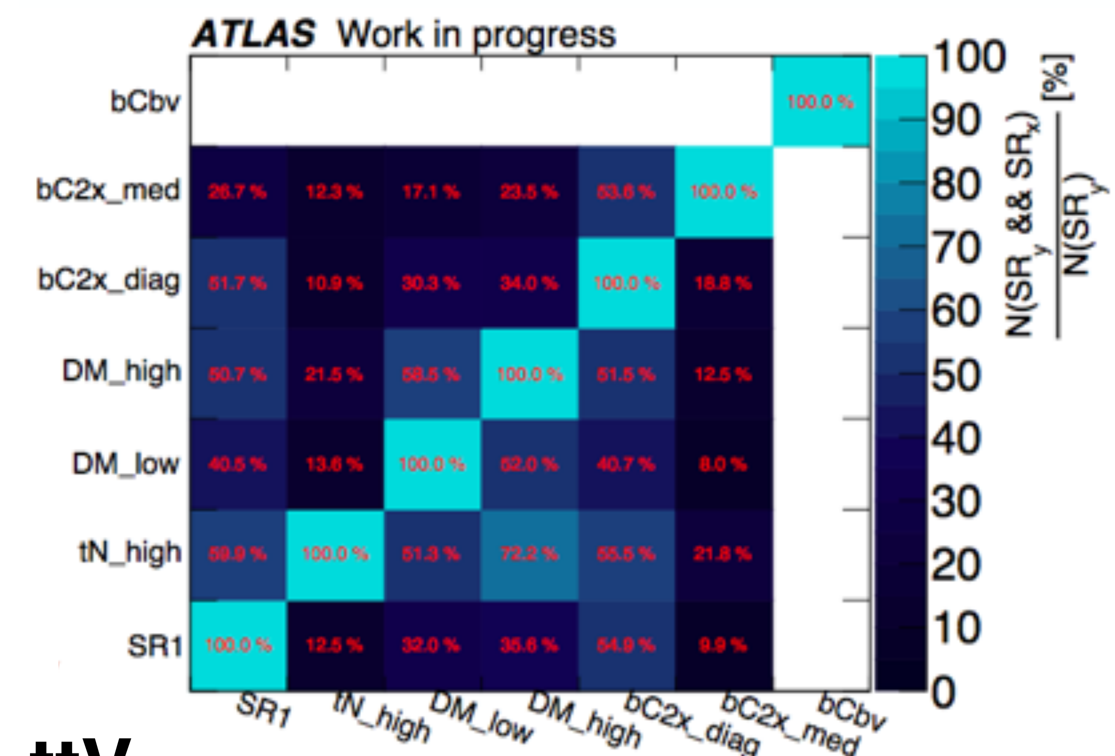
Signal-like backgrounds (e.g. ttV) have larger overlaps than ttbar/Wjets

- Excesses from common problem of ttbar/Wjets estimate unlikely

Sample	DM_low unique	DM_low and SR1	DM_low and bC2x_diag
ttbar	69 %	26 %	11 %
singletop	58 %	19 %	27 %
wjets_22	78 %	18 %	7 %
diboson	74 %	25 %	9 %
ttv	41 %	41 %	41 %

ttbar





ttV

Background estimate

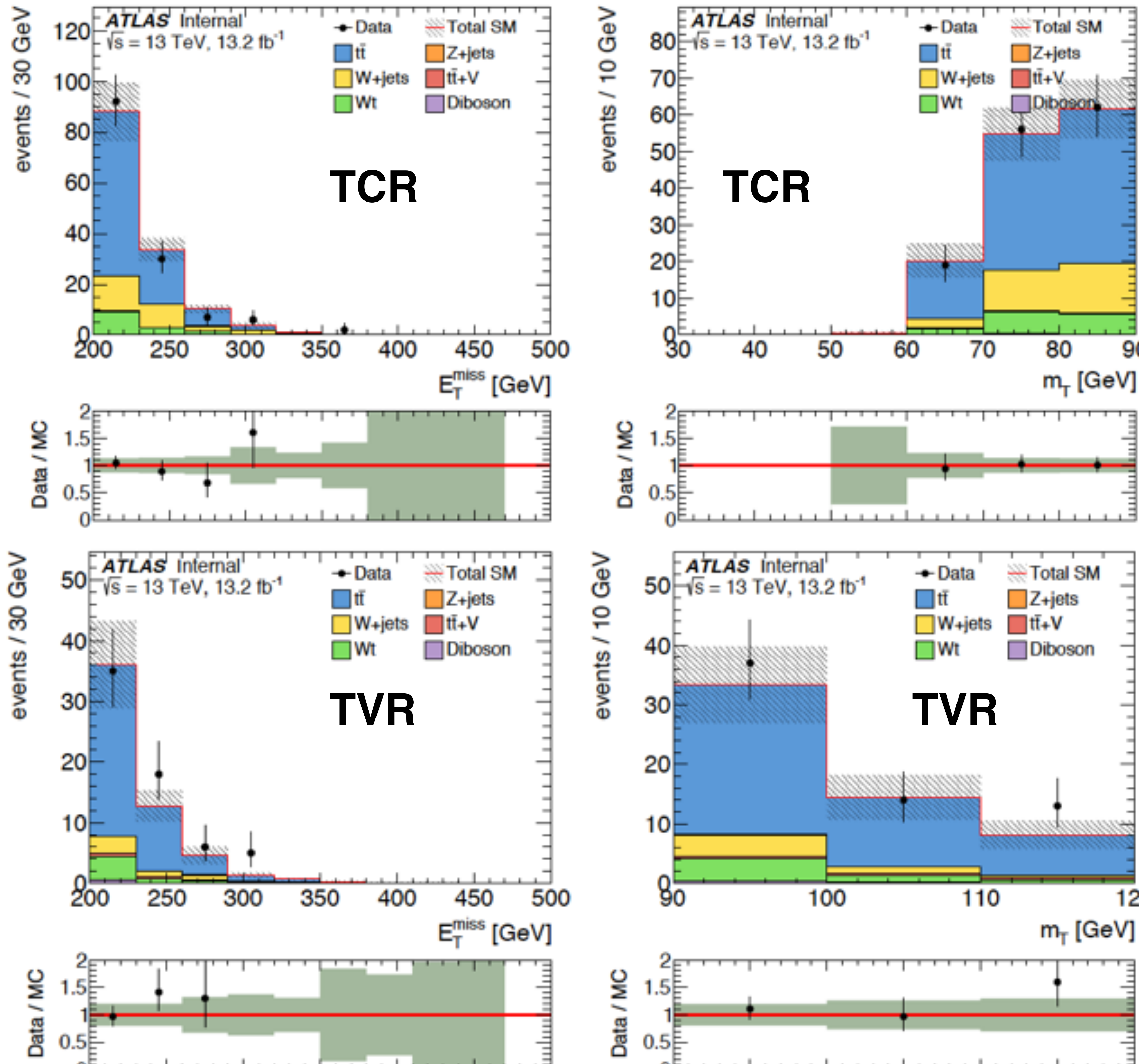
Distributions in CRs and VRs

ATLAS EXPERIMENT

E_T^{miss}: sensitive to signals

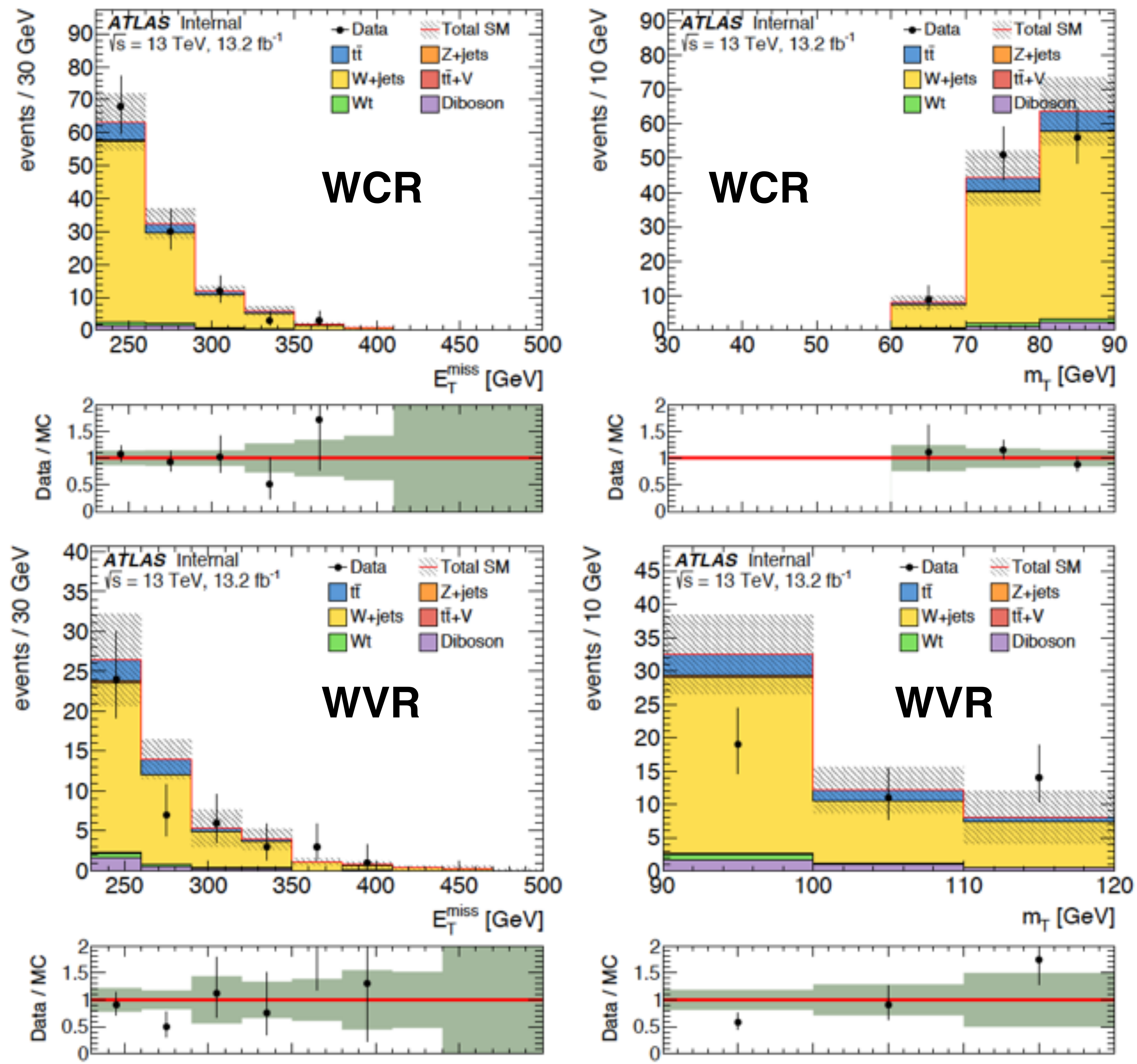
m_T: used for extrapolation

No apparent issues



Background estimate

Distributions in CRs and VRs



E_T^{miss}: sensitive to signals

m_T: used for extrapolation

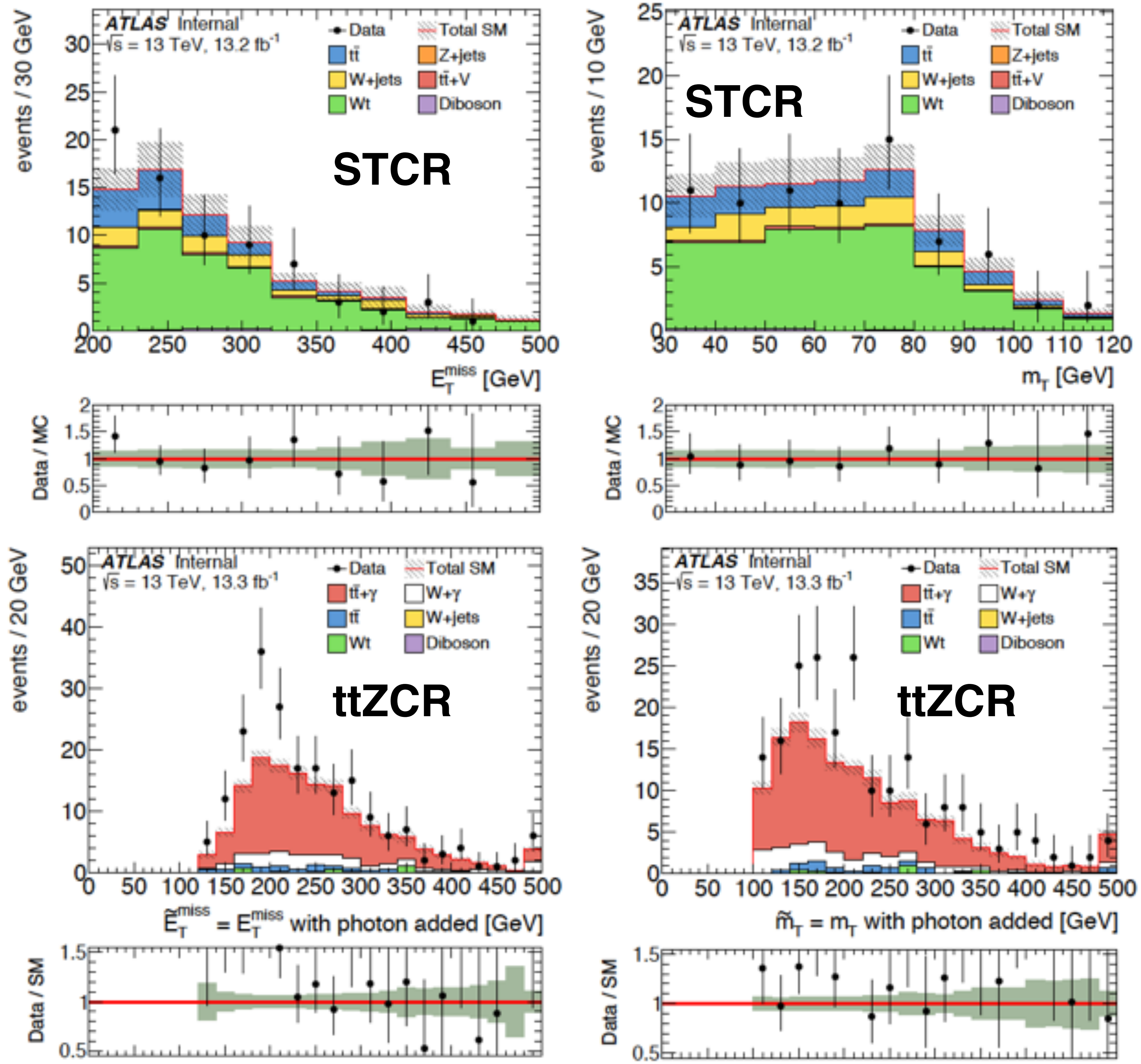
No apparent issues

Distributions in CRs and VRs

E_T^{miss}: sensitive to signals

m_T: used for extrapolation

No apparent issues



Non-canonical VRs

No NFs applied - not trivial which ones to use -
but: W+jets scaled down to 0.75 (consistent with most SR fits)

W - m_T-tail

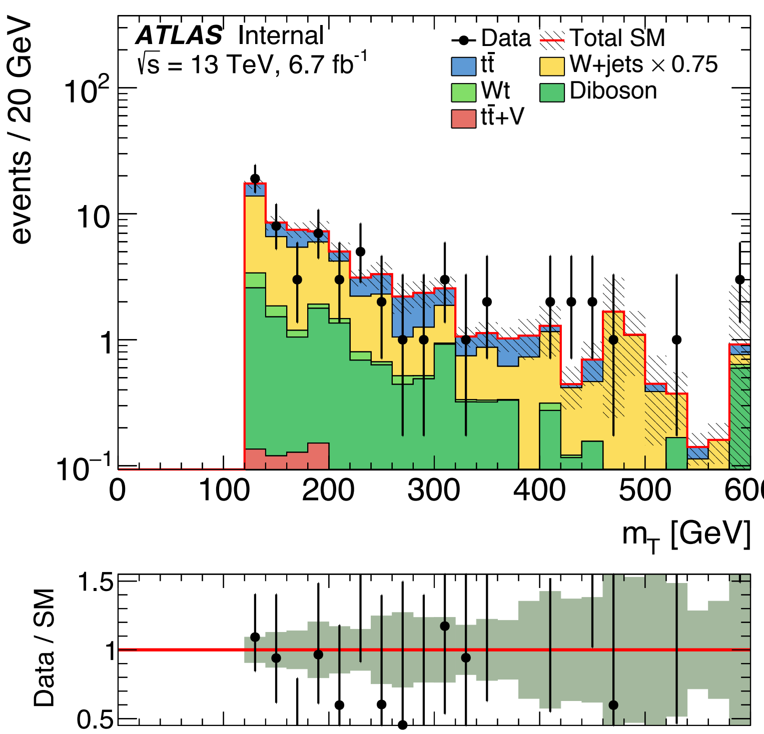
1. Four jets with $p_T > 100, 80, 50, 25$ GeV.
2. $E_T^{miss} > 200$ GeV.
3. $m_T > 100$ GeV.
4. Exactly zero b-jets.

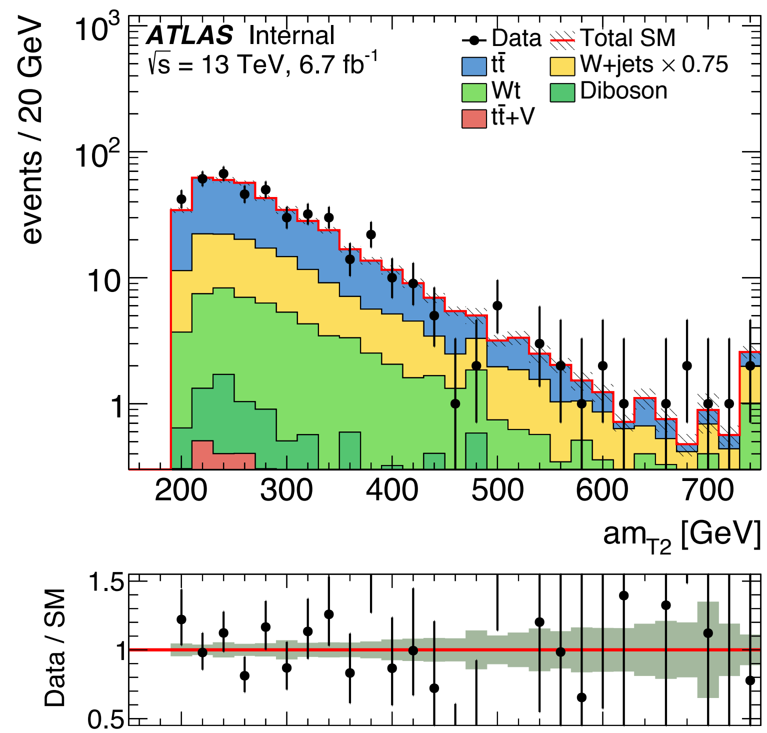
am_{T2}-tail

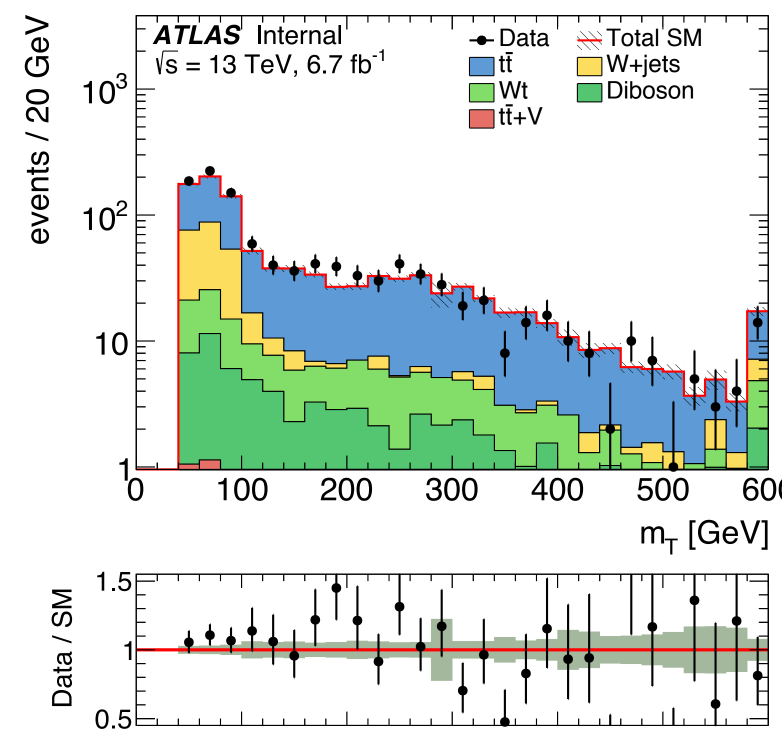
1. Four jets with $p_T > 80, 60, 60, 40$ GeV.
2. $E_T^{miss} > 200$ GeV.
3. $30 < m_T < 90$ GeV.
4. $am_{T2} > 200$ GeV.
5. $H_{T,sig}^{miss} > 8$.
6. Exactly 1 b-jet.

1L1τ

1. Four jets with $p_T > 80, 50, 40, 25$ GeV.
2. $E_T^{miss} > 200$ GeV.
3. $m_T > 100$ GeV.
4. At least one b-jet.
5. One loose reco τ and one signal lepton.
6. $m_T > 40$ GeV





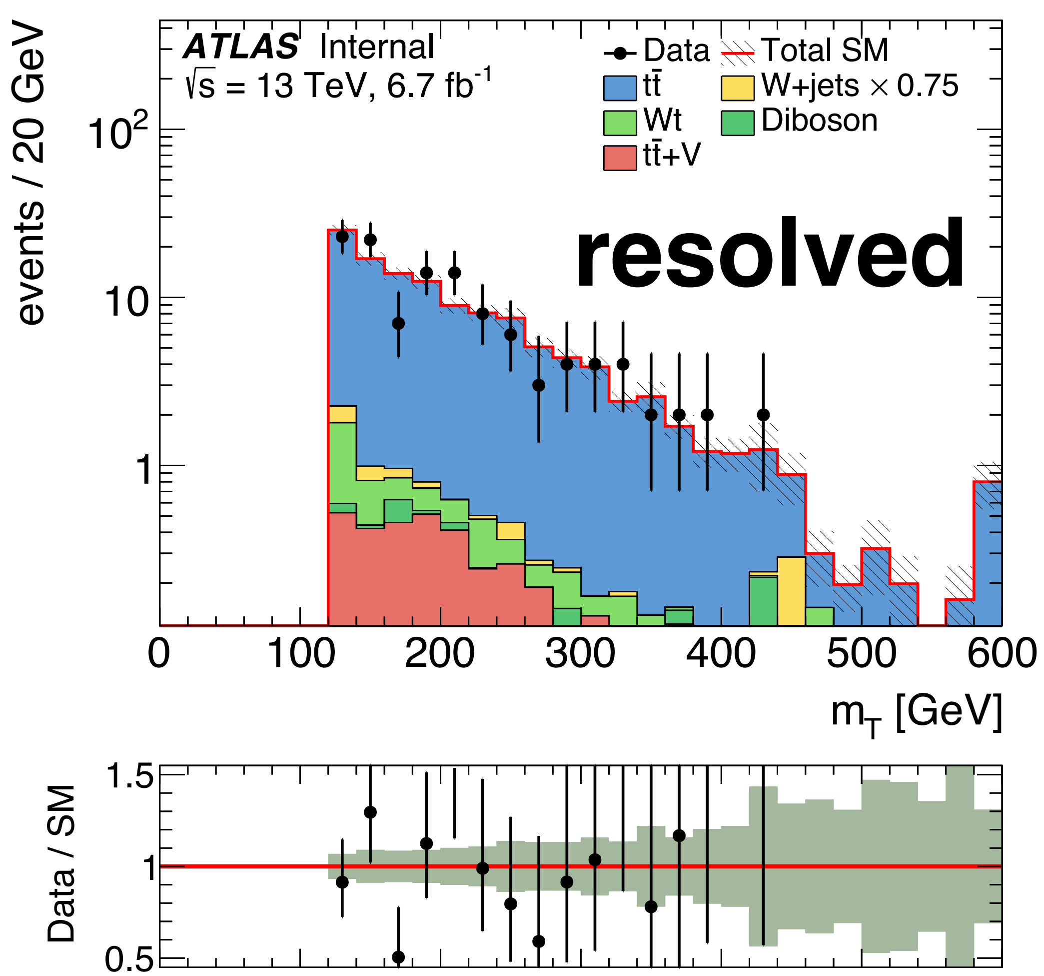


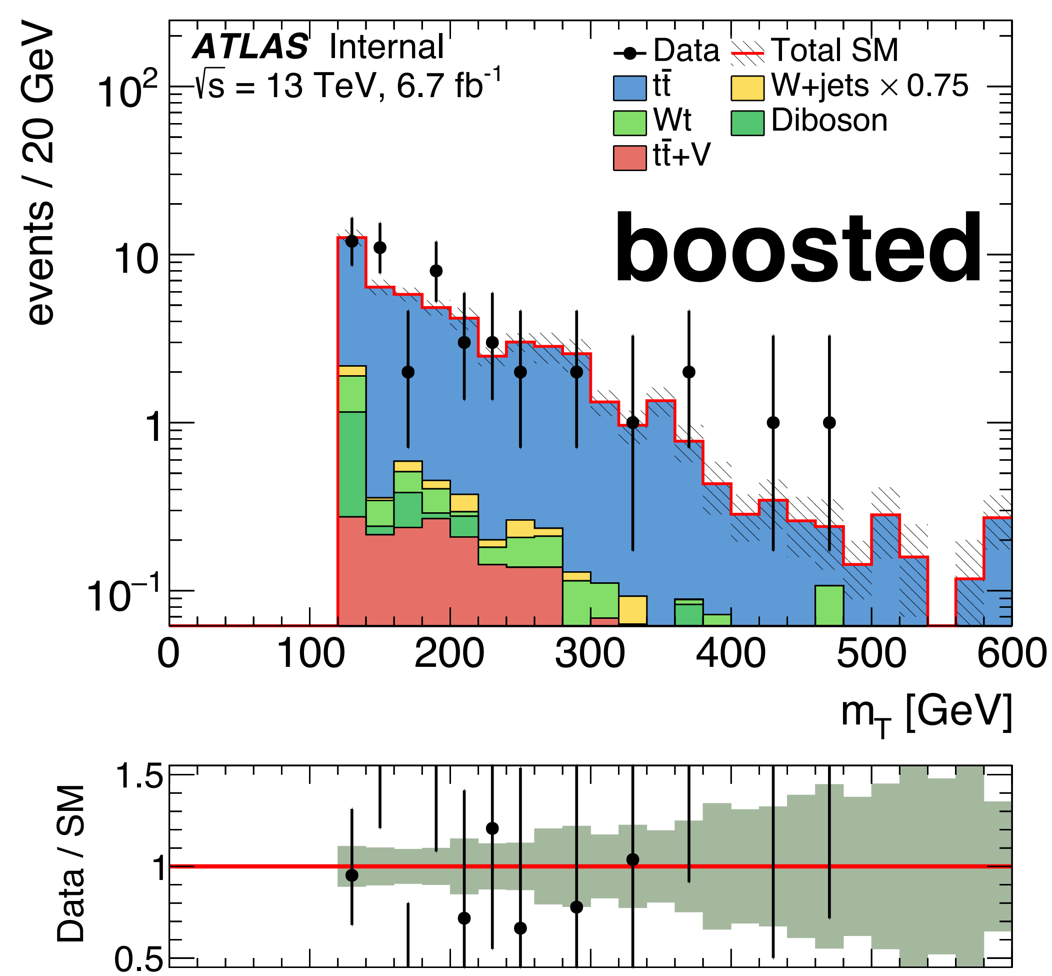
Background estimate

Non-canonical VRs

low-amT2

Selection identical to tN SRs, but an upper am_{T2} cut of 130 GeV





Background missing?

Higgs should be negligible (no derivations were available, not tested)

- most likely: ttH, but should be mostly removed by E_T^{miss} cut

Z+jets small but not negligible

- reintroduced on-the-way

Other possible small backgrounds: < 1%

bC2x_diag	total
ttbar	8.15 ± 0.48
single top	4.40 ± 0.33
W+jets	1.50 ± 0.21
ttbar+V	6.24 ± 0.13
diboson	0.31 ± 0.08
Z+jets	0.30 ± 0.15
tZ	0.14 ± 0.02
tttt	0.07 ± 0.01
ttWW	0.04 ± 0.01
tZW	0.03 ± 0.01
Total SM	21.16 ± 0.65
Data	37

DM_low	total
ttbar	4.80 ± 0.39
single top	1.35 ± 0.21
W+jets	3.70 ± 0.47
ttbar+V	4.73 ± 0.11
diboson	1.43 ± 0.21
Z+jets	0.14 ± 0.03
tZ	0.11 ± 0.02
tttt	0.00 ± 0.00
ttWW	0.01 ± 0.01
tZW	0.01 ± 0.01
Total SM	16.27 ± 0.69
Data	35

SR1	total
ttbar	8.05 ± 0.49
single top	3.10 ± 0.22
W+jets	3.39 ± 0.38
ttbar+V	6.03 ± 0.13
diboson	1.04 ± 0.19
Z+jets	0.51 ± 0.18
tZ	0.05 ± 0.01
tttt	0.06 ± 0.01
ttWW	0.05 ± 0.01
tZW	0.02 ± 0.01
Total SM	22.30 ± 0.72
Data	37

Background estimate

Focus on ttZ

Observed NF of roughly 1.5 → could point to missing background in CR

- Reminder: use ttγ to estimate ttZ

Indeed, W+γ was not included, but is ~10% of total events in CR

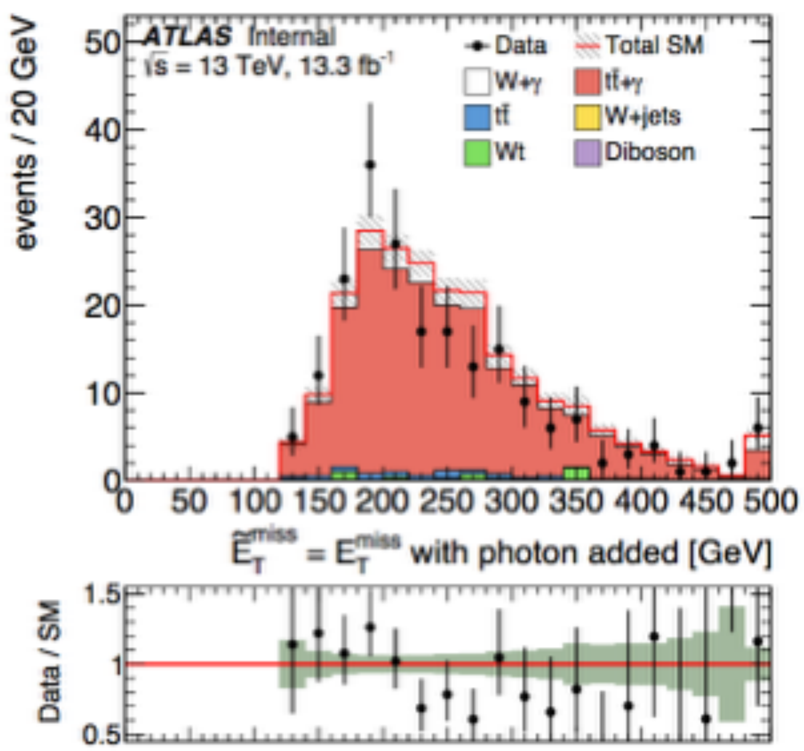
- consistent with 7 TeV ttγ analysis (also, this analysis lets one expect 3% Z+γ → neglected)

Inclusion of W+γ made NF go down, hence significance of excess went up

(table numbers all pre-fit)

ttZ CR DM low	total
ttgamma	112.75 ± 1.93
Wgamma	20.79 ± 0.56
ttbar	6.79 ± 0.91
single top	2.08 ± 0.45
W+jets	0.11 ± 0.06
ttbar+V	1.14 ± 0.04
diboson	0.20 ± 0.10
Z+jets	0.33 ± 0.10
Total SM	144.25 ± 2.26
Data	206

after fit, W+gamma is ~10%



Background estimate

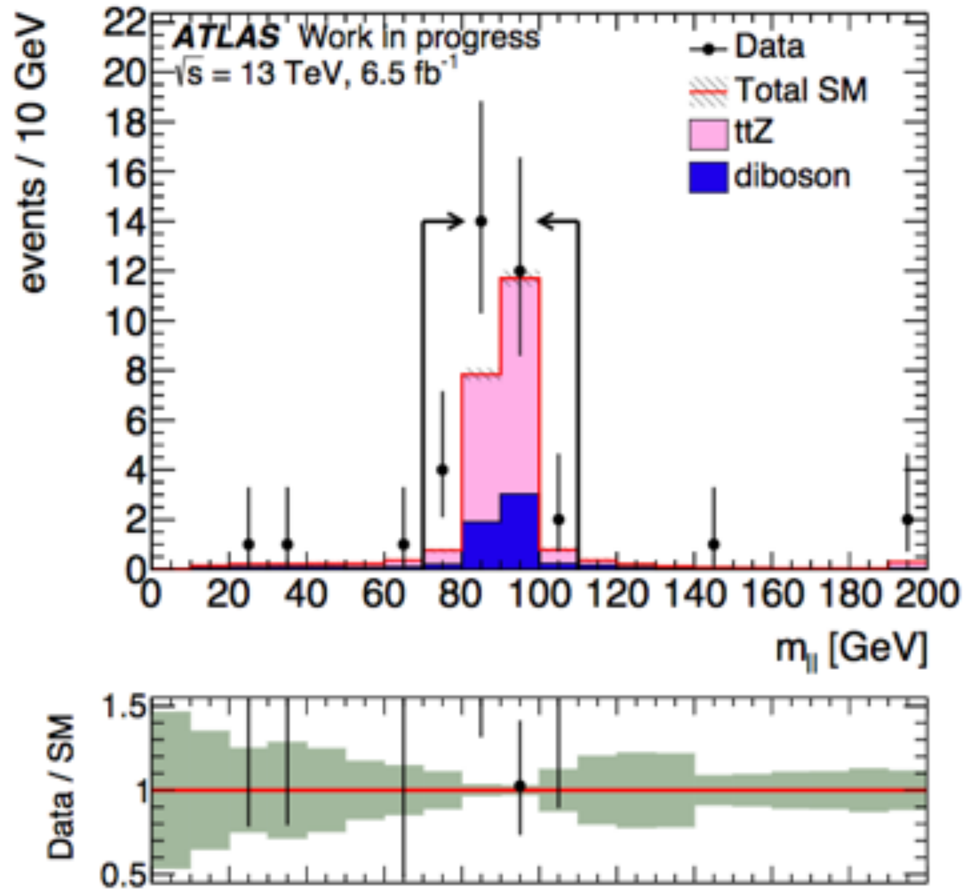
Focus on ttZ

To confirm high NF, trilepton VR for ttZ(ℓℓ) was built

- main issue: statistics!
- Dilepton system is treated as invisible to mimic ttZ(inv) E_T^{miss}

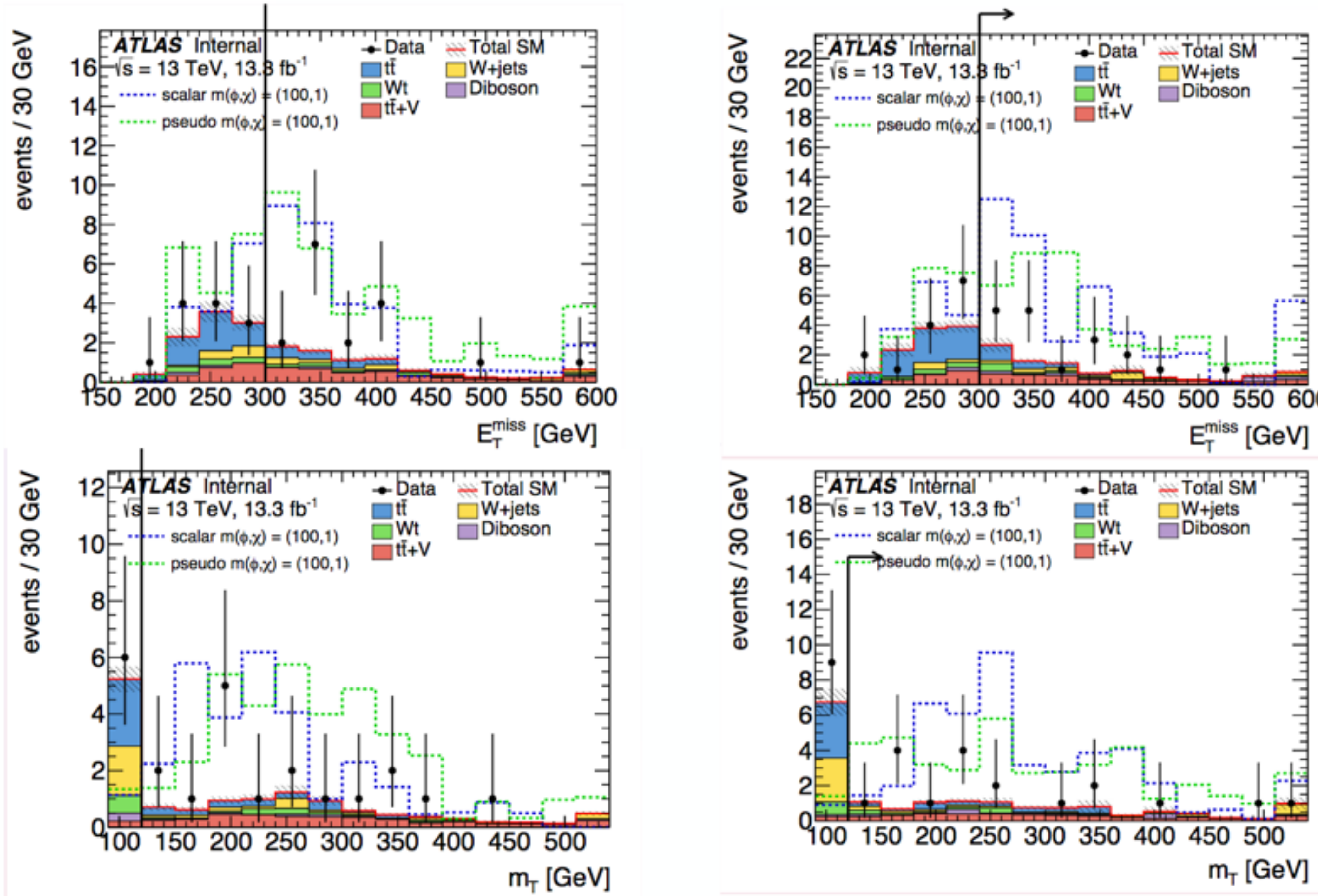
Observed data ~1.5 times above MC → NF seems correct

ttZll_CR	total
ttZ	15.85 ± 0.17
diboson	5.33 ± 0.79
Total SM	21.18 ± 0.81
Data	32



Lepton channels

No difference between electron and muon channel

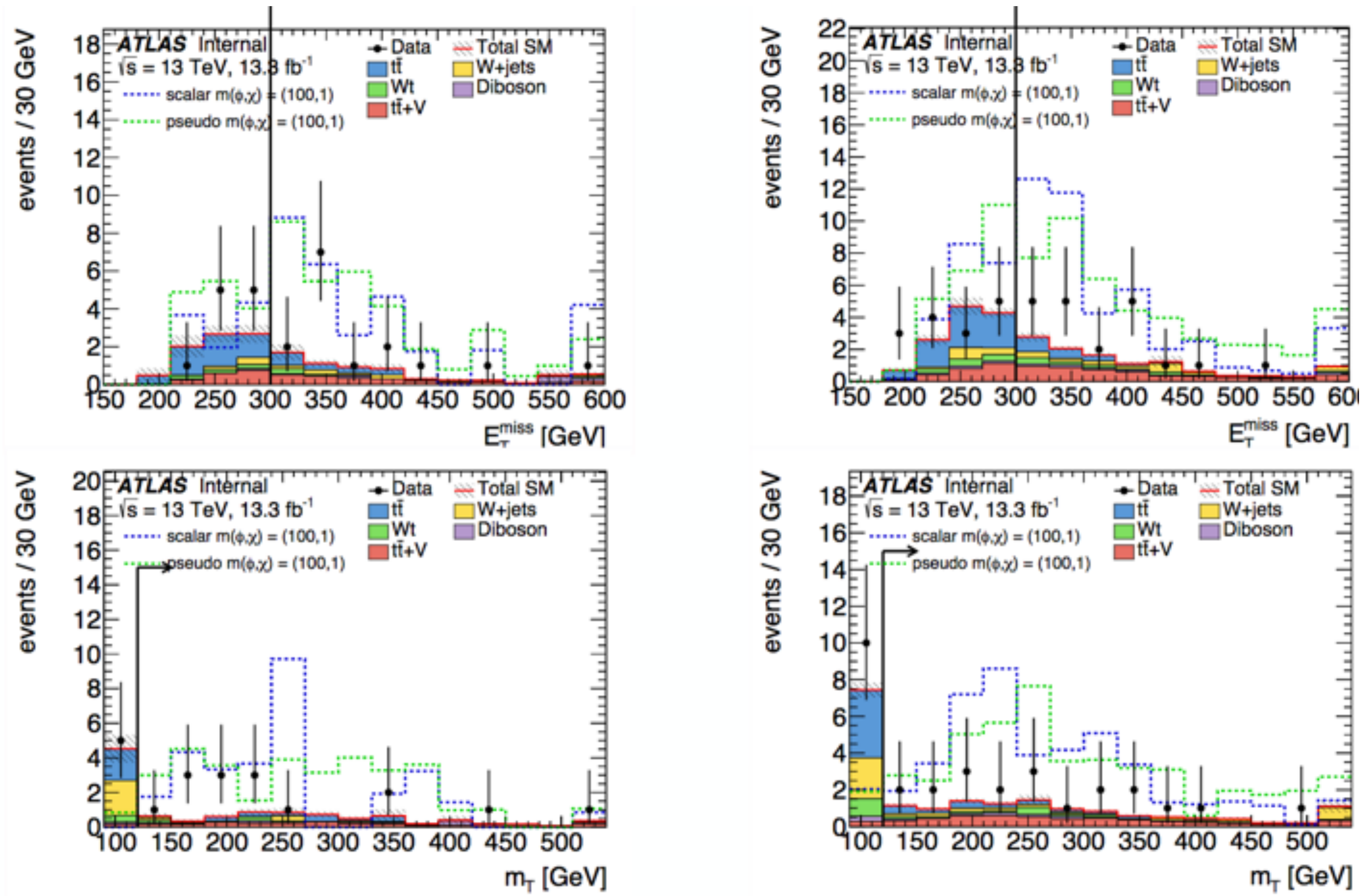


Electron

Muon

Pile-up

Excess is present for low and high pile-up

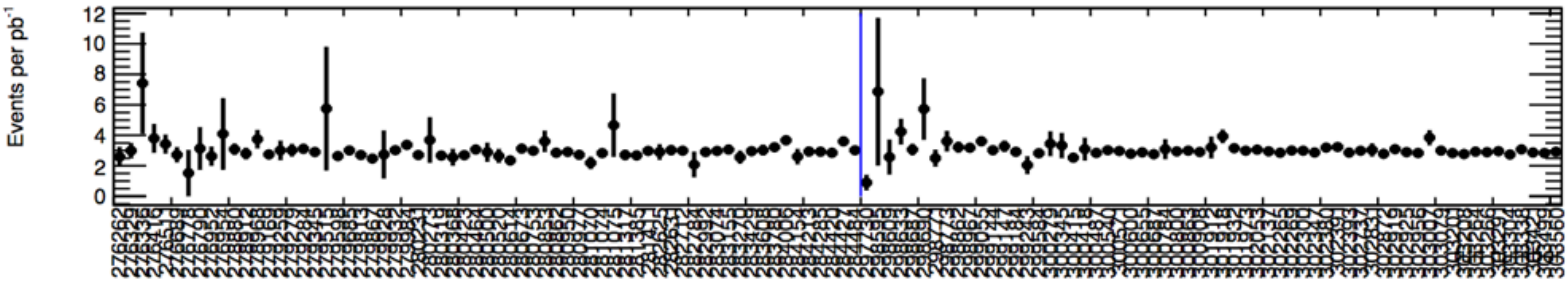


$\mu_{avg} < 15$ $\mu_{avg} > 15$

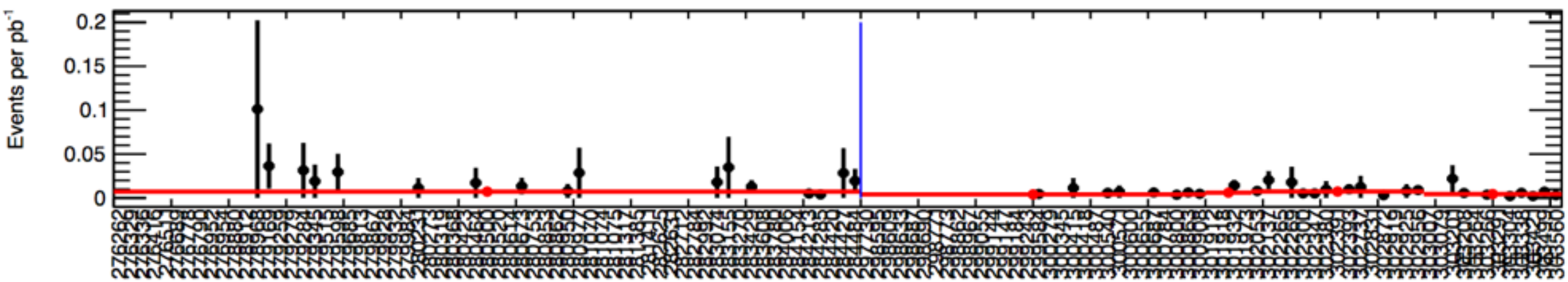
Events vs. Runs

ATLAS EXPERIMENT

- Nicely flat events per luminosity at preselection



- Also flat events per luminosity in the SRs (in red grouped into DS1.x/DS2)



SR1 systs - ttbar