Probing new physics at the LHC: searches for heavy top-like quarks with the ATLAS experiment

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Four questions, one dissertation

- **Why?** bother with "new physics"

Four questions, one dissertation

- **Why?** bother with "new physics"
- **Where?** is all happening

Four questions, one dissertation

- **Why?** bother with "new physics"
- **Where?** is all happening
- **What?** are we looking at

Four questions, one dissertation

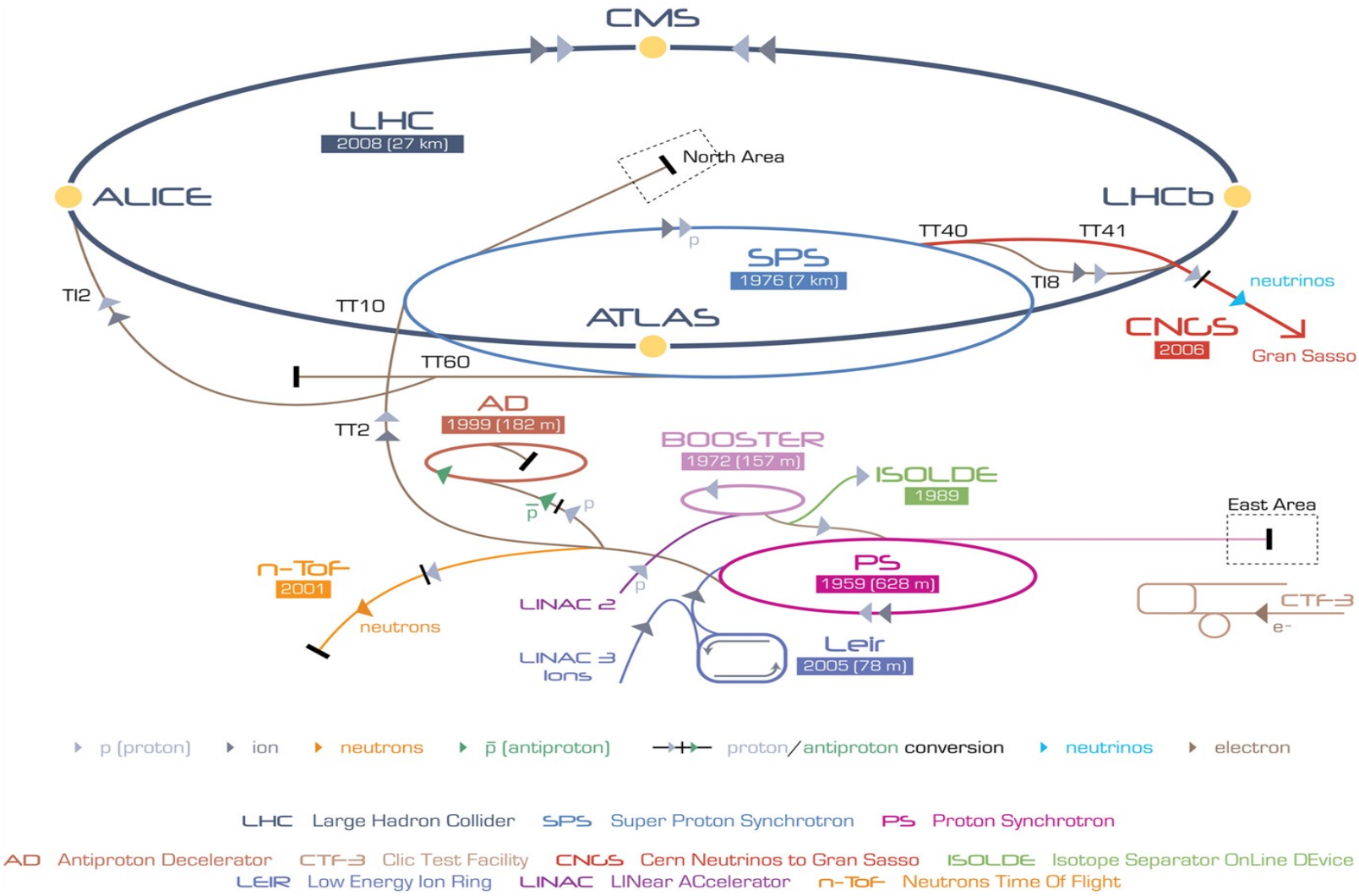
- **Why?** bother with "new physics"
- **Where?** is all happening
- **What?** are we looking at
- **How?**

Outline

Standard Model as an effective theory

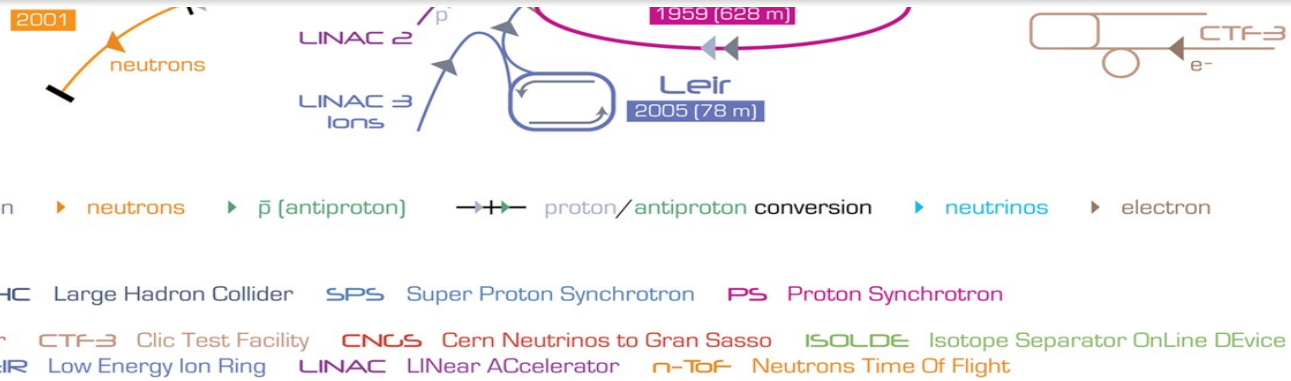
Outline

The LHC complex

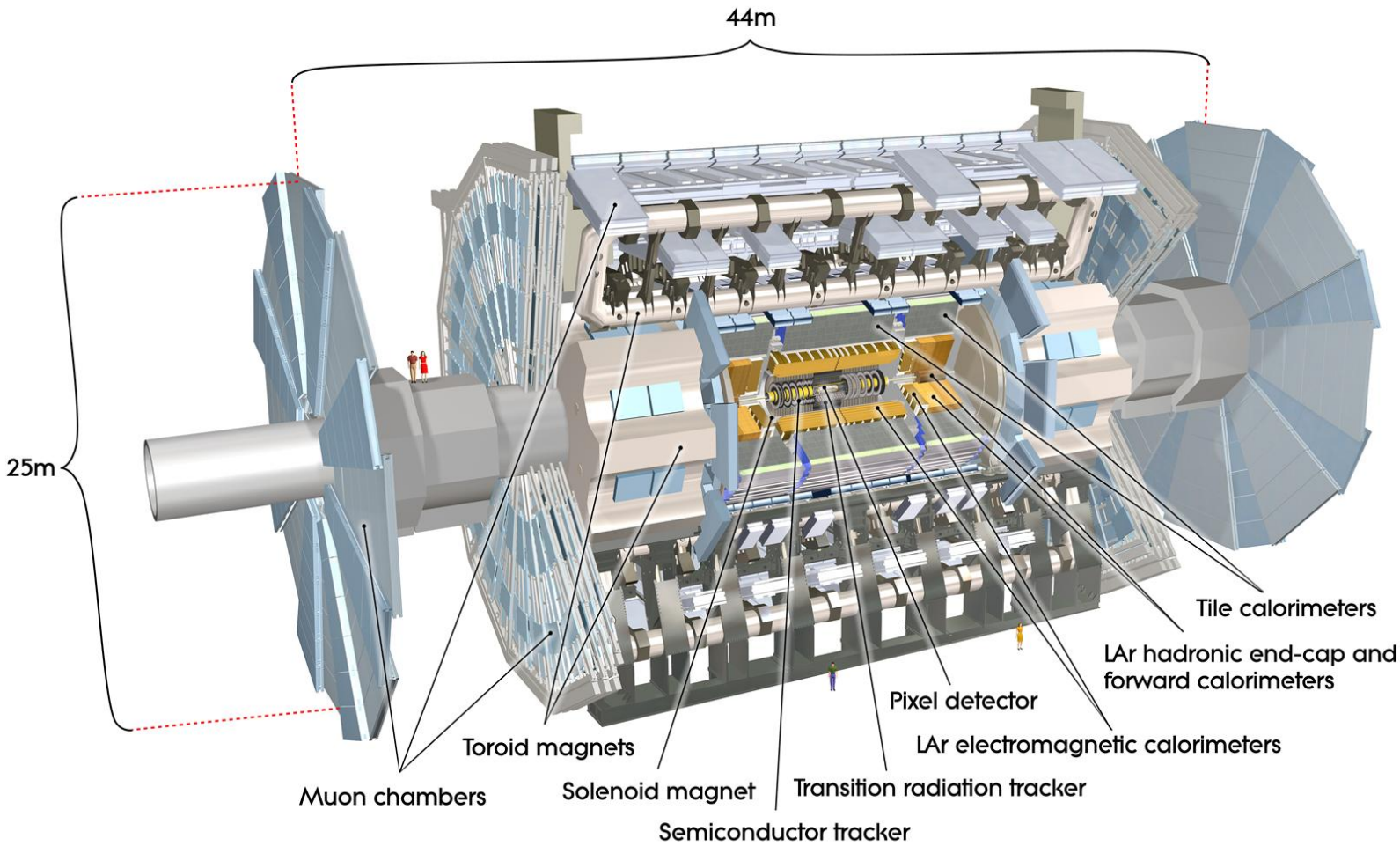


The LHC complex

Parameter	designed	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function $\beta*$ (m)	0.55	2.0/3.5	1.5/1.0	0.6
Max. No. bunches/beam	2808	368	1380	1380
Max. No. protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Emittance ε_n (μrad)	3.75	2.0	2.4	2.5
Max. $<\mu>$	19	4	17	37

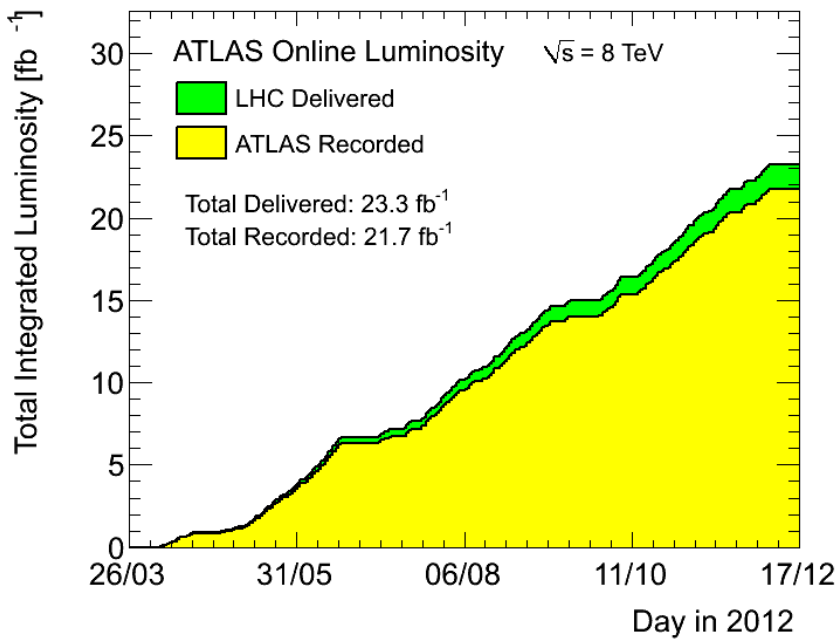


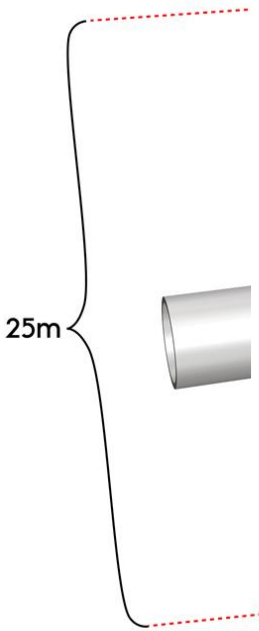
The ATLAS Detector

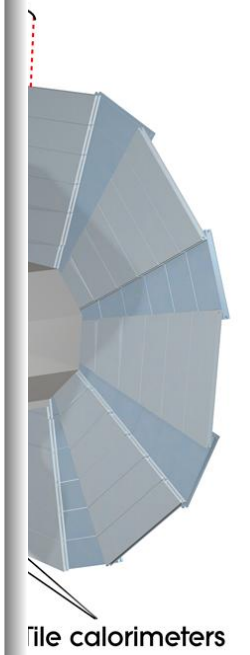


The ATLAS Detector

In 2012 21.7fb^{-1} collected at $\sqrt{s} = 8$ TeV!





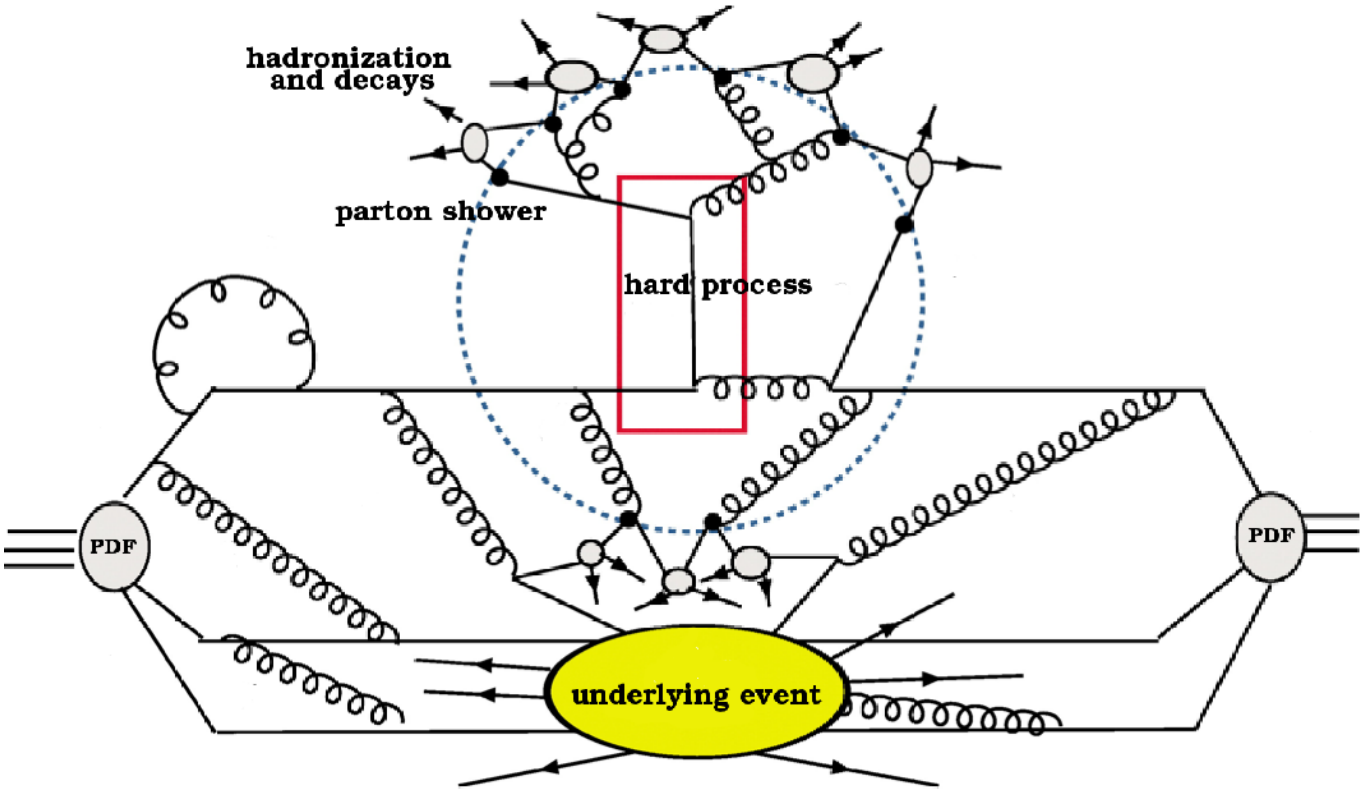


Will present results obtained with 14.3fb^{-1} of 2012 data

Outline

Modelling of hadron collisions

want to do physics at hadron colliders?
need a good understanding of incoming hadrons



Modelling of hadron collisions

Drawings from [1]

$E(p_1) = 4$ TeV

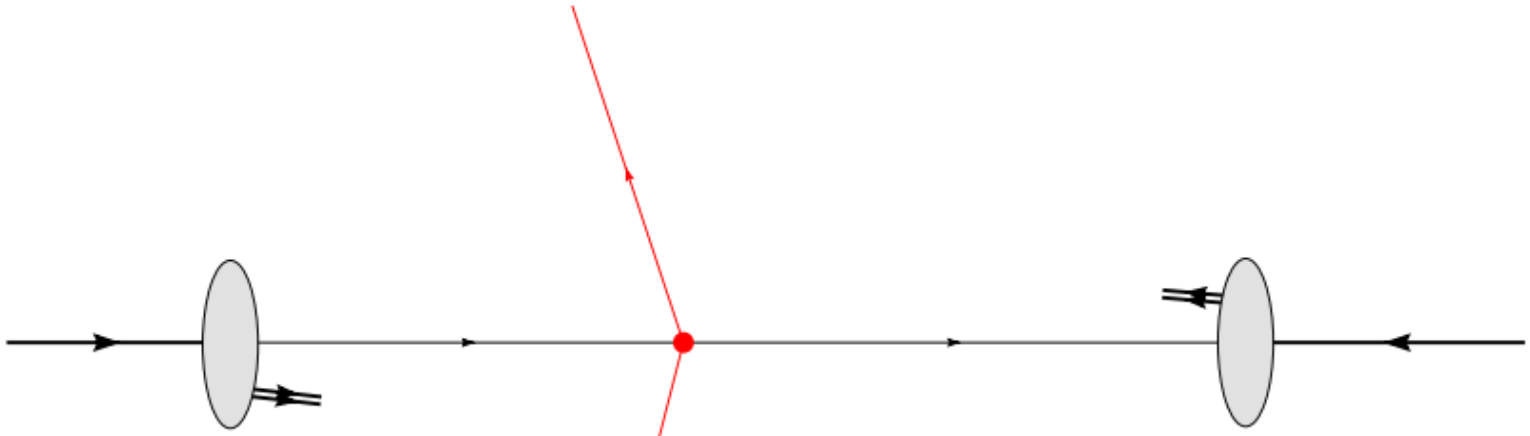
$E(p_2) = 4$ TeV

Quarks are distributed according to PDFs inside the proton

$\Downarrow$

intial energy unknown

Hard scattering of two partons

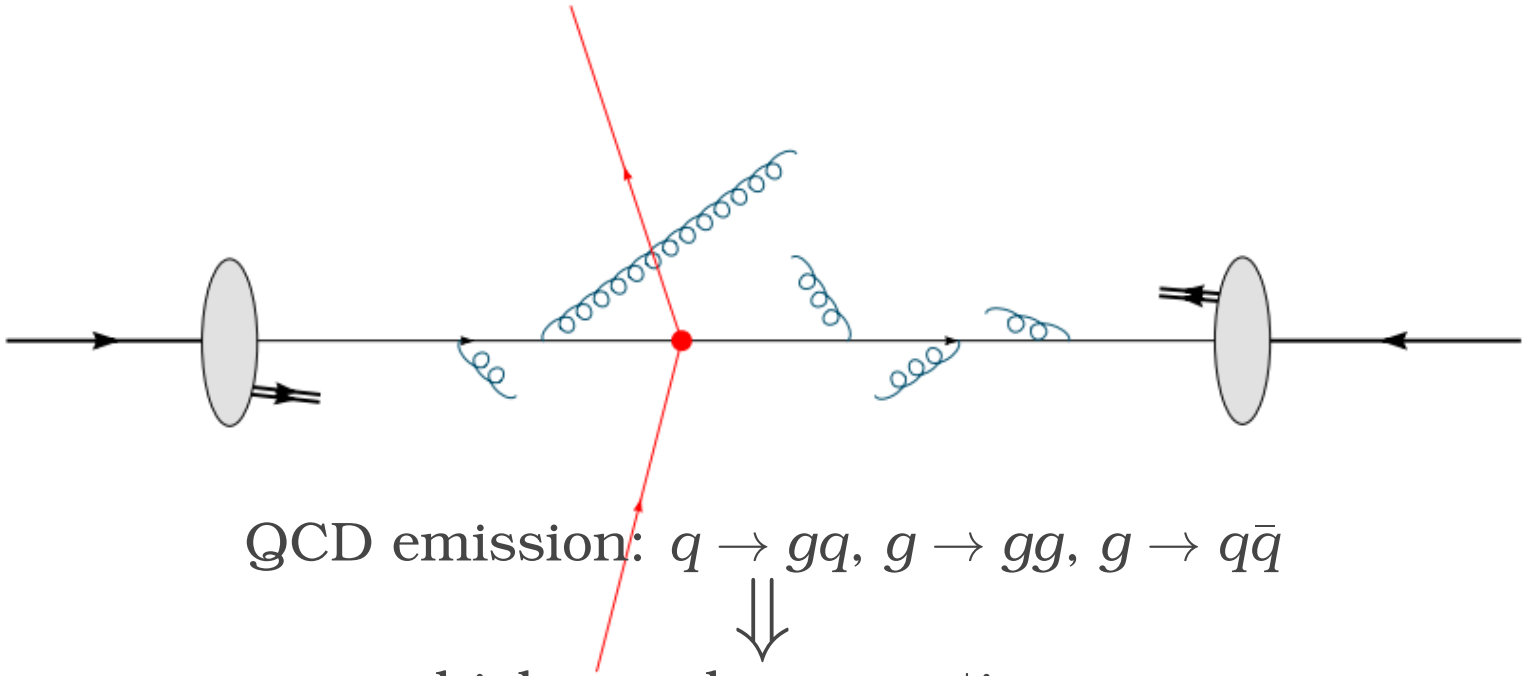


asymptotic freedom: high energy $\longleftrightarrow$ low α_S

$\Downarrow$

(fixed order) pQCD

Parton showering

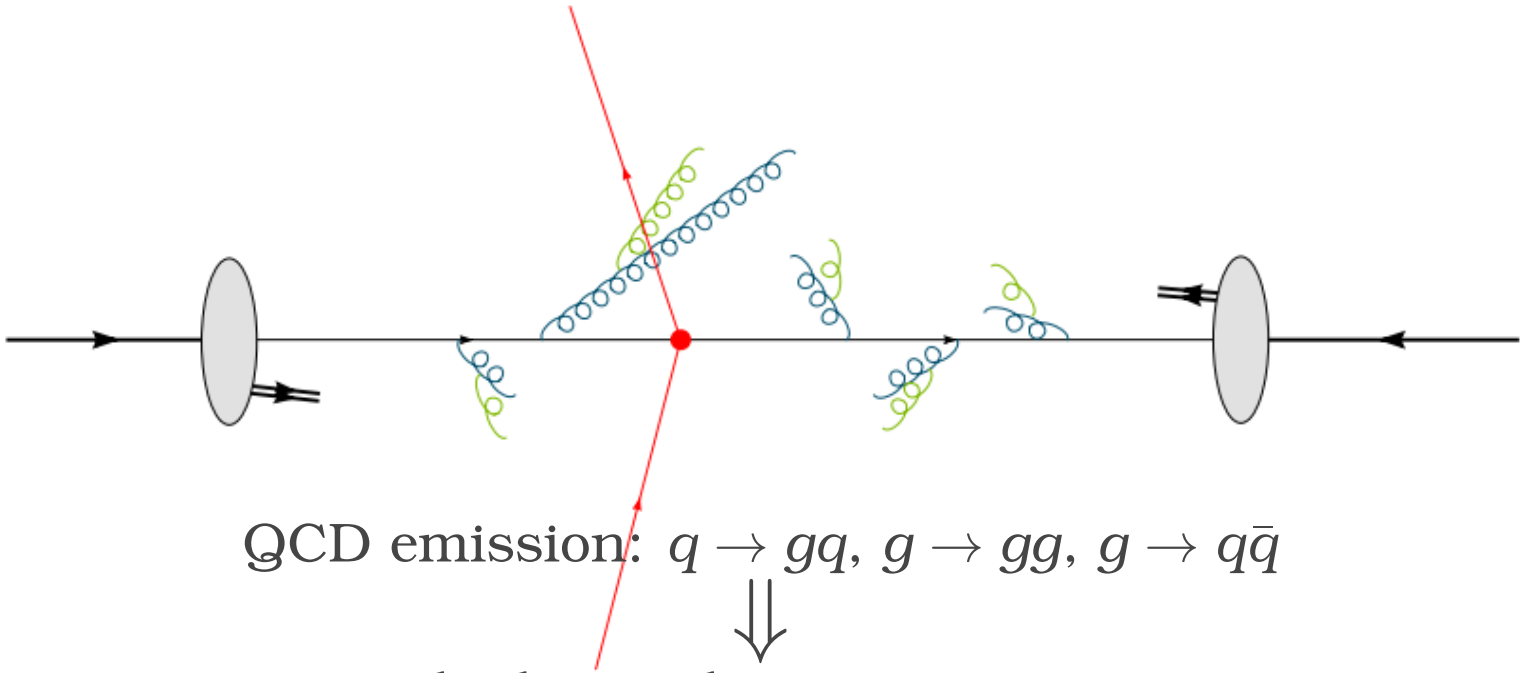


QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

$\Downarrow$

higher-order corrections

Parton showering



QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

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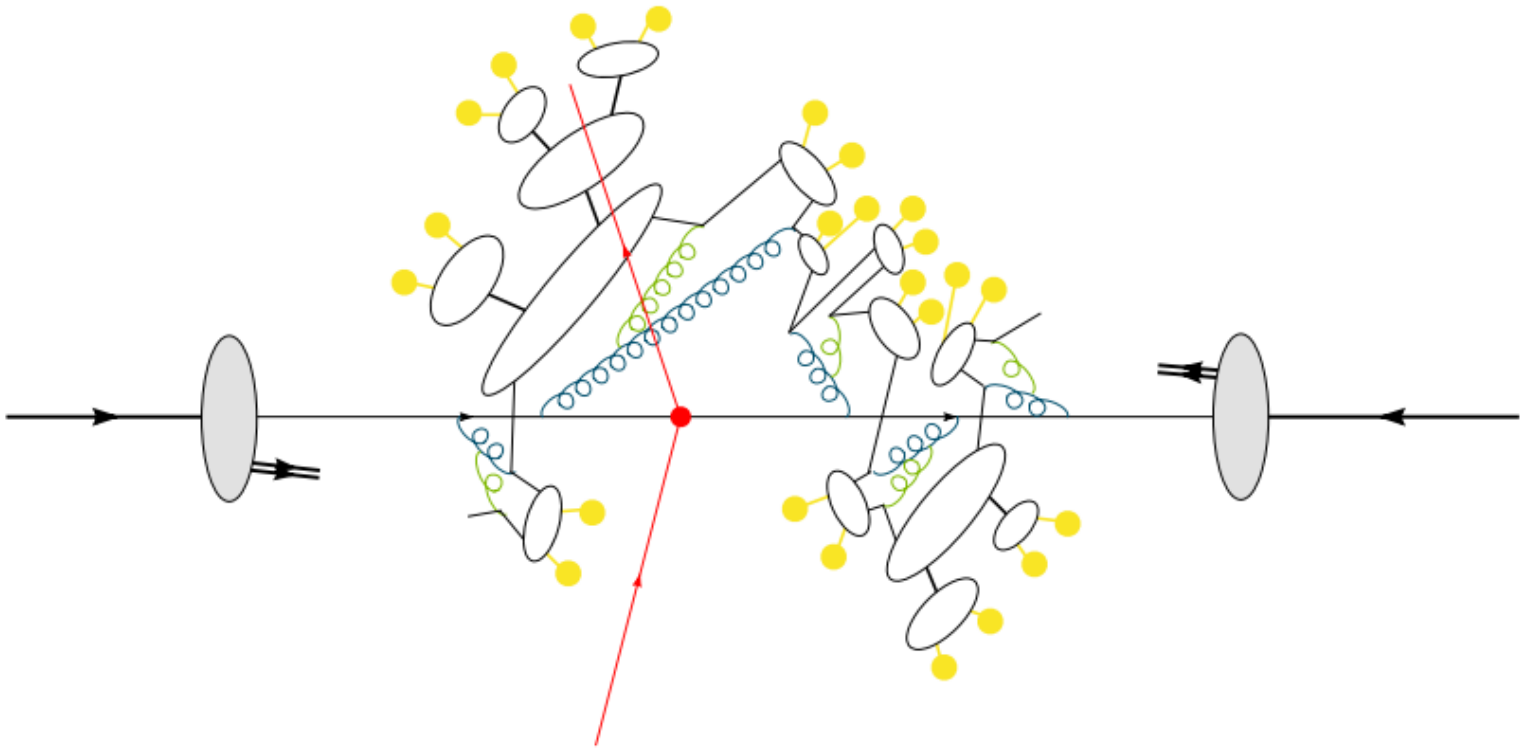
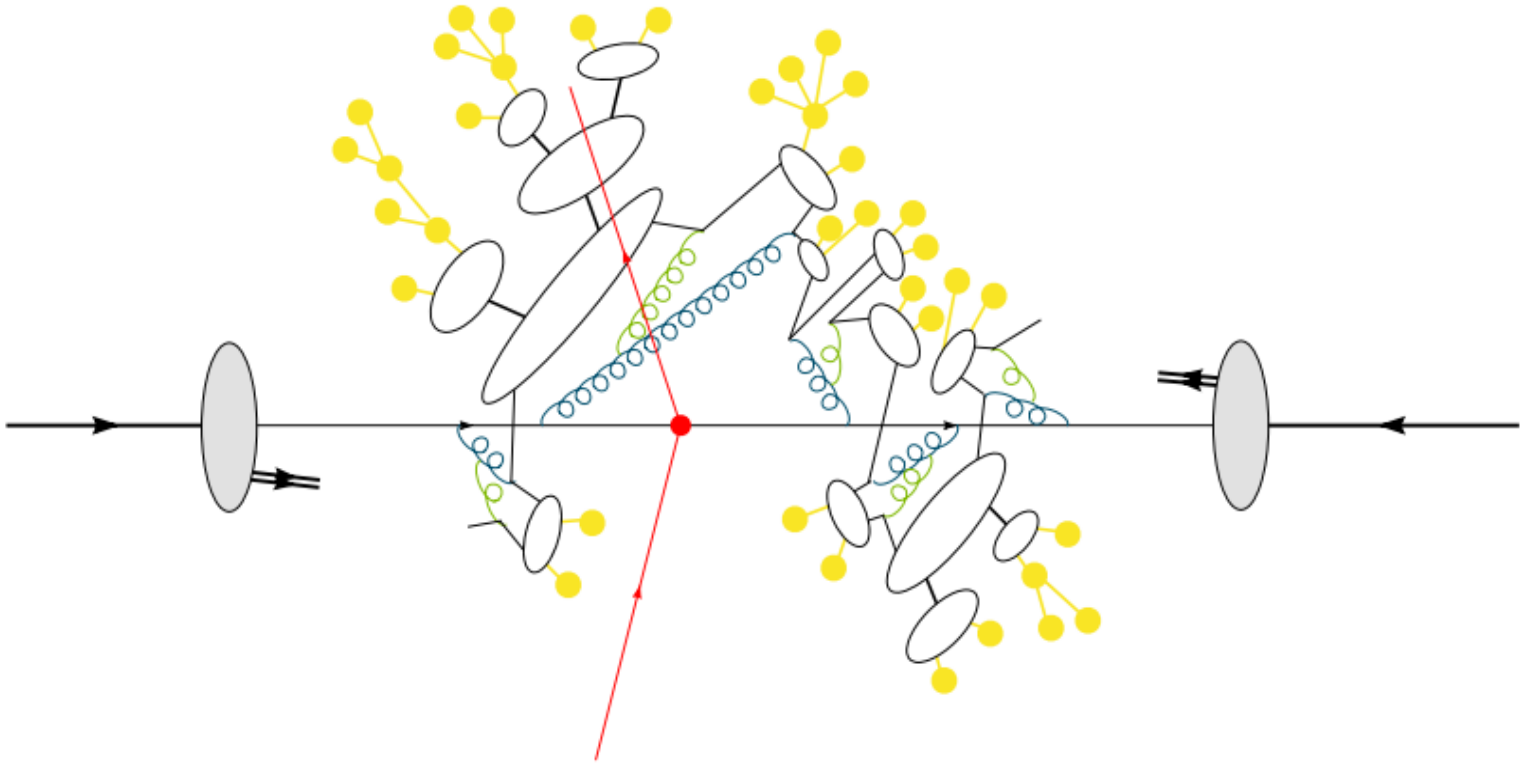
higher-order corrections

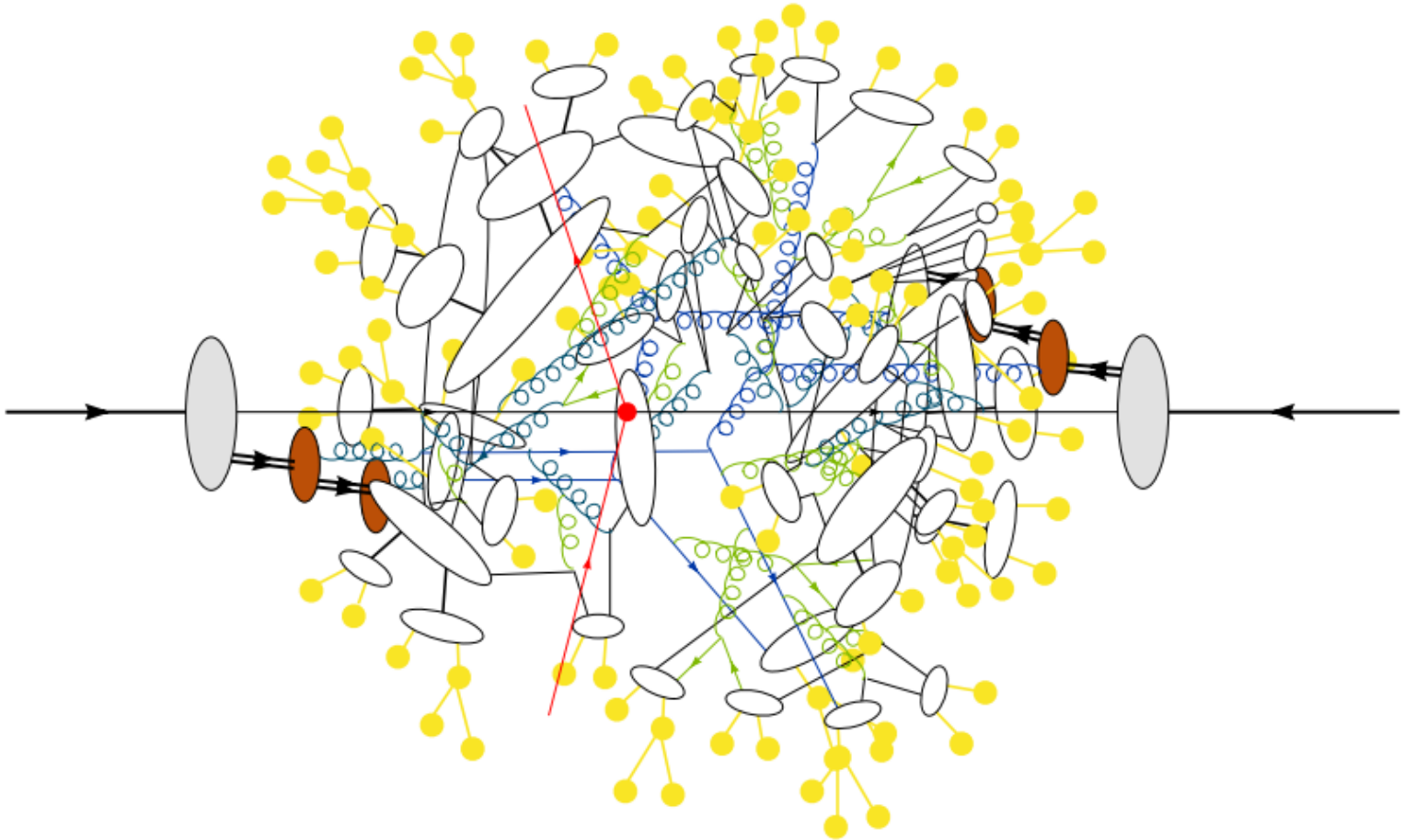
Hadronization



Final particle decays

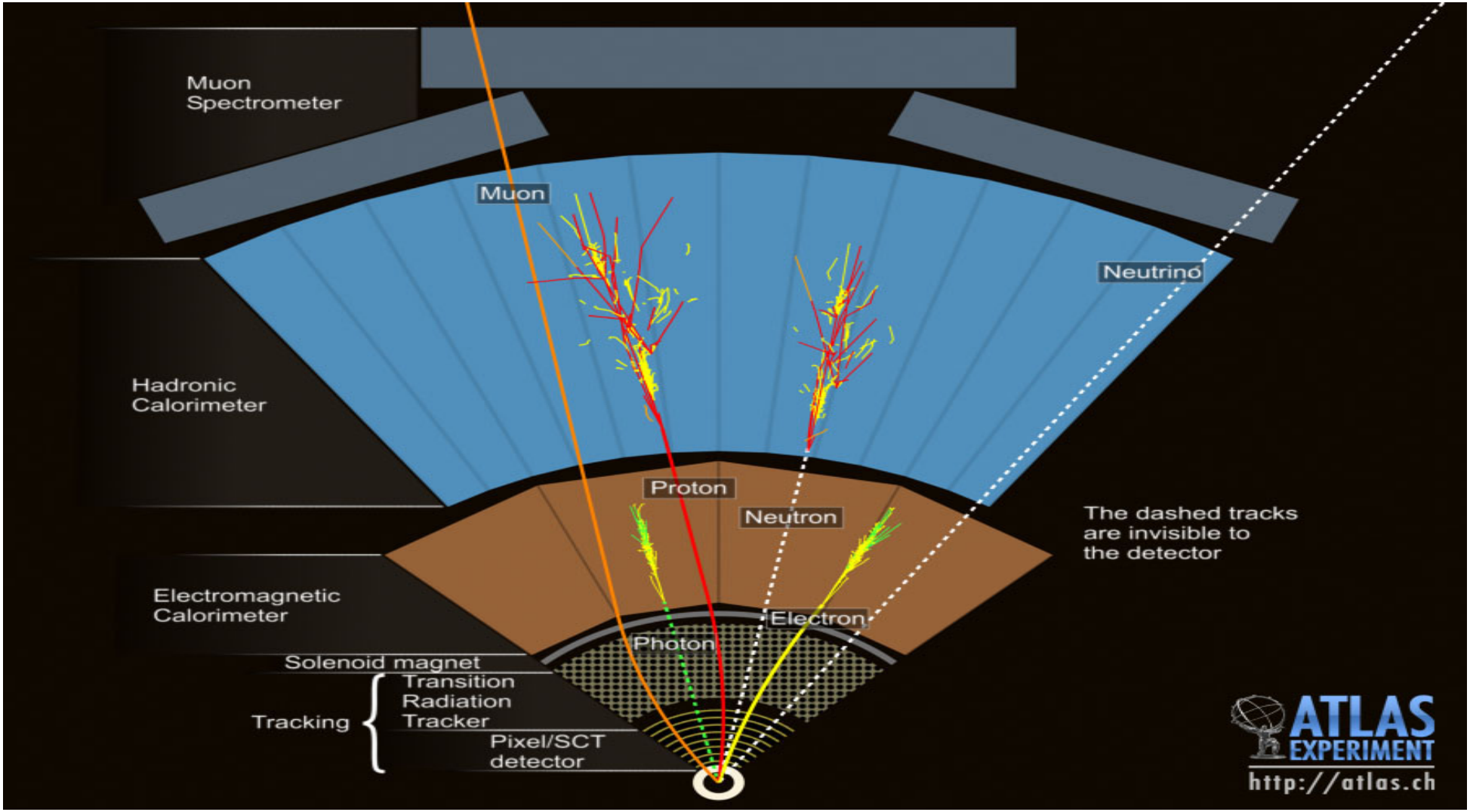


Underlying event simulation



Outline

Physics objects puzzle



One lepton

Many jets

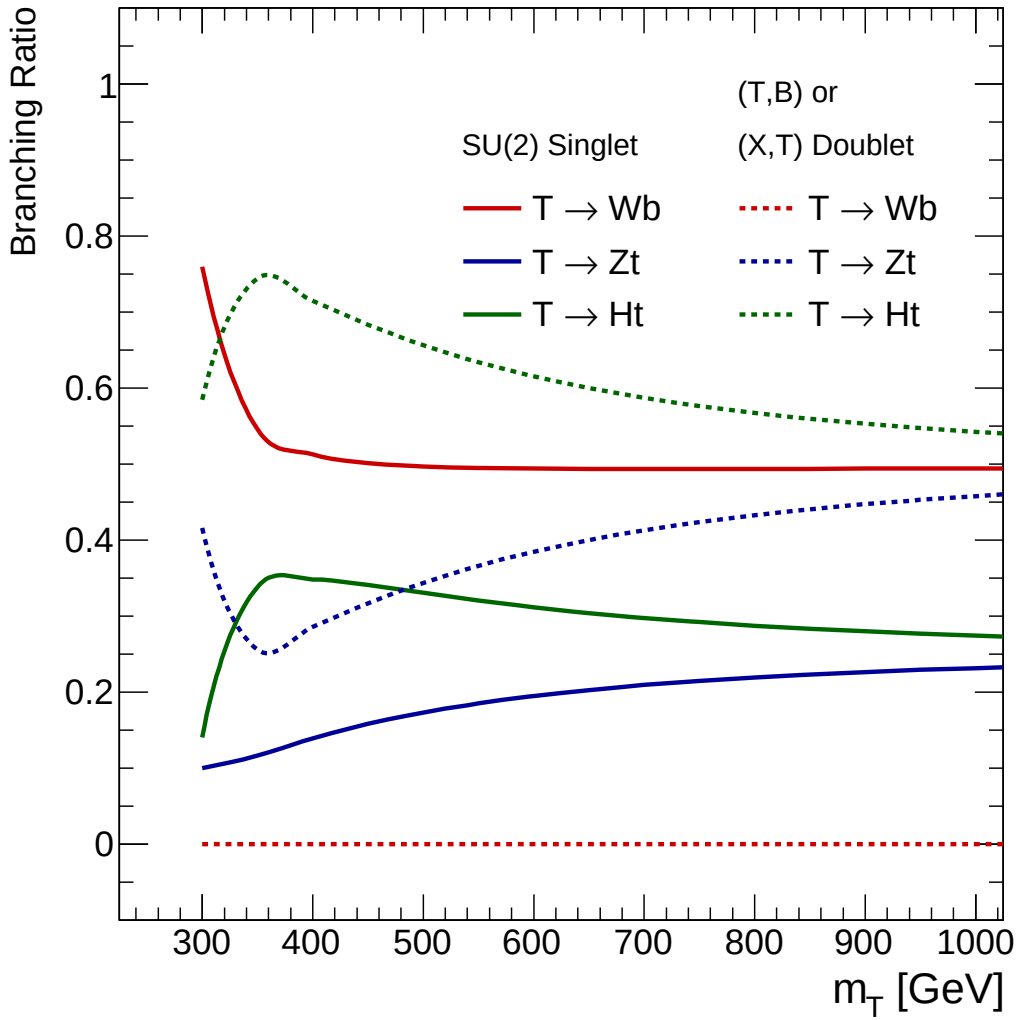
Missing transverse energy

Outline

Allowed decay modes

Singlet	Decay modes
$T(+2/3)$	W^+b, Ht, Zt
$B(-1/3)$	W^-t, Hb, Zb
$X(+5/3)$	W^+t
$Y(-4/3)$	W^-b

Doublet	Decay modes
$\begin{pmatrix} T \\ B \end{pmatrix}$	W^+b, Ht, Zt W^-t, Hb, Zb
$\begin{pmatrix} T \\ X \end{pmatrix}$	Ht, Zt W^+t
$\begin{pmatrix} B \\ Y \end{pmatrix}$	Hb, Zb W^-b

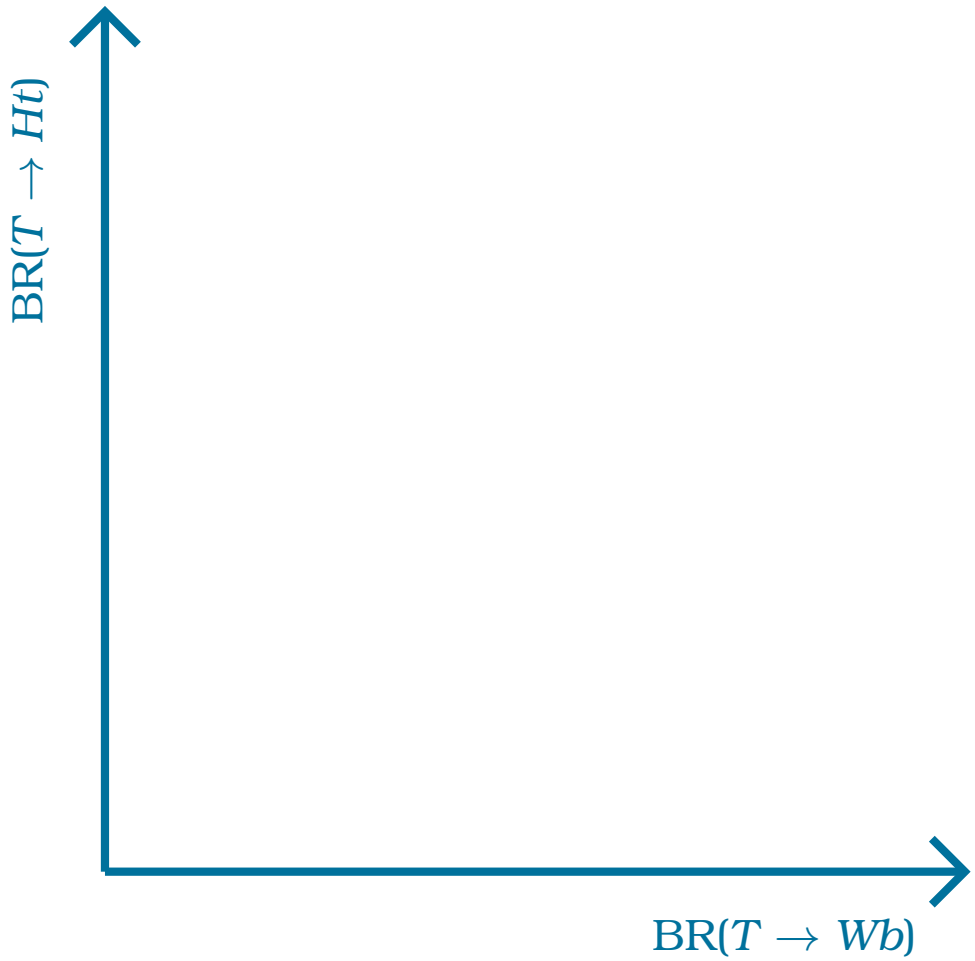


Model Independent Strategy

- Build a 2-dim plane to scan model mixing

BR($T \to Wb$)

Model Independent Strategy



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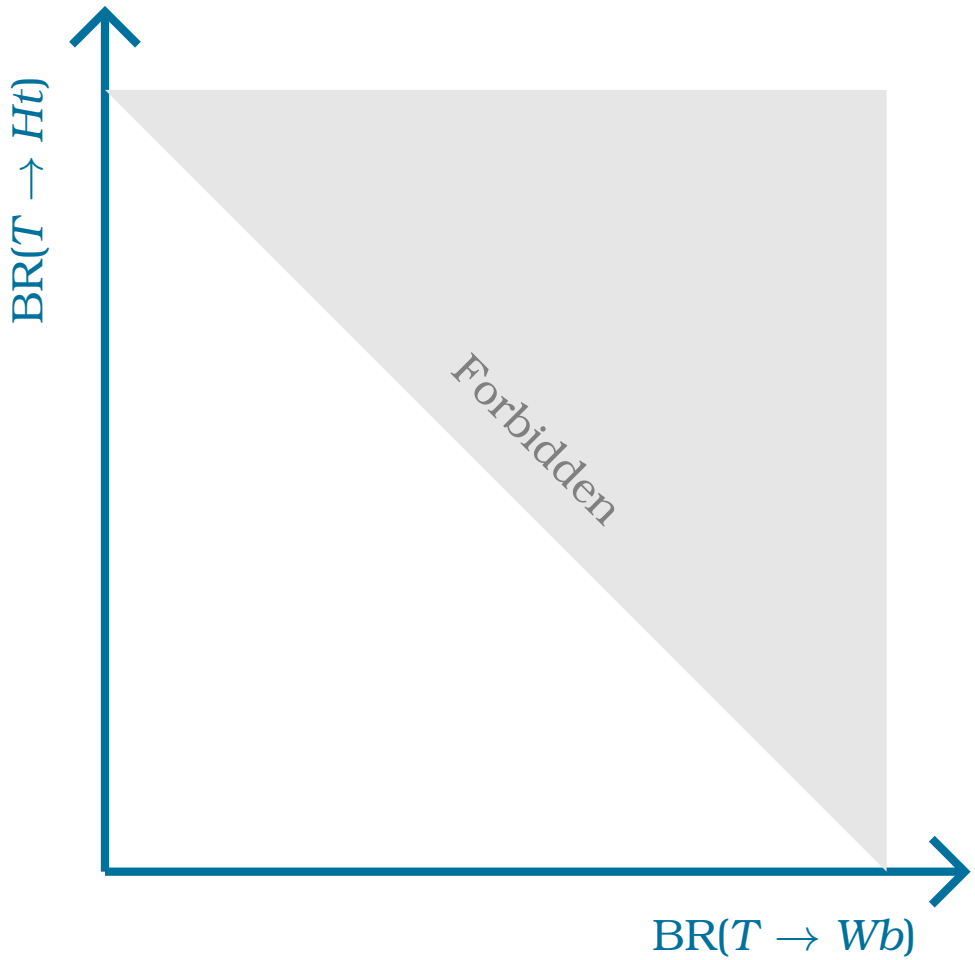
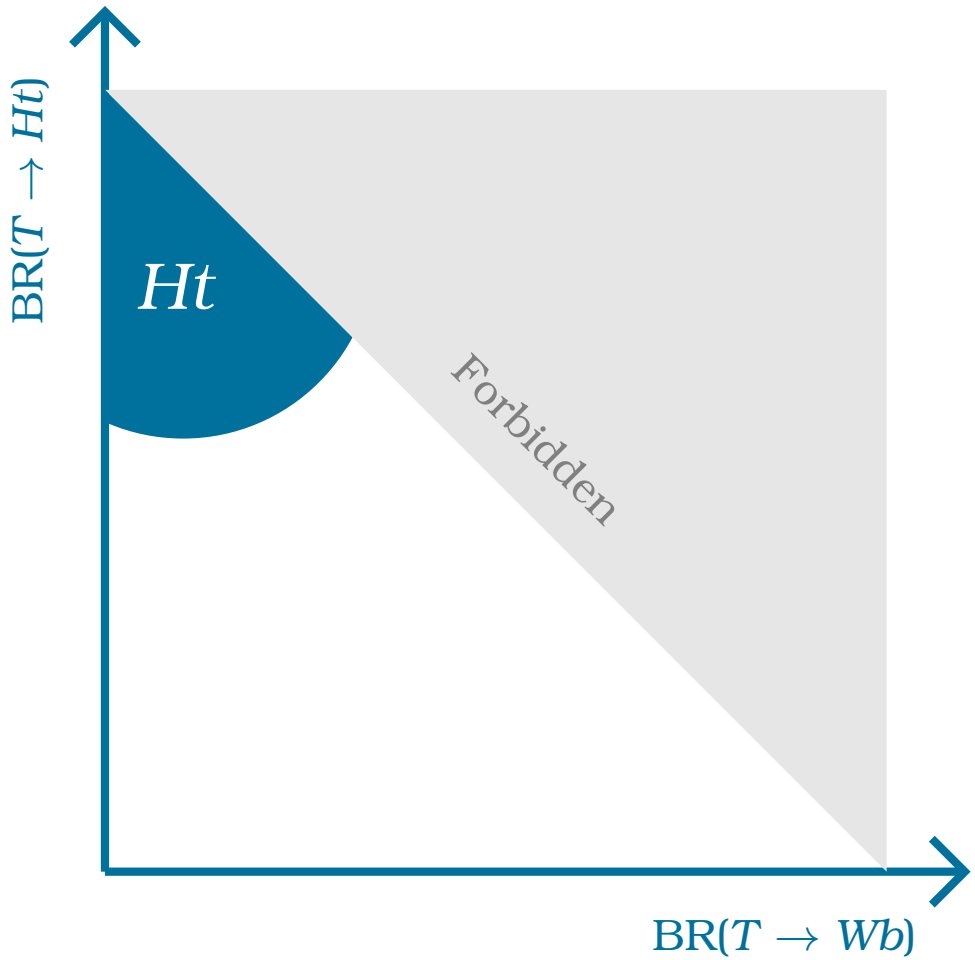
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is $1^{(a)}$

$^{(a)}$BR($T \to Zt$) = 1 - BR($T \to Ht$) - BR($T \to Wb$)

Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is $1^{(a)}$
- Different analyses are sensitive to different areas

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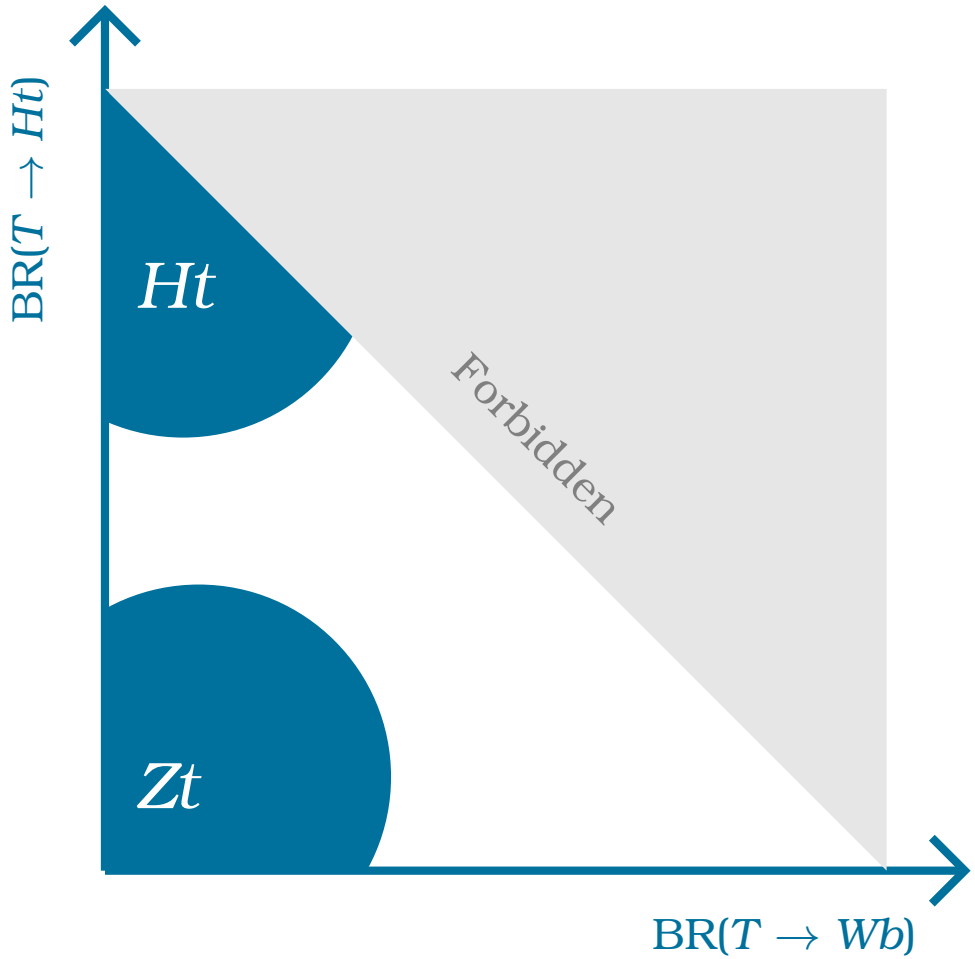
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
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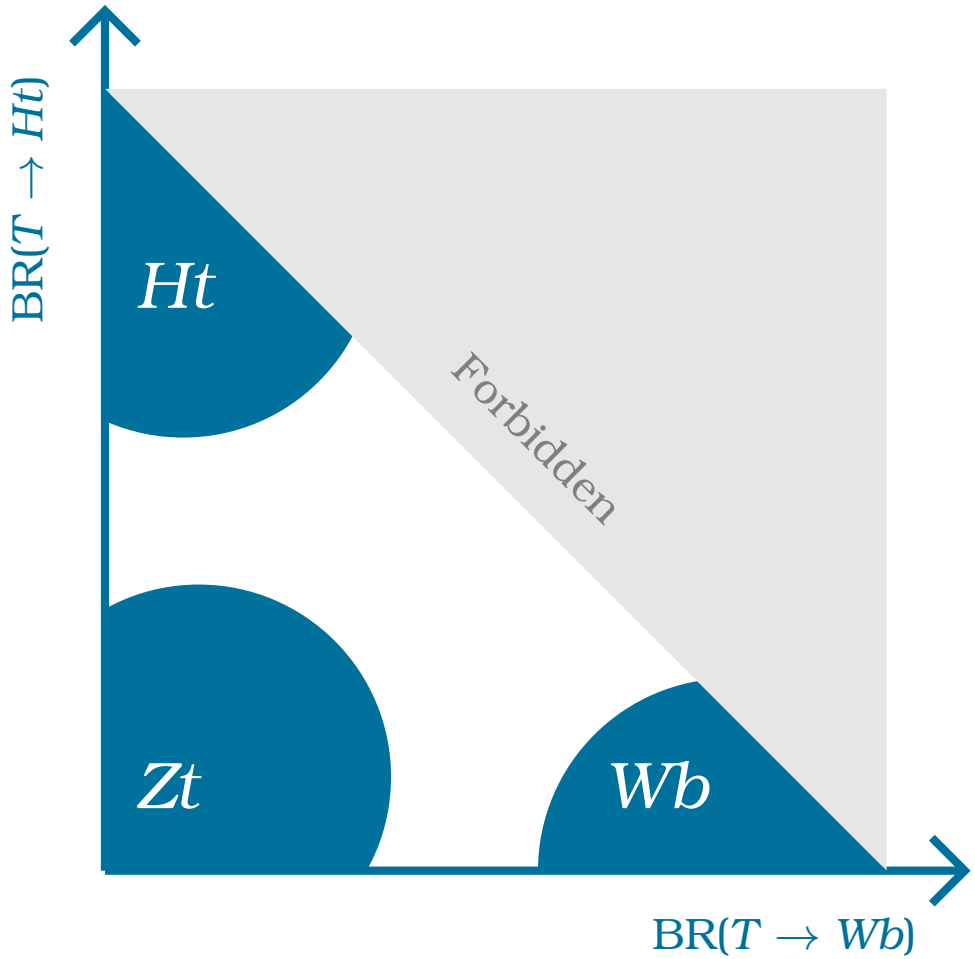
Model Independent Strategy



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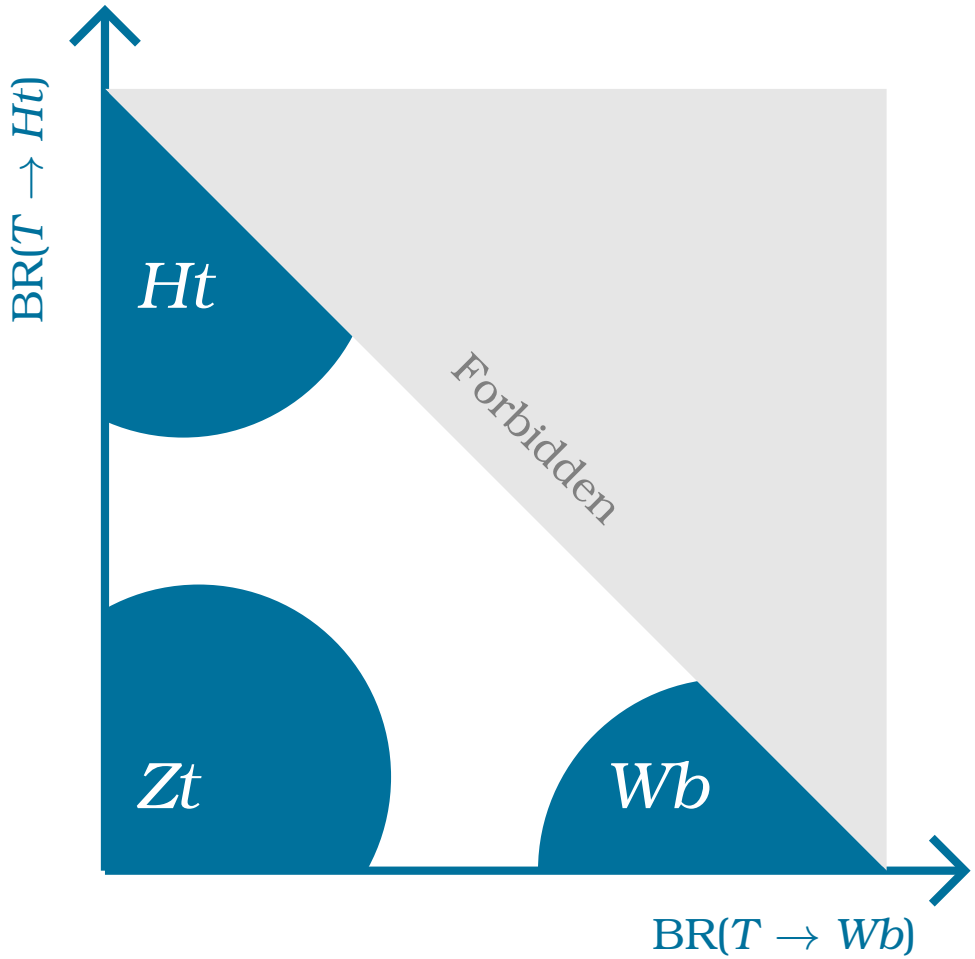
Model Independent Strategy



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- Different analyses are sensitive to different areas
- Set exclusion using CL_s technique [2, 3]

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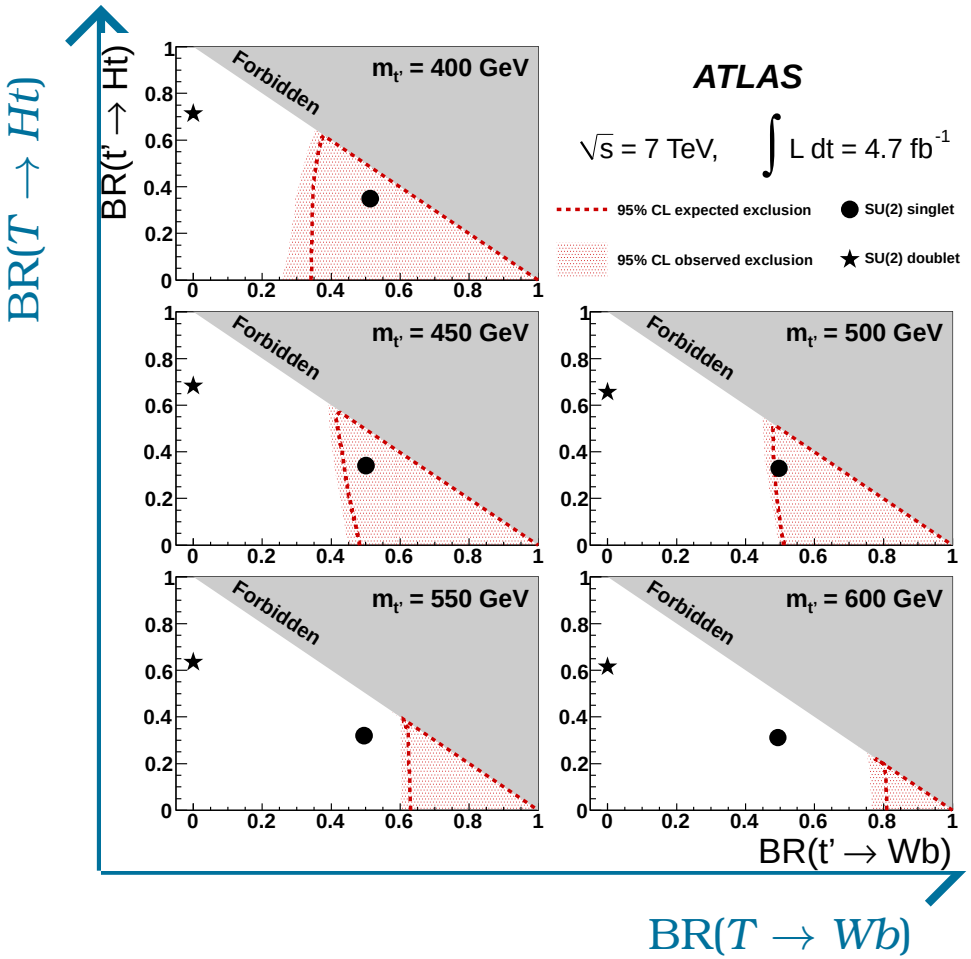
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
- Sum of BRs is 1[a]
- Different analyses are sensitive to different areas
- Set exclusion using CL_s technique [2, 3]
- First published results at 7 TeV *Phys.Lett.* **B718** (2012) [4]

[a] BR($T \to Zt$) = 1 - BR($T \to Ht$) - BR($T \to Wb$)

Preselection

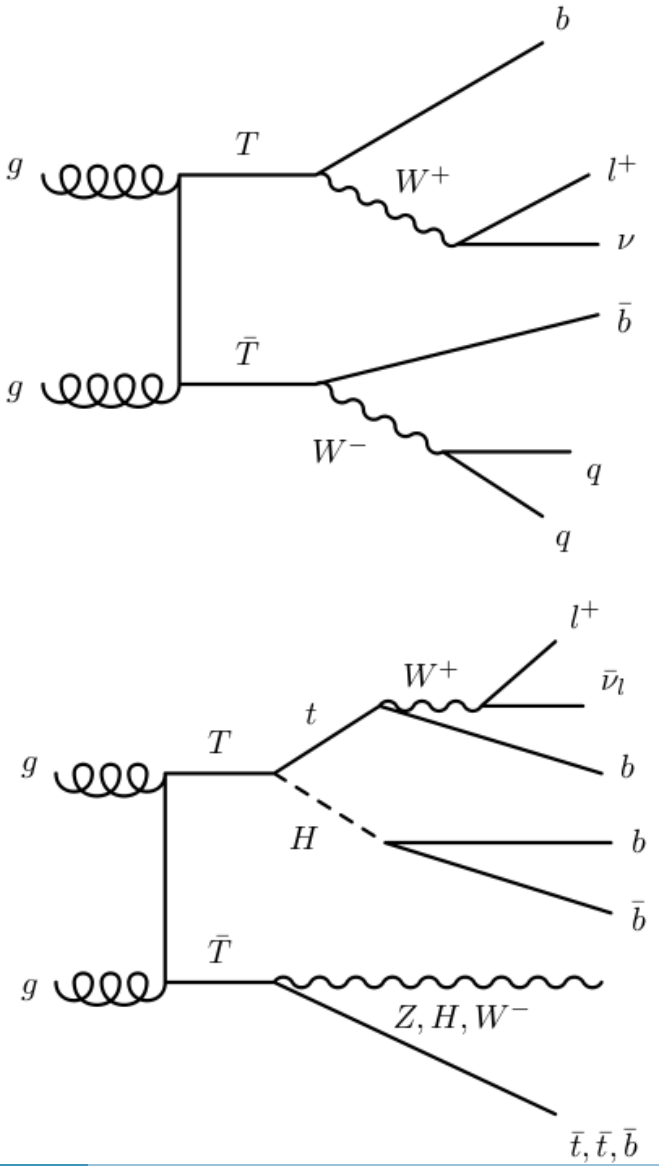
Two searches using common analysis framework:

- $T\bar{T} \to Wb + X$ — ATLAS-CONF-2013-060 [5]
- $T\bar{T} \to Ht + X$ — ATLAS-CONF-2013-018 [6]

Preselection stage	Requirements
Single lepton	One electron or muon matching trigger
QCD rejection	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV
Jet multiplicity	≥ 4 jets ≥ 1 b-tagged jets

orthogonality requirements:

- $T\bar{T} \to Wb + X$: reject events with $\geq$6 jets and $\geq$3 b-jets
- $T\bar{T} \to Ht + X$: reject events in the low b-tags channel with $H_{\mathrm{T}} < 700$ GeV



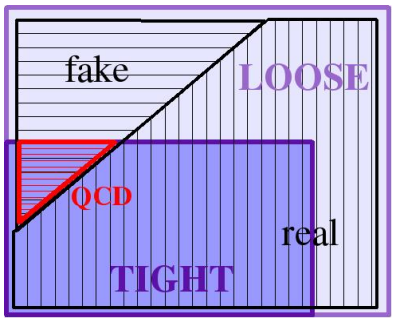
Background and signal modelling

Yields in the preselection region "blinded" as:
$H_T^{4j} < 800$ GeV (*)

	≥ 4 jets, ≥ 1 b-tags
Multi-jet	6264 ± 74
Single top	14375 ± 107
Diboson	548 ± 12
Z+jets	5804 ± 146
W+jets	35921 ± 525
$t\bar{t}$V	680 ± 2
$t\bar{t}$H (125)	220 ± 1
$t\bar{t}$ MC@NLO	202042 ± 285
Tot Bkg w/ MC@NLO	265854 ± 629
$T\bar{T}$ (600) chiral	36 ± 2
Data	256993 ± 507

(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- QCD multi-jet events have high cross-section
- Data-drive estimation
- Matrix-method



$$N_{\mathrm{fake}}^{\mathrm{tight}} = \frac{\epsilon_{\mathrm{fake}}}{\epsilon_{\mathrm{real}} - \epsilon_{\mathrm{fake}}} (N^{\mathrm{loose}} \epsilon_{\mathrm{real}} - N^{\mathrm{tight}})$$

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- s-channel and Wt production generated with MC@NLO+HERWIG
- t-channel generated with ACERMC+PYTHIA
- $m_t = 172.5$ GeV
- NNLO theoretical cross sections

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- Diboson production generated with `HERWIG`
- NLO theoretical cross section

Background and signal modelling

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- Z boson production in association with jets generated with up to five additional partons with ALPGEN+HERWIG
- Samples generated separately for Z+light jets, $Zb\bar{b}$+jets, and $Zc\bar{c}$+jets
- Inclusive NNLO theoretical cross section

Background and signal modelling

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- W boson production in association with jets generated with up to five additional partons with ALPGEN+HERWIG
- Samples generated separately for W+light jets, $Wb\bar{b}$+jets, $Wc\bar{c}$+jets, and Wc+jets
- Normalized to data-driven prediction

Background and signal modelling

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- $t\bar{t}$ produced in association with a W or Z boson generated with MADGRAPH+PYTHIA
- $m_t = 172.5$ GeV
- NLO theoretical cross section

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(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- $t\bar{t}$ produced in association with a Higgs boson generated with PYTHIA
- $m_t = 172.5$ GeV, $m_H = 125$ GeV
- Higgs decay modes considered: $H \to b\bar{b}$, $c\bar{c}$, gg, W^+W^-
- NLO theoretical cross section

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(*) $H_T^{4j} = p_{\mathrm{T}}(l) + E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{j=1}^{4} p_{\mathrm{T}}(j)$

- $t\bar{t}$ pair production in association with jets generated with MC@NLO+HERWIG
- $m_t = 172.5$ GeV
- NNLO theoretical cross section

but

MC@NLO does not model well high-jet multiplicity regions!

- Additional samples generated with ALPGEN+HERWIG
- Separate samples are generated for $t\bar{t}$+light jets with up to three additional light partons, and for $t\bar{t}$+heavy-flavour jets including $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$
- $m_t = 172.5$ GeV
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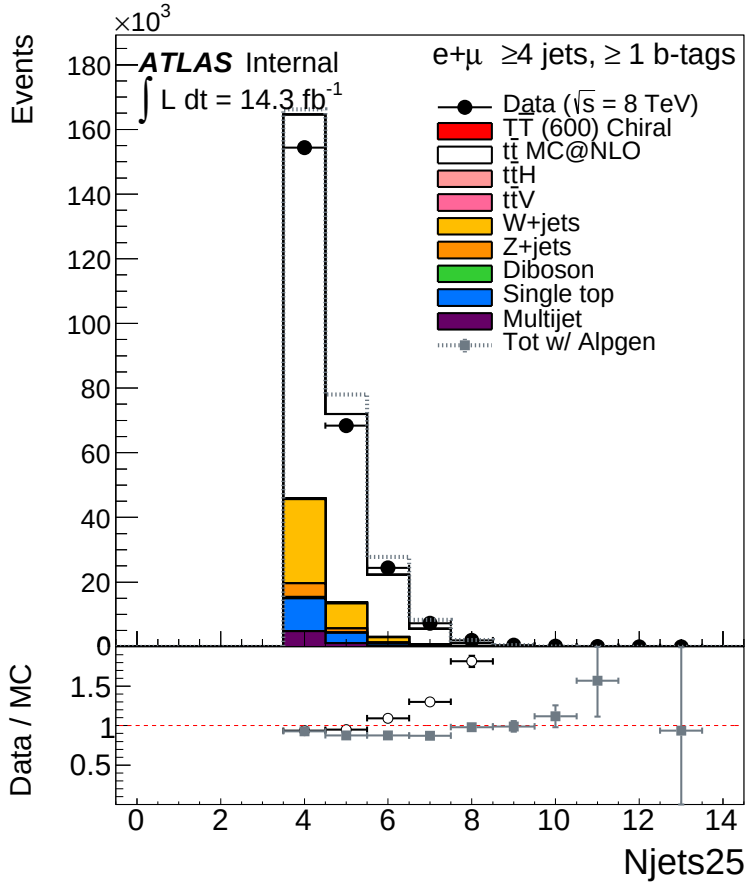
Yields for $t\bar{t}$ predicted with ALPGEN are ~3-8% higher than MC@NLO



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(*) $H_T^{4j} = p_T(l) + E_T^{miss} + \sum_{j=1}^{4} p_T(j)$

- $T\bar{T}$ singlet production generated with PROTOS+PYTHIA
- Branching ratio to each decay mode (Wb, Zt and Ht) is set to 1/3
- Events are reweighted at the analysis level in order to reproduce any desired branching ratio configuration
- m_T values generated from 350 GeV to 850 GeV in steps of 50 GeV
- $m_H = 125$ GeV, all Higgs boson decay modes are considered
- NNLO theoretical cross section

m_T (GeV)	$BR(T \to Wb)$	$BR(T \to Zt)$	$BR(T \to Ht)$
		Singlet	
600	0.494	0.194	0.312
		Doublet	
600	0.000	0.383	0.617

Systematic uncertainties - Shape and Norm

Systematic uncertainty	$T\bar{T} \to Wb + X$		$T\bar{T} \to Ht + X$	
	Status	Components	Status	Components
Luminosity	N	1	N	1
Lepton ID+reco+trigger	N	1	N	1
Jet vertex fraction efficiency	SN	1	SN	1
Jet energy scale	SN	1	SN	8
Jet energy resolution	SN	1	SN	1
b-tagging efficiency	SN	9	SN	9
c-tagging efficiency	SN	5	SN	5
Light jet-tagging efficiency	SN	1	SN	1
$t\bar{t}$ cross section	N	1	N	1
$t\bar{t}V$ cross section	N	1	N	1
$t\bar{t}H$ cross section	-	-	N	1
Single top cross section	N	1	N	1
Dibosons cross section	N	1	N	1
W+jets normalization	N	5	-	-
Z+jets normalization	N	1	-	-
V+jets normalization	-	-	N	1
Multijet normalization	-	-	N	1
$t\bar{t}$ modelling	SN	3	SN	3
V+jets modelling	SN	1	-	-
$t\bar{t}$+heavy-flavour fractions	-	-	N	1

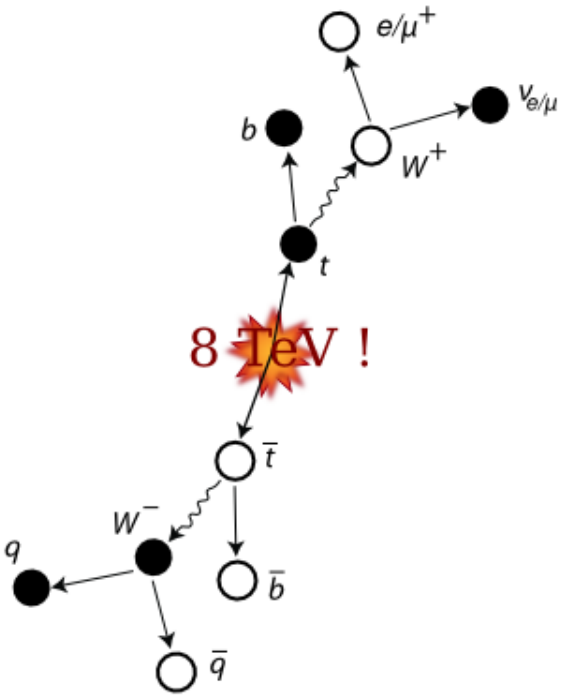
Outline

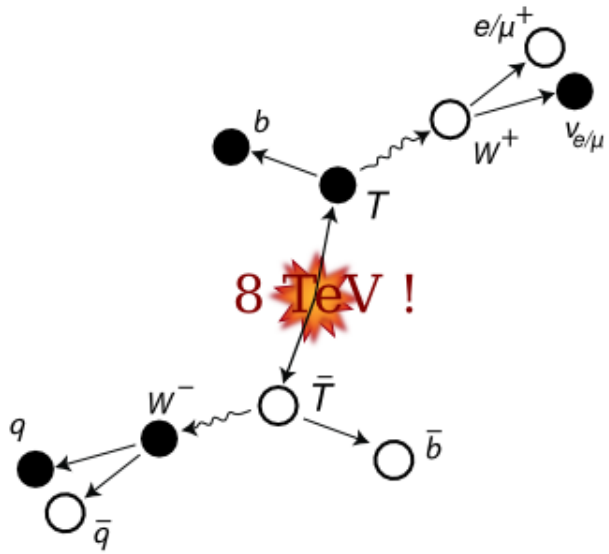
Strategy

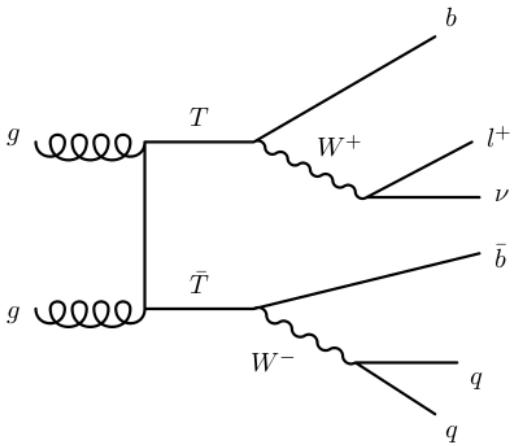
$T\bar{T} \rightarrow WbWb$

like

$t\bar{t} \rightarrow WbWb$







different boosted kinematics

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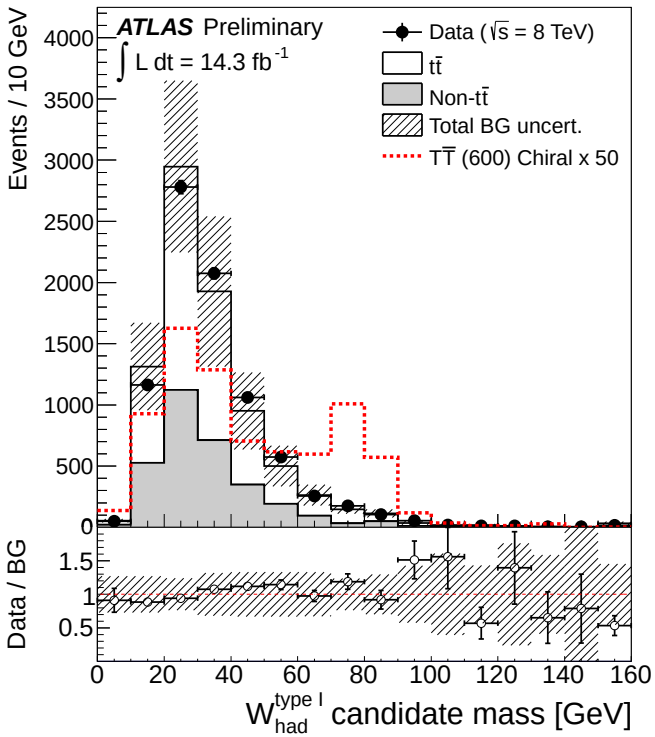
reconstruct the W boson from hadronic decay

merged jets $W_{\text{had}}^{\text{type I}}$ close-by jets $W_{\text{had}}^{\text{type II}}$

W boson reconstruction

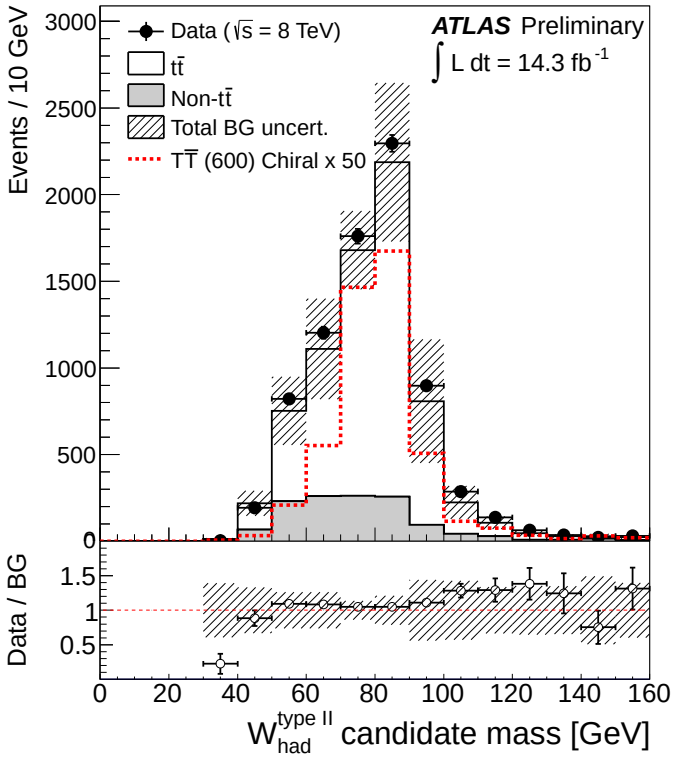
$W_{\text{had}}^{\text{type I}}$



one jet
$p_{\text{T}} > 250$ GeV
$60 < M < 120$ GeV

no $W_{\text{had}}^{\text{type I}}$
di-jet system
$\Delta R(j,j) < 0.8$
$p_{\text{T}} > 200$ GeV
$60 < M < 120$ GeV

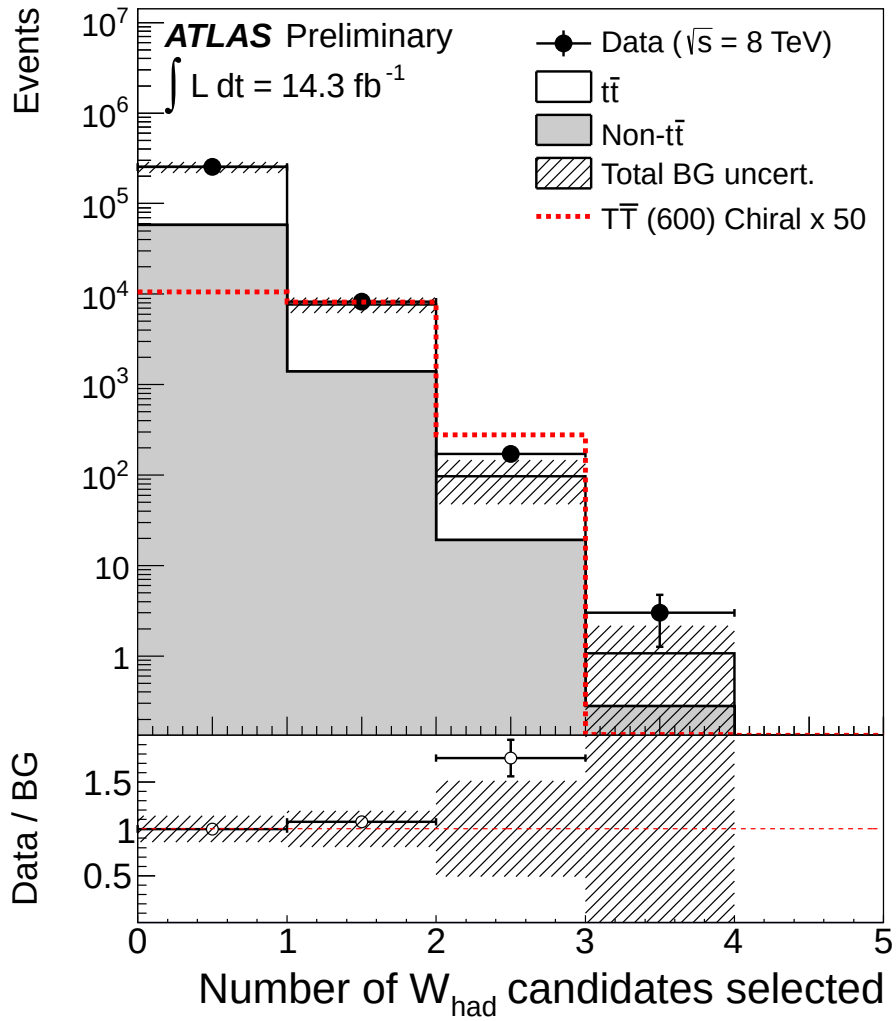
$W_{\text{had}}^{\text{type II}}$



W_{lep} reconstructed using lepton and "neutrino":
p_X, p_Y from $E_{\text{T}}^{\text{miss}}$, p_Z from $M_W^2 = (P_l + P_\nu)^2$

Event selection

	LOOSE selection	
SR0	Preselection	
SR1	+	≥ 1 W_{had} candidates
SR2	+	$H_T^{4j} > 800$ GeV
SR3	+	$p_{\text{T}}(b_1) > 160$ GeV
SR4	+	$p_{\text{T}}(b_2) > 80$ GeV
SR5	+	$\Delta R(\ell, \nu) < 1.2$
	TIGHT selection	
SR5	LOOSE selection	
SR6	+	$\min\Delta R(\ell, b) > 1.4$
SR7	+	$\min\Delta R(W_{\text{had}}, b) > 1.4$



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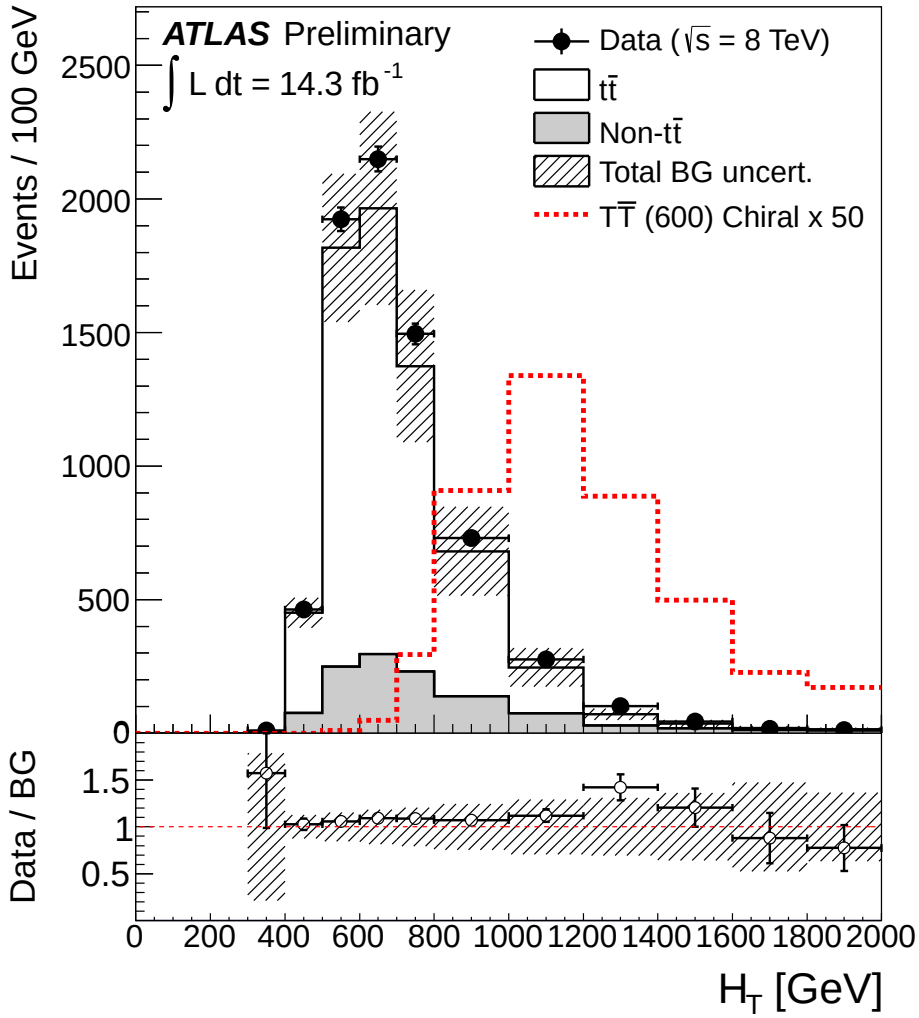

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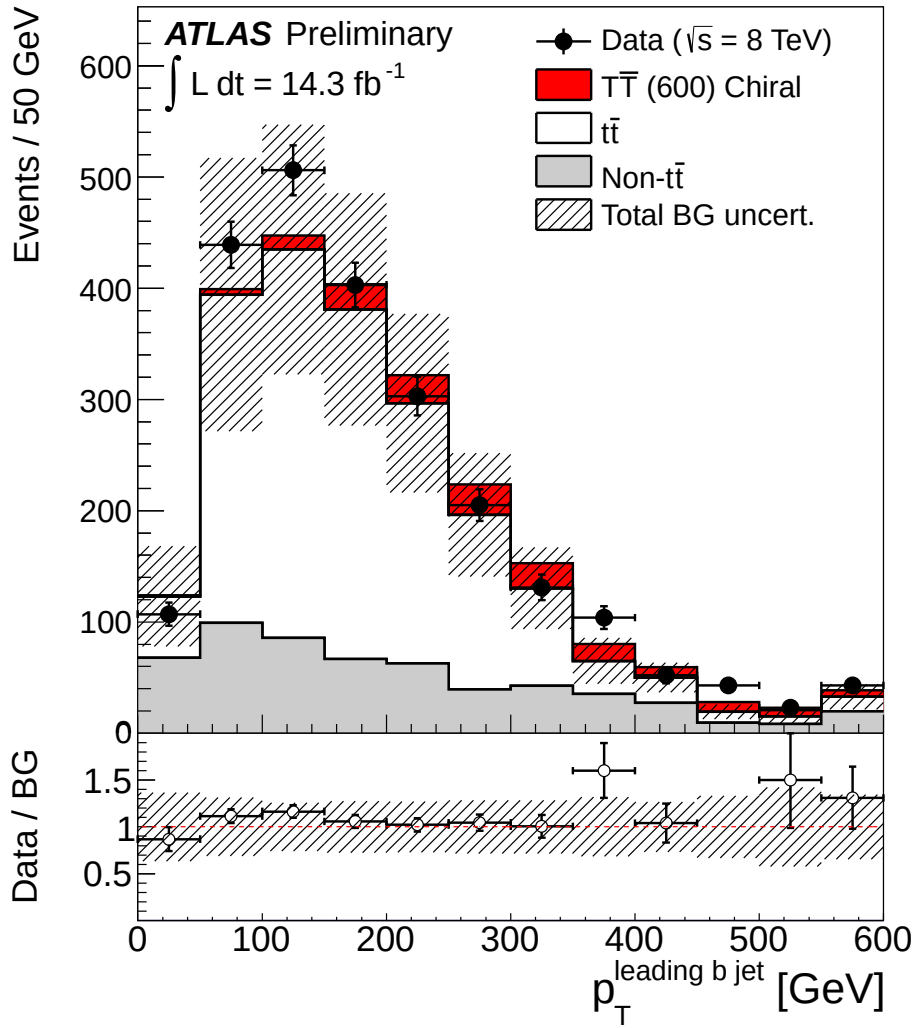

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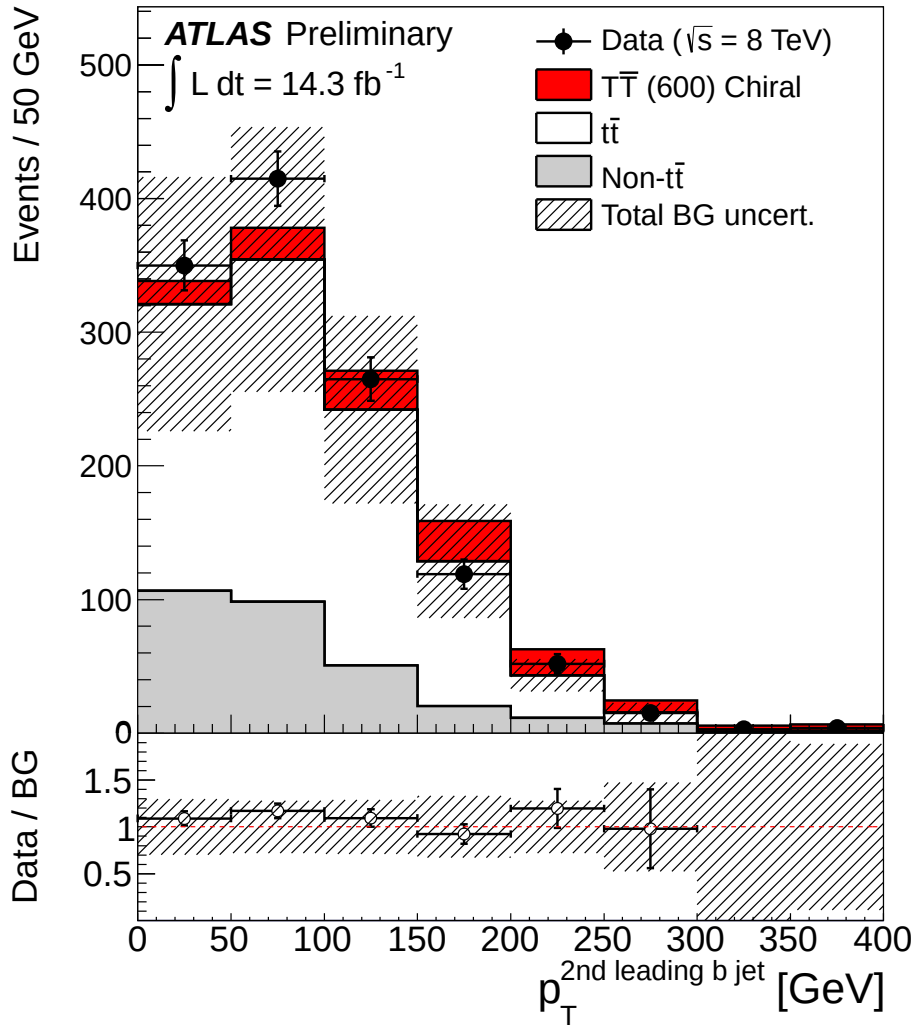

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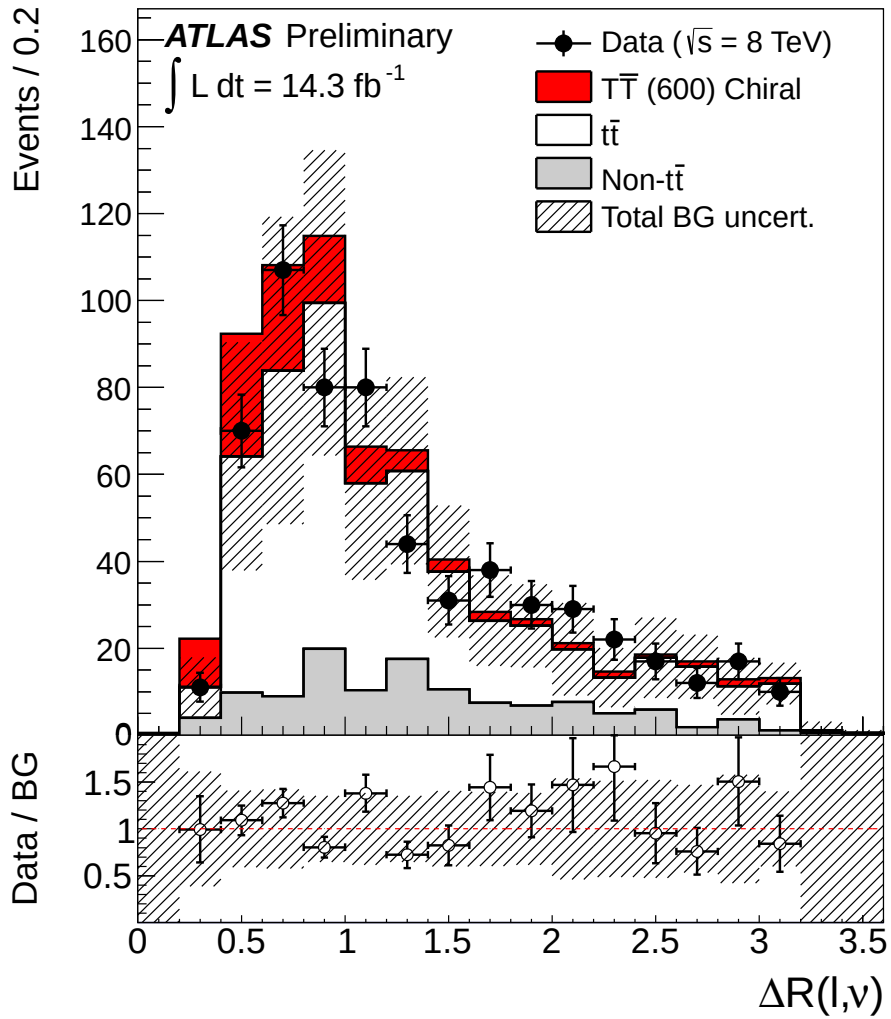

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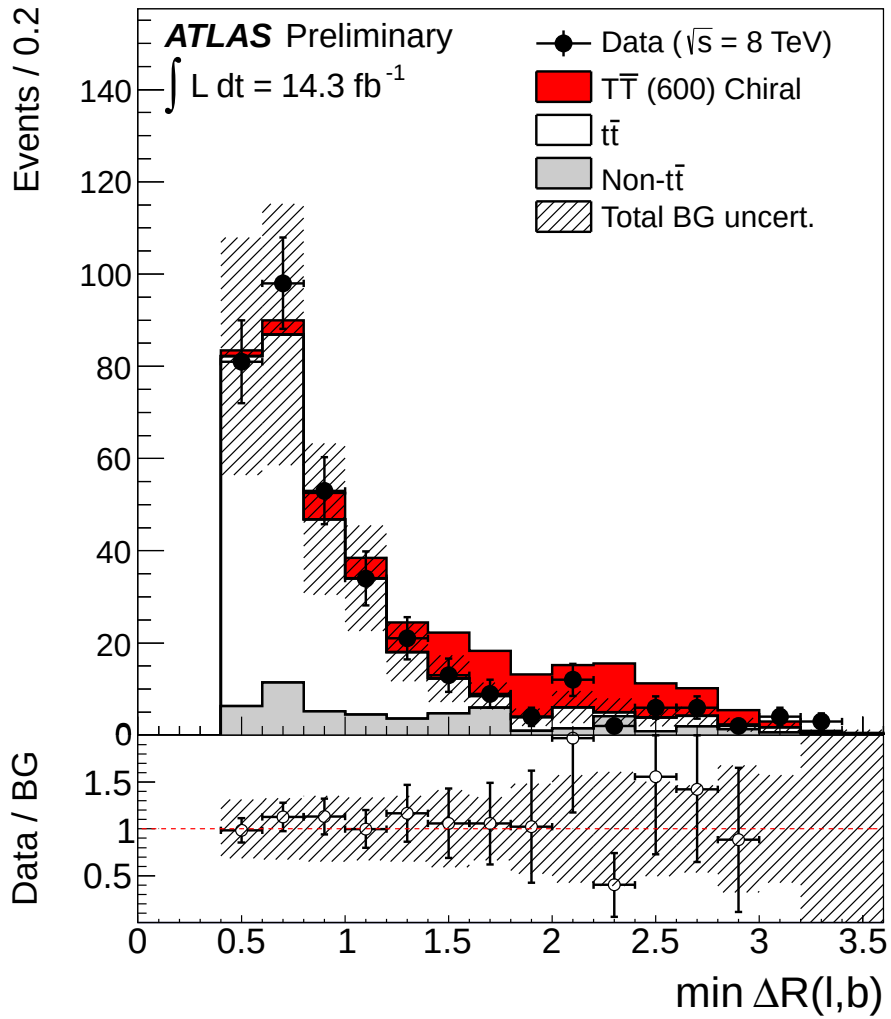

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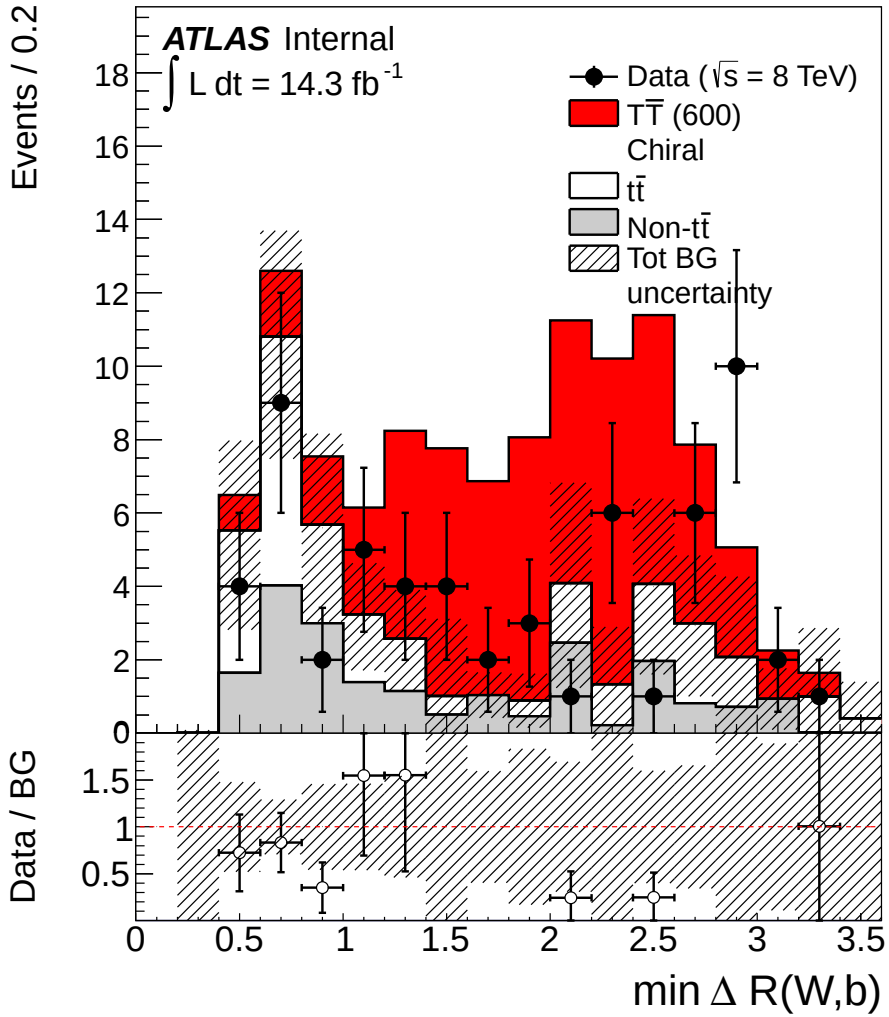

Comparison data vs prediction

Check agreement between data and background prediction

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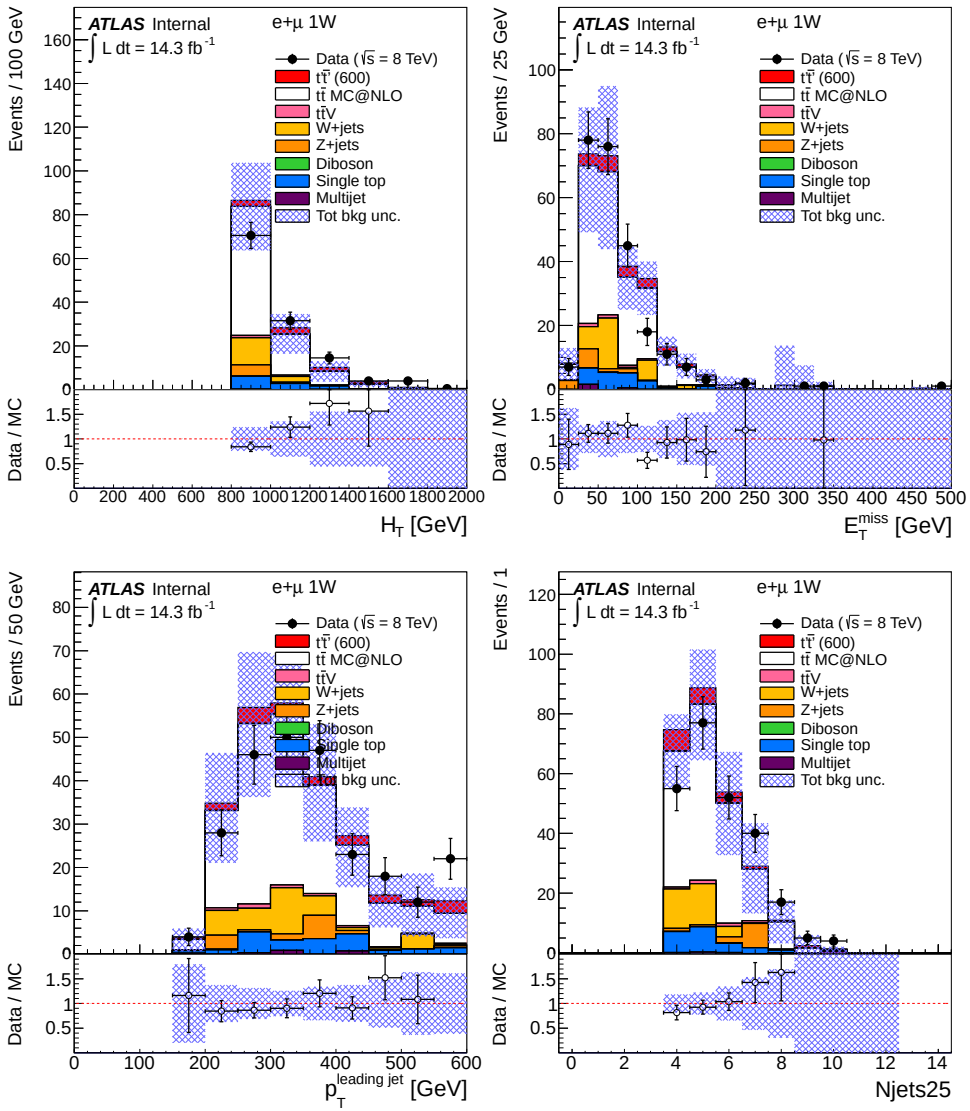
Define regions depleted in signal

	LOOSE but $\Delta R(\ell, \nu) > 1.2$
$t\bar{t}'$(600 GeV)	$18.47 \pm 1.48\ ^{+1.09}_{-1.64}$
$t\bar{t}$	$173.13 \pm 8.82\ ^{+46.92}_{-48.59}$
W+jets	$30.64 \pm 9.78\ ^{+13.74}_{-12.43}$
Z+jets	$11.68 \pm 5.93\ ^{+5.89}_{-6.96}$
Diboson	$0.29 \pm 0.19\ ^{+0.17}_{-0.17}$
Single top	$21.46 \pm 2.54\ ^{+2.60}_{-2.54}$
$t\bar{t}V$	$4.21 \pm 0.16\ ^{+1.33}_{-1.33}$
Multijet	$0.49 \pm 0.91 \pm 0.25$
Total bkg.	$241.90 \pm 14.70\ ^{+53.57}_{-55.95}$
Data	250



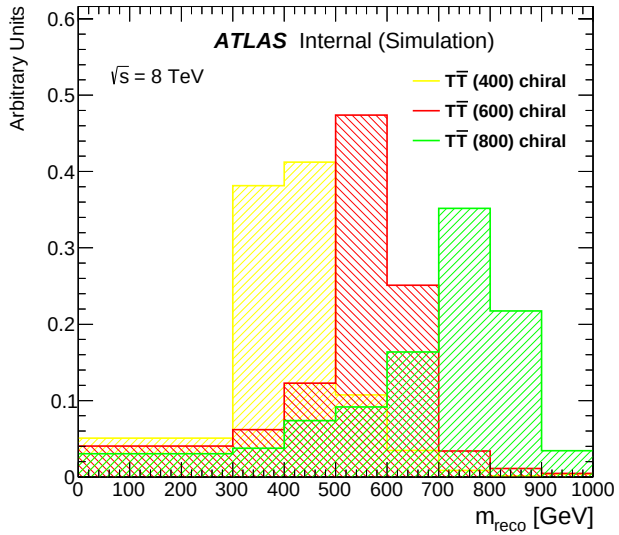
Yields in signal region

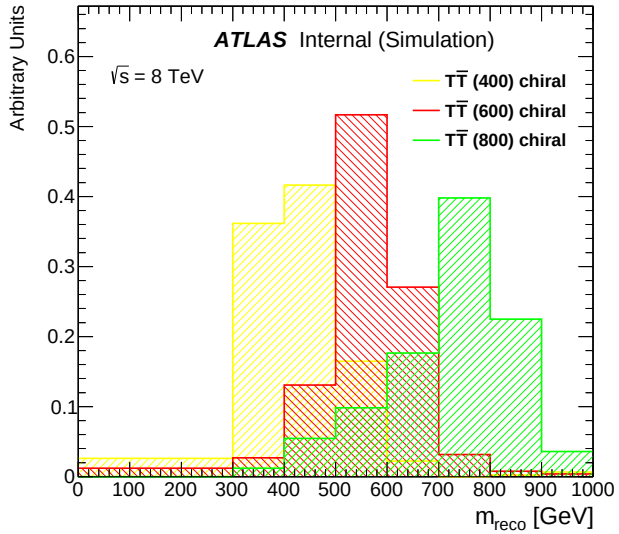
		Loose	Tight
merged	$t\bar{t}$	264 ± 80	10 ± 6
	$t\bar{t}V$	5.1 ± 1.8	0.5 ± 0.2
	W+jets	16 ± 11	6 ± 5
	Z+jets	1.1 ± 1.4	0.2 ± 0.5
	Single top	30 ± 7	4.4 ± 1.6
	Dibosons	0.21 ± 0.15	0.06 ± 0.05
	Tot.Bkg.	317 ± 90	21 ± 9
	Data	348	37
	$T\bar{T}(600$ GeV)		
	Chiral t'	88 ± 10	54 ± 7
	T Singlet	41 ± 4	20.3 ± 2.2

Discriminating variable $\Rightarrow$ T reconstructed mass

$\Downarrow$

Pair b-jets and W boson candidates in order to get $\min\Delta(M_{\text{lep}}, M_{\text{had}})$





Reconstructed mass

	LOOSE selection	
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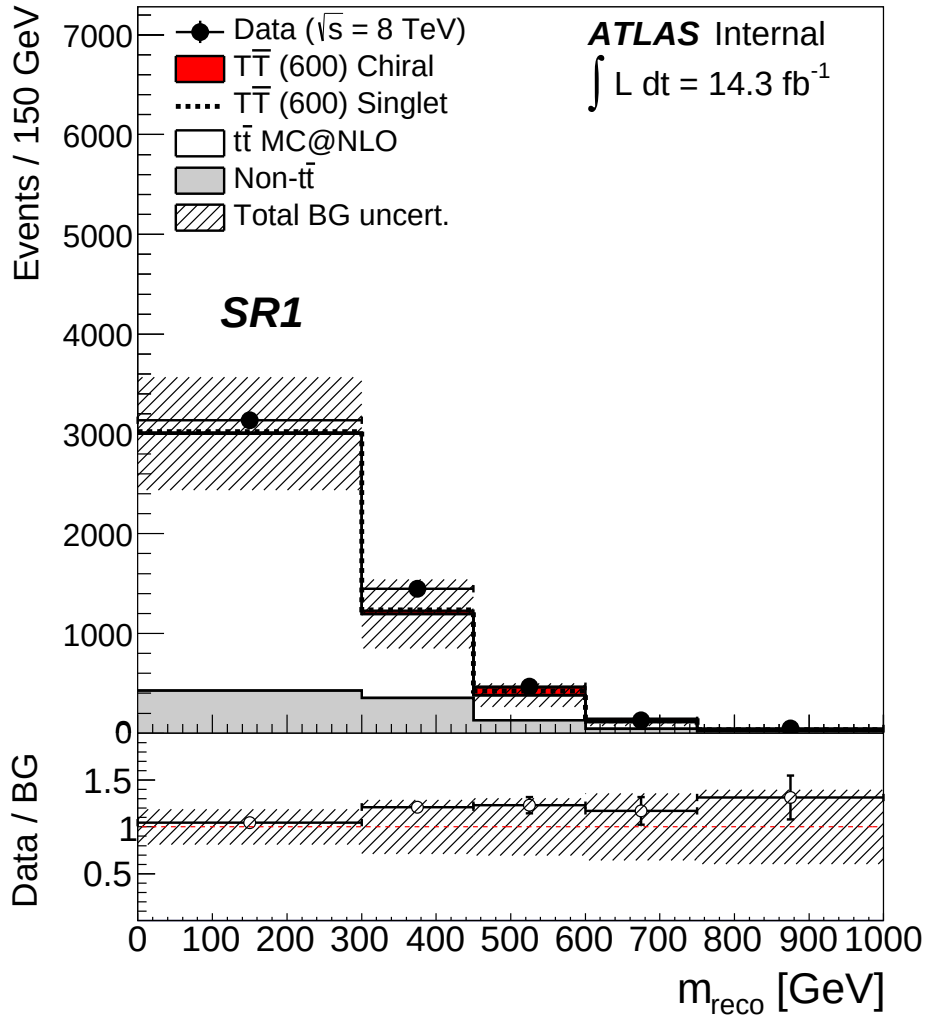

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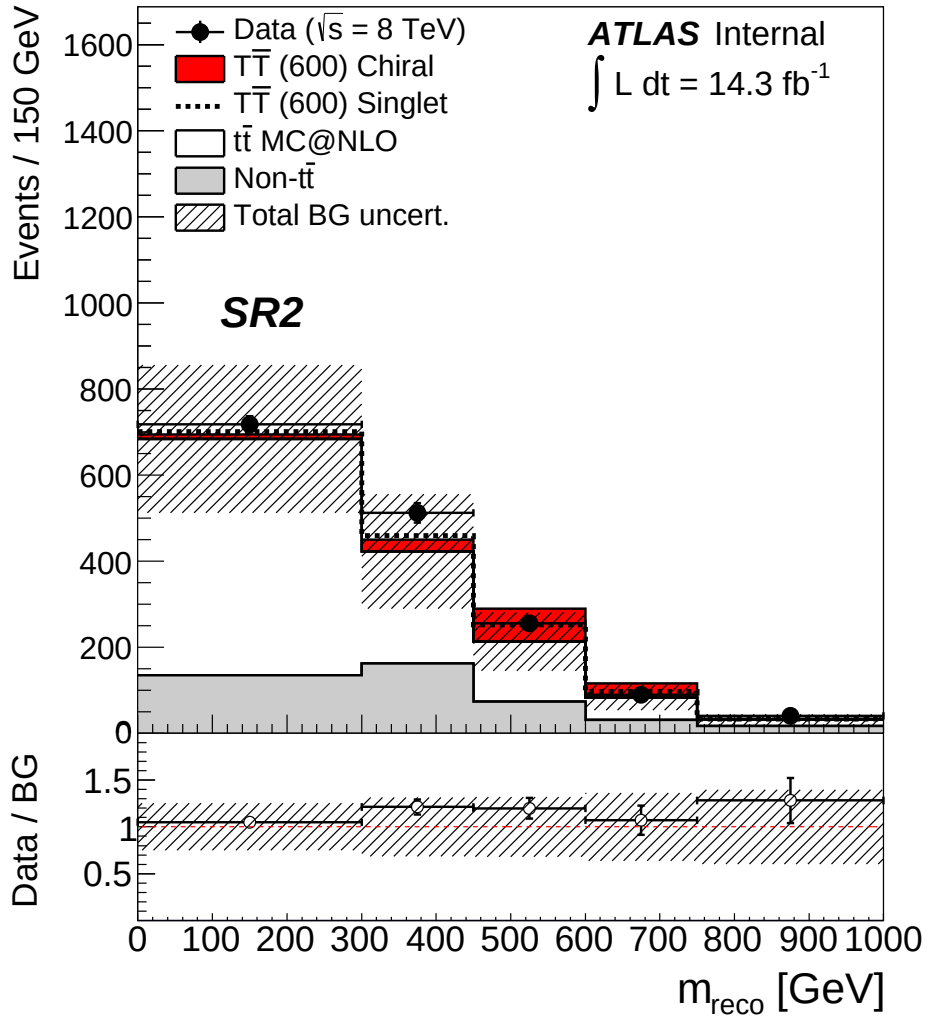

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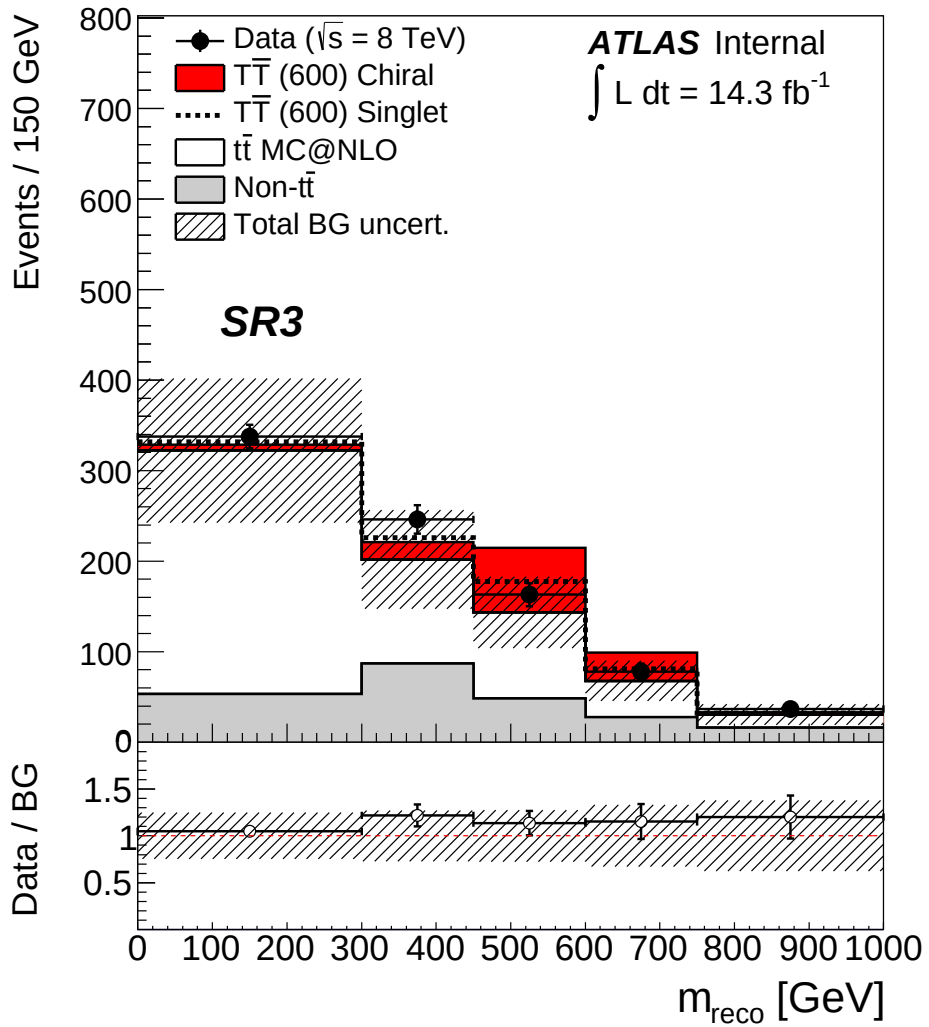

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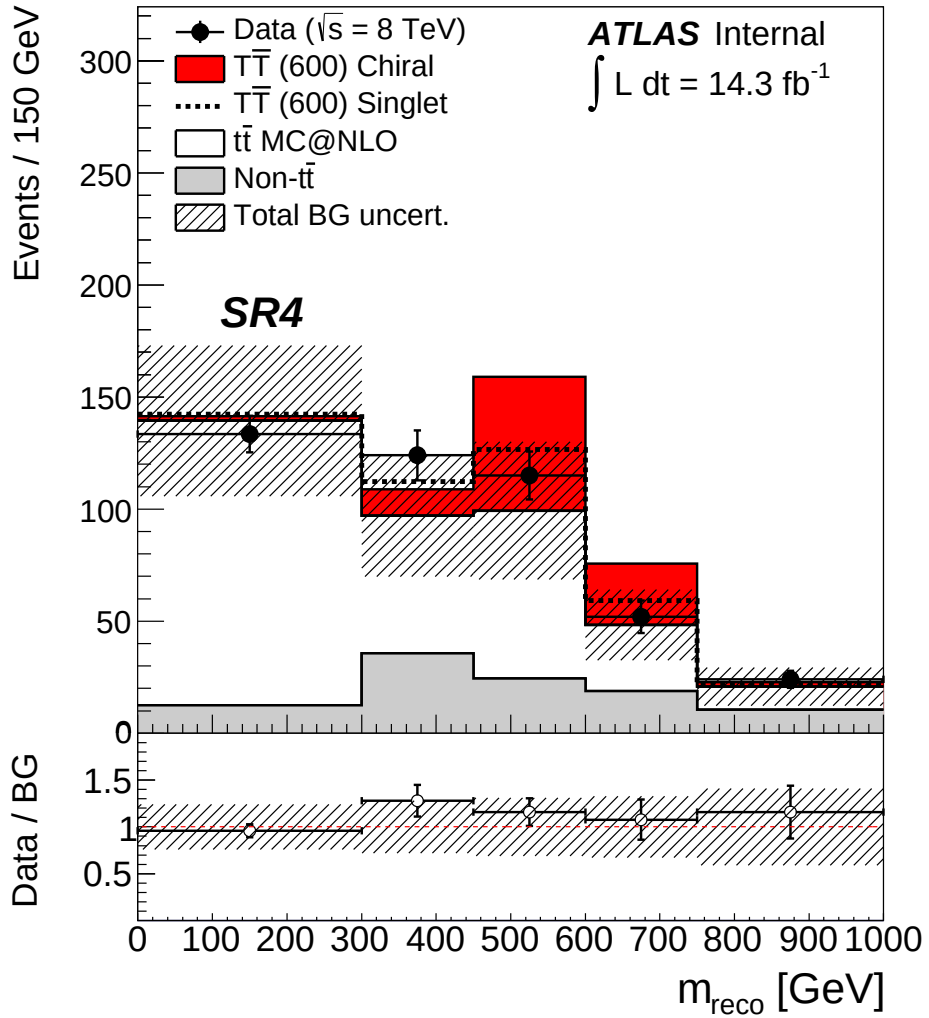

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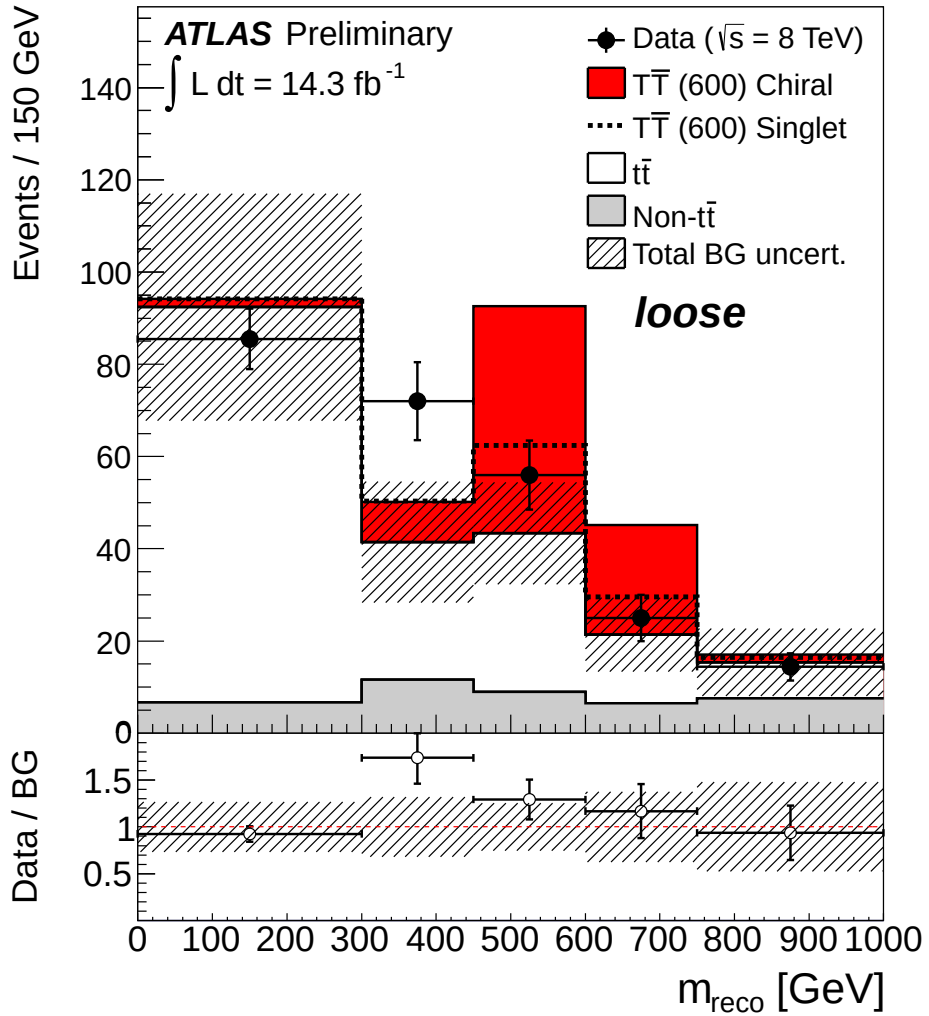

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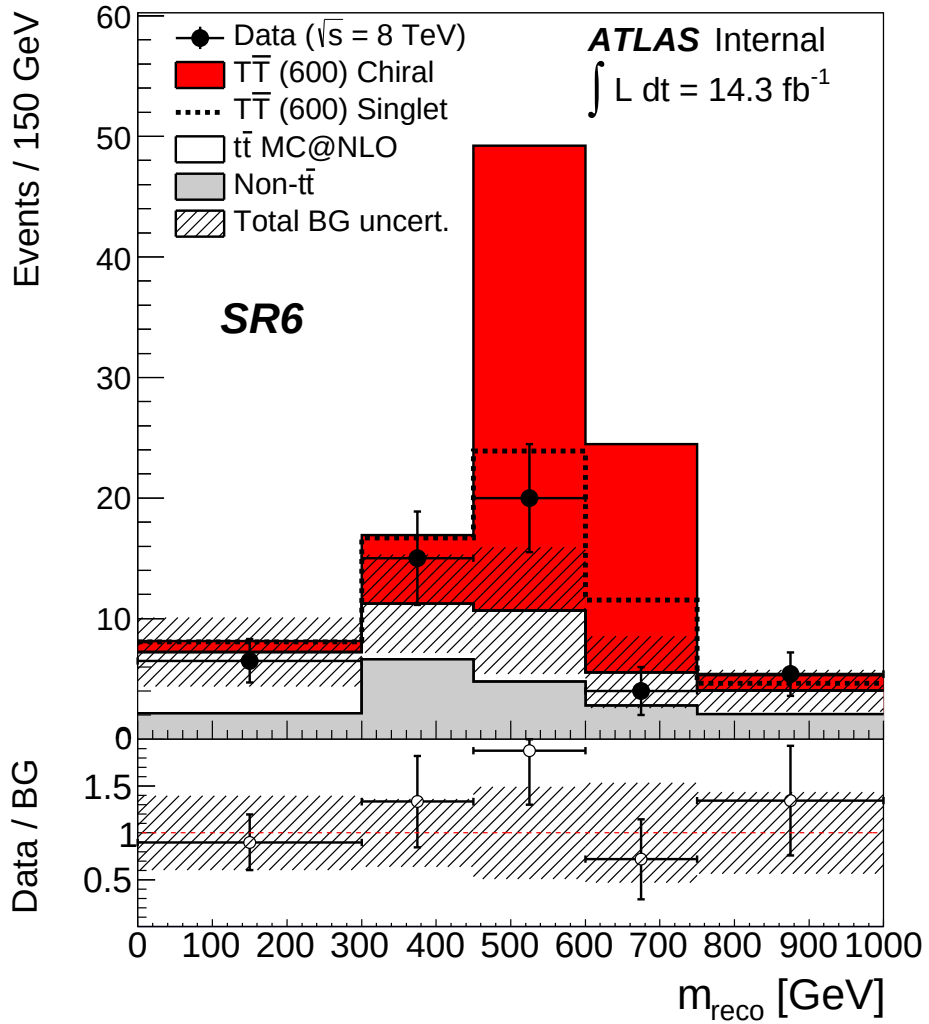

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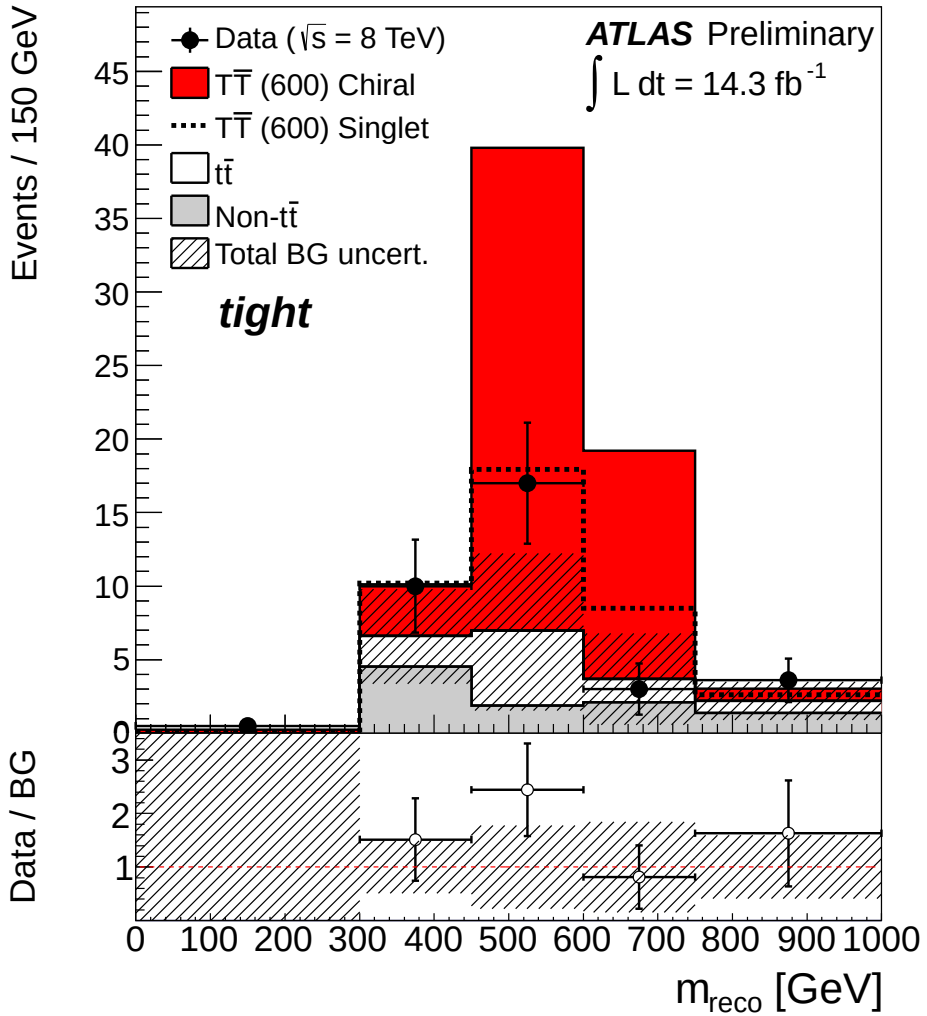
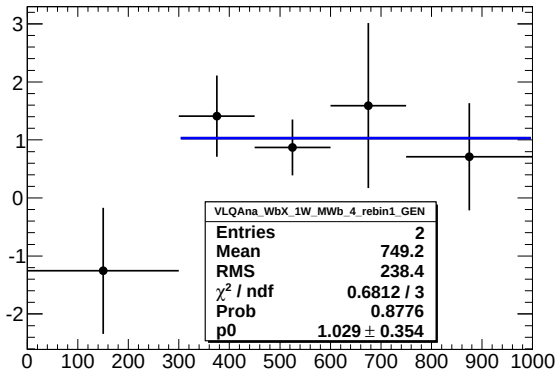
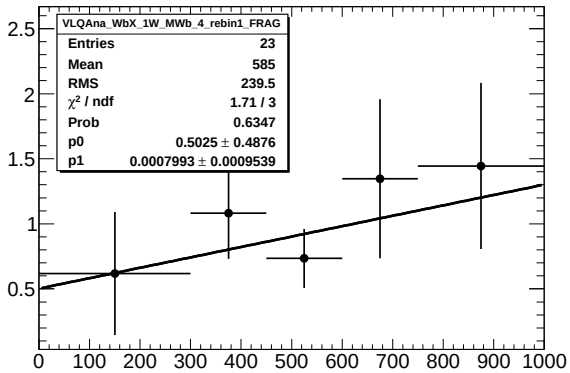
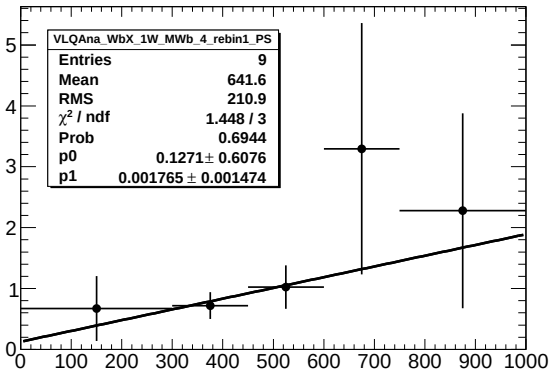


Most relevant systematic uncertainties

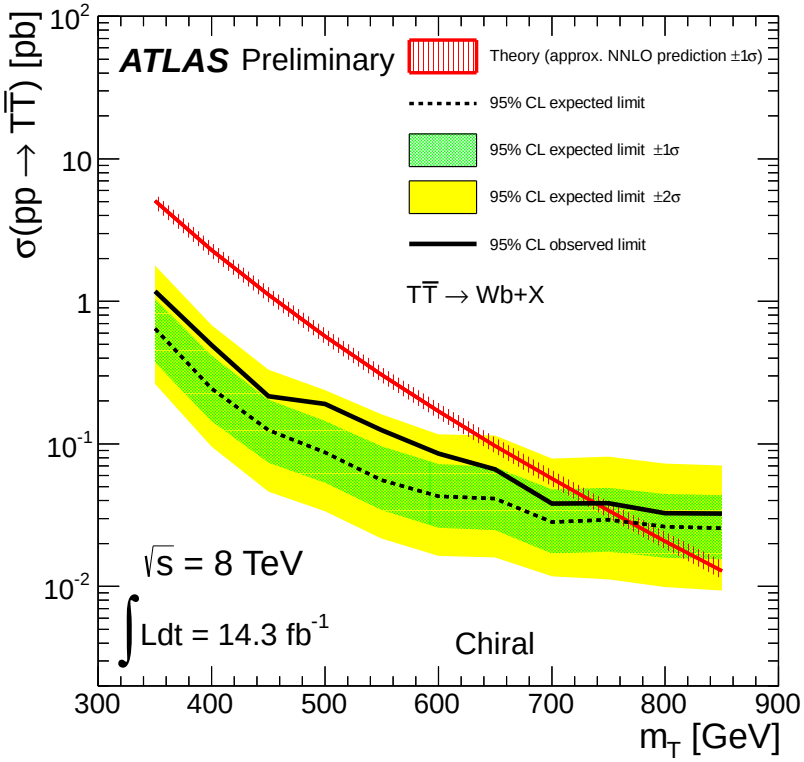
	$T\bar{T}$ (600 GeV)	$t\bar{t}$	Non-$t\bar{t}$
Total [%]	+14/-15	+59/-59	+42/-35
Main contributions [%]			
Jet energy scale	+6.6/-8.4	+15/-15	+33/-22
$t\bar{t}$ modelling: NLO MC generator	–	+48/-48	–
$t\bar{t}$ modelling: PS and fragm	–	+25/-25	–
$t\bar{t}$ modelling: ISR/FSR	–	+8.8/-8.8	–

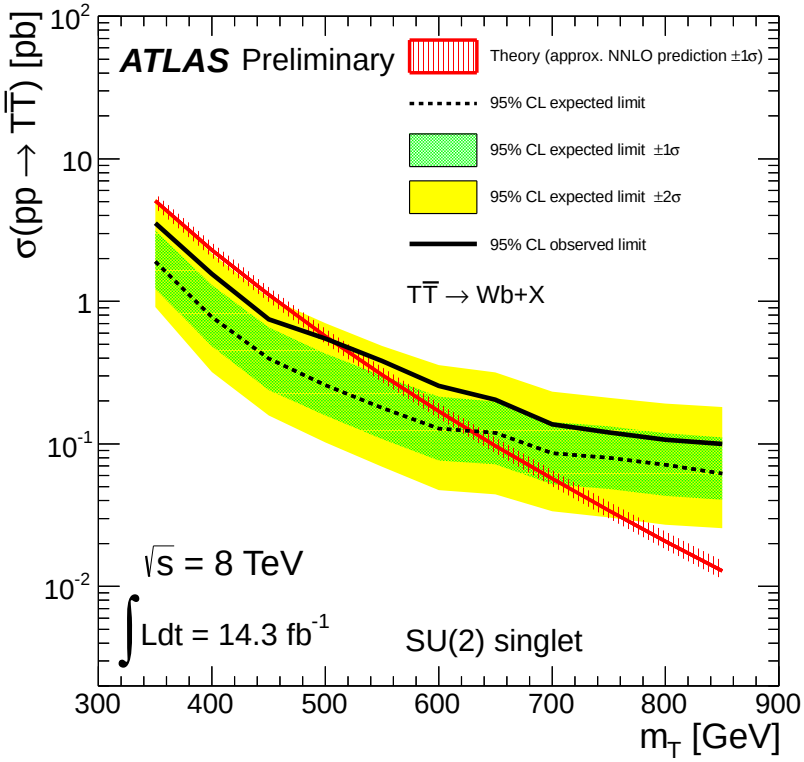






Results


ATLAS Preliminary
Theory (approx. NNLO prediction ±1σ)
95% CL expected limit
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
TT̄ → Wb+X
√s = 8 TeV
∫Ldt = 14.3 fb-1
Chiral
σ(pp → TT̄) [pb]
mT [GeV]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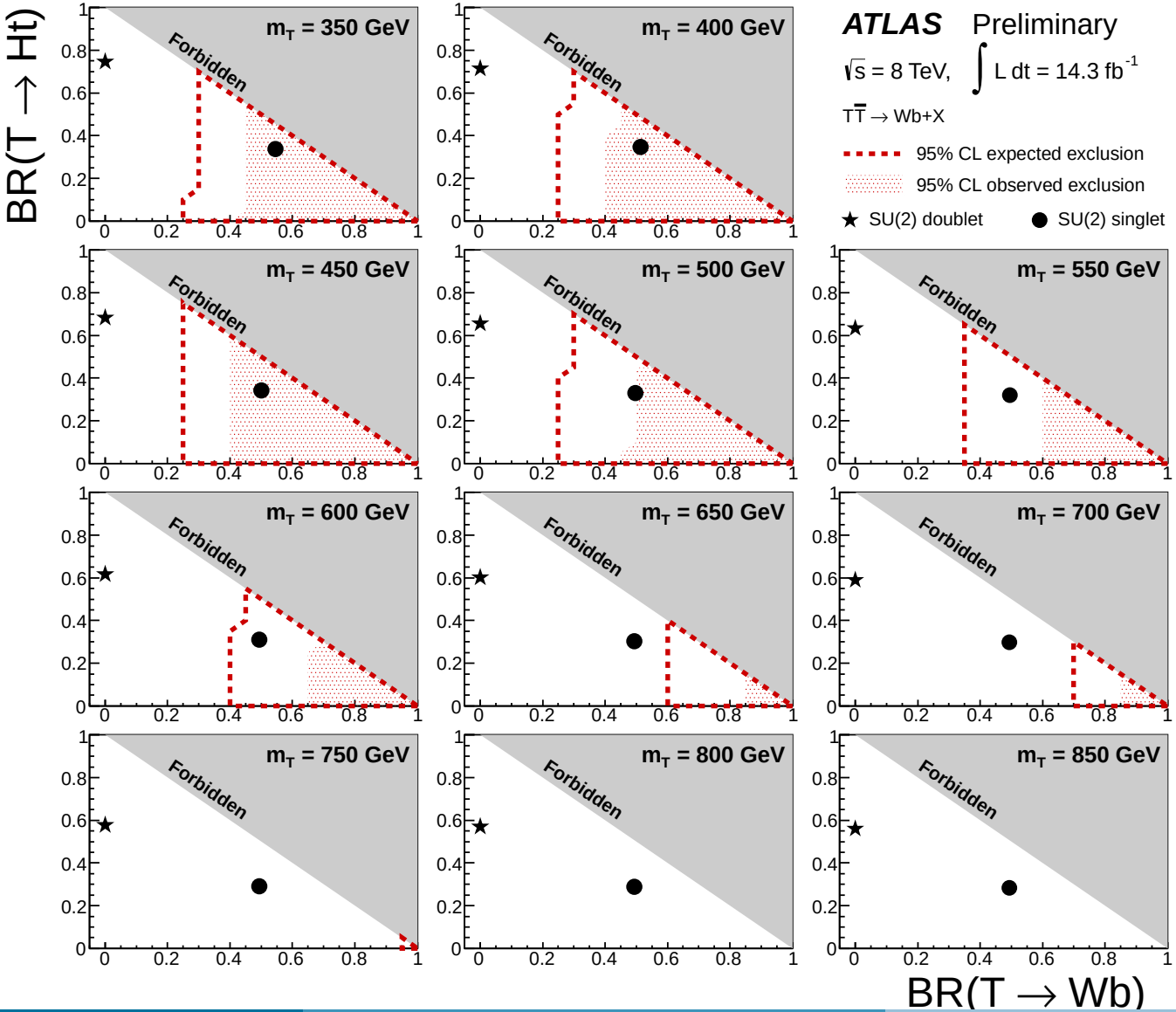
95% CL expected limit ±1σ
95% CL expected limit ±2σ
95% CL observed limit
TT̄ → Wb+X
√s = 8 TeV
∫Ldt = 14.3 fb-1
SU(2) singlet
σ(pp → TT̄) [pb]
mT [GeV]

Results


ATLAS Preliminary
√s = 8 TeV, ∫ L dt = 14.3 fb-1
TT̄ → Wb+X
95% CL expected exclusion
95% CL observed exclusion
SU(2) doublet
SU(2) singlet
mT = 350 GeV
mT = 400 GeV
mT = 450 GeV
mT = 500 GeV
mT = 550 GeV
mT = 600 GeV
mT = 650 GeV
mT = 700 GeV
mT = 750 GeV
mT = 800 GeV
mT = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)

Outline

Outline

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References I

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Presentation of search results: The CL(s) technique.
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[4] ATLAS Collaboration.
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[7] M. Lamont.

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BACKUP SLIDES

LHC parameters

Parameter	designed	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function $\beta*$ (m)	0.55	2.0/3.5	1.5/1.0	0.6
Max. No. bunches/beam	2808	368	1380	1380
Max. No. protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Bunch spacing (ns)	25	150	75/50	50
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	2.1×10^{32}	3.7×10^{33}	7.7×10^{33}
Emittance ε_n (μrad)	3.75	2.0	2.4	2.5
Max. $< \mu >$	19	4	17	37

Table: Overview of some parameters for the LHC performance comparing the design values with their time evolution during the first long run operation in 2010-2013 [7].

$T\bar{T} \to Wb + X$ 7 TeV vs 8 TeV

Selection		7 TeV	8 TeV
Preselection		One electron or muon$^{(+)}$	
		$E_{\mathrm{T}}^{\mathrm{miss}} > 35(20)$ GeV for electron (muon) channel	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
		$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV	
		≥ 3 jets for $W_{\mathrm{had}}^{\text{type I}}$ ≥ 4 jets for $W_{\mathrm{had}}^{\text{type II}}$	≥ 4 jets$^{(*)}$
		≥ 1 b-tagged jets$^{(**)}$	
		orthogonality cut reject events with ≥ 6 and ≥ 3 b-tagged je	
LOOSE selection		Preselection ≥ 1 W_{had} candidates$^{(\mathrm{x})}$	
		$H_{\mathrm{T}}^{4j} > 750$ GeV	$H_{\mathrm{T}}^{4j} > 800$ GeV