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

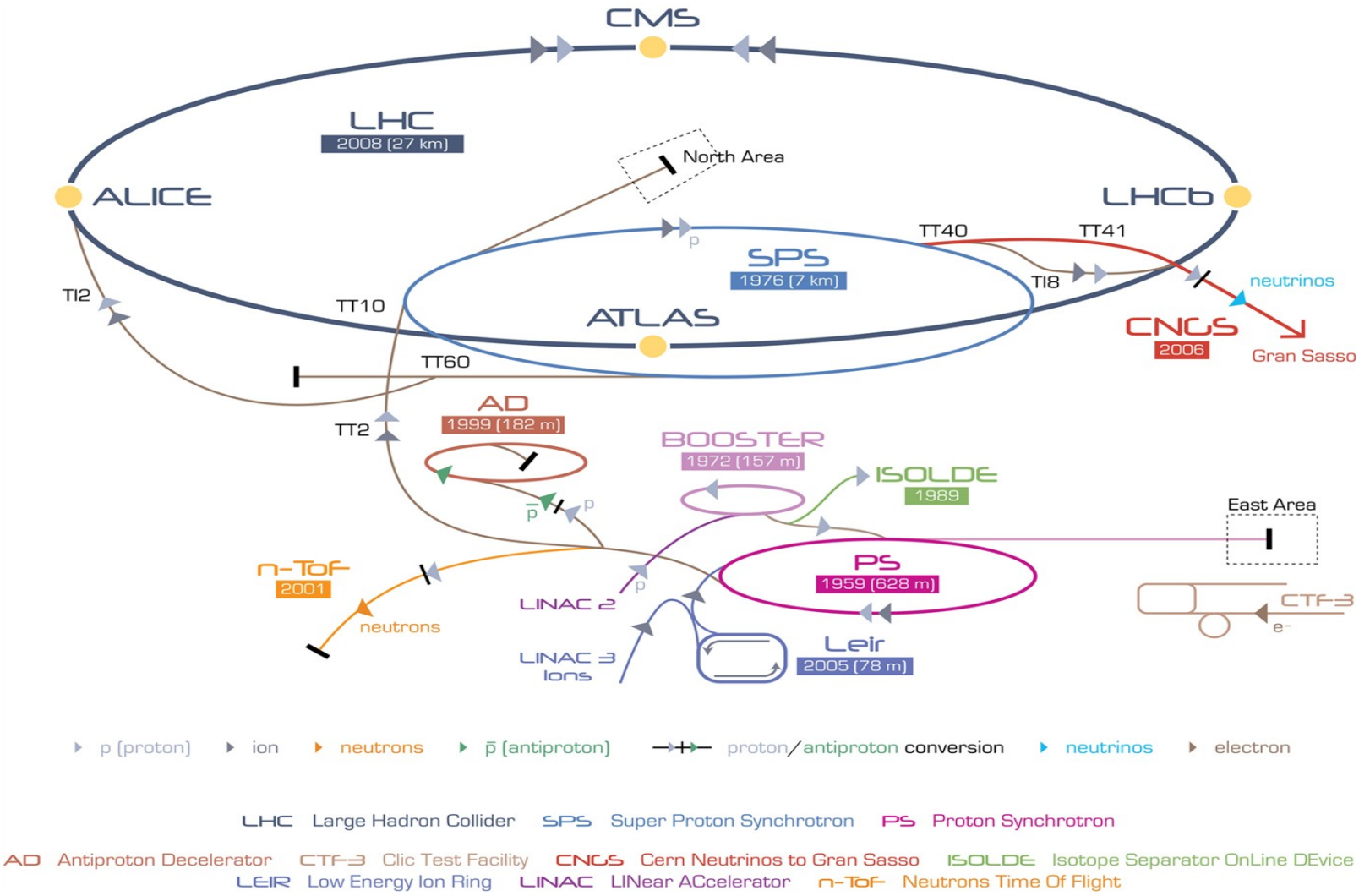
- **Why?** bother with "new physics"
- **Where?** is all happening
- **What?** are we looking at
- **How?**

Outline

Standard Model as an effective theory

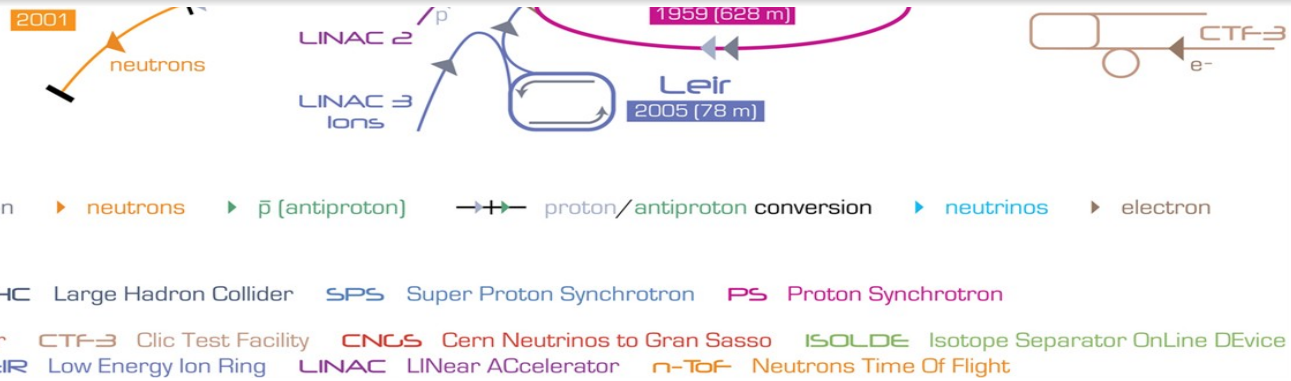
Outline

The LHC complex

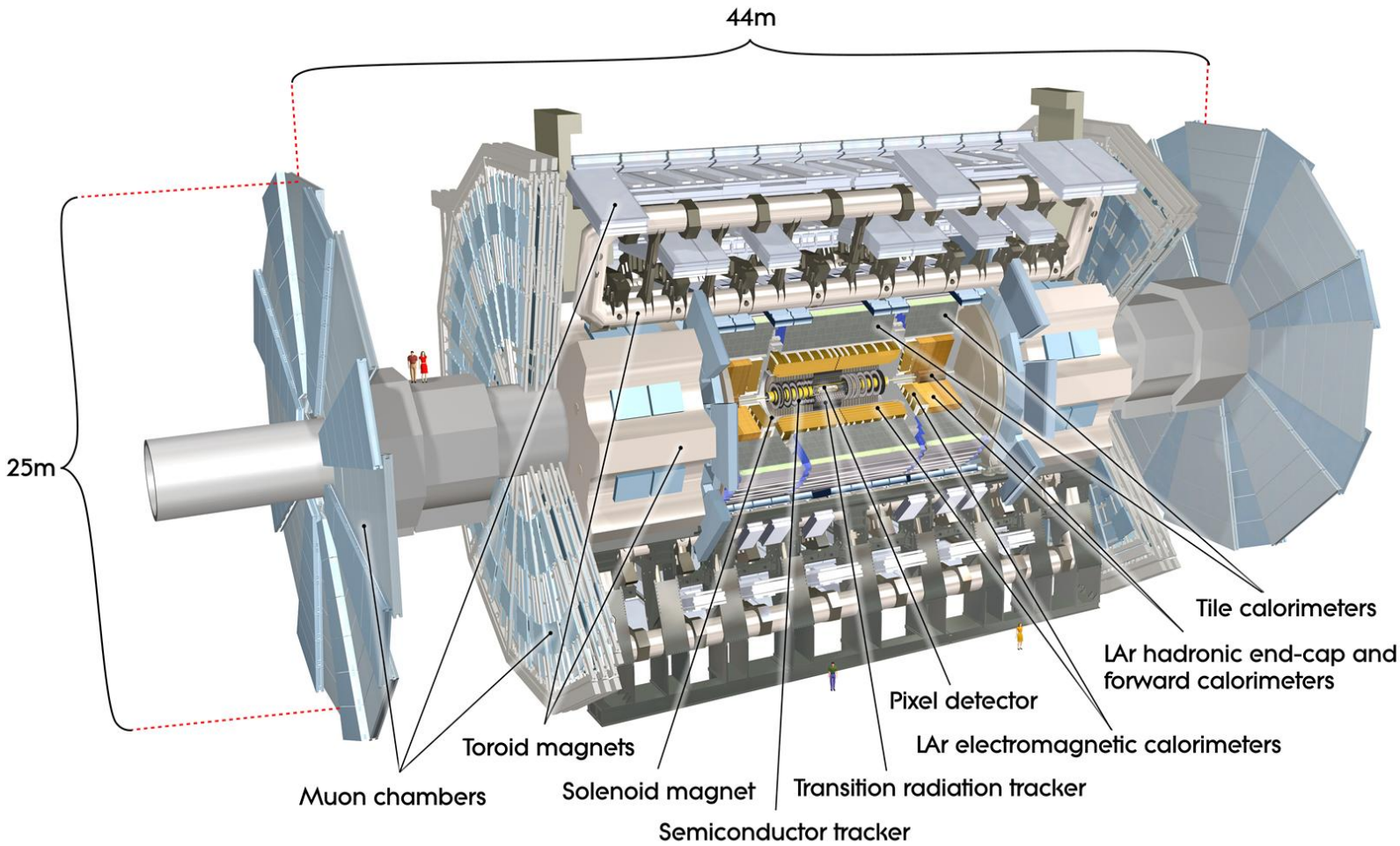


The LHC complex

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

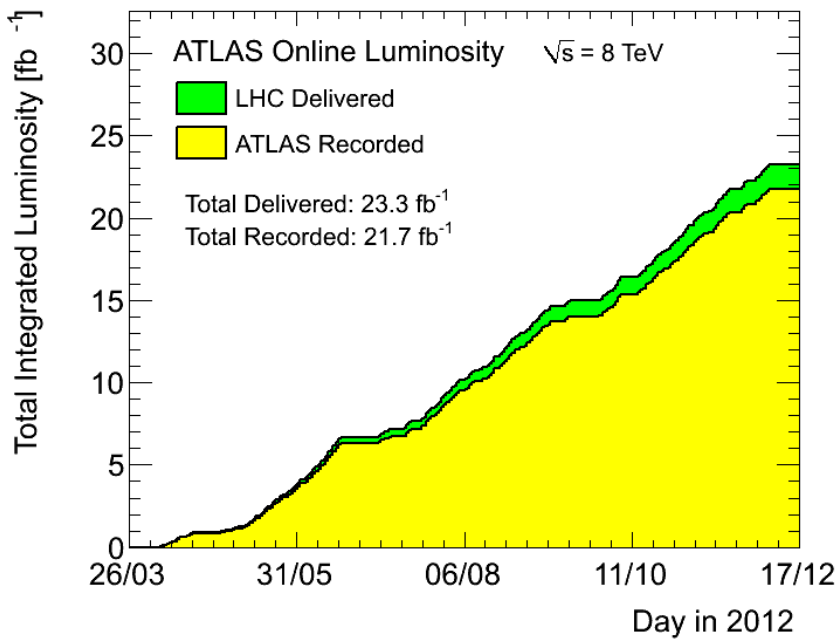


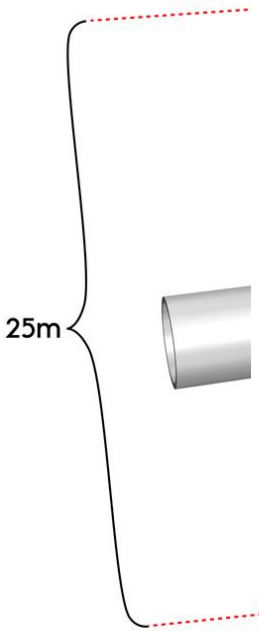
The ATLAS Detector

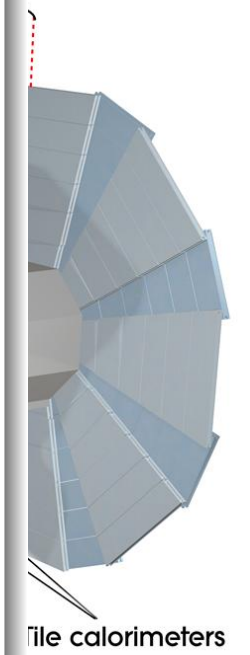


The ATLAS Detector

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







Tile calorimeters

onic end-cap and
calorimeters

Toroid magnets

LAr electromagnetic calorimeters

Muon chambers

Solenoid magnet

transition radiation tracker

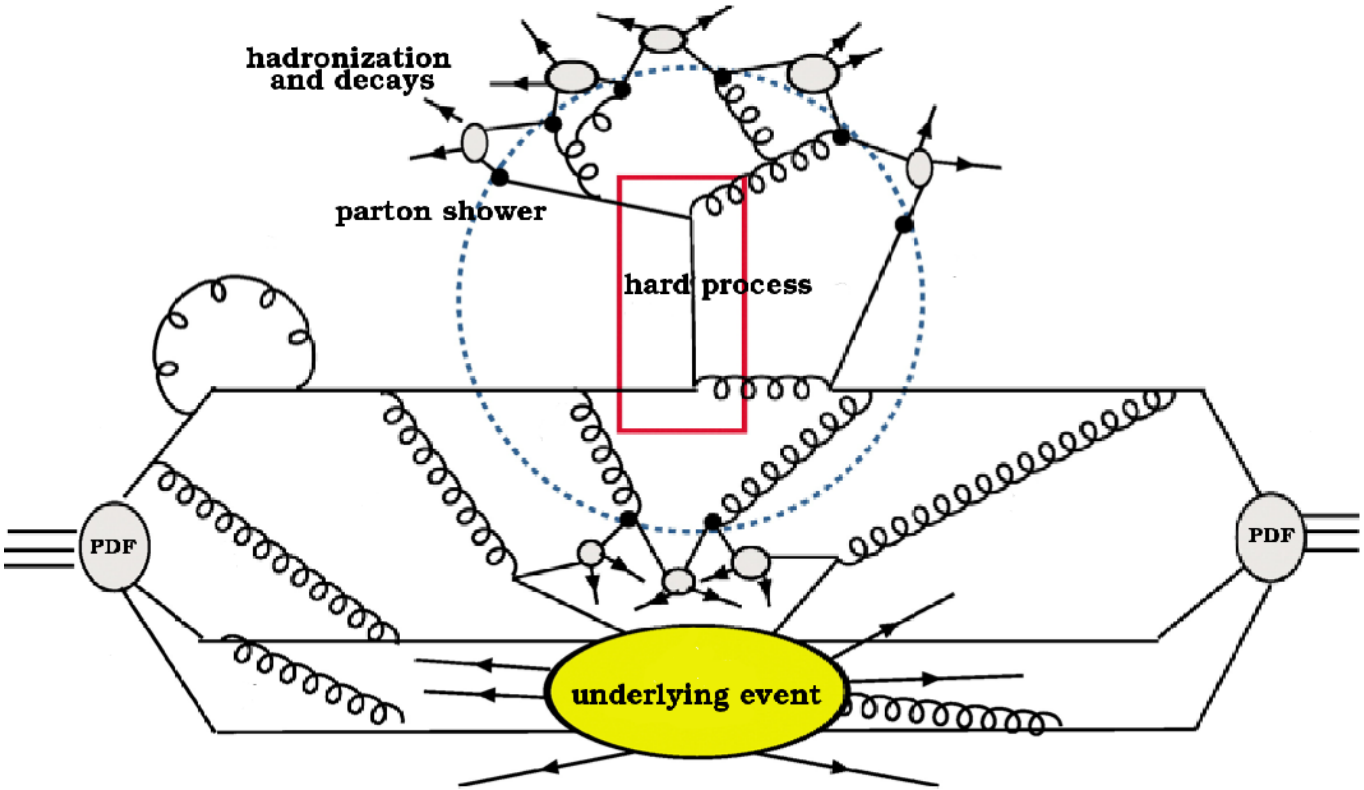
Semiconductor tracker

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

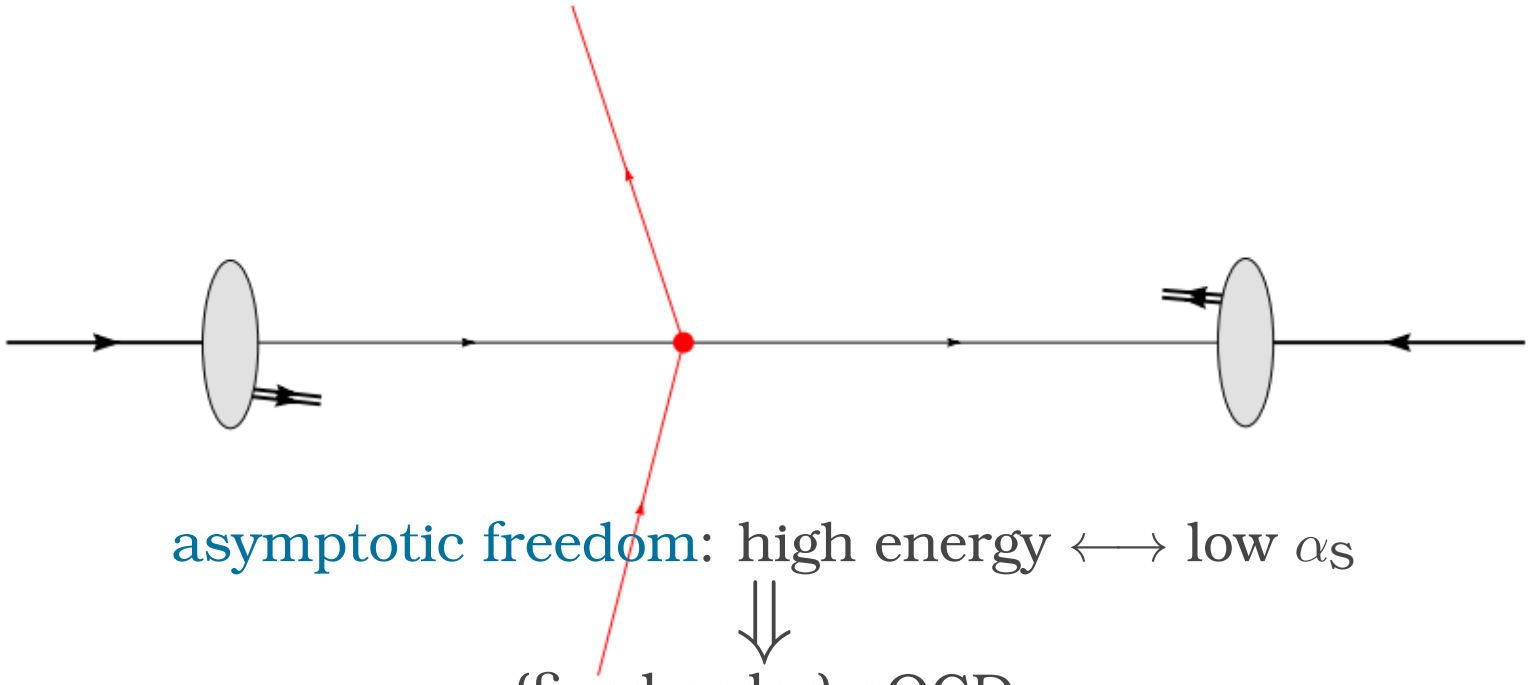
$E(p_2) = 4$ TeV

Quarks are distributed according to PDFs inside the proton

$\Downarrow$

intial energy unknown

Hard scattering of two partons

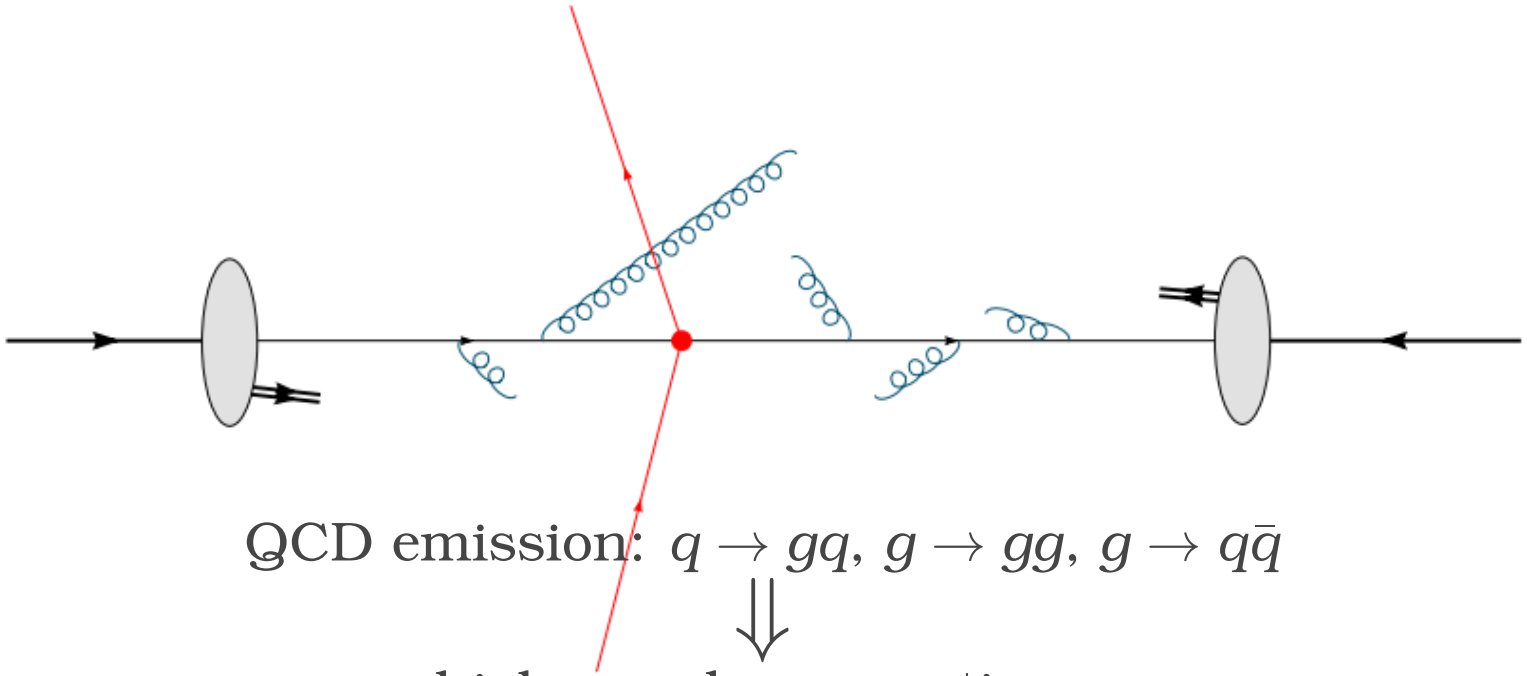


asymptotic freedom: high energy $\longleftrightarrow$ low α_S

$\Downarrow$

(fixed order) pQCD

Parton showering

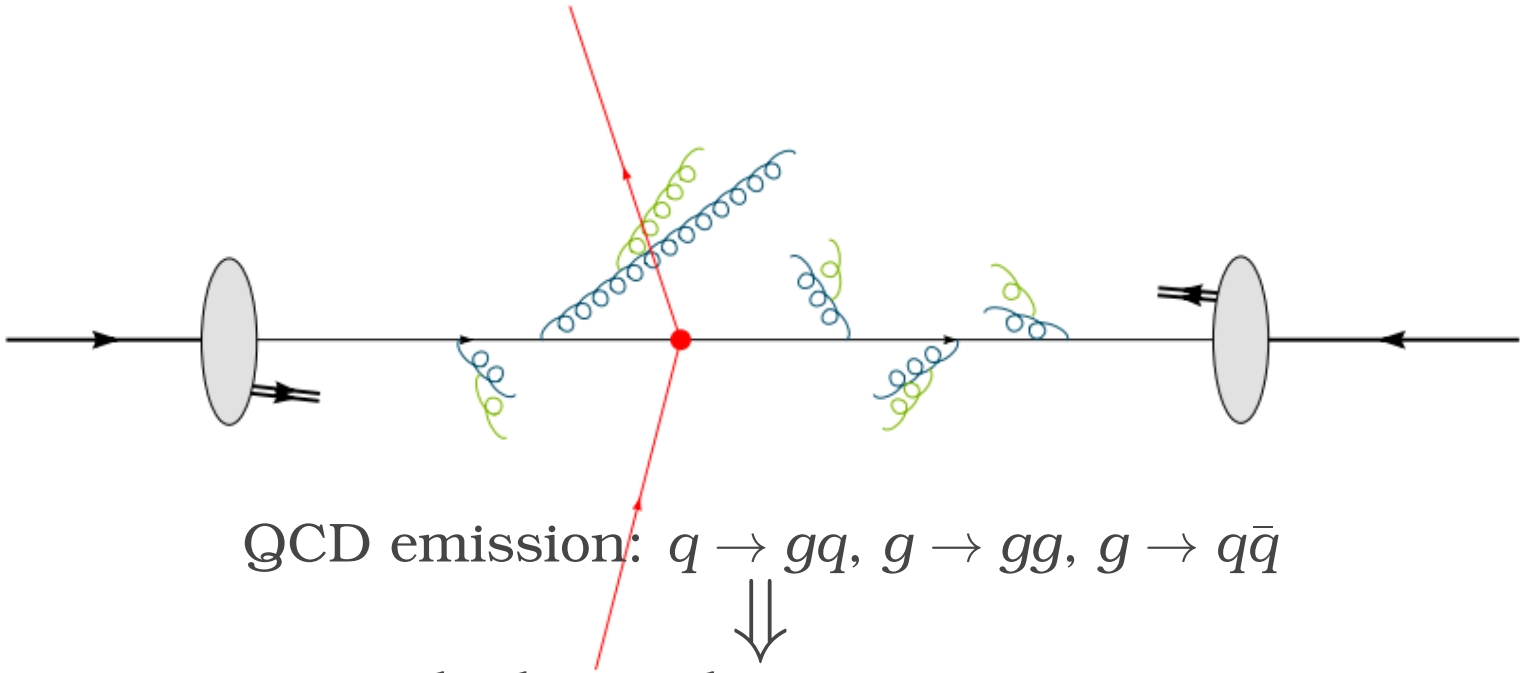


QCD emission: $q \to gq$, $g \to gg$, $g \to q\bar{q}$

$\Downarrow$

higher-order corrections

Parton showering



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

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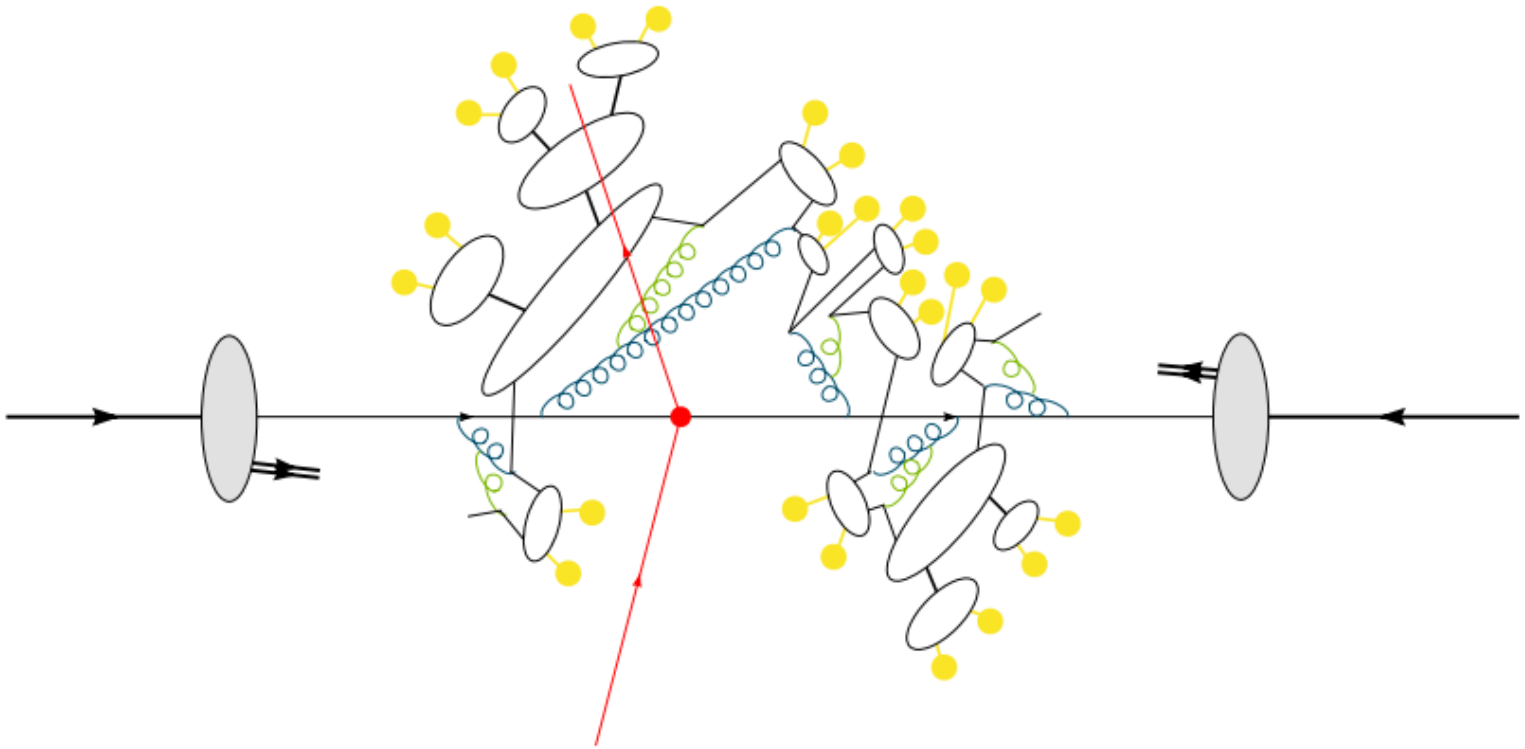
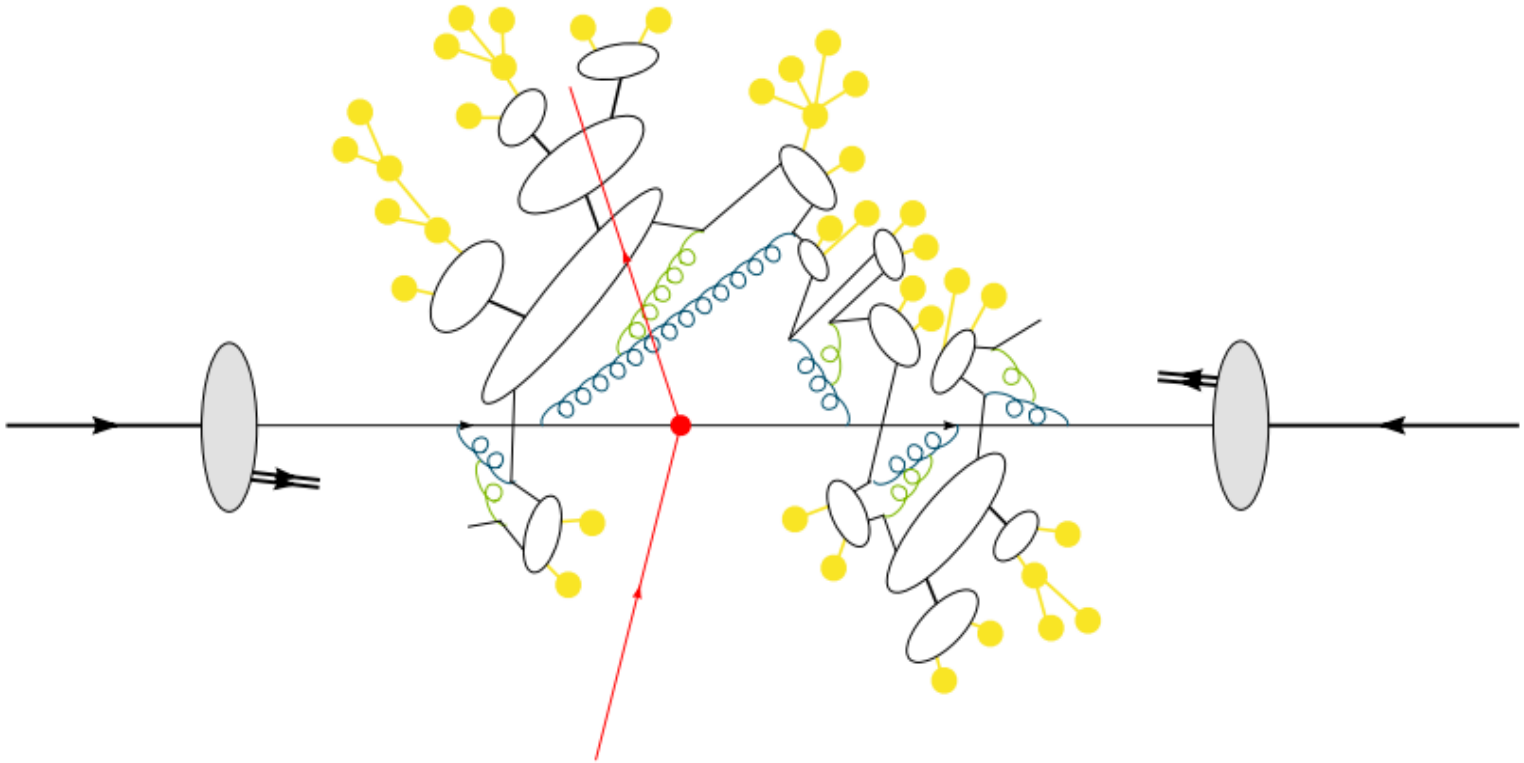
higher-order corrections

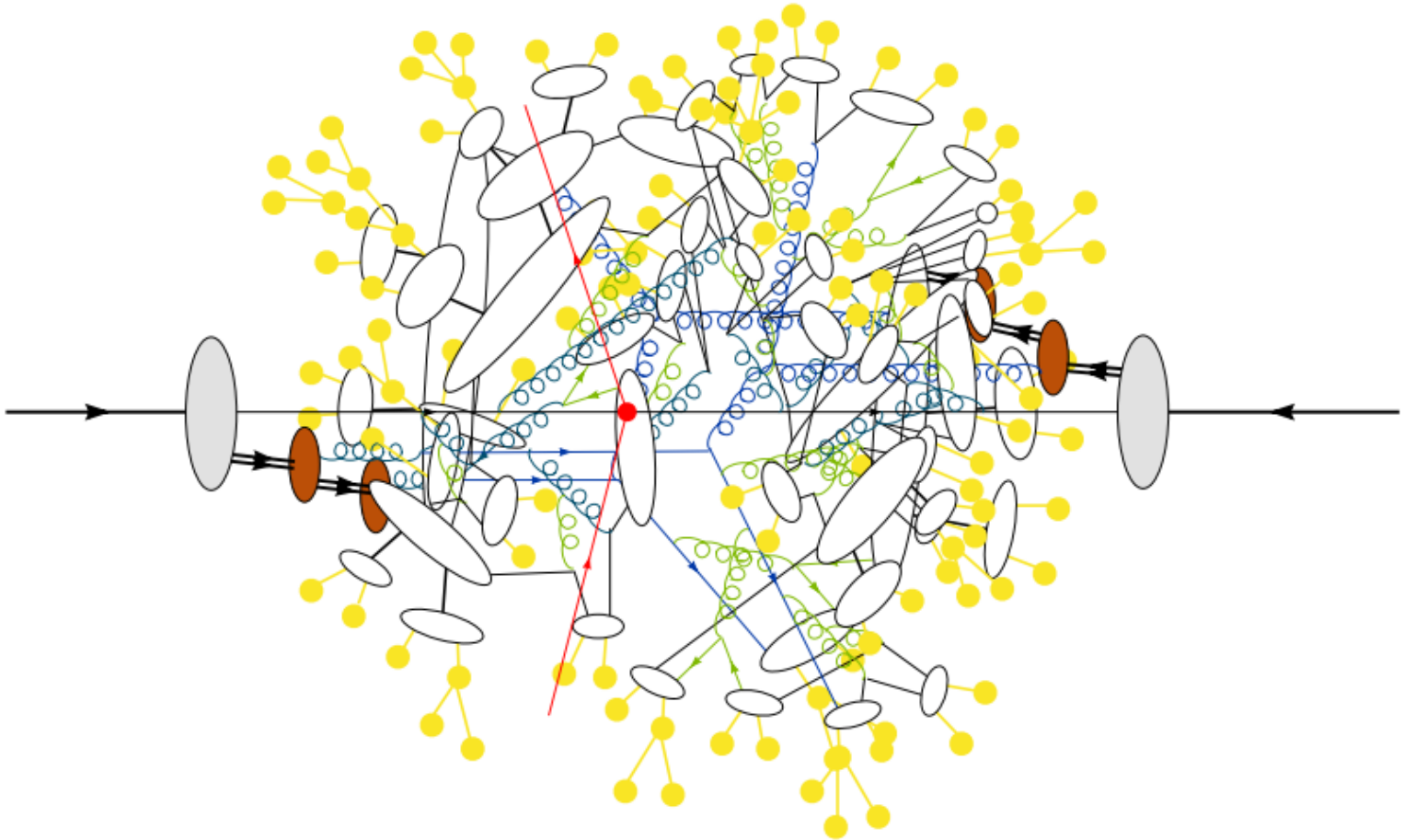
Hadronization



Final particle decays

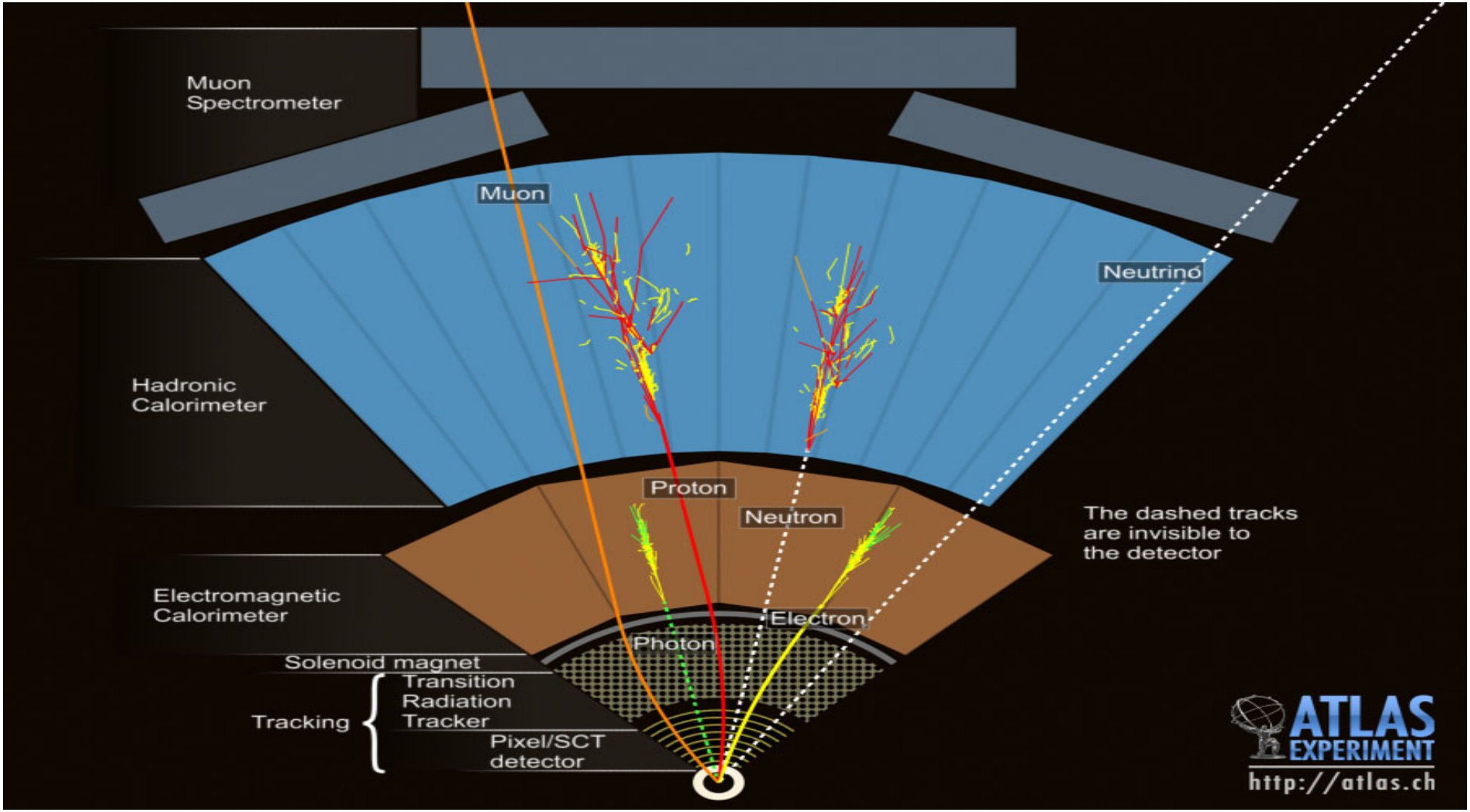


Underlying event simulation



Outline

Physics objects puzzle



One lepton

Many jets

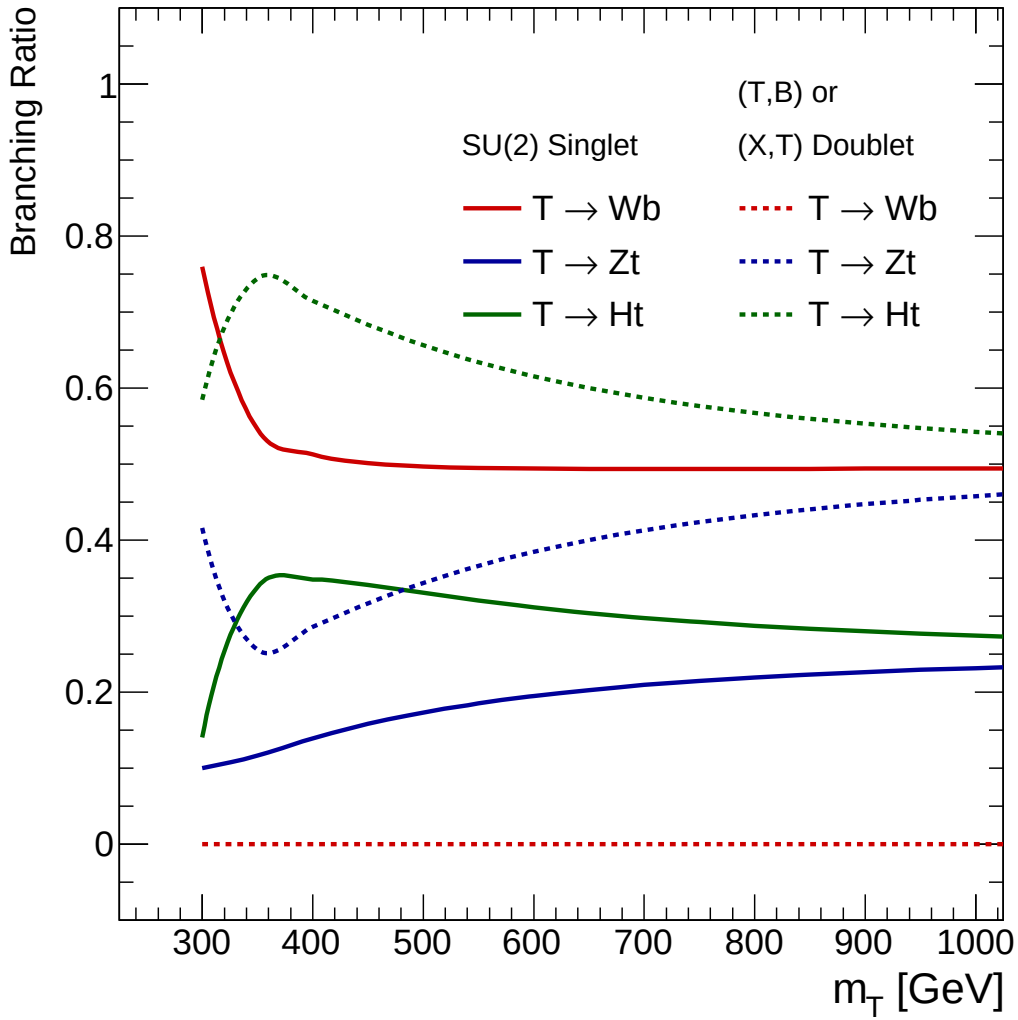
Missing transverse energy

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

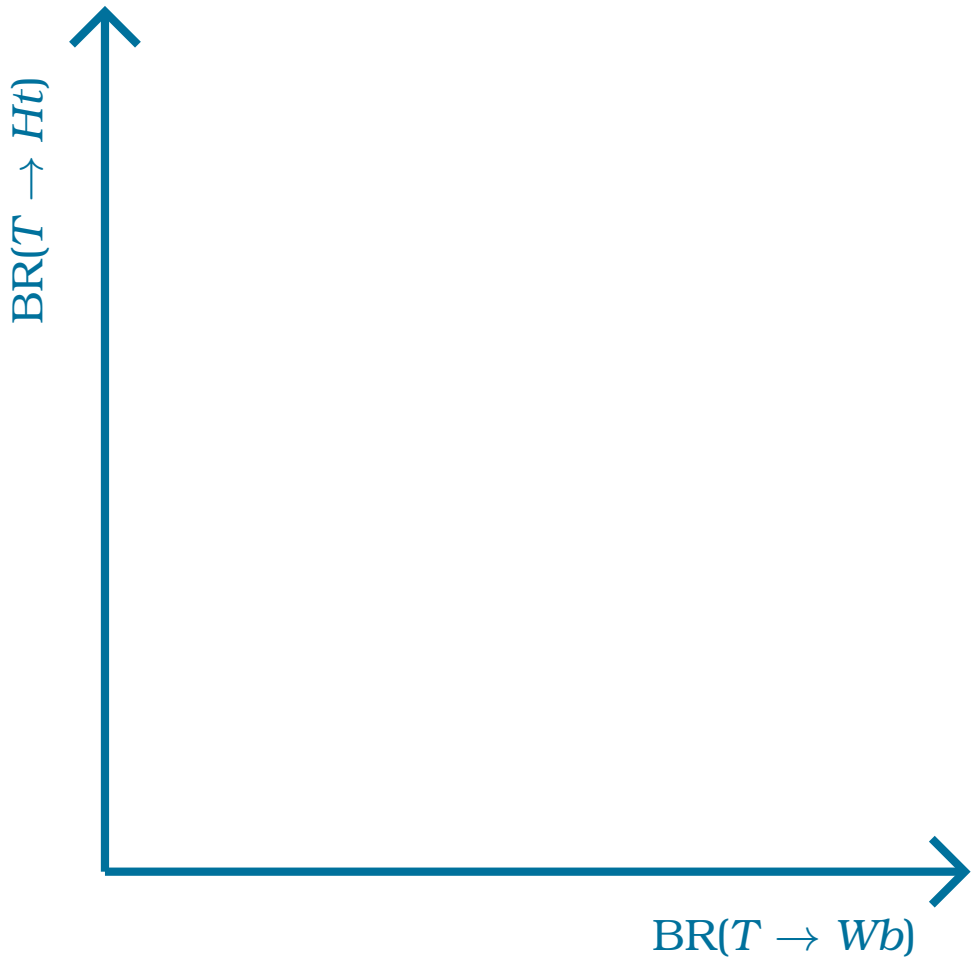


Model Independent Strategy

- Build a 2-dim plane to scan model mixing

BR($T \to Wb$)

Model Independent Strategy



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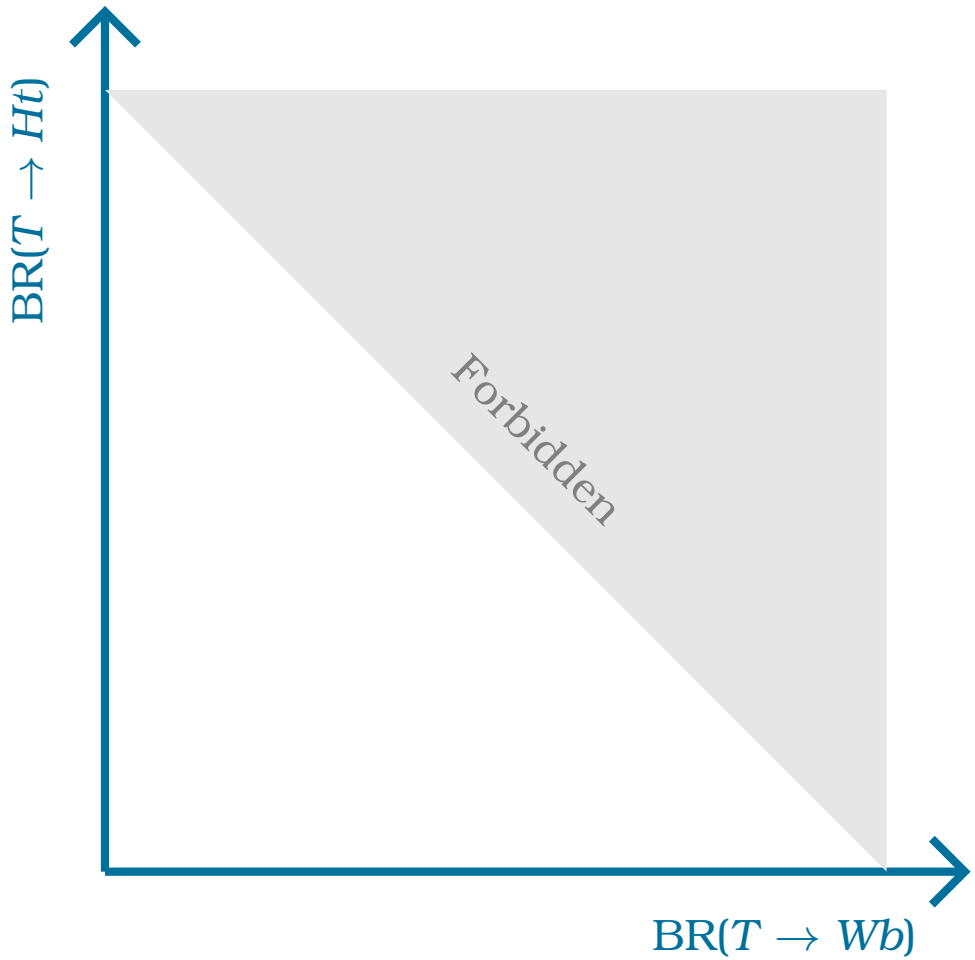
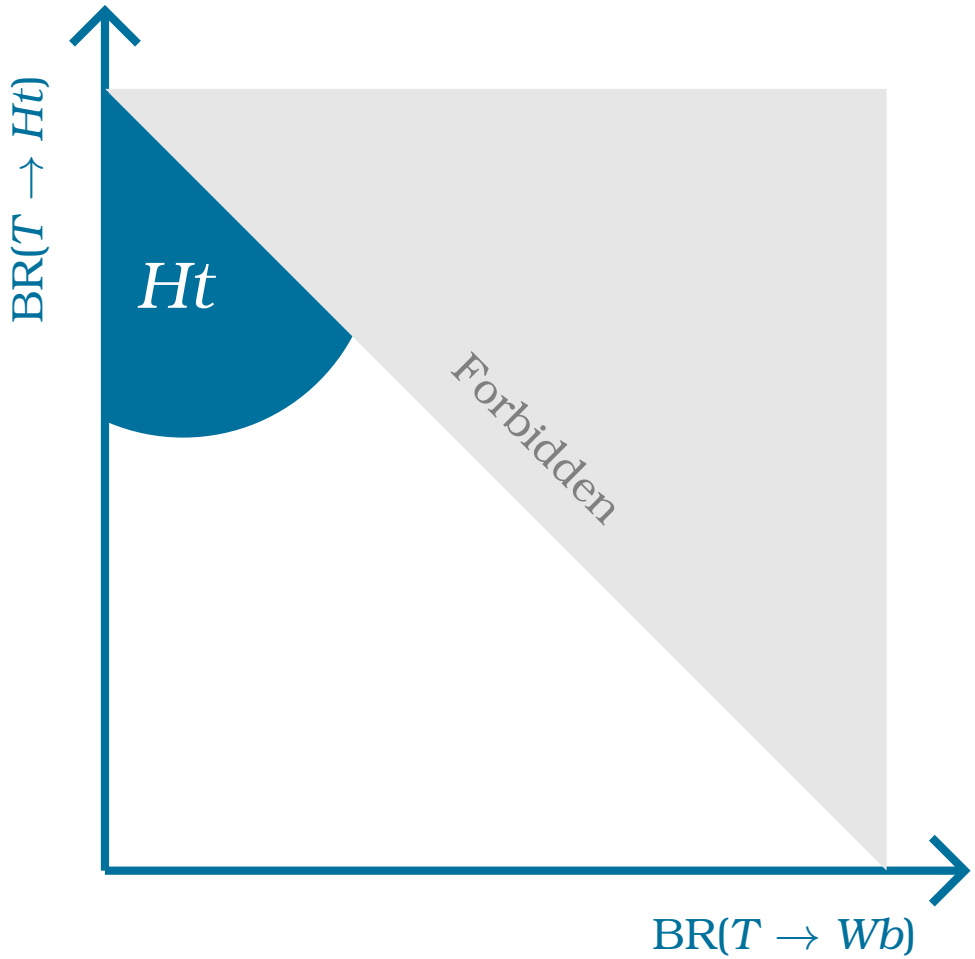
Model Independent Strategy



- 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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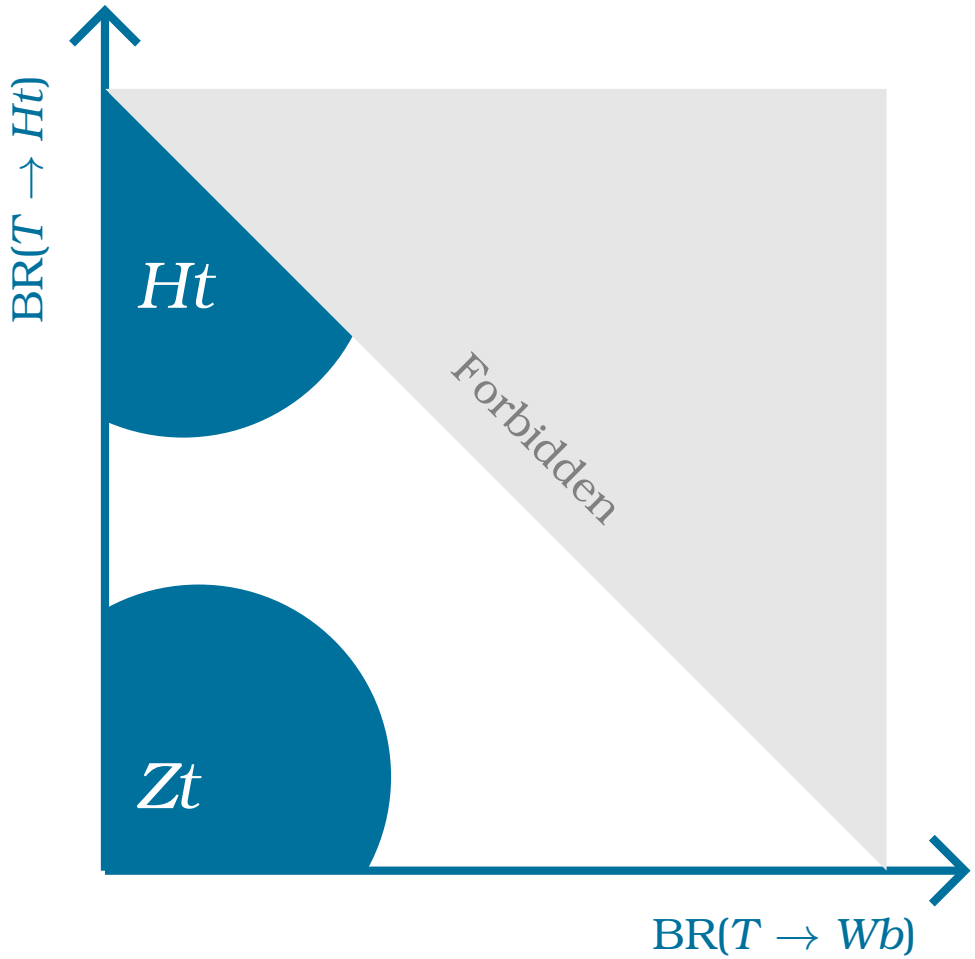
Model Independent Strategy



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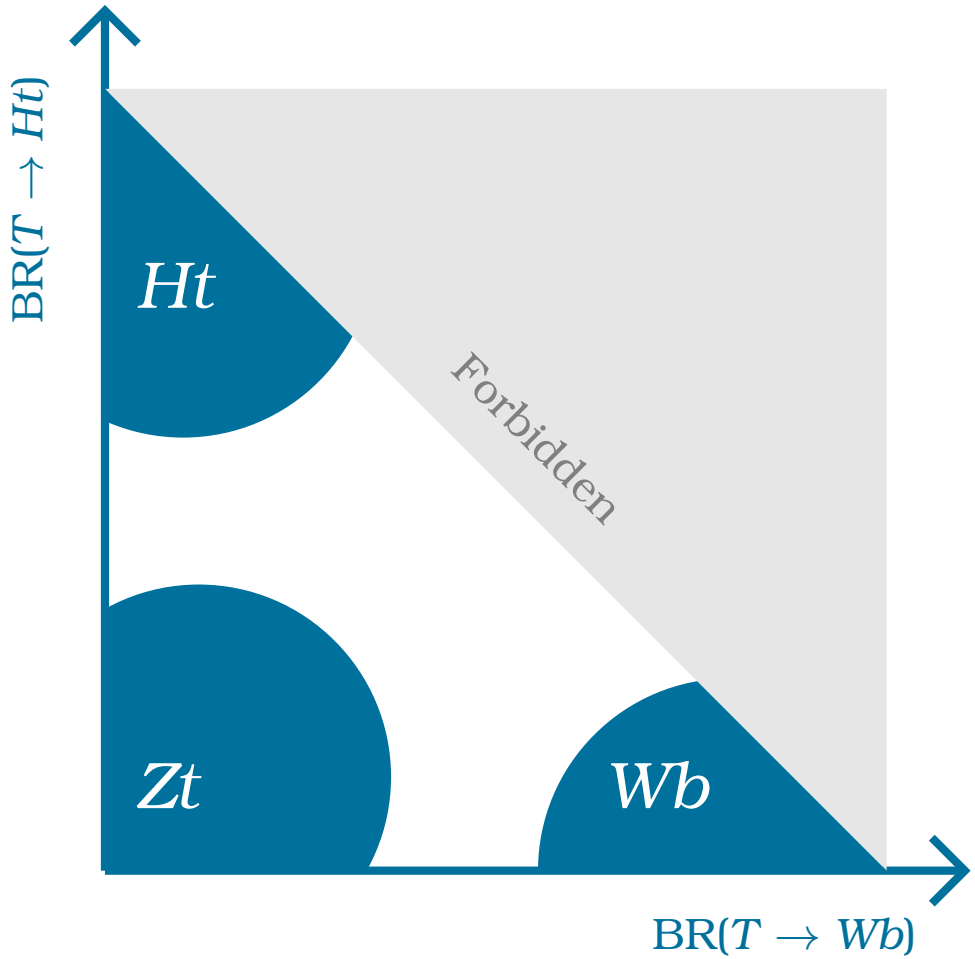

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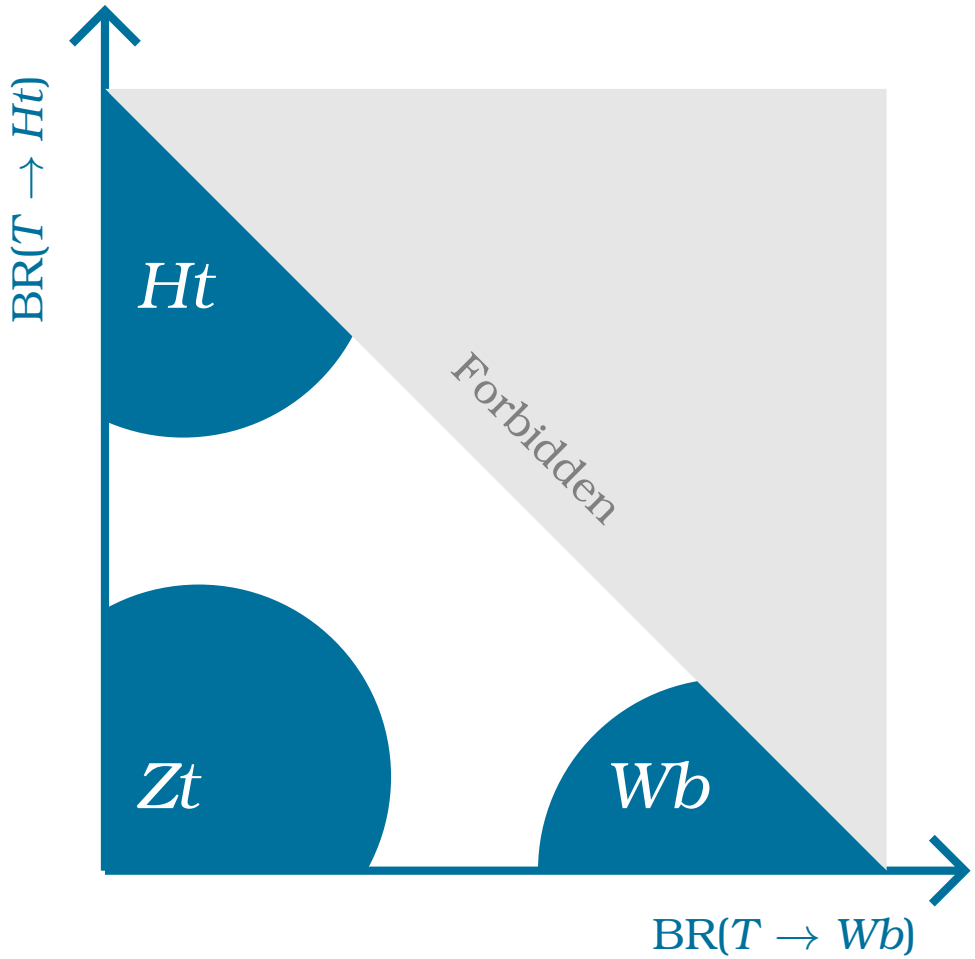
Model Independent Strategy



- Build a 2-dim plane to scan model mixing
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- Different analyses are sensitive to different areas
- Set exclusion using CL_s technique [2, 3]

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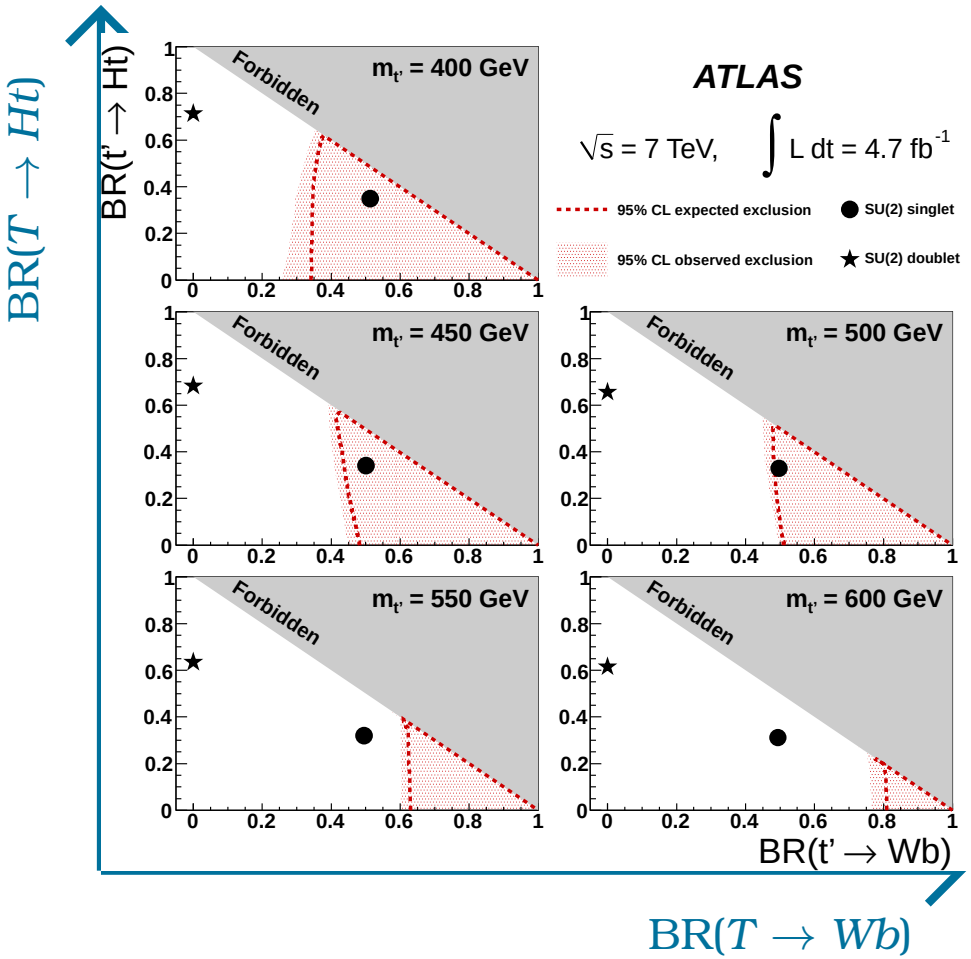
Model Independent Strategy



- 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

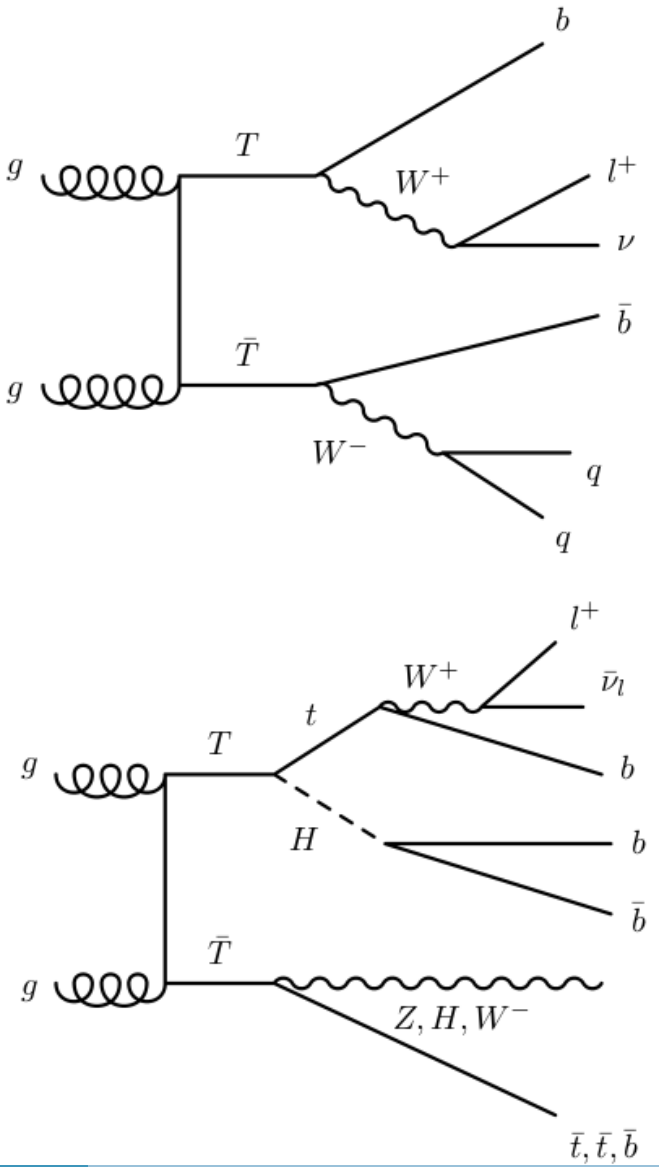
Two searches using common analysis framework:

- $T\bar{T} \to Wb + X$ — 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



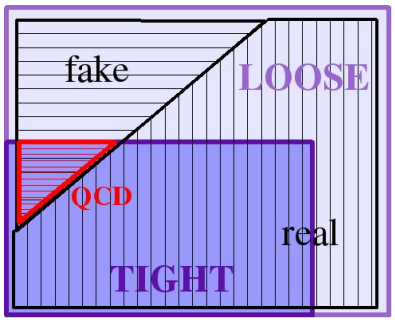
Background and signal modelling

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

Background and signal modelling

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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
- NNLO theoretical cross section

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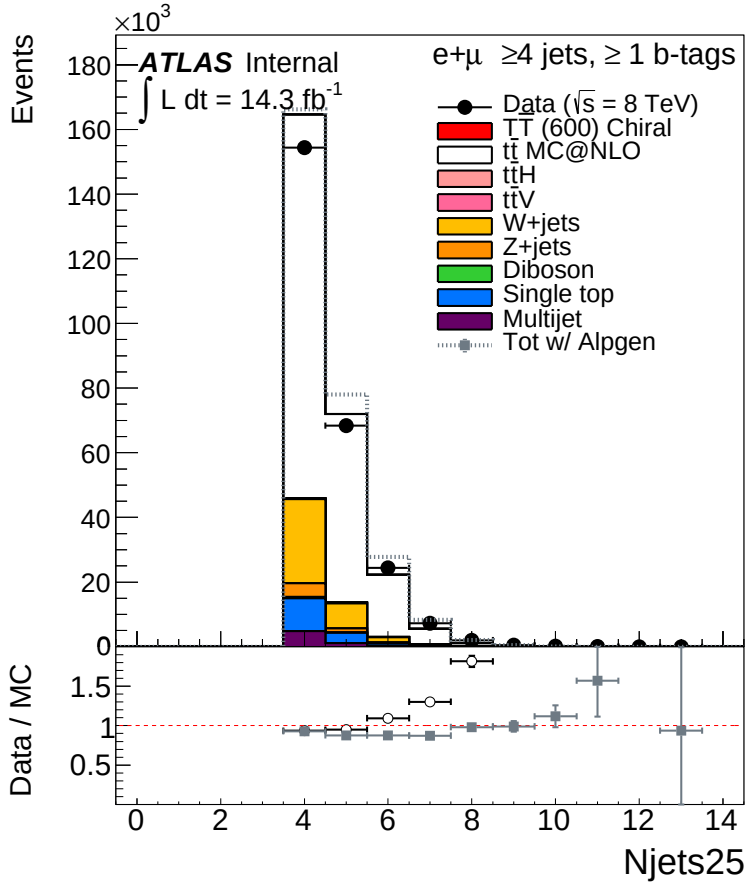
Yields for $t\bar{t}$ predicted with ALPGEN are ~3-8% higher than MC@NLO



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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

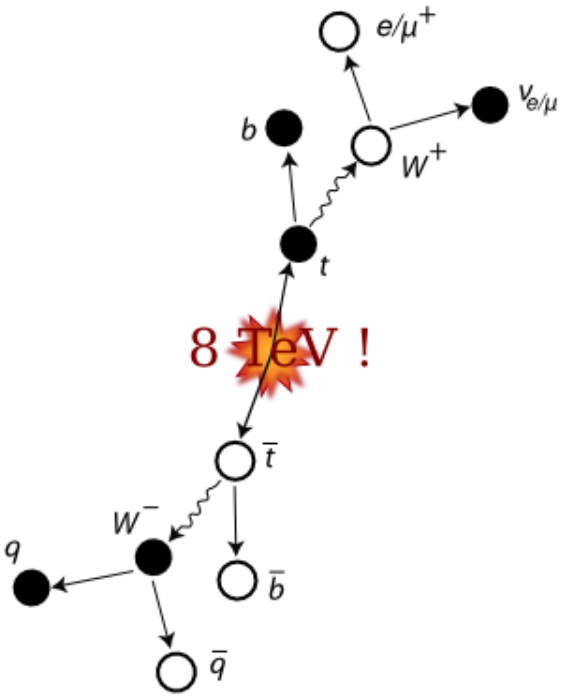
Outline

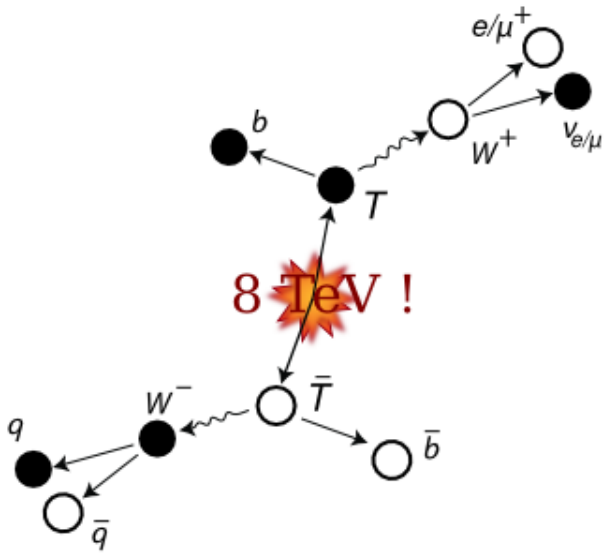
Strategy

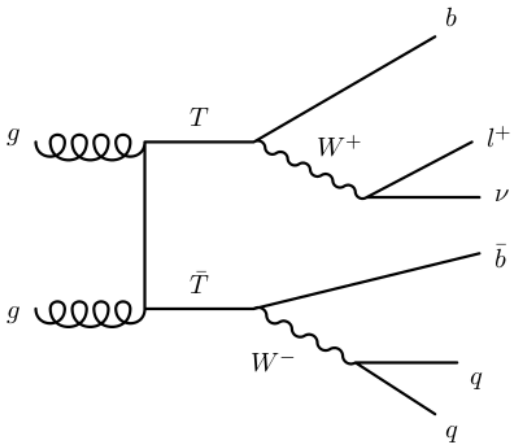
$T\bar{T} \rightarrow WbWb$

like

$t\bar{t} \rightarrow WbWb$







different boosted kinematics

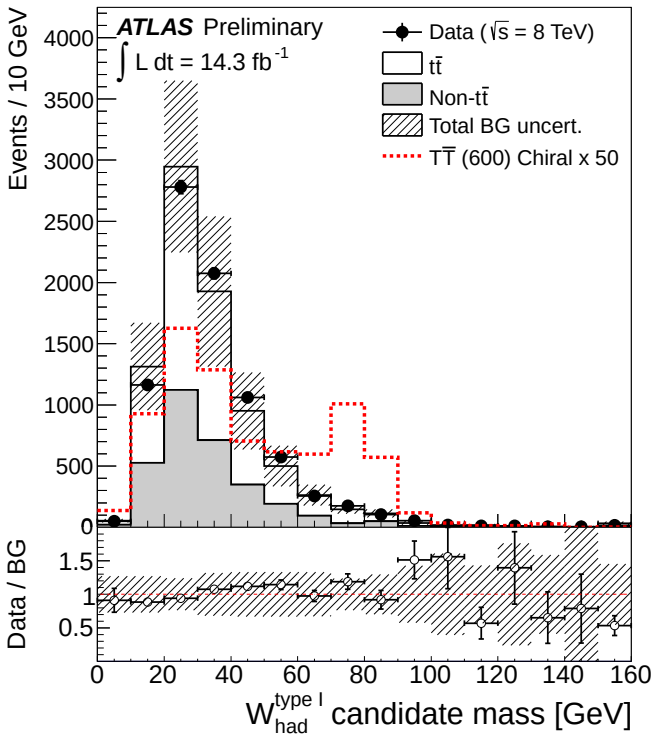
⇓

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

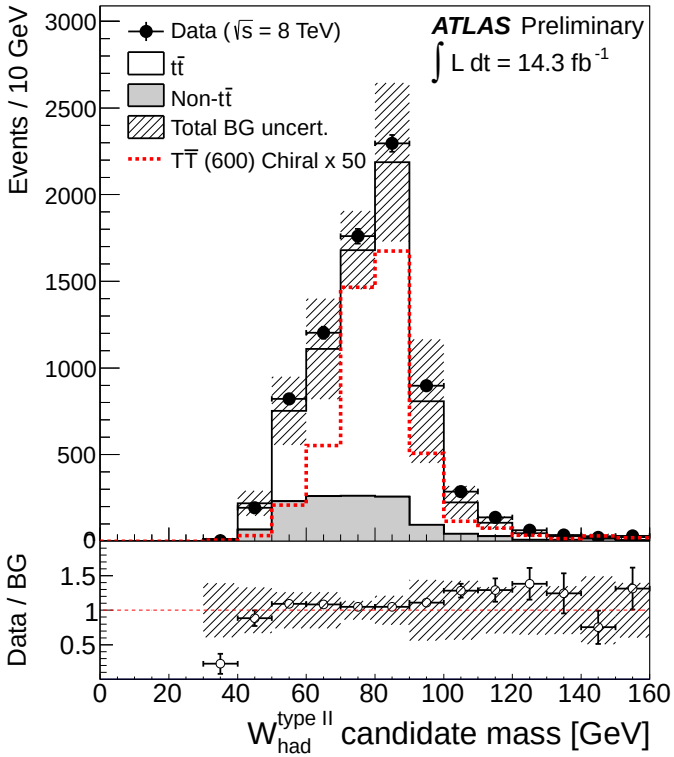
$W_{\text{had}}^{\text{type I}}$



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

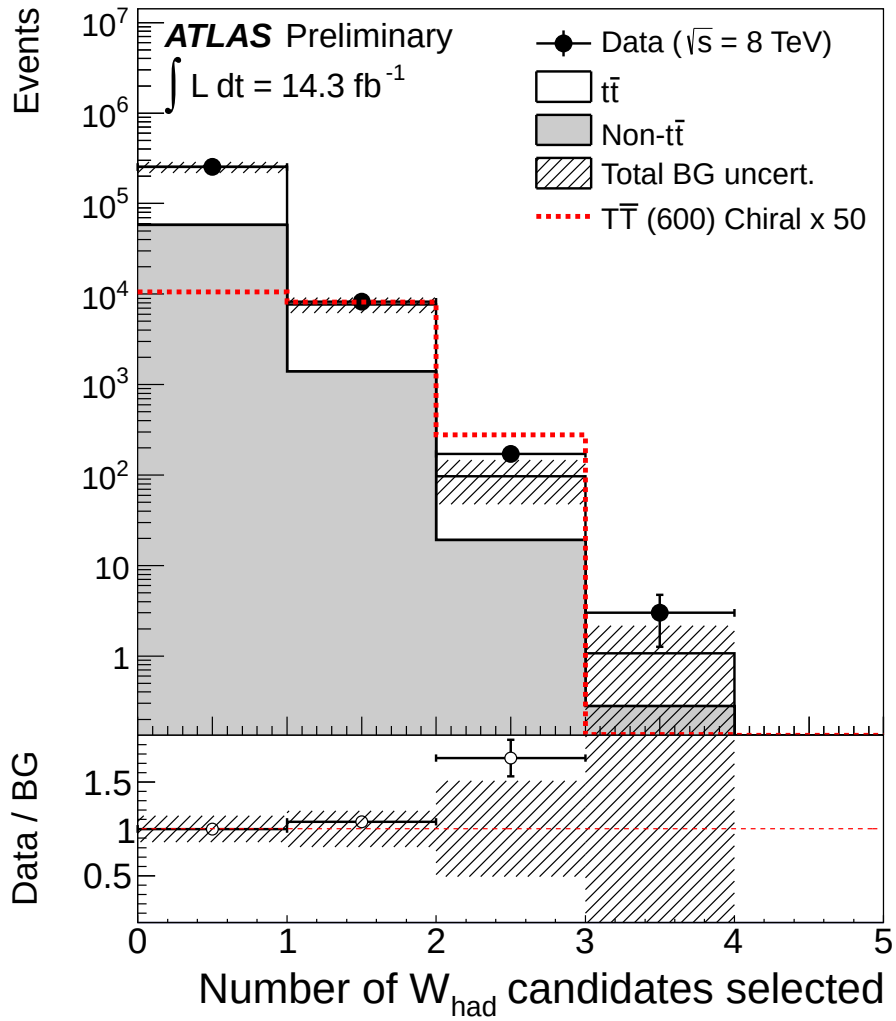
$W_{\text{had}}^{\text{type II}}$



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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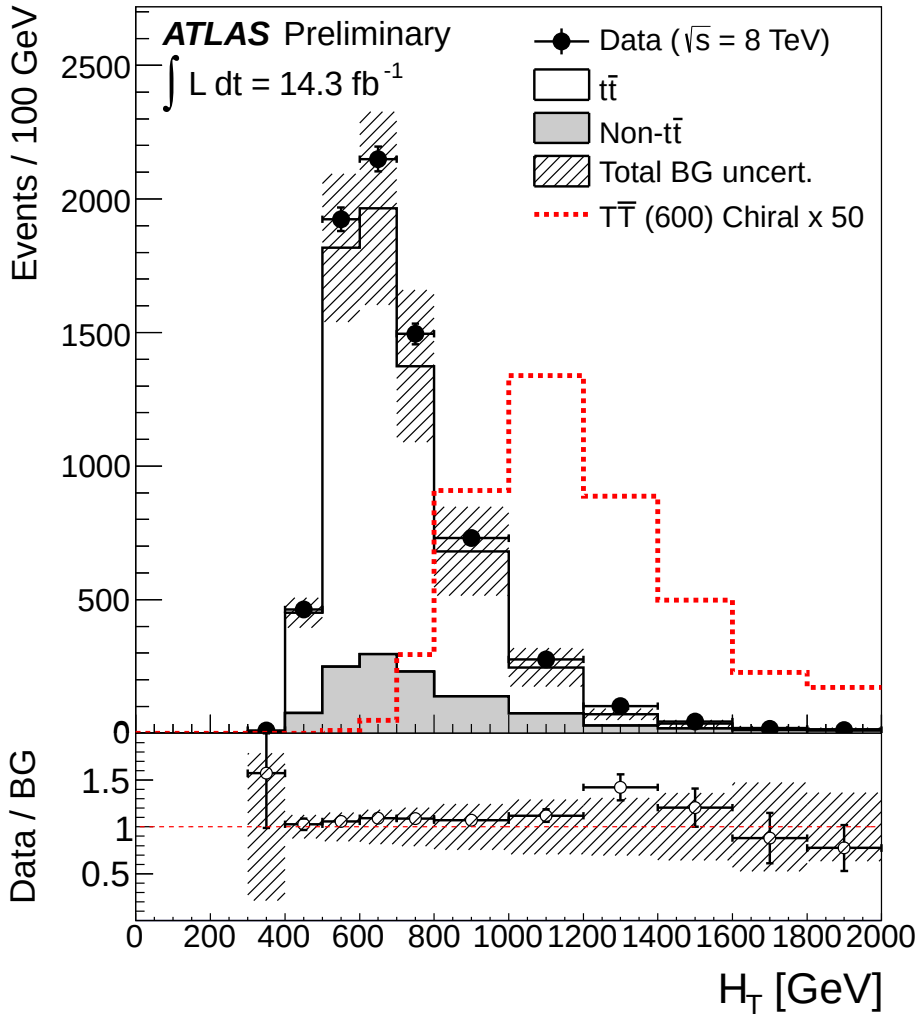

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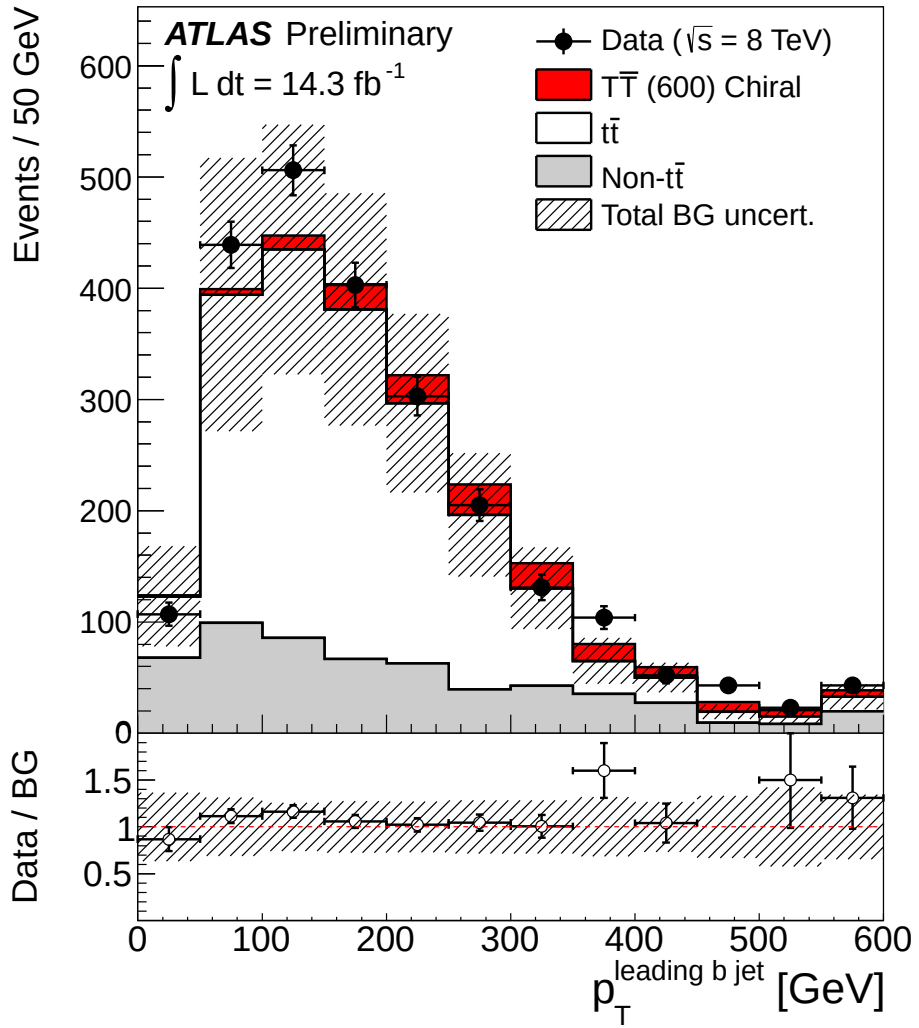

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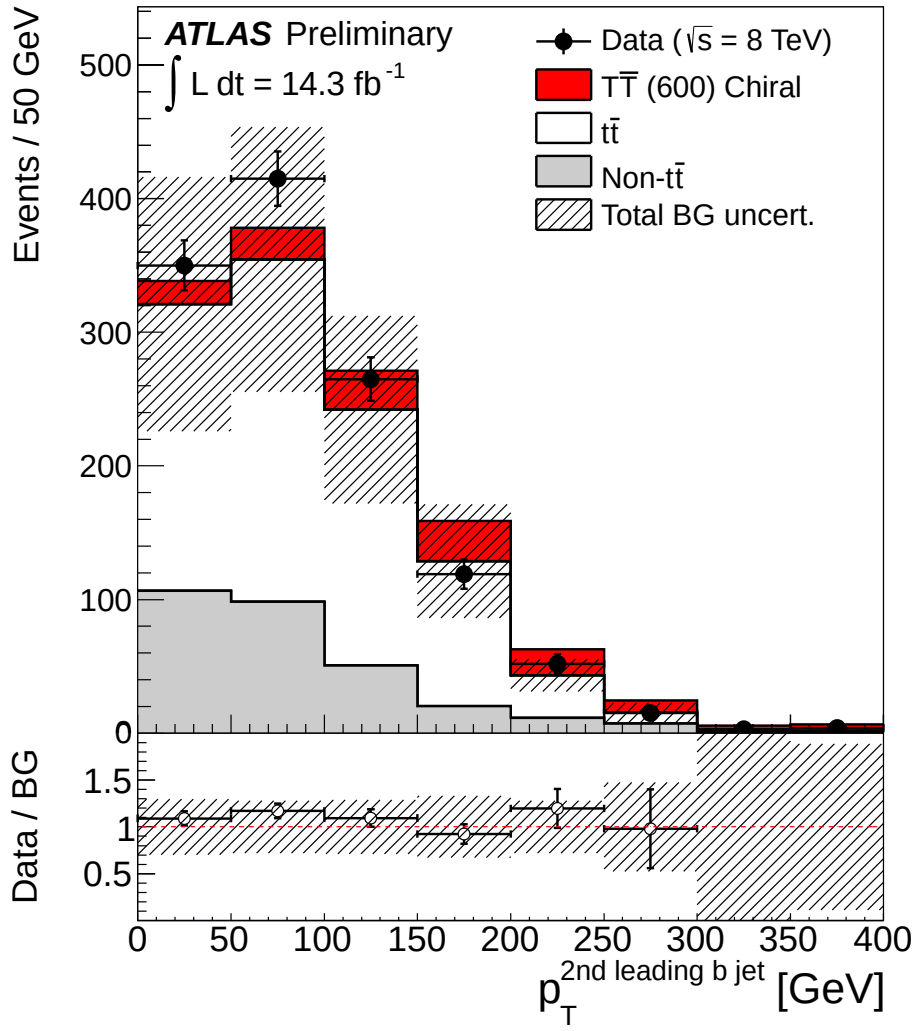

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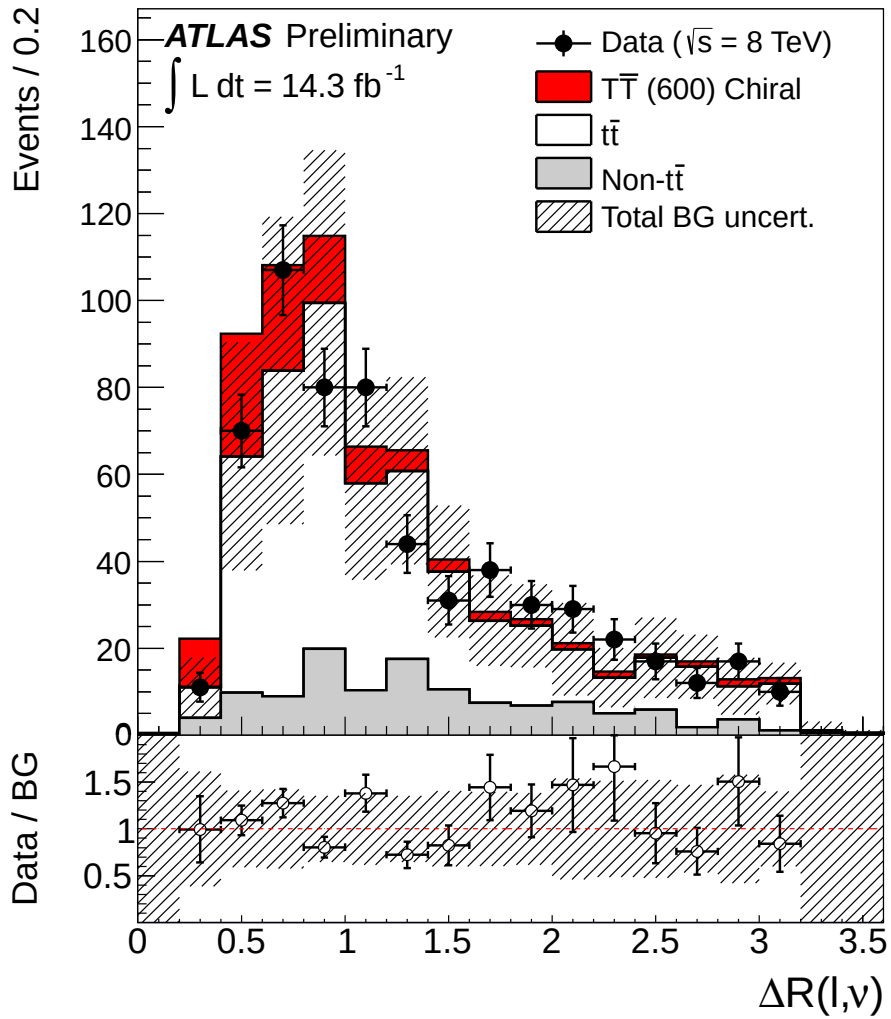

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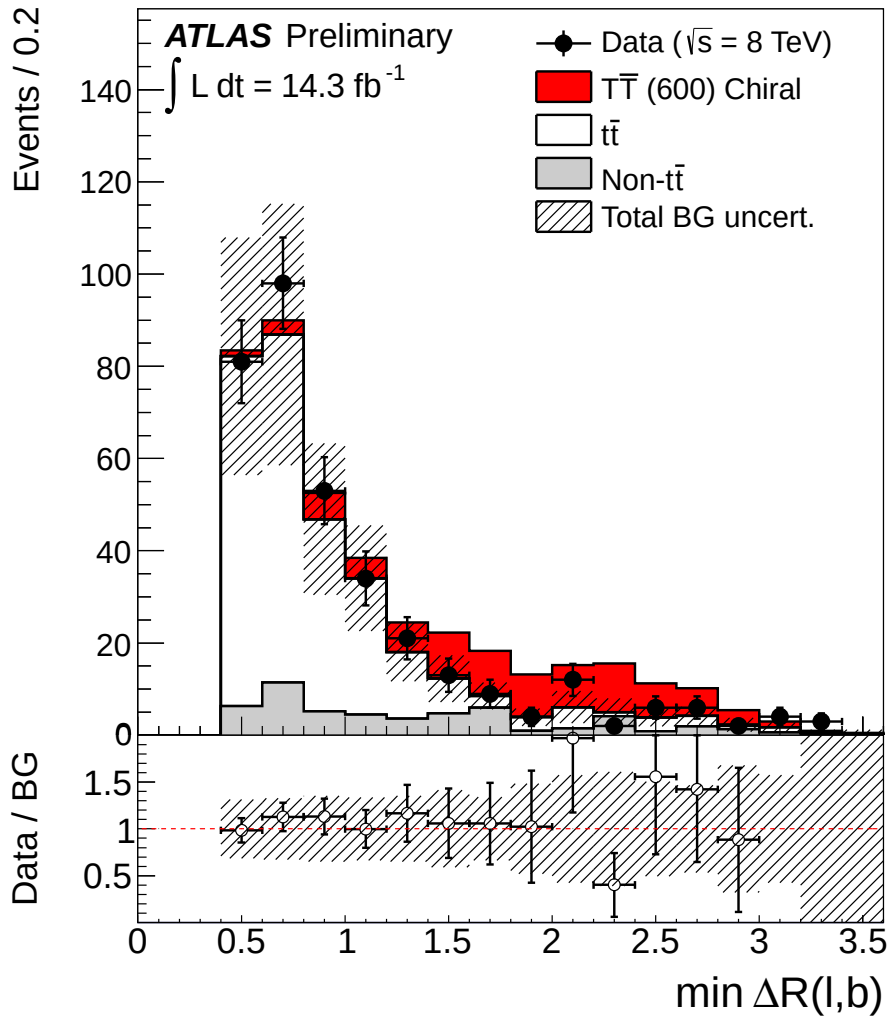

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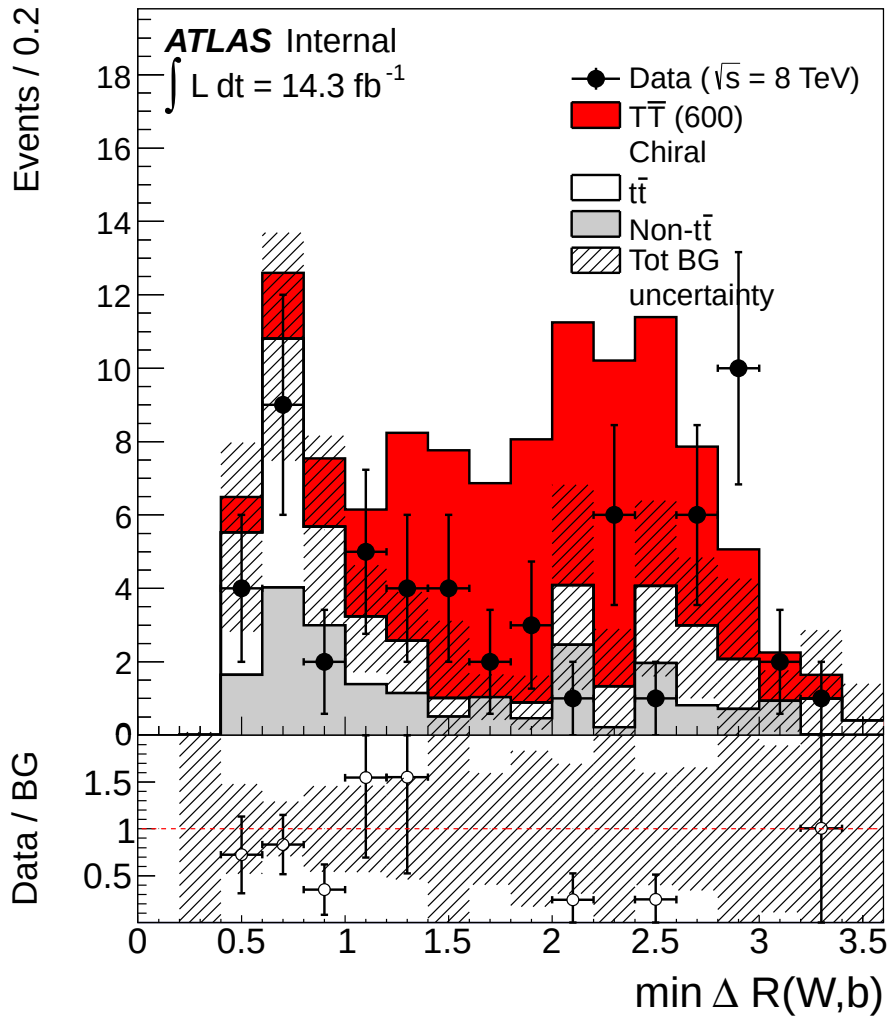

Comparison data vs prediction

Check agreement between data and background prediction

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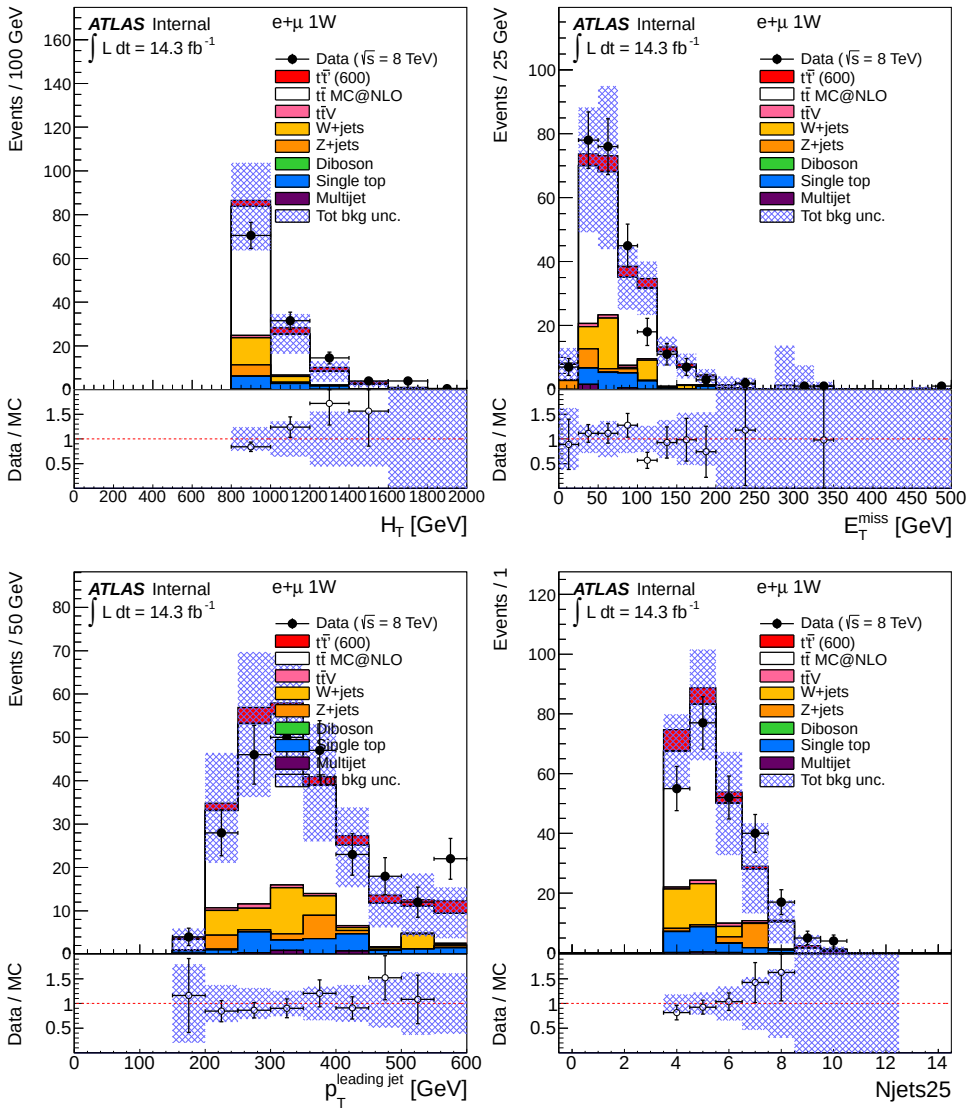
Define regions depleted in signal

	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



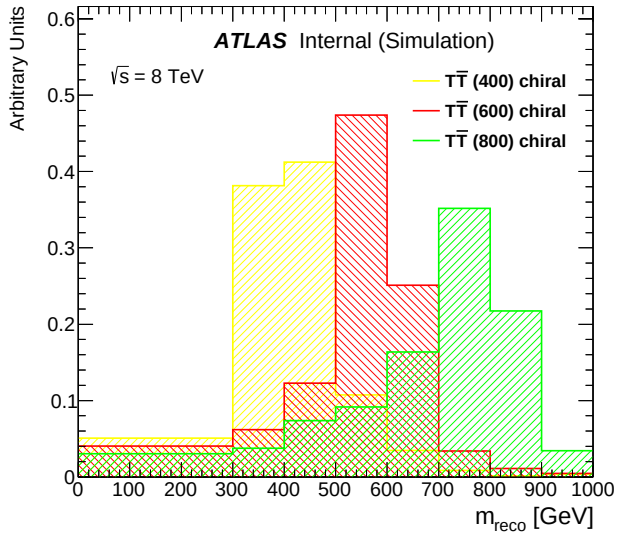
Yields in signal region

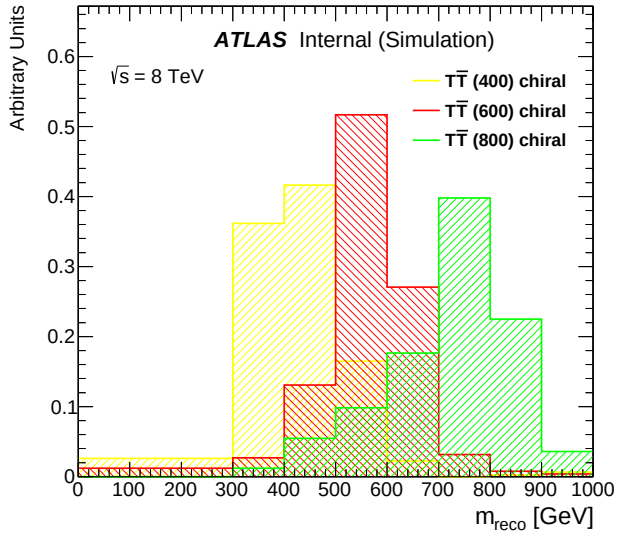
		Loose	Tight
merged	$t\bar{t}$	264 ± 80	10 ± 6
	$t\bar{t}V$	5.1 ± 1.8	0.5 ± 0.2
	W+jets	16 ± 11	6 ± 5
	Z+jets	1.1 ± 1.4	0.2 ± 0.5
	Single top	30 ± 7	4.4 ± 1.6
	Dibosons	0.21 ± 0.15	0.06 ± 0.05
	Tot.Bkg.	317 ± 90	21 ± 9
	Data	348	37
	$T\bar{T}(600$ GeV)		
	Chiral t'	88 ± 10	54 ± 7
	T Singlet	41 ± 4	20.3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

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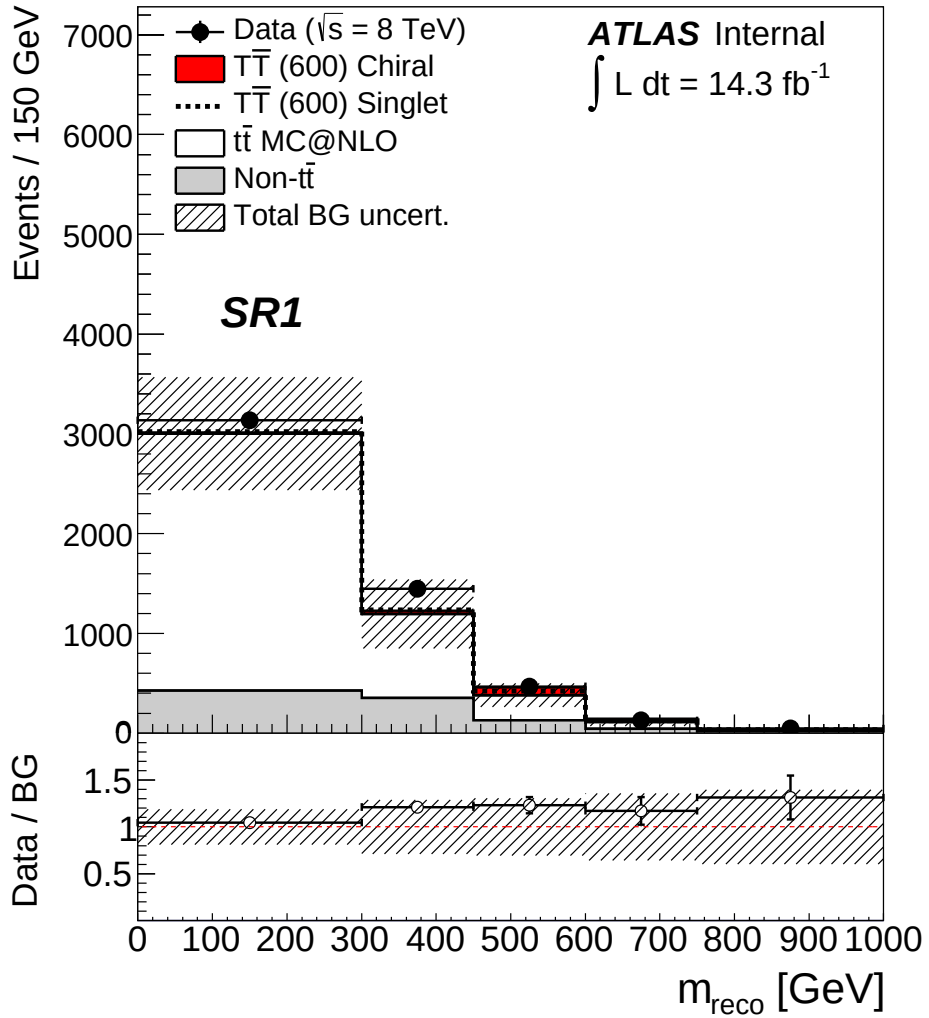

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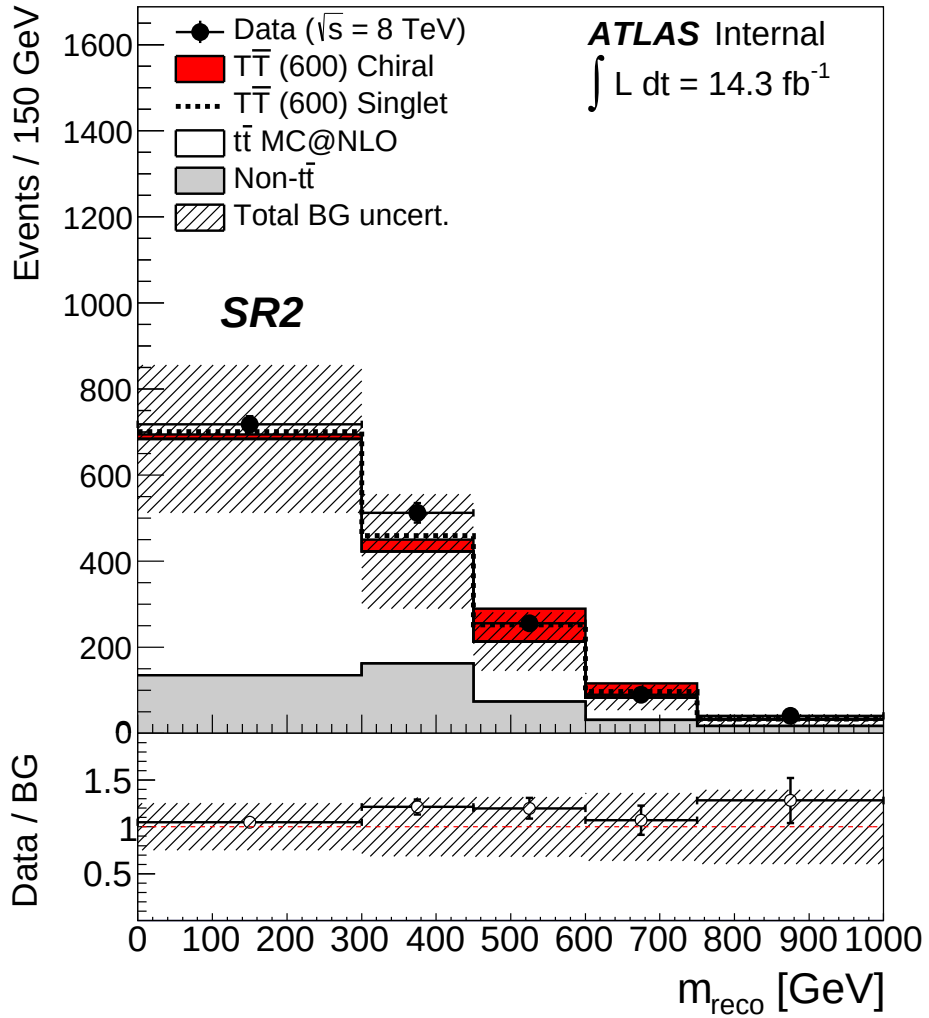

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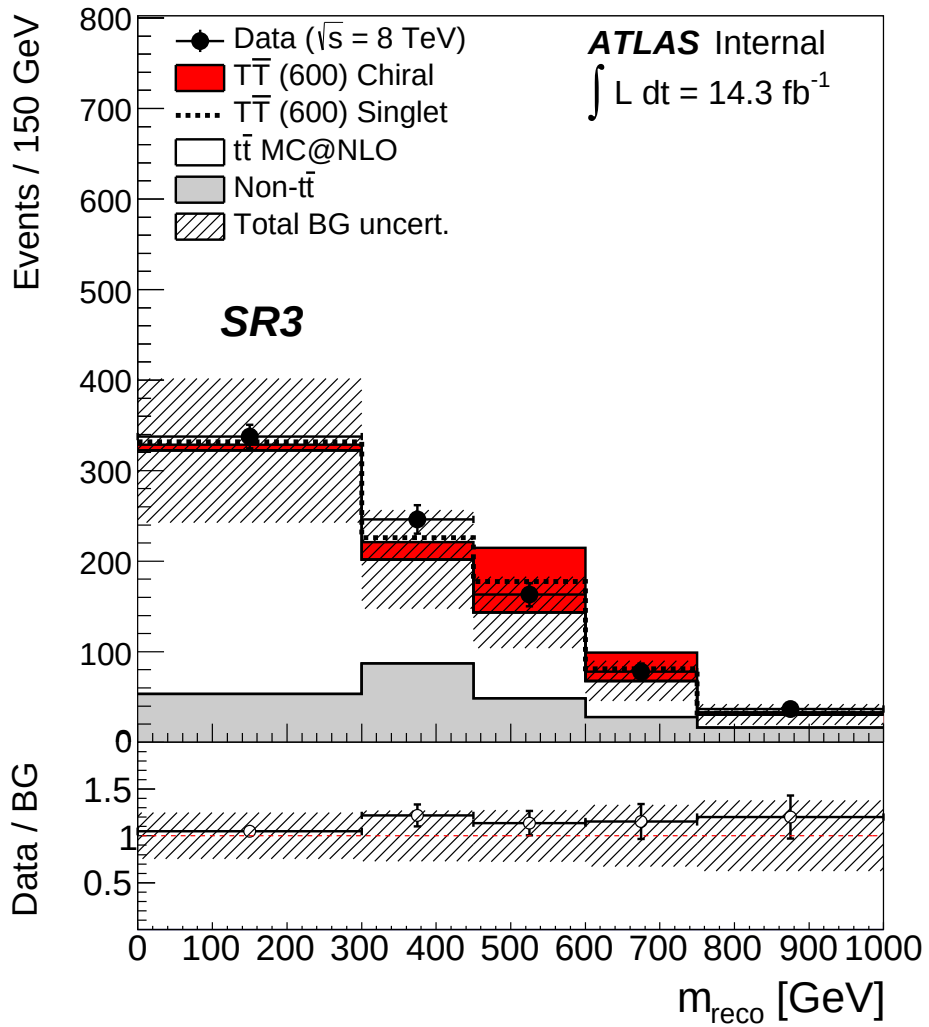

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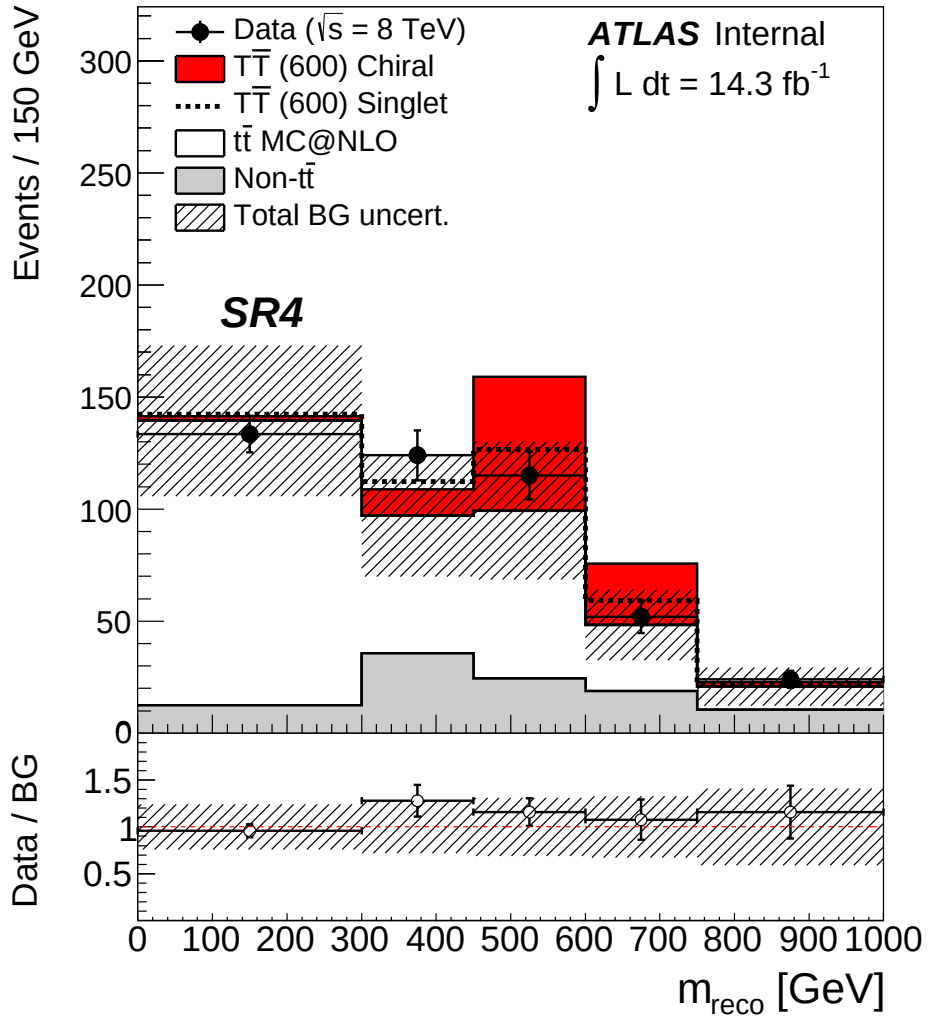

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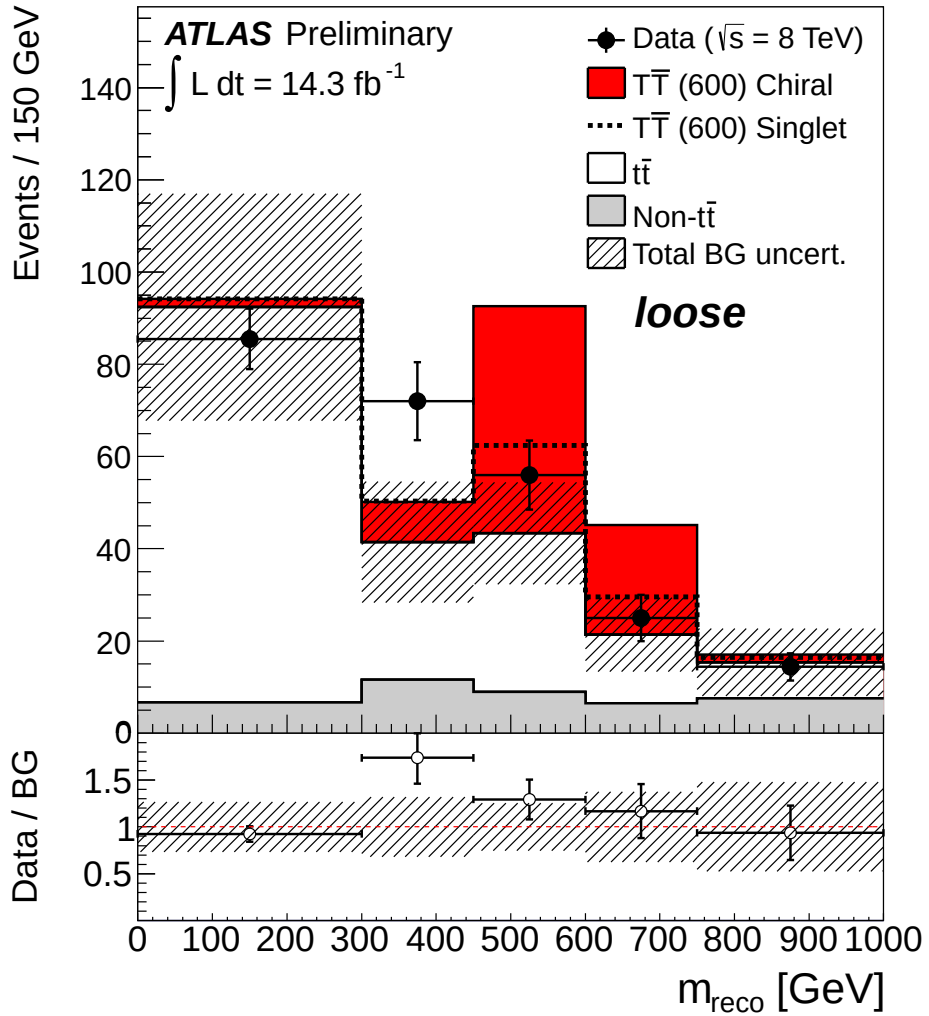

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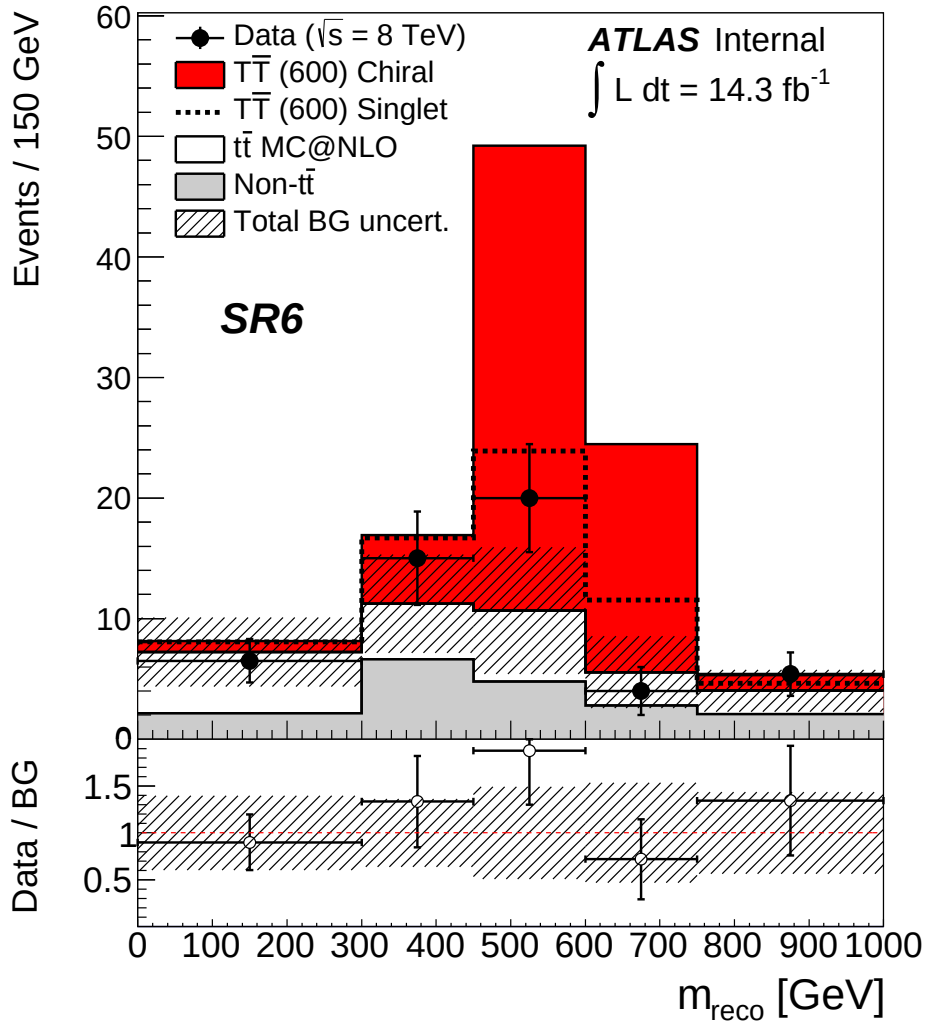

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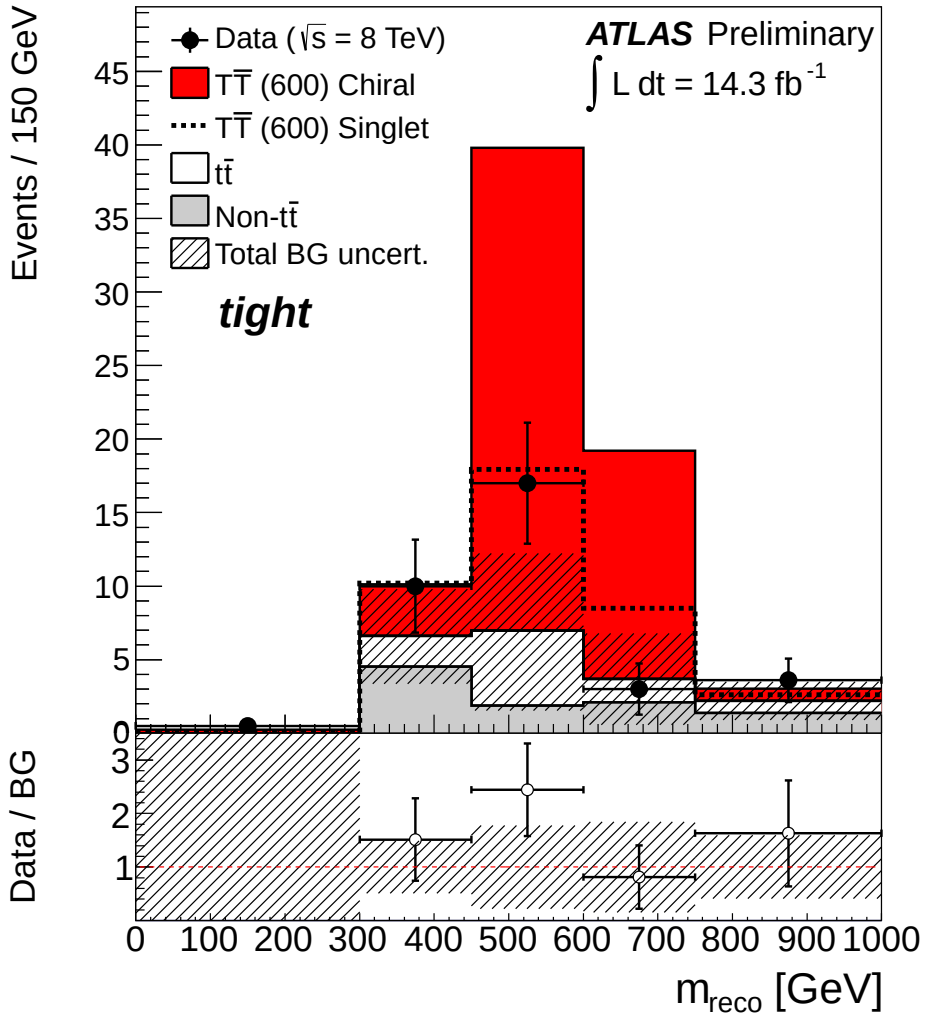

Strategy

Strategy

Outline

Outline

Outline

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[1] S. Gieseke.
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Search for pair production of heavy top-like quarks decaying to a high-p_{T} W boson and a b quark in the lepton plus jets final state at $\sqrt{s} = 7$ TeV with the ATLAS detector.
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References II

[5] ATLAS Collaboration.

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Search for heavy top-like quarks decaying to a higgs boson and a top quark in the lepton plus jets final state in pp collisions at $\sqrt{s} = 8$ tev with the atlas detector.

ATLAS-CONF-2013-018, Mar 2013.

[7] M. Lamont.

The First Years of LHC Operation for Luminosity Production.

in Proceedings of 4th International Particle Accelerator Conference (IPAC 2013), 2013.

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 $W_{\mathrm{had}}^{\mathrm{type\ I}}$ ≥ 4 jets for $W_{\mathrm{had}}^{\mathrm{type\ II}}$	≥ 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