Search for top-antitop resonances

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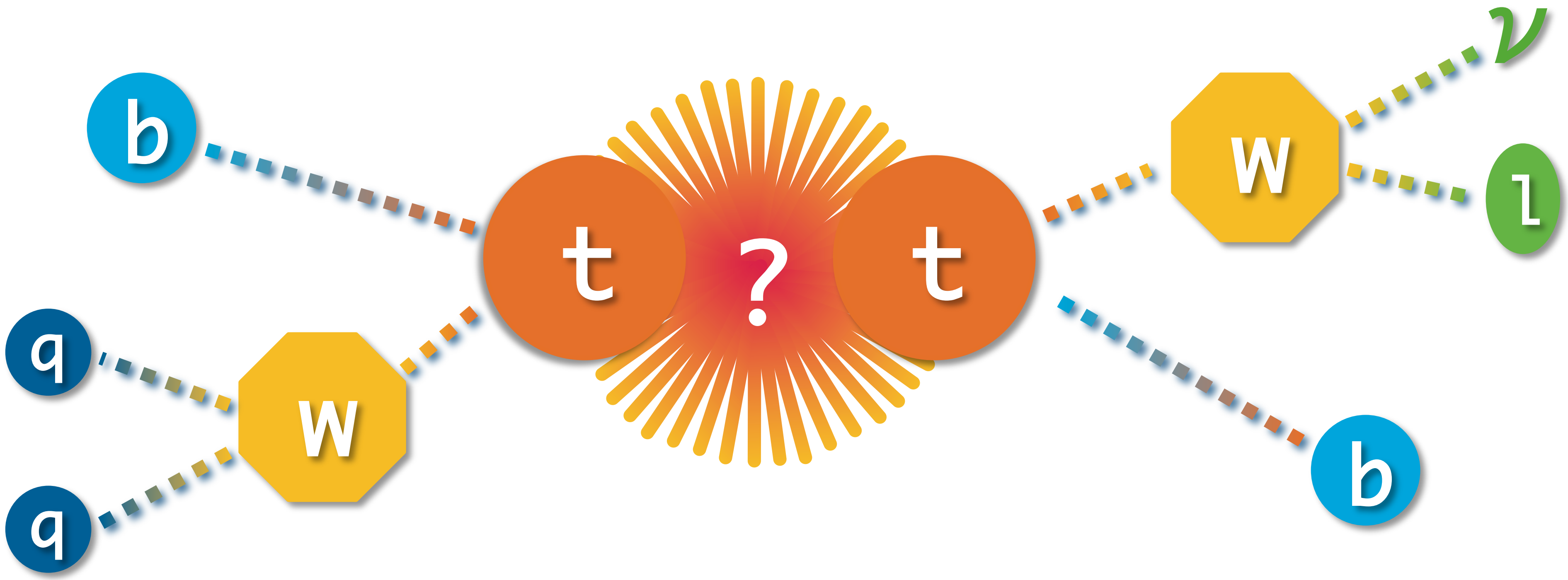
for the ATLAS and CMS collaboration



Programme

New Resonances decaying in top pairs

- Strategies
- Recent Publications and Teams

CMS and ATLAS analyses

- Selection
- Uncertainties
- Results

Outlook

Colour Code:

- ATLAS
- CMS

Search for new Resonance decaying in top-antitop

- SM with the newly discovered Higgs boson is a great framework to work with, but still presents some grey areas
- Top plays often an important role in many new physics scenarios and its study may enlighten these grey areas.

- Many models predicts new heavy resonances decaying predominantly in top pairs:
  - Alternative electroweak symmetry breaking process:
    - Strong EW symmetry breaking

      Ex: TopColor-assisted technicolor, composite Higgs scenarios
    - Higgs sector: top is the most massive particle in SM

      ➜ large coupling to Higgs like particles

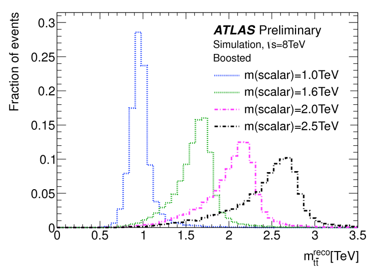
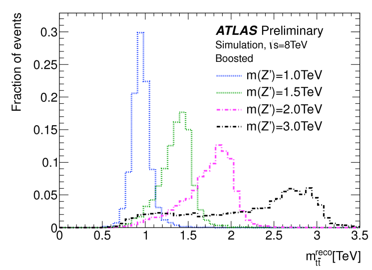
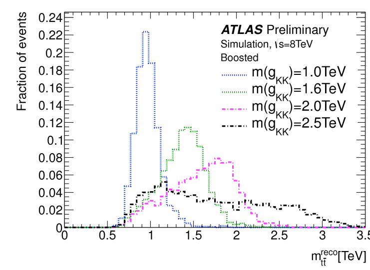
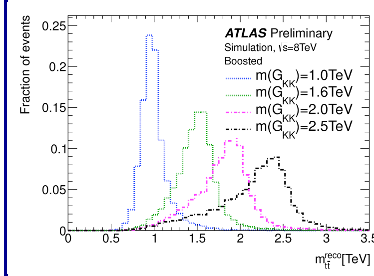
      Ex: 2HDM models
  - Solution to the hierarchy problem:
    - Extra-dimension:

      Ex: RS models with warped extra-dimension: bulk RS gluon or graviton

Analyses strategy

- Resonance properties depends on the model
- Analyses must keep sensitivity to all the different possibilities
  - Mass, Width, Spin, Colour, …

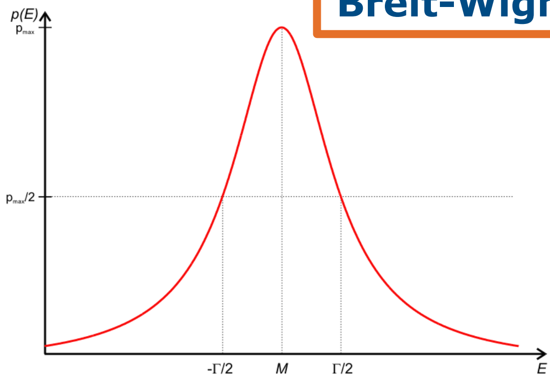
⇨ Use “benchmark” signals to cover the different possibilities
  - Scan in mass from ~400-500 GeV to several TeV
  - Scan in width if not defined by the model

Model	**Scalar produced through gluon fusion**	**Top-colour assisted technicolour Generic Z’**	**RS Kaluza-Klein excitation of the gluon**	**Bulk RS Kaluza-Klein excitation of the graviton**
Spin	0	1	1	2
Colour	singlet	singlet	octet	octet
Width	0.66%	1.2% - 2%-3% 1.2%-10%	15.3%+10-40% 15-20%	3-6%
Exemple of reconstructed mass distributions				

Heavy resonances ?

➜ New heavy particles with short lifetime that appear as resonances

Breit-Wigner



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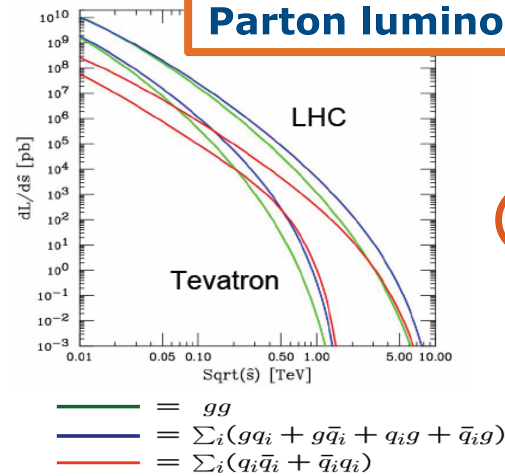
Parton luminosity



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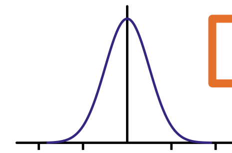
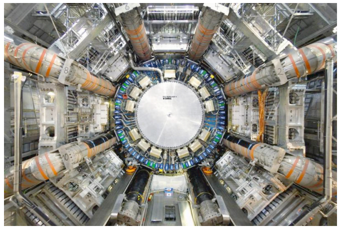
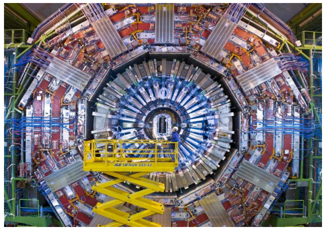
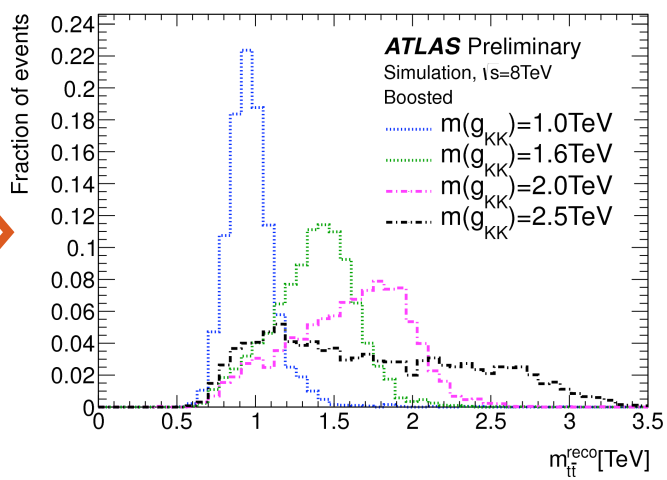
Detector Resolution







⇨



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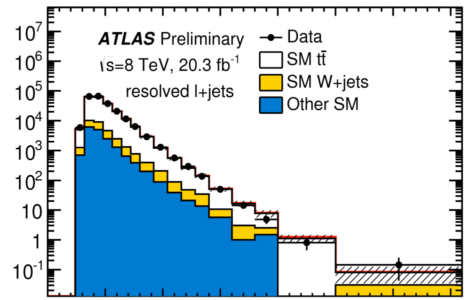

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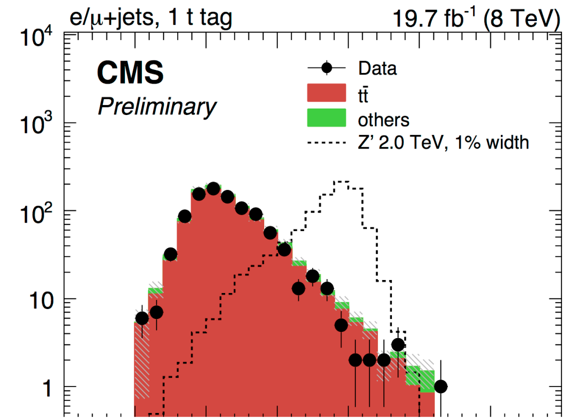
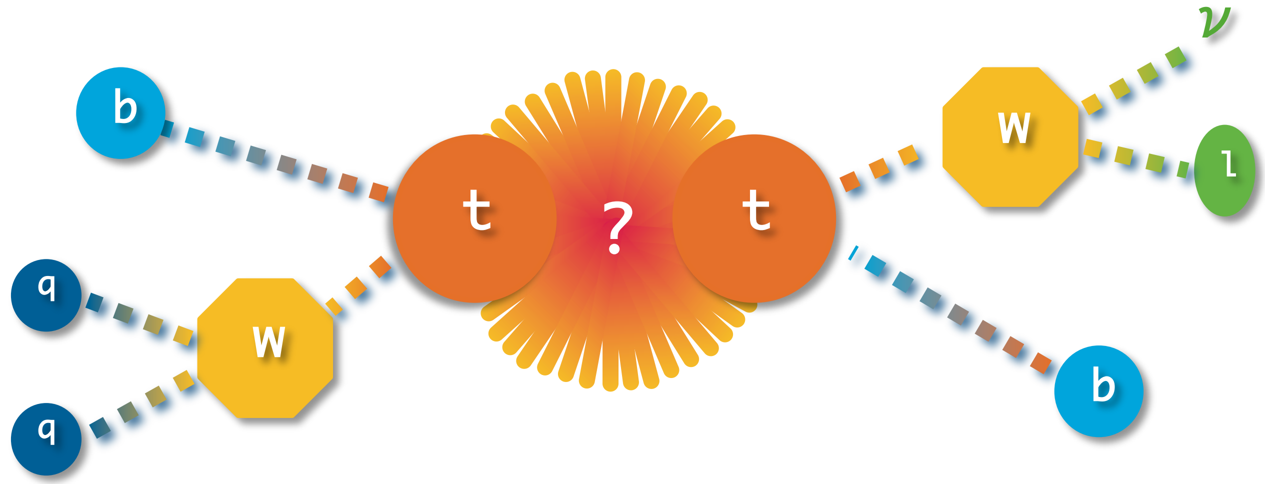


SM background Interferences ?

Bump or hole, narrow or wide, over smooth falling background

Topology



W decays specify the channels:

- All hadronic: 6 jets
- Lepton+jets: l(e,μ)ν, 4 jets
- Dilepton: 2l, 2ν, 2jets

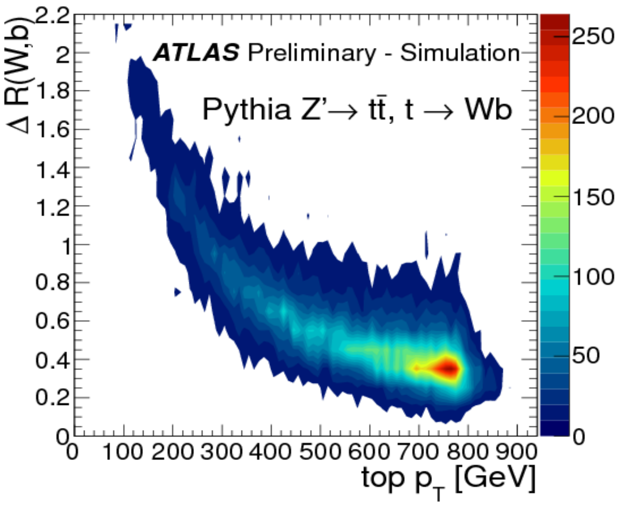
Backgrounds:

- SM ttbar (irreducible: same signature as signal)
- Single top
- W+jets and Z+jets
- Multijets
- diboson, ttV

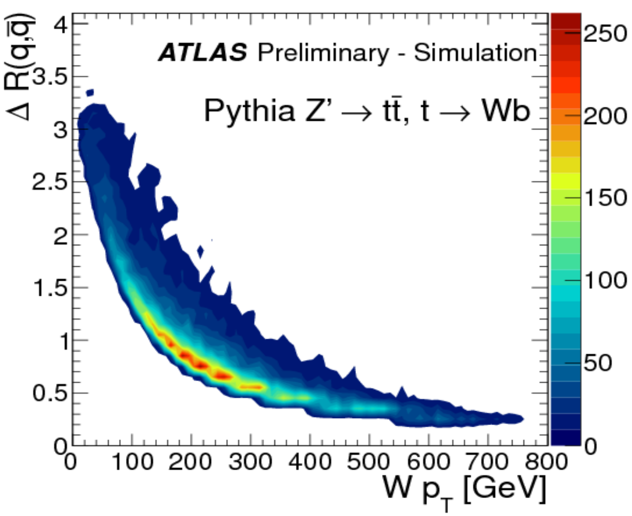
Boosted ?

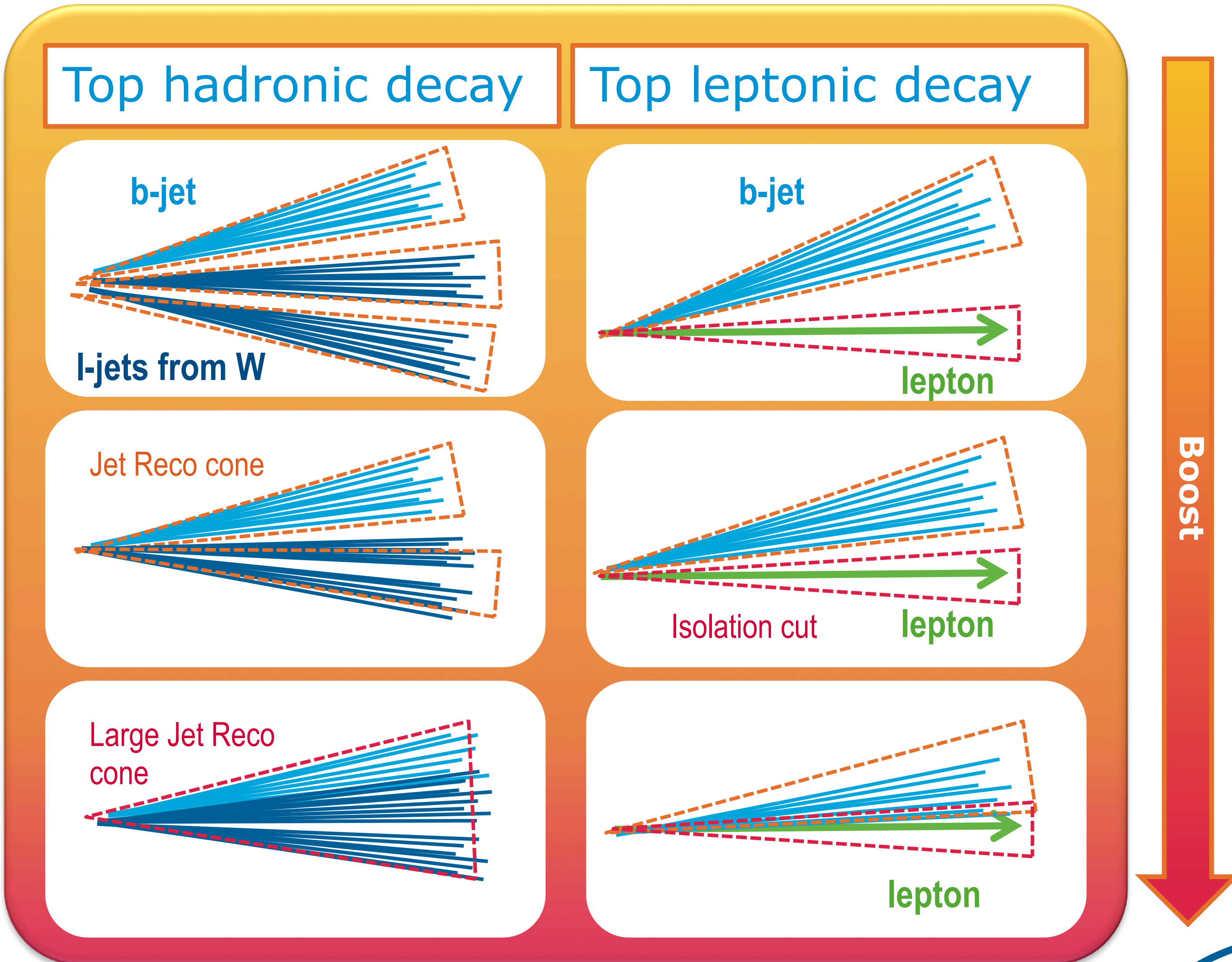
When resonance is heavy (> TeV), the top are boosted

⇨ top decay products tend to be close to each other



$\Delta R \sim 2m/p_T$





Analyses and teams

Latest LHC results: 8 TeV ~20 fb^{-1} run1

CMS

- **l+jets:** B2G-12-006; **all hadronic:** B2G-12-005; **ll:** B2G-12-007
- **All channel combination:** B2G-13-008
- l+jets and all hadronic combination: B2G-13-001, hep-ex:1309.2030, Phys. Rev. Lett. 111 (2013) 211804

ATLAS

- **l+jets analysis:** ATLAS-CONF-2015-009

French Teams: involved in lepton+jets final state

CMS

- IPNL Stéphane Perries, Viola Sordini,
  Sébastien Brochet (PHD finished) and Anne-Laure Pequegnot (PHD 2nd year)
  ➜ in charge of the totality of the threshold (low mass) analysis,

ATLAS

- LPC Samuel Calvet, Loïc Valéry, Silvestre Marino Romano Saez (PHD ? year)
  ➜ reconstruction performances for resolved selection, b-tagging and analysis coordination
- LPSC Sabine Crépé-Renaudin, Pierre-Antoine Delsart,
  Clément Camincher (PHD 1st year)
  ➜ boosted selection (jet substructure, lepton isolation)

ATLAS and CMS analyses

French teams involved in lepton+jets analyses which is the channel with the highest sensitivity

➜ will focus on that channel

➜ will also show CMS combination results

ATLAS and CMS slightly differ in their strategy for the l+jets channel:

- CMS has 2 different analyses: one optimized for the low mass region (resolved or threshold analysis), the other for the boosted one
  - resolved analysis estimates background with data
  - boosted analysis estimates background with simulation and normalisation from fit
- ATLAS has one analysis: events that failed the boosted selection go in the resolved one
  - backgrounds are estimated using simulation except W+jets (mixed) and multijets background (data only)

Both divide their samples as a function of the number of b-tag jet and t-tagged for the CMS boosted one

Signals

- Generic Z' / Topcolour Assisted Techicolour (NLO KF=1.3)
  - Pythia 8.1; MSTW2008LO PDF
  - MadGraph 4.4 + Pythia (MLM matching scheme), CTEQ6L PDF

- Kaluza-Klein excitation of SM gluon: width and cross-section fixed by the resonance's mass Γ/mg =~15%
  - MadGraph 5 + Pythia 8.1; MSTW2008LO PDF
  - Pythia 8 (NLO KF 1.3)

- Kaluza-Klein excitation of SM graviton
  - MadGraph 5 + Pythia 8.1; CTEQ6L1 PDF

- Scalar signal (interference neglected)
  - MadGraph_aMC@NLO (LO ME); CTEQ6L1 PDF
  - MadGraph 5.1 + Pythia 6

Colour Code:
- ATLAS
- CMS

Backgrounds

- SM ttbar
  - Powheg-box r2330.3 (hdamp parameter set to top mass, mtop=172.5 GeV)+ Pythia 6.427 (Perugia 2011C tune); CT10 PDF;
  - Powheg + Pythia; CT10 PDF
- Single top
  - Powheg-box r2330.3 + Pythia 6.427; CT10 PDF
  - Powheg + Pythia; CT10 PDF
- W+jets
  - Alpgen+Pythia 6.427 (Perugia 2011C tune); CTEQ66L1 PDF
    and data-driven Heavy-flavor fraction and Charge-Asymmetry normalization
  - Madgraph 5.1 + Pythia (MLM matching scheme)
- Z+jets
  - Alpgen + Pythia
  - Madgraph 5.1 + Pythia (MLM matching scheme)
- Diboson
  - Sherpa (WW, WZ, ZZ)
  - Pythia 6.2
- ttbar+V
  - Madgraph5 + Pythia 6.427 (ttbar+ W, ttbar+ Wj, ttbar+ Z, ttbar+ Zj)
- Multi-jets
  - Data-driven method (matrix method)
  - data for resolved, negligeable for boosted

Colour Code:
- ATLAS
- CMS

Trigger strategy

CMS

Resolved analysis

- single isolated lepton
  + 3 central jets
  p_T (μ)>17 GeV, p_T (jet)>30 GeV
  p_T (e)>25 GeV, p_T (jet)>30 GeV

Boosted analysis

- 1 μ
  p_T(μ) > 40 GeV
- 1 e + 2 jets
  p_T(e) > 35 GeV
  p_T(jet) >100 GeV, 25 GeV

ATLAS

Electron channel

Combination of triggers

- 1 e isolated or not at different thresholds

Muon channel

Combination of triggers

- 1 μ isolated or not at different thresholds
- or large R=1.0 jets to compensate lost of efficiency due to muon detector structure support

Colour Code:
- ATLAS
- CMS

Object Definition

Electrons

- $E_T > 25$ GeV, $|\eta| < 2.47$ (outside cracks) and isolated*
- longitudinal IP < 2 mm, matched to trigger object
- $E_T > 30$ GeV, $|\eta| < 2.5$, isolated (< 0.1), **resolved**
- $p_T > 35$ GeV, $|\eta| < 2.1$, **boosted**

Muons

- $p_T > 25$ GeV, $|\eta| < 2.5$ (outside cracks) and isolated*
- longitudinal IP < 2 mm; transverse IP/σ(IP) < 3, matched to trigger object
- $p_T > 26$ GeV, $|\eta| < 2.1$, isolated (< 0.12) **resolved**
- $p_T > 45$ GeV, $|\eta| < 2.1$, **boosted**

Jets

- Ak_T 0.4 jets $p_T > 25$ GeV, $|\eta| < 2.5$ (+ for $p_T < 50$ GeV JVF > 0.5)
- Ak_T 1.0 jets with trimming, pT> 300 GeV, $|\eta| < 2.0$ (pT >380 for large jet trigger)
- Ak_T 0.5 $p_T > 30$ GeV, $|\eta| < 2.4$
- CA 0.8 $p_T > 400$ GeV $|\eta| < 2.4$ **boosted**

Missing transverse energy

- $E_T^{miss} > 20$ GeV and $E_T + m_T(l\nu) > 60$ GeV
- $E_T^{miss} > 20$ GeV

Colour Code:
- ATLAS
- CMS

Boosted tools: lepton isolation

CMS

- Resolved analysis:

$I = \Sigma_R\,[p_T\,(\text{hadrons})+p_T\,(\text{photons})]$
electron: $R = 0.3$; cut: $I < 10\%\ p_T(\text{lepton})$
muon: $R = 0.4$; cut: $I < 12\%\ p_T(\text{lepton})$

- Boosted analysis:

No isolation requirement

but $\Delta R(\text{lepton,closest jet})>0.5$ OR $p_{Trel}(\text{lepton,closest jet})>25\text{GeV}$

ATLAS

"Mini-isolation": isolation cone size decreases with p_T to keep good efficiency even at high boost:

$\text{MiniIso} = \Sigma_R\ p_T\,(\text{tracks})$
$R = 10\ \text{GeV}/p_T\,(\text{lepton})$
Cut: $\text{MiniIso10} < 5\%\ p_T(\text{lepton})$

Boosted tools: top tagging

ATLAS

➜ Input: Ak_t 1.0 jets constituents cluster

Variables:

- Jet mass, m_j : calculated with the 4 momenta of the jet constituent (clusters taken as massless)
- First k_t splitting scale, $\sqrt{d_{12}}$: Building the jet with the k_T algorithm, using the 2 last subjets (1,2) in the last step:

$$d_{12} = \min(p^2_{T,1}, p^2_{T,2})\ \Delta R^2_{12} / R^2$$

Cuts

- p_T(large jet) > 300 GeV
- m_j > 100 GeV
- $\sqrt{d_{12}}$ > 40 GeV

Boosted tools: top tagging

CMS t-tagging

➜ Input: CA 0.8 jet (j) particle flow constituent

Decomposition

- Start with last CA step: 2 subjets js_1 js_2
- if $\Delta R(js_1,js_2) > 0.4 - 0.0004\ p_T(j)$ and $p_T(j_i) > 0.05\ p_T(j)$, decomposition succeeded
- restart process with all subjets j_i that pass the p_T cut, $j_i \rightarrow j$

Cuts

- mj near top mass
- $N_{subjet} = 3$
- min pairwise of 3 highest p_T subjet = near m_W
- $\tau_{32} = \tau_3 / \tau_2 < 0.7$

➜ N-Subjettiness τ_N : how close to N subjets is the jet ?

- recluster the jet until having N subjets
- calculate τ_N : p_T weighted sum of the angular separation between each jet constituent and the closest subjet axis

$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} R}$$

Selection

ATLAS

- 1 lepton with at least 1 small jet in $\Delta R(l,j)<1.5$
  ➜ the highest p_T one is jsel (should be the b-jet)
- Boosted selection:
  - 1 large jet tagged as a top with $\Delta R(Ljet,jsel)>1.5$, $\Delta\Phi(l,Ljet)>2.3$
  - $\geq$1 small jet with btag
- Resolved selection
  - event failing boosted topology
  - $\geq$ 4 small jets with $\geq$1b tagged
- events classified wrt lepton flavour and b-tag jets (2 b-tad, lep/had top b-tagged)

CMS

- 1 lepton with at least 2 jets
- Resolved selection
  - $\geq$ 4 jets, leading p_T > 70 GeV second p_T > 50 GeV
  - events classified wrt lepton flavour and b-tag jets
- Boosted selection ➜ **New in combination note !**
  - events classified as a function of lepton flavor the nber of t-tagged CA8 jets; if no t-tagged jet, events classified as a function of b-tagged jet

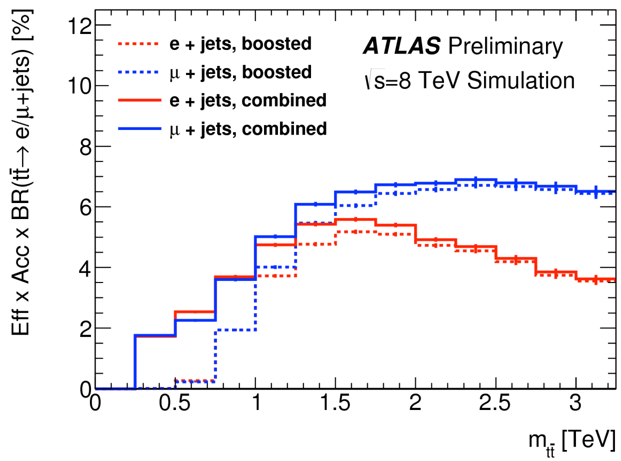
Selection Efficiency

CMS

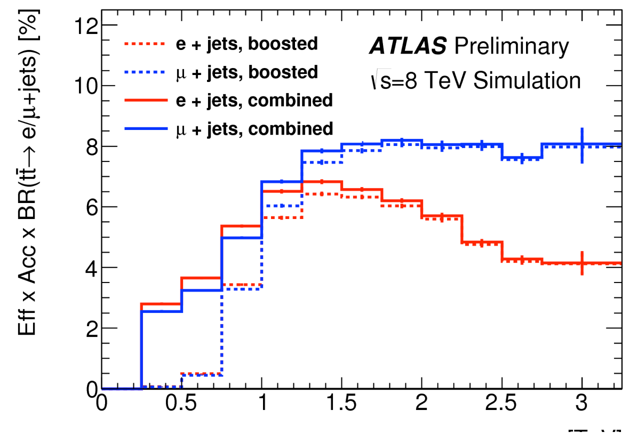
- Resolved Analysis: 7-13 % for resonance masses between 0.6 to 1.5 TeV
- Boosted Analysis: 13 -24 % for resonance masses between 1 to 3 TeV

ATLAS

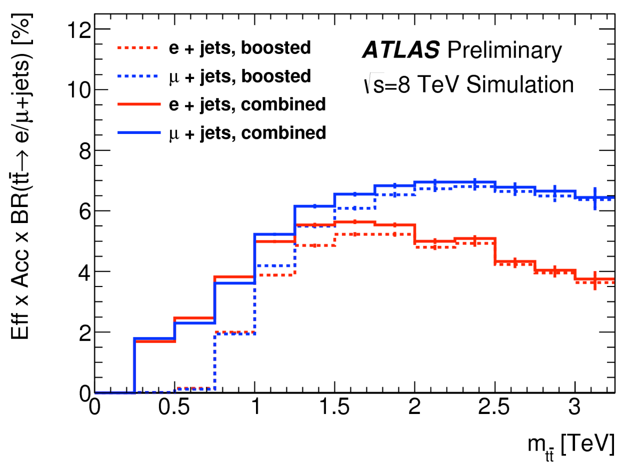
Z′



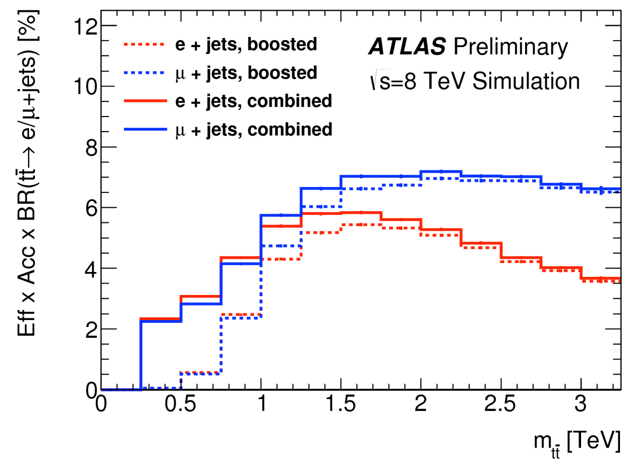
scalar



g_{KK}



G_{KK}



Top mass reconstruction

Invariant mass is calculated assigning each object to the particles issued from the top decays:

leptons, $p_T(\nu)=E_T^{Miss}$, b-jets, jets

➜ $p_Z(\nu)$ needs to be calculated and jets assigned to one of the top

➜ $p_Z(\nu)$ from $m(l,\nu)=m(W)$

Resolved Analyses

- Minimize a χ^2 using W and top mass, top p_T to choose the best ν solution and the best jet assignment
  - ➜ Good assignment in ~ 80% of the events

Boosted Analyses

ATLAS

- ν: if no real solution vary E_T^{Miss}, if 2 real solutions take the smallest one then
- no ambiguity: large jet assigned to hadronic top, jsel to leptonic top b-quark

CMS

- χ^2 with leptonic and hadronic top mass build; solution that minimize the χ^2 is kept if $\chi^2 < 10$ (W+jets background rejection)

Background Evaluation

ATLAS

Uses simulation for most of the backgrounds but for W+jets and multijets

- **W+jets:** normalisation and flavour fractions are derived from data using the W charge asymmetry
- **multi-jets:** data used with the matrix method that benefit from the different probability for a real/fake lepton to pass a tight identification cut

CMS

Uses a likelihood fit on data

- **Resolved**: uses a fixed shape pdf for the background
- **Boosted**: use simulated samples and a binned likelihood fit on the different channels (lepton flavour, tagging categories)

  ➜ extract background normalisation, CA8 t-tagging and subjet b-tagging efficiencies

Colour Code:
- ATLAS
- CMS

Uncertainties

➜ Reconstructed object and Background/signal modelling that affects normalisation and/or shape

Reconstructed object

- leptons: 0.5-3%
- JES, JER: few %, vs η 5-8%
- pile-up reweighting
- b-tagging: 2-3% low pT, 5-8% high pT
- t-tagging in simu: 25%

Background/signal modelling

- ttbar: 15% for mtt > 1 TeV
- W+jets: 9%/23% light/heavy flavour jets
- Z+jets σ: 50%
- single top (Wt): 23%
- diboson: 20%
- bkd and signal pdf
- lumi: 2.6%

Reconstructed object

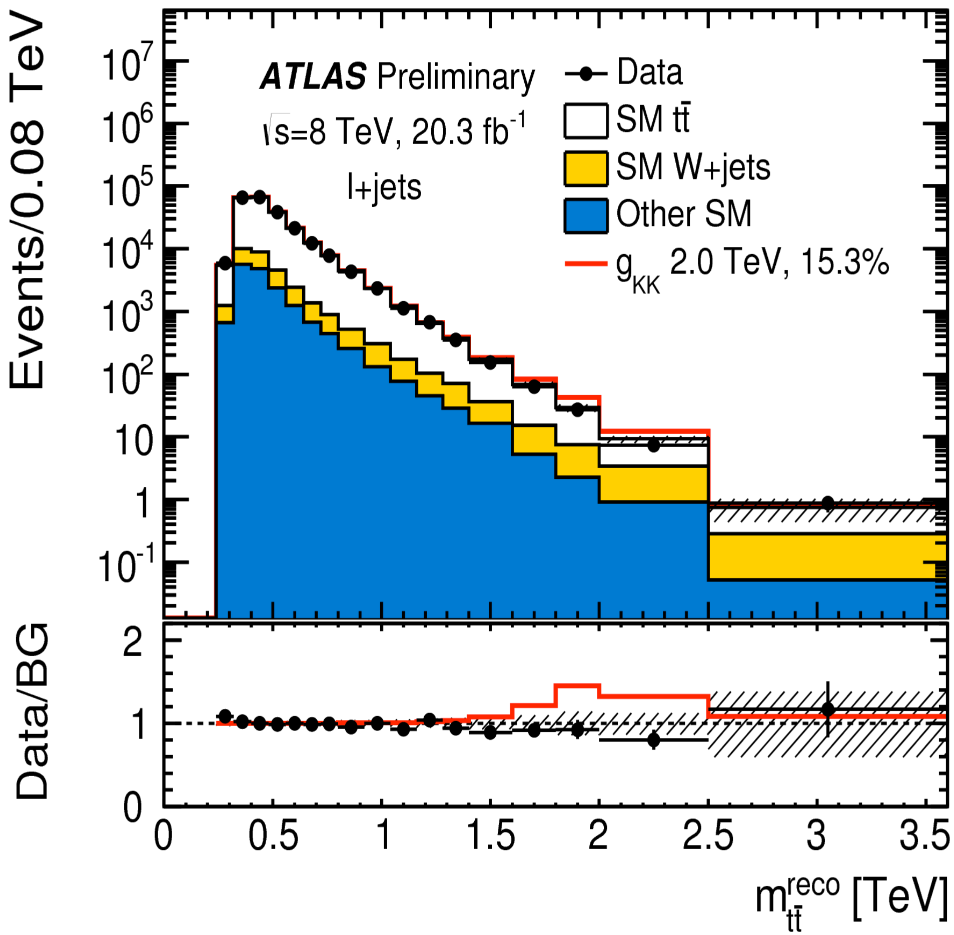
- leptons eff: <1%
- JES, JER small jet 5.6%, large jet 10%
- b-tagging: <2% resolved, 17.1% boosted ana

Background/signal modelling

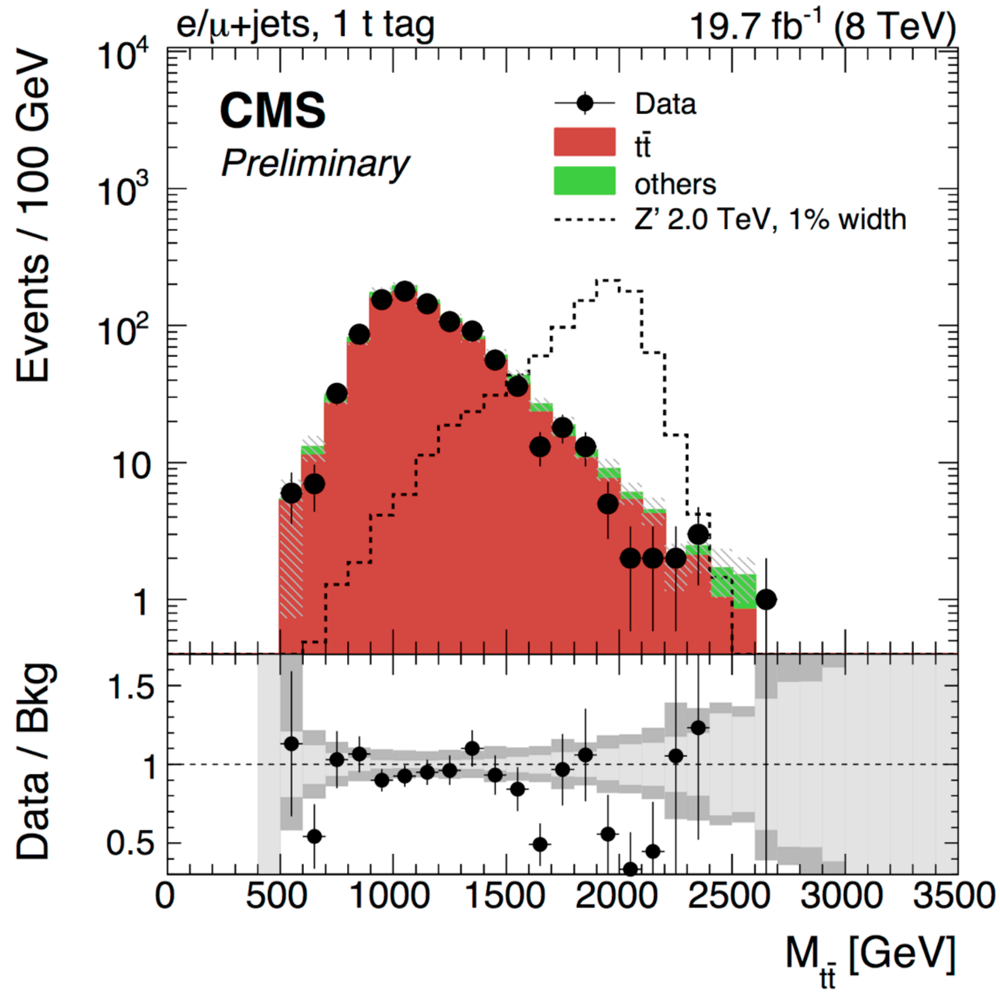
- ttbar σ: 6.5%, PDF
- W+jets normalisation
- Z+jets: 48%
- single top: 7.7%
- diboson: 34%
- multijets: 20%
- PDF few%, parton shower, frag 4.8%
- lumi: 2.8%

Results

ATLAS



CMS



➜ No Excess…

Limit Settings

ATLAS

Local excess or deficits search with BumpHunter

➜ no deviation found

⇨ Upper limits set on σ x BR with a profile likelihood test using Histfitter

CMS

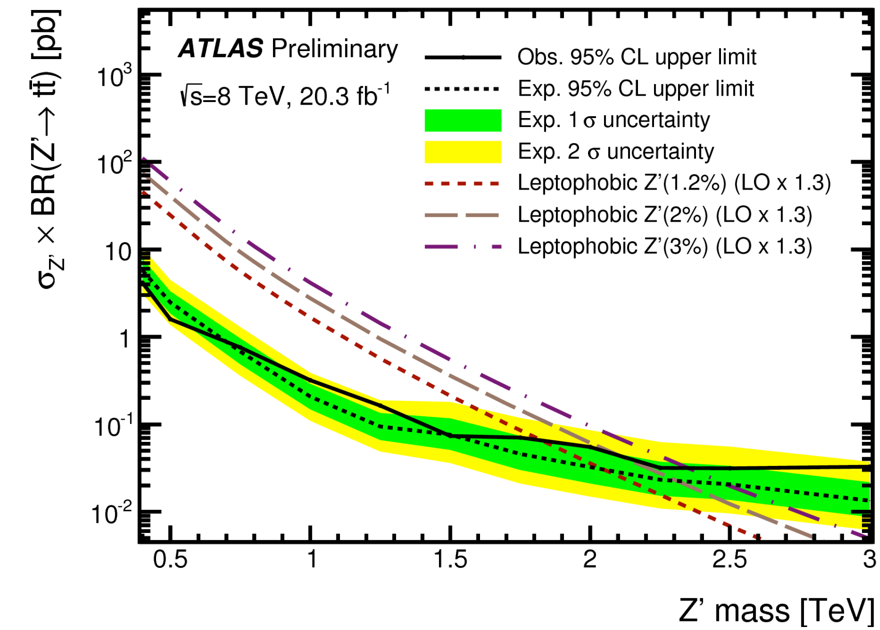
Bayesian Statistical method is used to derive 95% CL upper limits on the σ x BR using template based evaluation

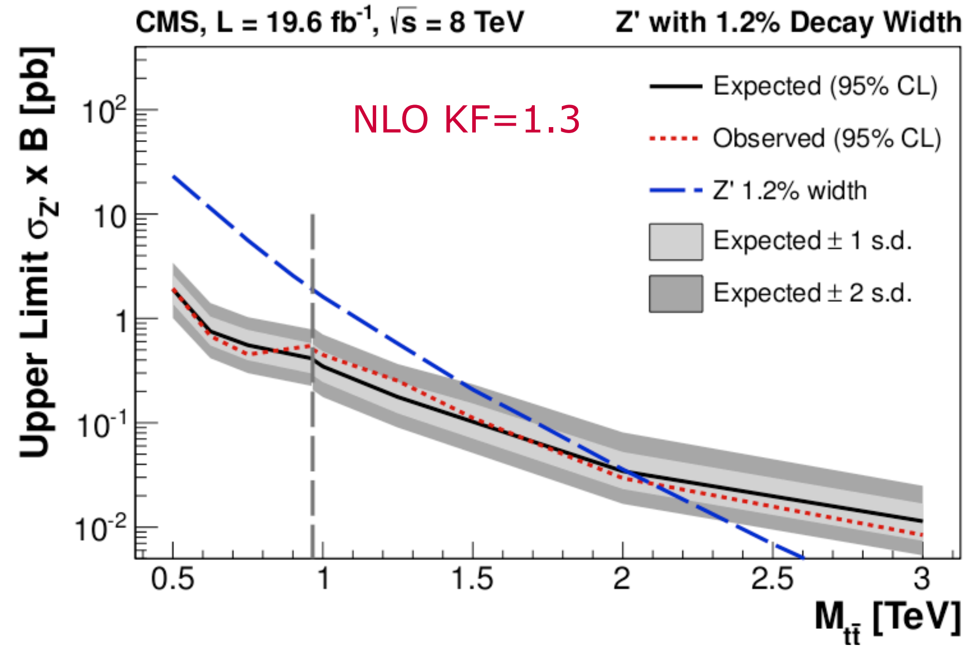
Colour Code:
- ATLAS
- CMS

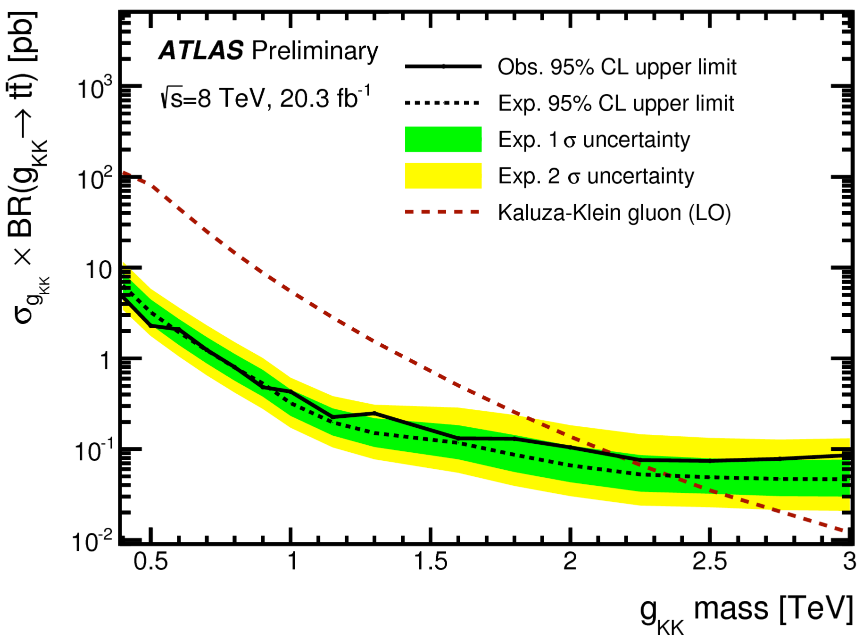
Limits: l+jets

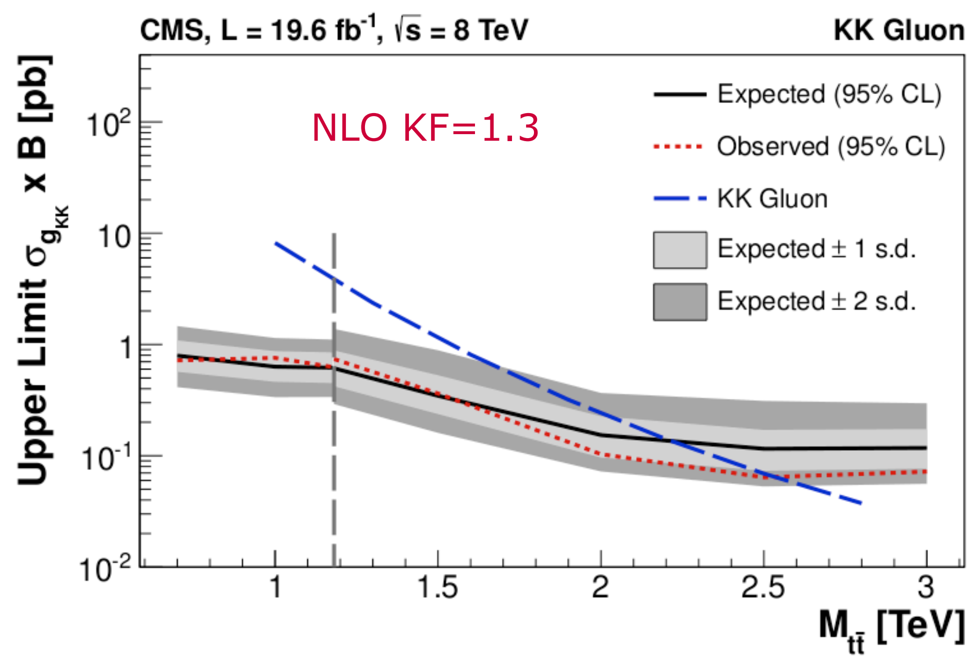
ATLAS

CMS

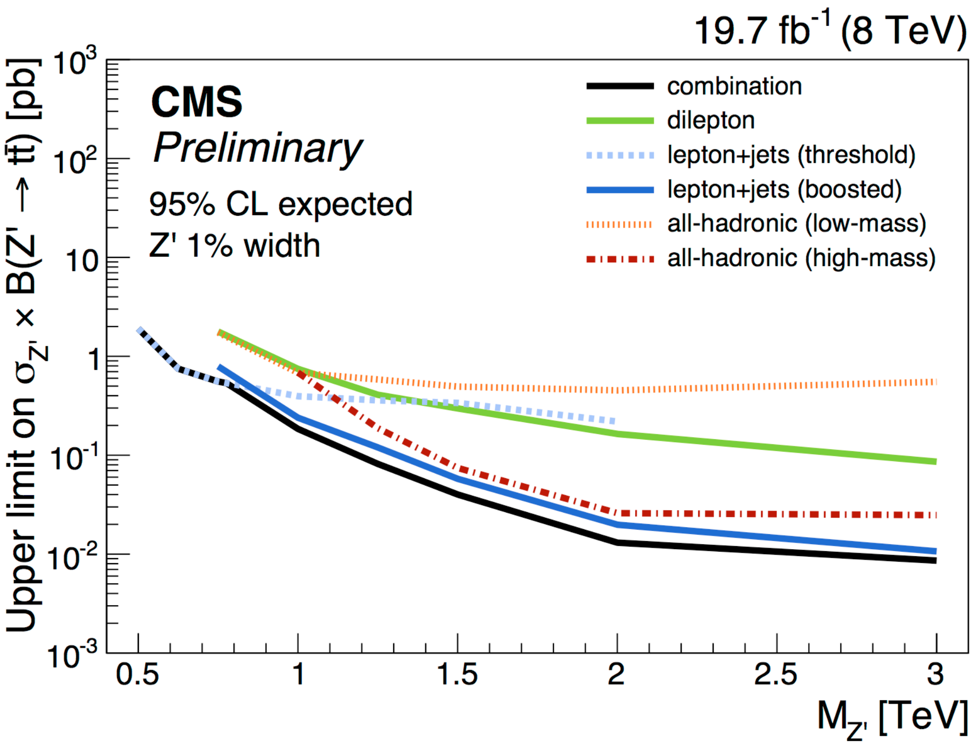


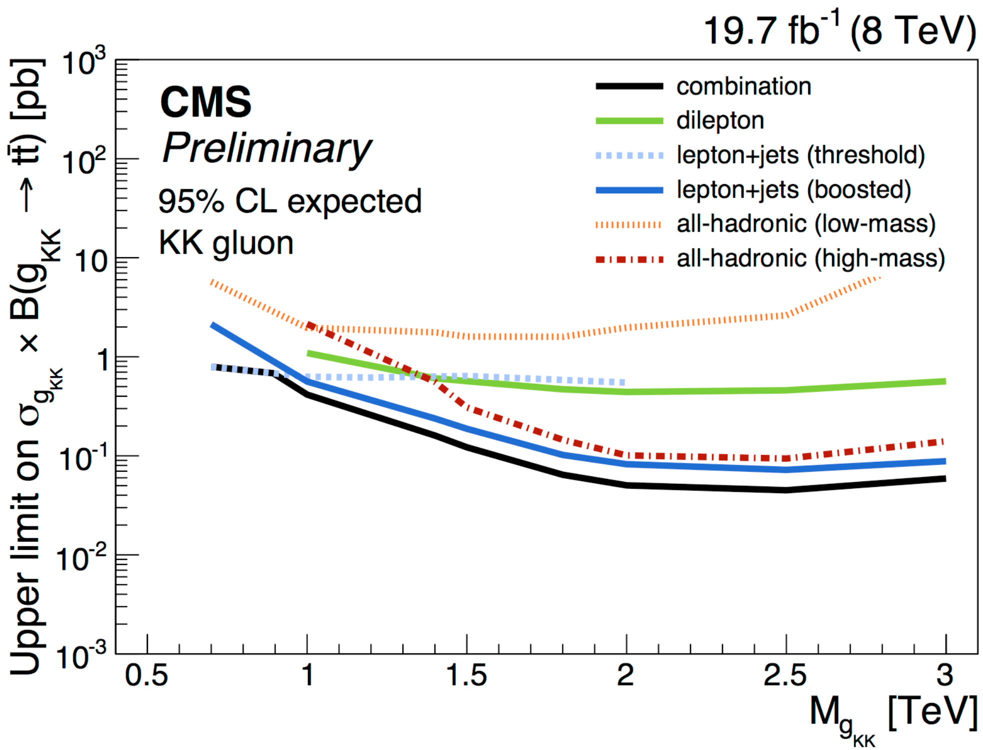






Combined CMS limits





Limits

Models	Scalar produced through gluon fusion ! No interference	Top-colour assisted technicolour/ generic Z'	RS Kaluza-Klein excitation of gluon	Bulk RS Kaluza-Klein excitation of graviton
Spin	0	1	1	2
Colour	singlet	singlet	octet	octet
Width	0.66%	1.2%	15.3%	3-6%
ATLAS l+jets Exp Obs	3.0-0.03 pb	2.0 TeV 1.8 TeV	2.3 TeV 2.2 TeV	2.5-0.03 pb
CMS l+jets Exp Obs	m=500&750GeV 0.8 & 0.3 pb	2.2 TeV 2.3 TeV	2.5 TeV* 2.5 TeV*	
CMS combined Exp Obs		2.4 TeV 2.4 TeV	2.7 TeV* 2.8 TeV*	

* k-factor on cross-section=1.3 for CMS
(no k-factor used by ATLAS)

Conclusion

Both experiments looks for heavy resonances decaying in top-antitop pair using the full run1 8 TeV sample (~ 20 fb^{-1})

As soon as resonance mass reach the ~ TeV, top are boosted and boosted technics need to be developed to keep good sensitivity

⇨ these analyses were nice laboratories to test pioneering technics

Data are in agreement with SM expectations

⇨ limits set on various theoretical models in the 2-3 TeV mass range and for σ x BR ~ few pb to 0.01 pb

⇨ low mass range explored also down to 400 GeV

⇨ results available in HEPDATA

Run 2 is starting, we will have the opportunity to

⇨ improve the use of model (interference for scalar model,…)

⇨ be sensitive to processes with smaller cross-section in the full mass range

⇨ reach higher mass resonances

Let's see what 13 TeV data will tell us…

Conclusion

Thanks to Viola Sordini and Samuel Calvet !

Bonus

Object definition (II)

Overlap removal

- e/jet if DR<0.4 e 4 momentum removed from the jet, if $\Delta R<0.2$ after removal e removed from the event and added back to the jet
- muon removed if $\Delta R < 0.04+10$ GeV/pT
- e or μ 4 momentum subtracted from the jet if $\Delta R(l,jet) < 0.5$

Colour Code:
- ATLAS
- CMS

Selection Tools

b-tagging

- Multivariate technics (IP, secondary vertex and decay topology) applied to Ak_T 0.4 jets
  - WP eff 70% on ttbar
- Secondary Vertex Algorithm (CSV) applied to AKT 0.5 jets,
  - WP 70% efficiency fake rate 1%
- CSV also applied on CA jets:
  - 63% efficiency WP

Boosted tools

- Lepton mini-isolation
  - used by ATLAS
- Top-tagging to identify the large jet as coming from a top
  - cut based
  - CMS t-tagging algorithm

Colour Code:
- ATLAS
- CMS

ATLAS Background Evaluation

W+jets

Data used to get normalisation and flavour fraction comparing the W boson charge asymmetry in data and MC ⇨ allows to reduce the systematics

Scale factor CA = $(N_{W+} + N_{W-})_{data}$ / $(N_{W+} + N_{W-})_{MC}$

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D_{corr+} - D_{corr-})$$

N_W = Nber of events with W in data
D_{corr} = Nber of events with lepton in data
r_{MC} = Bber(W^+)/Nber(W^-) in MC

Charge asymmetric contributions of single top, VV, ttV are evaluated in MC are subtracted.
Charge symmetric processes (ex ttbar) cancel in the difference.

Similar method is used to extract K-factor for flavour fractions (bbar, ccbar, c, light)

Multijets

Matrix method is used on data: it uses the different efficiency for prompt and non-prompt lepton coming from a jet to pass a tight identification cut cut

$$N_L = N_{prompt} + N_{multi\text{-}jets}$$
$$N_T = \varepsilon \times N_{prompt} + f \times N_{multi\text{-}jets}$$

ε and f are measured on control samples
$N_{prompt} + N_{multi\text{-}jets}$ are obtained solving the 2 equations

CMS Background Evaluation and fit

➜ In situ with the likelihood fit on data

Resolved analysis

using data and background fixed shape pdf in the 4 different channels

Signal: superposition of Gaussian kernel

Background: $$\frac{\left(1-\frac{m}{\sqrt{s}}\right)^{c_1}}{\left(\frac{m}{\sqrt{s}}\right)^{c_2+c_3 \ln \frac{m}{\sqrt{s}}}}$$

Boosted analysis

use simulated samples and a binned likelihood fit on the different channels (lepton flavour, tagging categories)

➜ extract background normalisation, CA8 t-tagging and subjet b-tagging efficiencies

Event Yield

CMS

Sample	electron+jets channel $N_{\text{b-tag}} = 0$	electron+jets channel $N_{\text{b-tag}} \geq 1$	muon+jets channel $N_{\text{b-tag}} = 0$	muon+jets channel $N_{\text{b-tag}} \geq 1$
$t\bar{t}$	2583.8	4372.9	2854.5	4718.5
W+jets (+b)	25.7	35.8	21.5	34.6
W+jets (+c)	319.8	23.2	421.1	37.4
W+jets (+light)	1985.8	49.6	2282.0	62.4
Z+jets	76.3	5.9	121.3	9.6
Diboson	29.3	3.3	43.1	4.9
Single Top	266.6	384.5	284.4	418.2
Total Background	5287 ± 703	4875 ± 658	6028 ± 741	5285 ± 629
Data	5346	4820	5959	5339

ATLAS

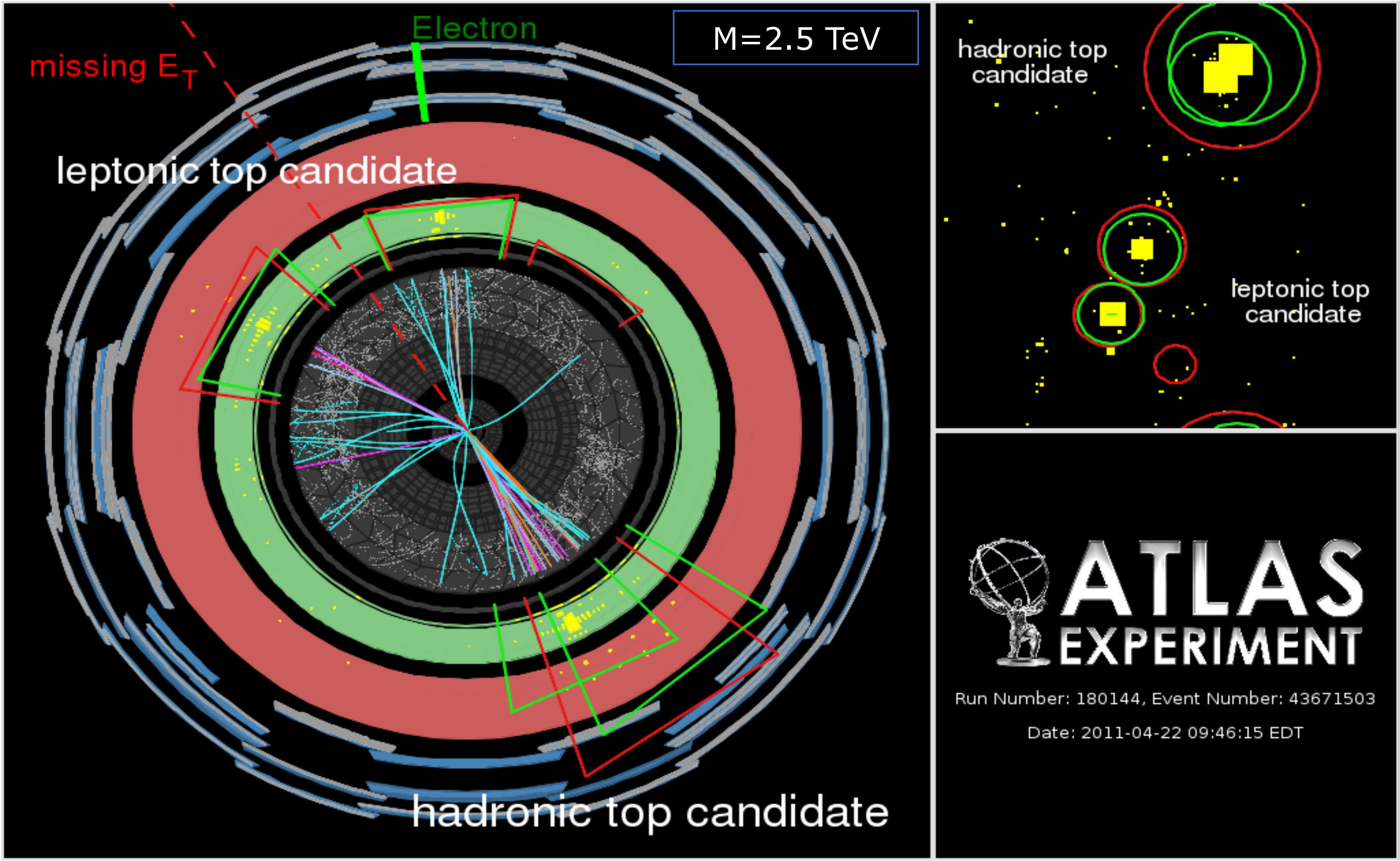
Resolved-topology selection

Type	e+jets	μ+jets	Sum
$t\bar{t}$	93,000 ± 11,000	91,000 ± 11,000	184,000 ± 22,000
Single top	3,800 ± 400	3,800 ± 400	7,600 ± 800
$t\bar{t}V$	274 ± 13	267 ± 13	541 ± 25
Multi-jet e	5,300 ± 1,100	–	5,300 ± 1,100
Multi-jet μ	–	1,050 ± 240	1,050 ± 240
W+jets	6,600 ± 800	7,100 ± 800	13,700 ± 1500
Z+jets	1,400 ± 330	650 ± 130	2,000 ± 400
Di-bosons	320 ± 50	310 ± 50	620 ± 100
Total	110,000 ± 12,000	105,000 ± 12,000	215,000 ± 24,000
Data	114,377	108,953	223,330

Boosted-topology selection

Type	e+jets	μ+jets	Sum
$t\bar{t}$	4,100 ± 600	4,000 ± 600	8,100 ± 1200
Single top	138 ± 20	154 ± 20	290 ± 40
$t\bar{t}V$	37 ± 4	38 ± 4	75 ± 7
Multi-jet e	91 ± 18	–	91 ± 18
Multi-jet μ	–	8.6 ± 1.6	8.6 ± 1.6
W+jets	260 ± 50	290 ± 50	550 ± 100
Z+jets	31 ± 6	17 ± 5	48 ± 9
Di-bosons	21 ± 4	20 ± 4	41 ± 7
Total	4,700 ± 600	4,500 ± 600	9,200 ± 1200
Data	4,148	4,058	8,206

Single Lepton Boosted ttbar



Top mass reconstruction

Resolved Analyses

➜ Lowest χ^2 allows to choose best ν solution and best jet assignment

➜ Good assignment in ~ 80% of the events

ATLAS

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{\mathrm{T},jjb} - p_{\mathrm{T},j\ell\nu}) - (p_{\mathrm{T},t_h} - p_{\mathrm{T},t_\ell})}{\sigma_{\mathrm{diff}\, p_\mathrm{T}}}\right]^2$$

CMS

$$\chi^2 = \chi^2_{m(tlep)} + \chi^2_{m(thad)} + \chi^2_{m(whad)} + \chi^2_{p_\mathrm{T}(\mathrm{t\bar{t}})}$$

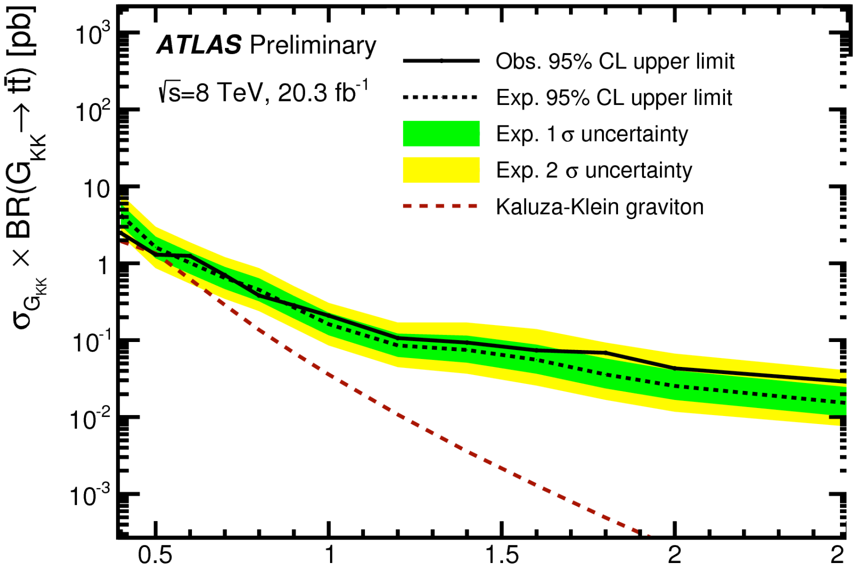
$$\chi^2_x = (x_{meas} - x_{MC})^2 / \sigma^2_{MC}$$

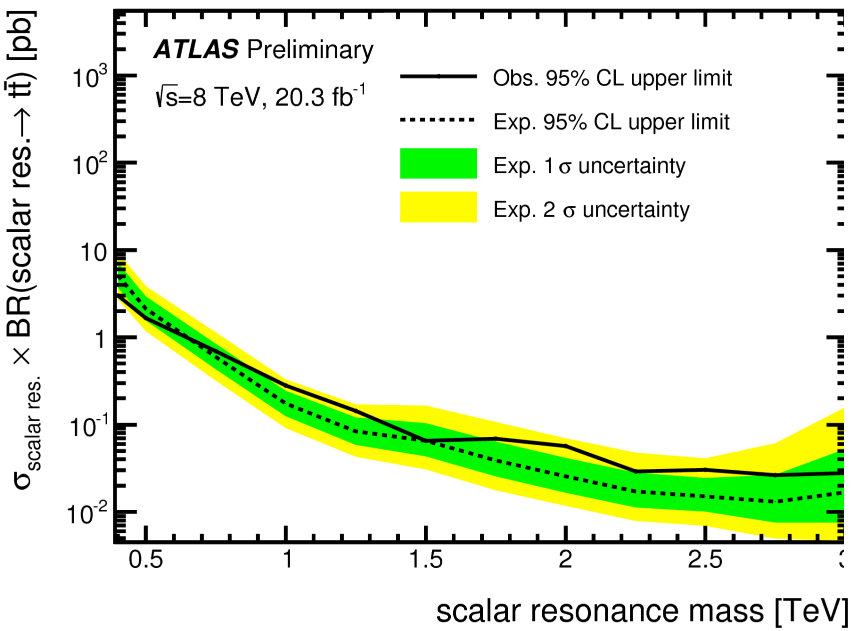
Colour Code:
- ATLAS
- CMS

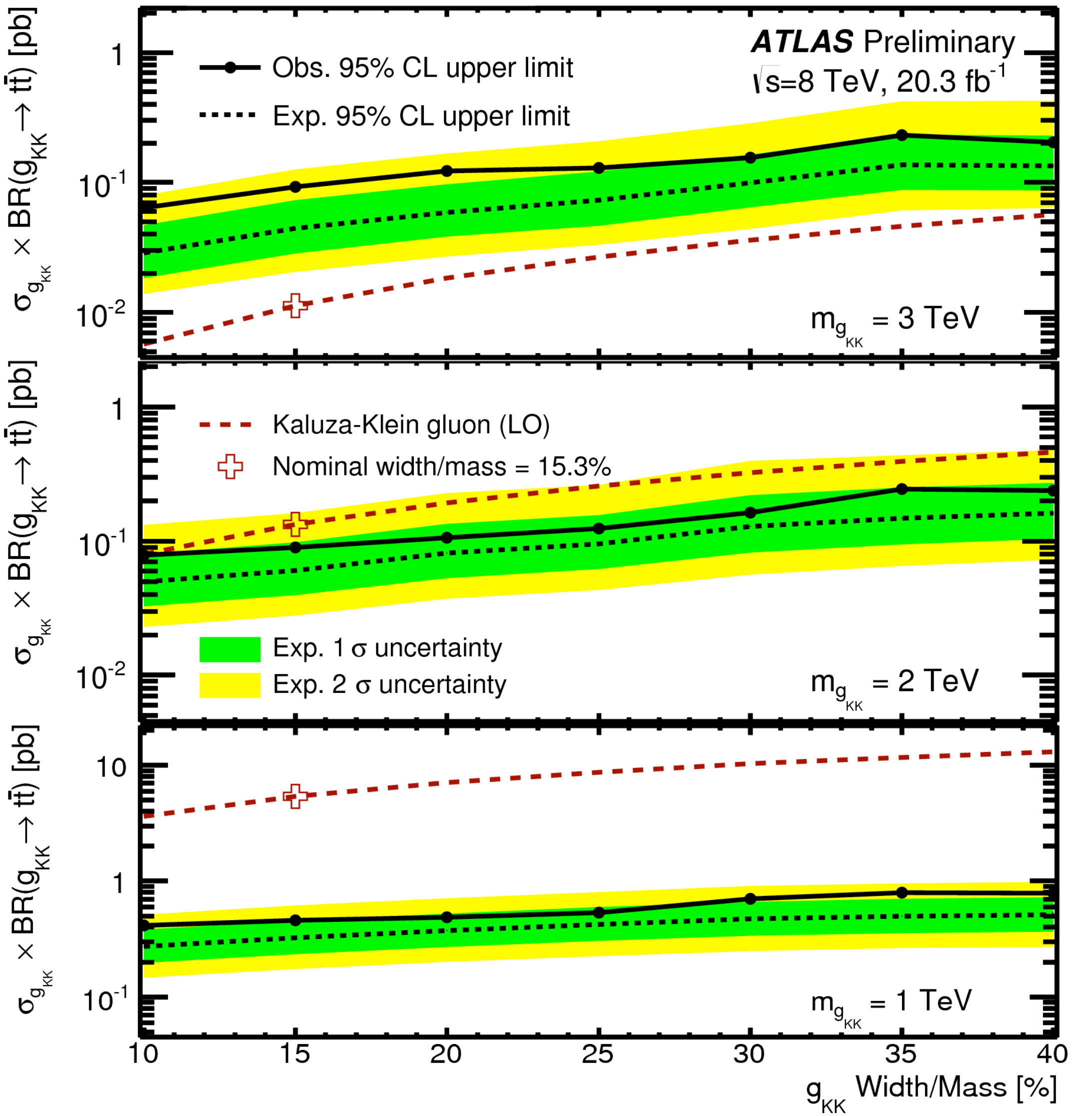
Systematic Uncertainties

Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Resolved selection yield impact [%] Z'	Boosted selection yield impact [%] total bkg.	Boosted selection yield impact [%] Z'
Luminosity	2.5	2.8	2.6	2.8
PDF	2.4	3.6	4.7	2.3
ISR/FSR	3.7	–	1.2	–
Parton shower and fragmentation	4.8	–	1.5	–
$t\bar{t}$ normalisation	5.3	–	5.5	–
$t\bar{t}$ EW virtual correction	0.2	–	0.5	–
$t\bar{t}$ Generator	0.3	–	2.6	–
$t\bar{t}$ Top quark mass	0.6	–	1.4	–
W+jets Generator	0.3	–	0.1	–
Multi-jet norm, e+jets	0.5	–	0.2	–
Multi-jet norm, μ+jets	0.1	–	< 0.1	–
JES+JMS, large-radius jets	0.1	2.1	9.7	2.8
JER+JMR, large-radius jets	< 0.1	0.2	0.6	0.2
JES, small-radius jets	5.6	2.6	0.4	1.4
JER, small-radius jets	1.8	1.4	< 0.1	0.2
Jet vertex fraction	0.8	0.8	0.2	< 0.1
b-tagging b-jet efficiency	1.1	2.0	2.9	17.1
b-tagging c-jet efficiency	0.1	0.7	0.1	2.1
b-tagging light-jet efficiency	< 0.1	< 0.1	0.5	0.2
Electron efficiency	0.3	0.6	0.6	1.3
Muon efficiency	0.9	1.0	1.0	1.1
MC statistical uncertainty	0.4	6.0	1.3	1.8
All systematic uncertainties	10.8	8.8	13.3	18.0

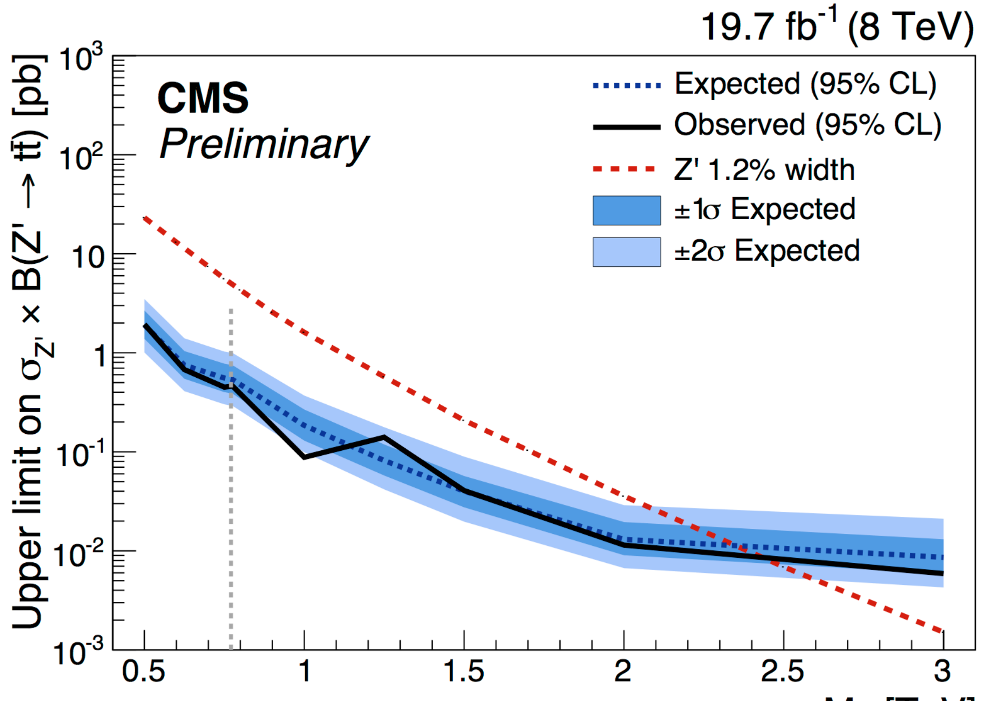
ATLAS Limits II

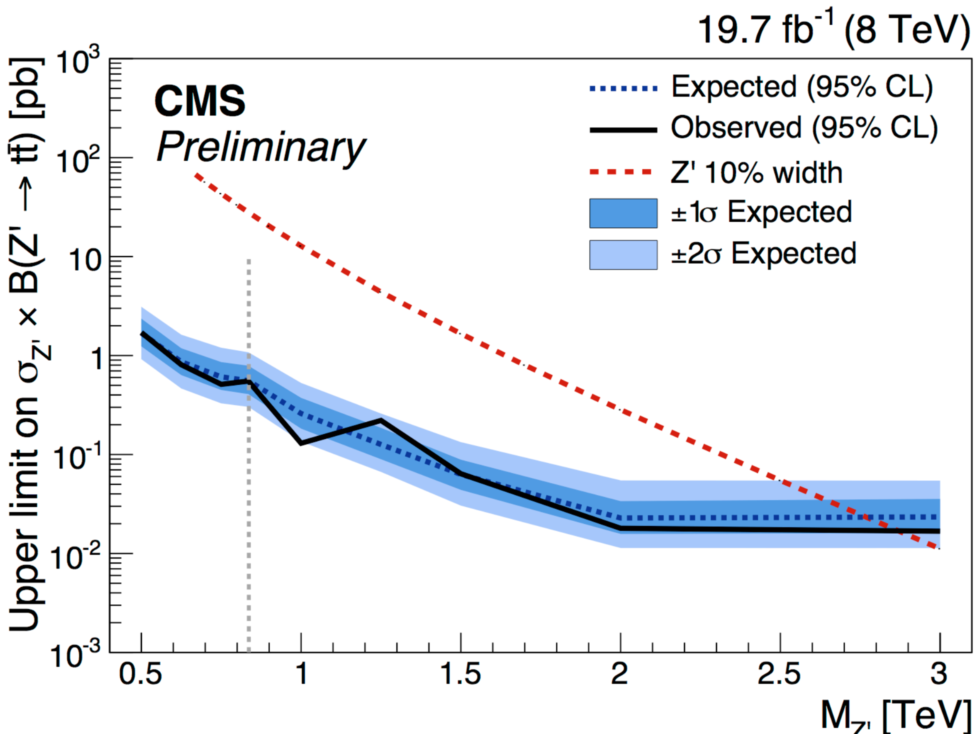


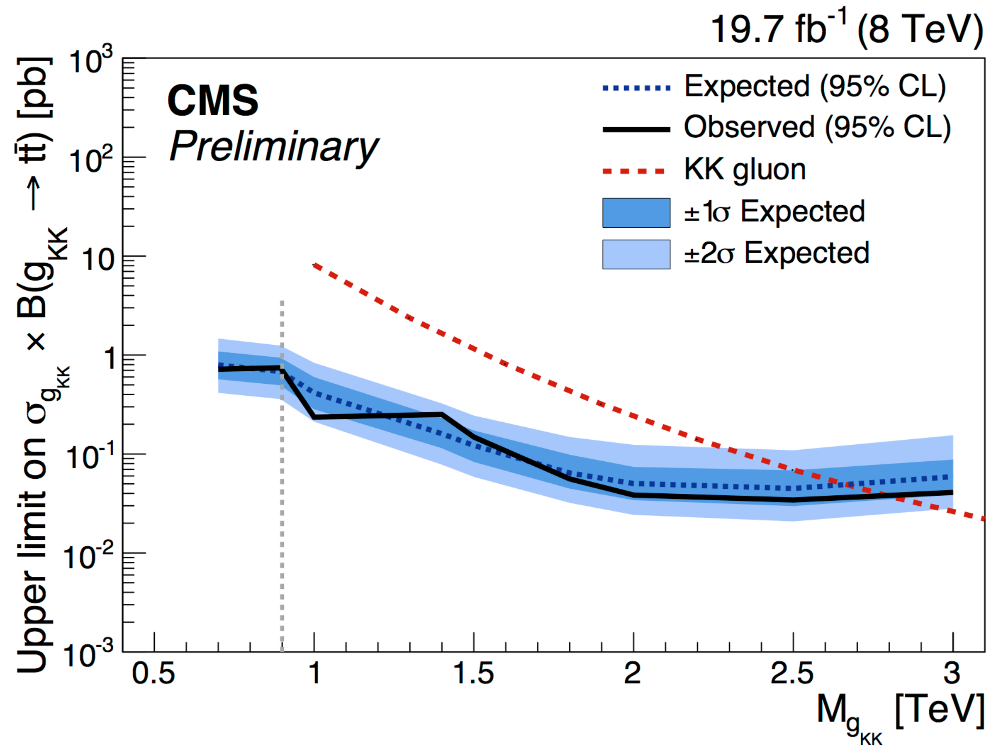




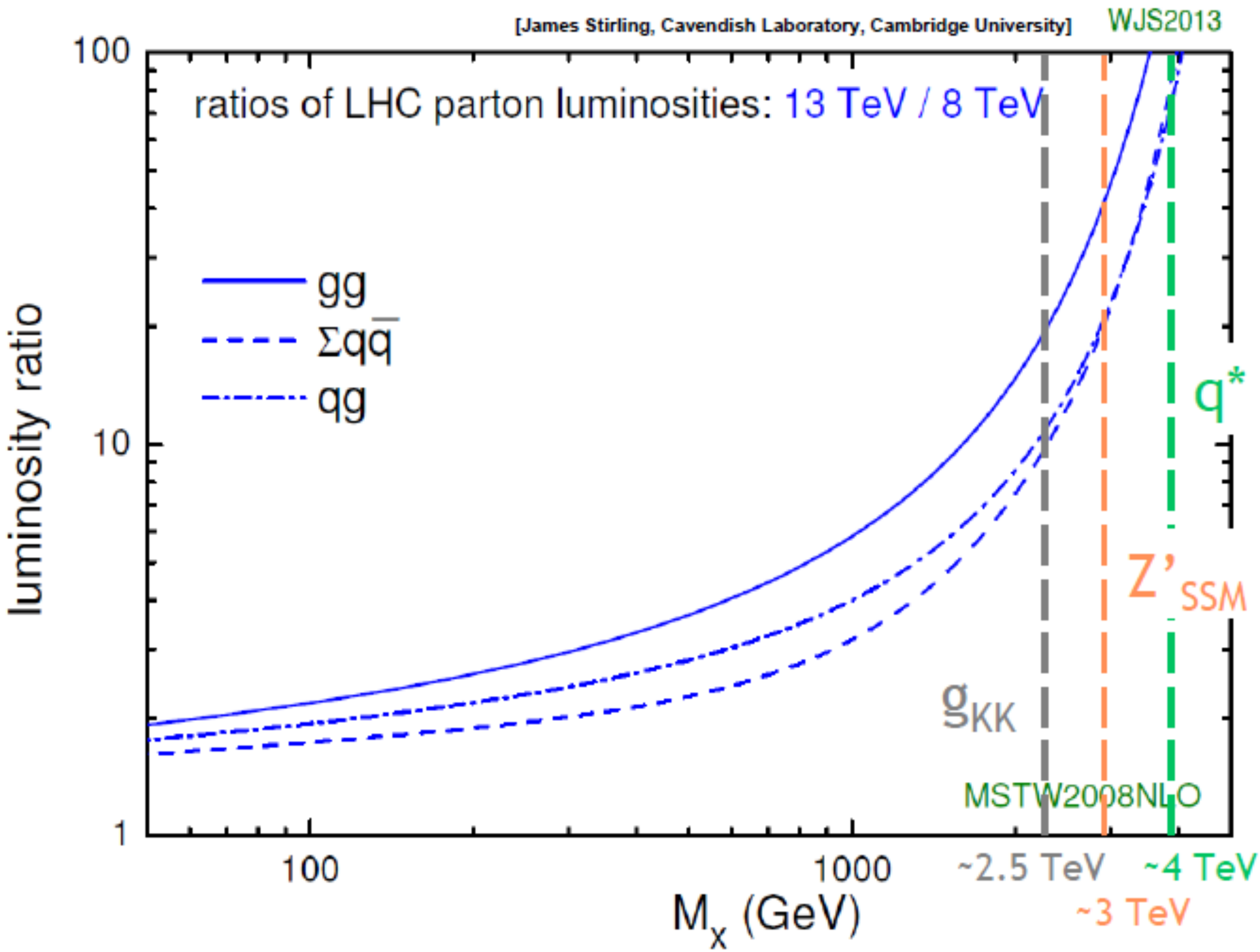
Combined CMS limits II



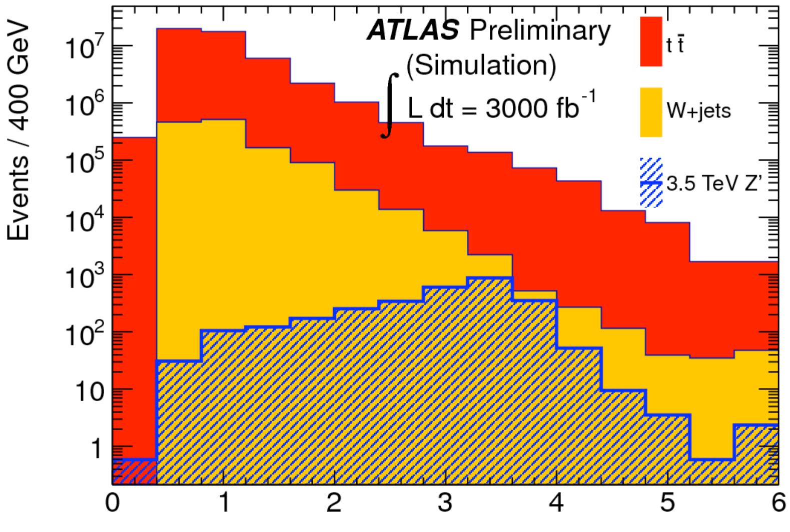


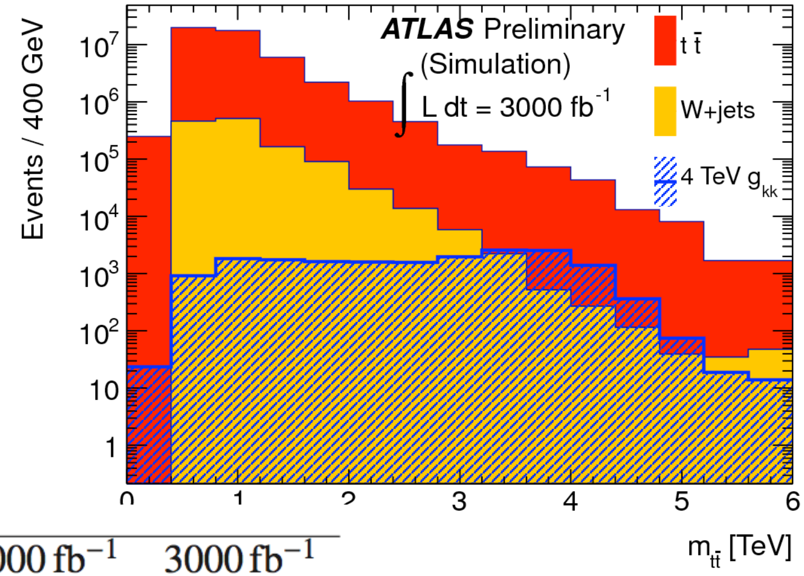


Outlook

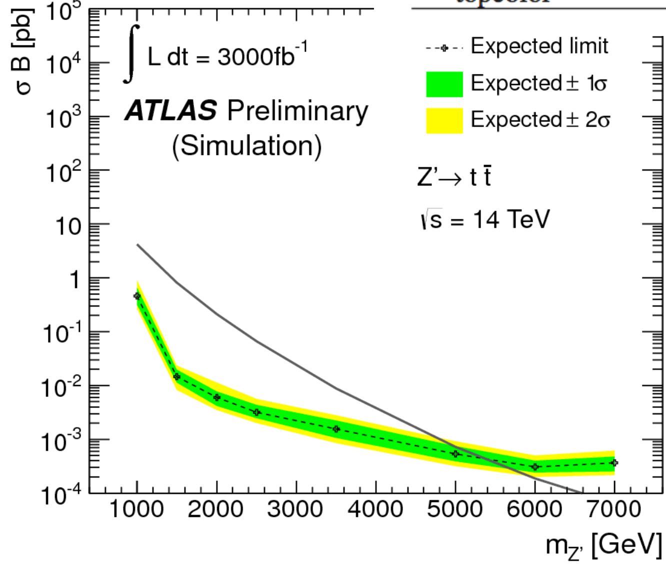

[James Stirling, Cavendish Laboratory, Cambridge University]
WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
q*
Z'SSM
gKK
MSTW2008NLO
luminosity ratio
100
10
1
100
1000
~2.5 TeV
~4 TeV
~3 TeV
Mx (GeV)

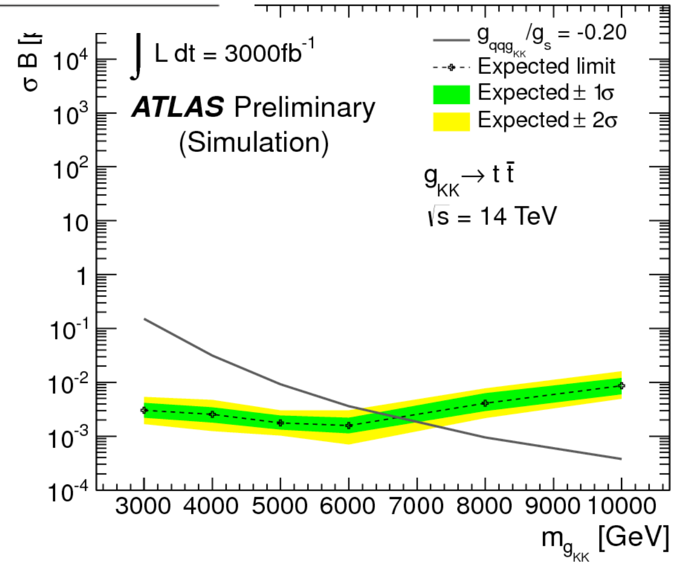
Sensitivity at high luminosity





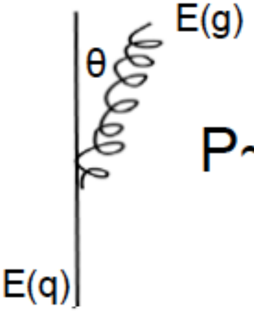
model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)



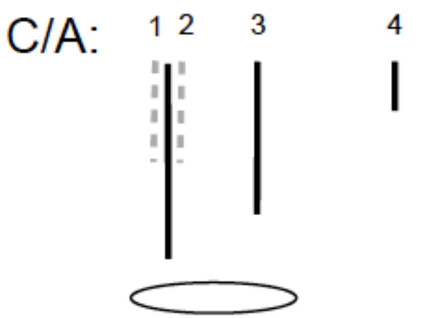


Clustering algorithms

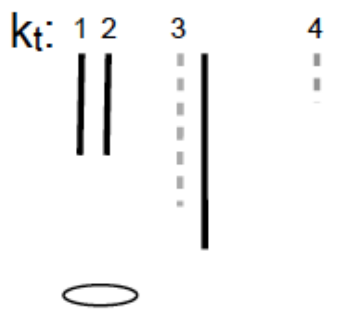
Credit: Xiaoxiao Wang



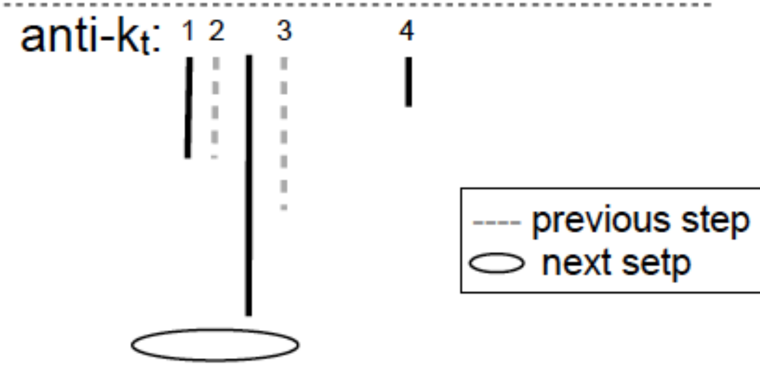
$$P \sim \int \alpha_s \frac{dE}{E}\frac{d\theta}{\theta} \quad \begin{cases} \text{collinear} \\ \text{infrared} \end{cases} \quad \Longrightarrow \quad d_{ij} = \min(p_{Ti}^{2n}, p_{Tj}^{2n}) \frac{\Delta R_{ij}^2}{R^2}, \quad \begin{cases} k_T: & n=1, \\ C/A: & n=0, \\ \text{anti}-k_T: & n=-1, \end{cases}$$



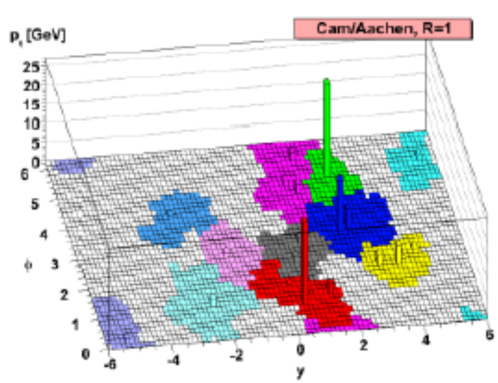
closer (ΔR) objects first

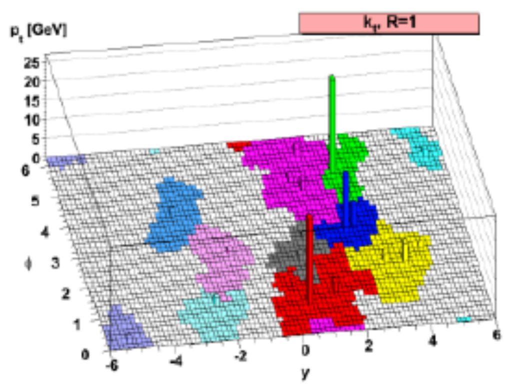


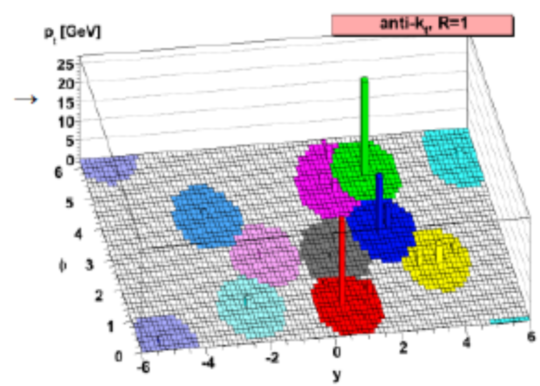
softer objects first



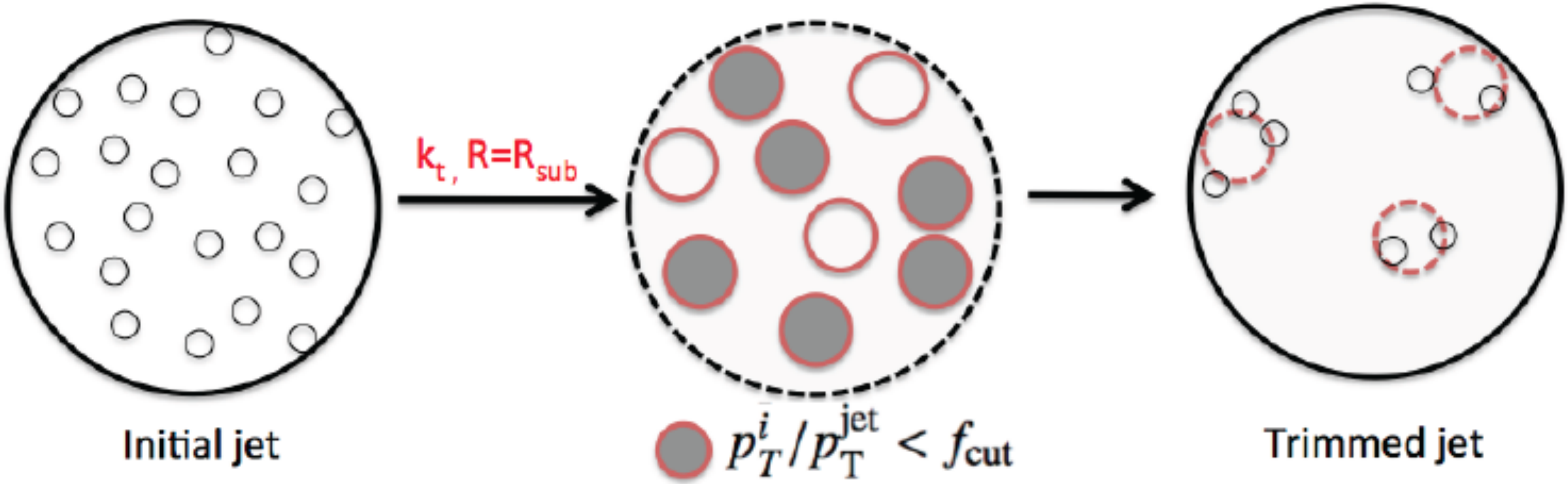
harder objects first





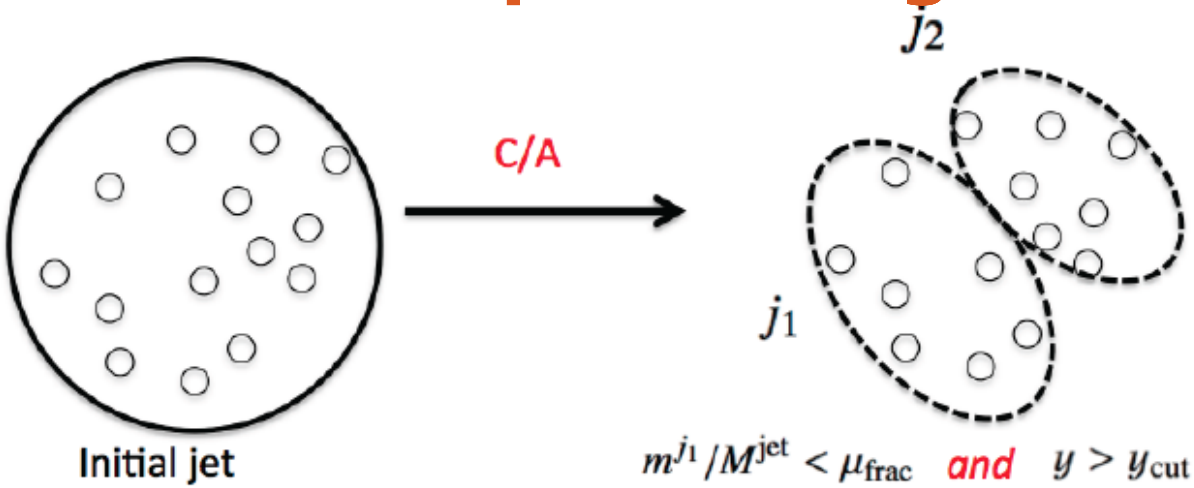


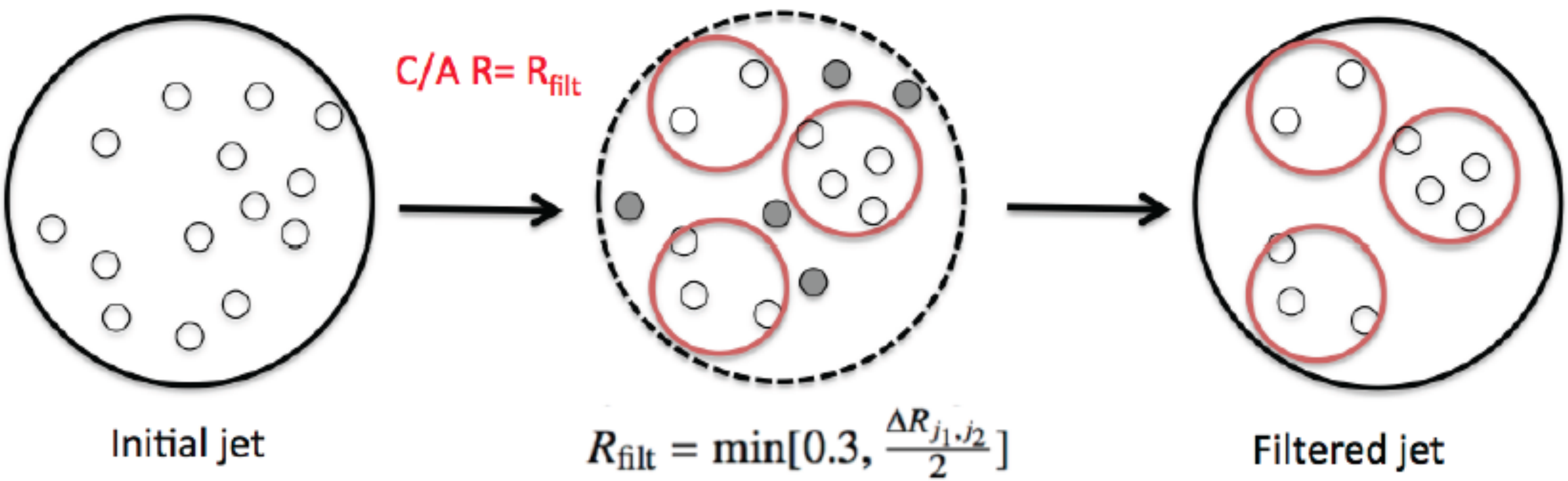
Grooming algorithms: trimming



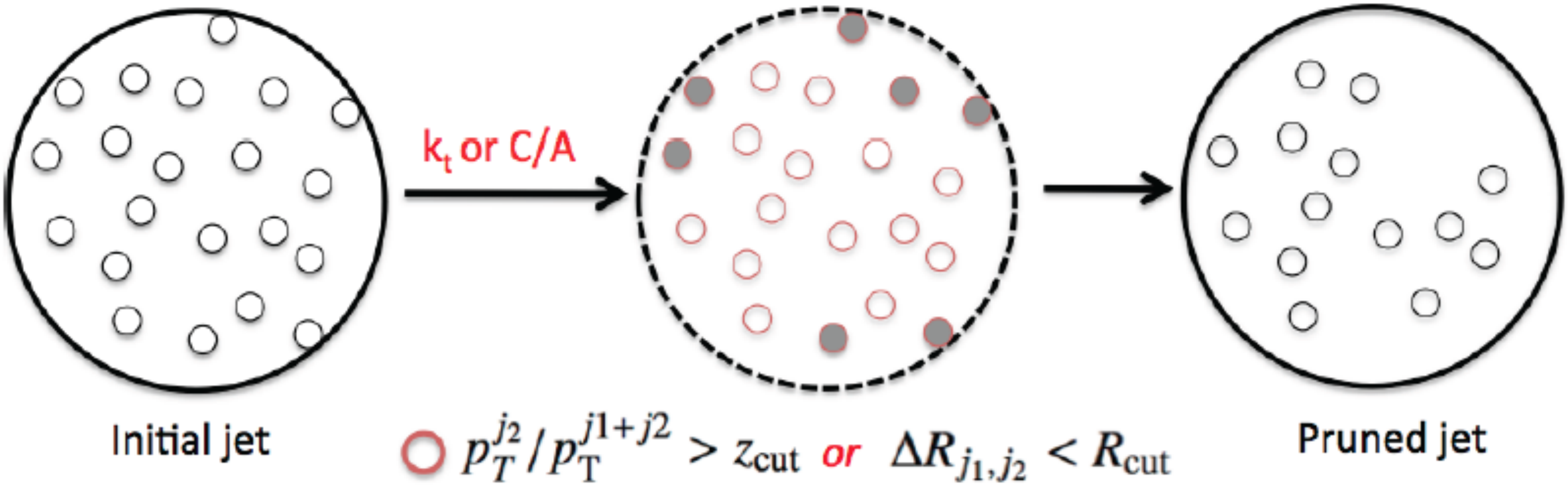
Rsub=0.3 and fcut=0.05

Grooming algorithms: mass drop+filtering



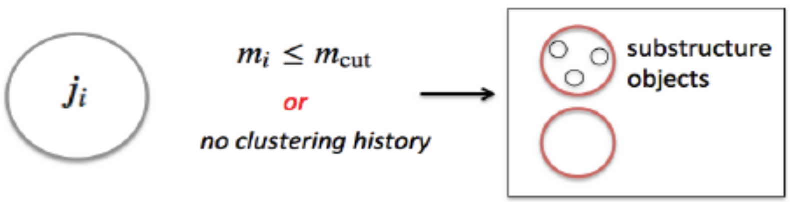


Grooming algorithms: pruning

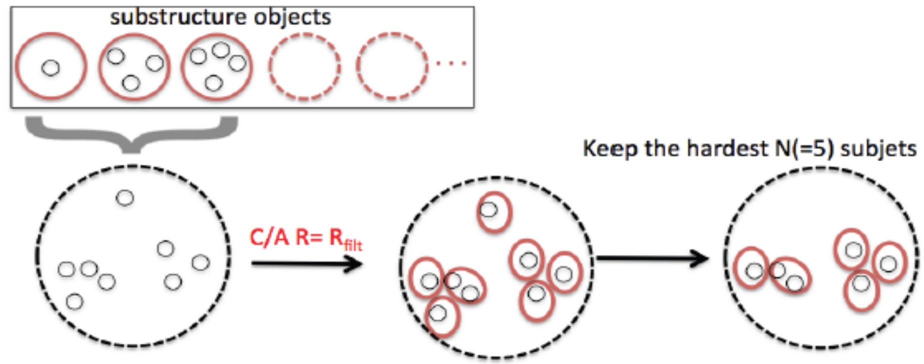


HEPTopTagger

- A multi-step algorithm starting from a large CA jet
- Mass drop filtering
- Form up newsubjets
- Impose Top and W mass constraints

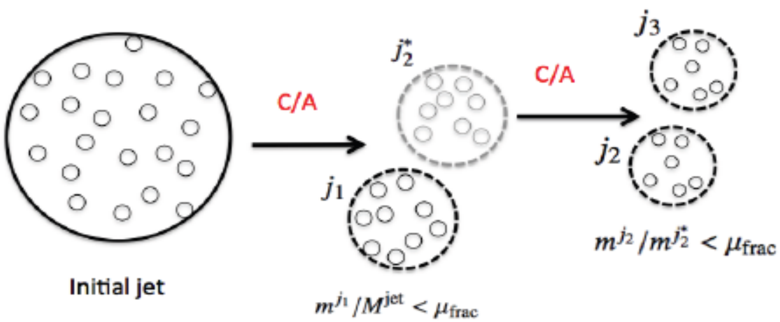


(a) Every object encountered in the de-clustering process is considered a 'substructure object' if it is of sufficiently low mass or has no clustering history.

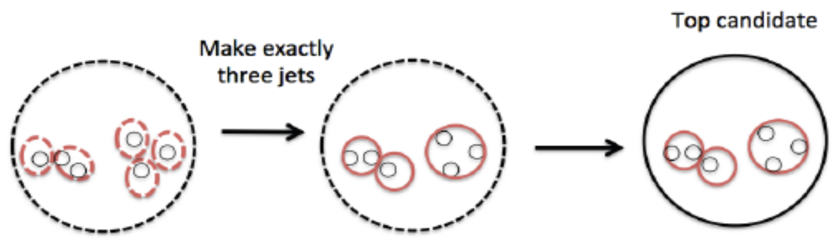


$R_{filt} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}, \frac{\Delta R_{j_1,j_3}}{2}, \frac{\Delta R_{j_2,j_3}}{2}]$

(c) For every triplet-wise combination of the substructure objects, recluster into subjets and select the N_{subjet} leading-p_T subjets, with $3 \leq N_{subjet} \leq N_i$ (here, $N_{subjet} = 5$).



(b) The mass-drop criterion is applied iteratively, following the highest subjet-mass line through the clustering history, resulting in N_i substructure objects.



$m_{ab} = M_W(1 \pm 0.15) \quad (a, b = j_1, j_2, j_3)$

(d) Recluster the constituents of the N_{subjet} subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.