先端加速器LHCが切り拓くテラスケールの素粒子物理学

2013年5月25日

Exotics (Non-SUSY) Search

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Higgs Discovery!!

A Higgs boson（質量126 GeV）が発見された！

次に来る質問

「標準模型のヒッグスボソン? or 何か別のヒッグス？？」

で、ちょっと調べてみると ....

What is it?

Little Higgs?

Lone Higgs?

Slim Higgs?

Higgsless??

Phantom Higgs?

Composite Higgs?

Twin Higgs?

SM Higgs?

Private Higgs?

Intermediate Higgs?

Fat Higgs?

Gauge-Higgs?

Littlest Higgs?

Twin Higgs?

Fermiphobic Higgs?

これはさすがにないか。。。

Axion-Higgs?

Question

Measurement of Higgs properties (coupling, spin, parity) is therefore most important *as this is model independent*

But, we also need theory (model) to get idea where to look next after Higgs discovery

126 GeV Higgs observation

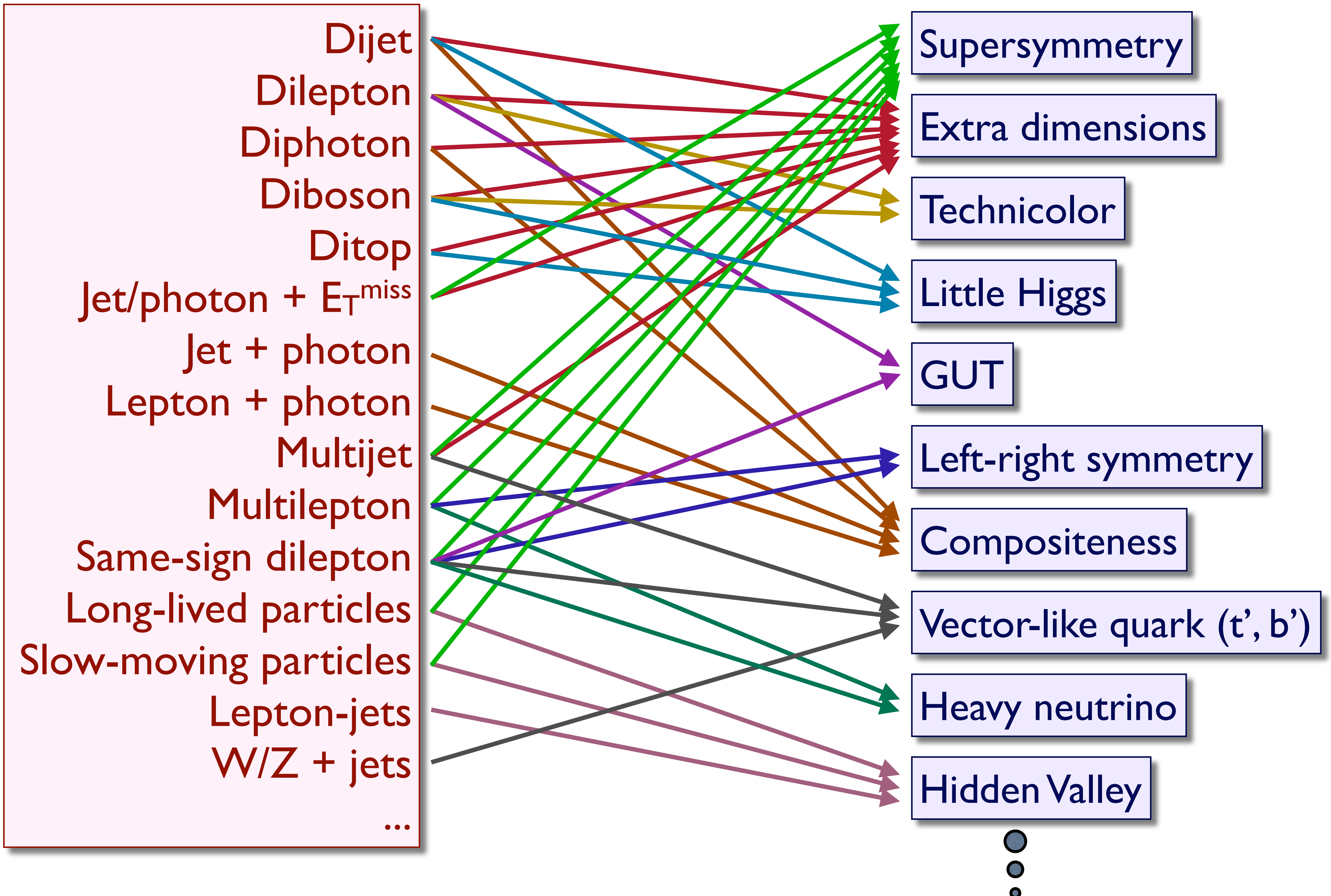
→ Any implication to BSM scenarios postulated to explain EWSB, gauge/flavor hierarchy, ...?

→ 浜口さん（SUSY）
尾田さん（UED）

→ Do we need to re-think about search strategy for exotics (non-SUSY) phenomena?

Exotics探索の基本Strategyをおさらいすると、、、

Signature-based Search

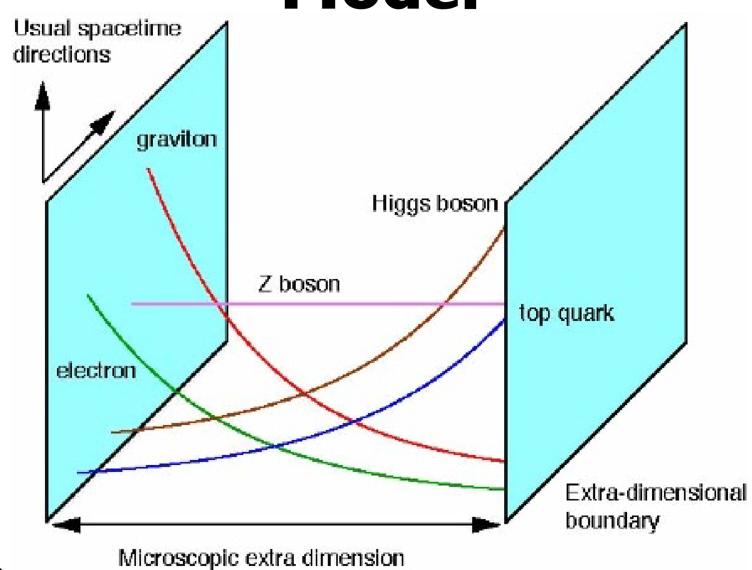


終状態のイベントトポロジーを元に探索するチャンネルを決める

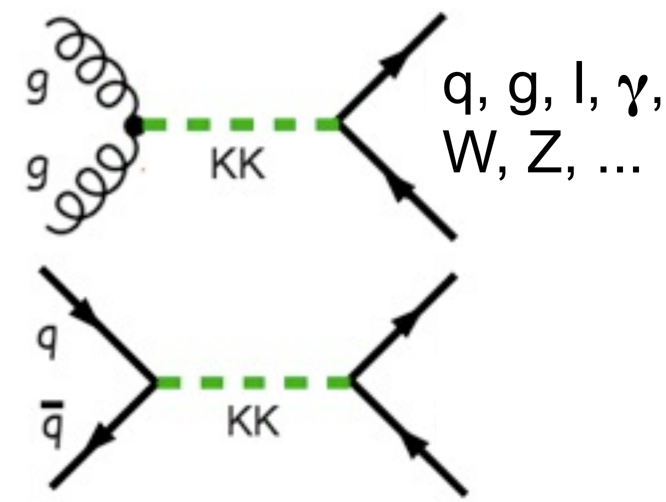
Motivation of this Talk

126GeVの発見を受けて、探すべきBSM signatureは変わるか？

Model



LHC Phenomenology



Discovery/ Exclusion Channel

- Dijet/Dilepton
- Diboson
- Ditop
- Jet/photon + E_T^{miss}
- Multijet
- ...

14TeV LHCでどこまで模型に制限を加えられるか？

....と言っても模型への制限を調べるのは大変なので、京大基研の研究会（3月26-29日）での議論をいくつか参考にしています。

LHC vs Beyond the Standard Model - 素粒子物理学の最先端 -

http://www2.yukawa.kyoto-u.ac.jp/~ynakai/program.html

126 GeVの発見を元に実験・模型の両面から進むべき方向を議論する

126 GeV + 模型 ➔ 模型で解決できる問題は何か？どういう実験で検証できるか？
126 GeV + 実験（DM, g_μ-2, flavor, ..）➔ どういう模型が示唆されるか?

Exotics Search "Matrix"

Expected sensitivity in signature-based search

典型的な Signature

	ADD			RS1		Bulk RS		UED	Technicolor	New Fermion	New Boson
	G	s-ch	t-ch	G	g	G	g				
Dijet		●	●	△	△				?		●
Dilepton/Diphoton		●		●					●		●
Ditop				○?		●	●				○
Diboson						●			●		○
Jet/photon + E_T^{miss}	●							○			
Multijet (incl. b-jet)			●							●	
Multilepton								●?	○?	○	
Same-sign dilepton			○							●	
W/Z + jets										●	

Implication from 125 GeV

126GeVのHiggs発見で、このMatrixの見直しは必要？

- Dijet, Dileptonなどは常に大事（QCD, Drell-Yan生成）
- Higgsを含めることで粒子スペクトラム(→終状態)が変わる？
- Higgs測定で影響を受けるパラメータ領域はあるか？

	ADD			RS1		Bulk RS		UED	Techni color	New Fermion	New Boson
	G	s-ch	t-ch	G	g	G	g				
Dijet		●	●	△	△				?		●
Dilepton/Diphoton		●		●					●		●
Ditop				○?		●	●				○
Diboson						●			●		○
Jet/photon + E_T^{miss}	●							○			
Multijet (incl. b-jet)			●							●	
Multilepton								●?	○?	○	
Same-sign dilepton			○							●	
W/Z + jets										●	

→これらについて調べてみる

Dilepton/Dijet Signature

	ADD			RS1		Bulk RS		UED	Techni color	New Fermion	New Boson
	G	s-ch	t-ch	G	g	G	g				
Dijet		●	●	△	△				?		●
Dilepton/Diphoton		●		●					●		●

様々なBSM模型に幅広く感度がある

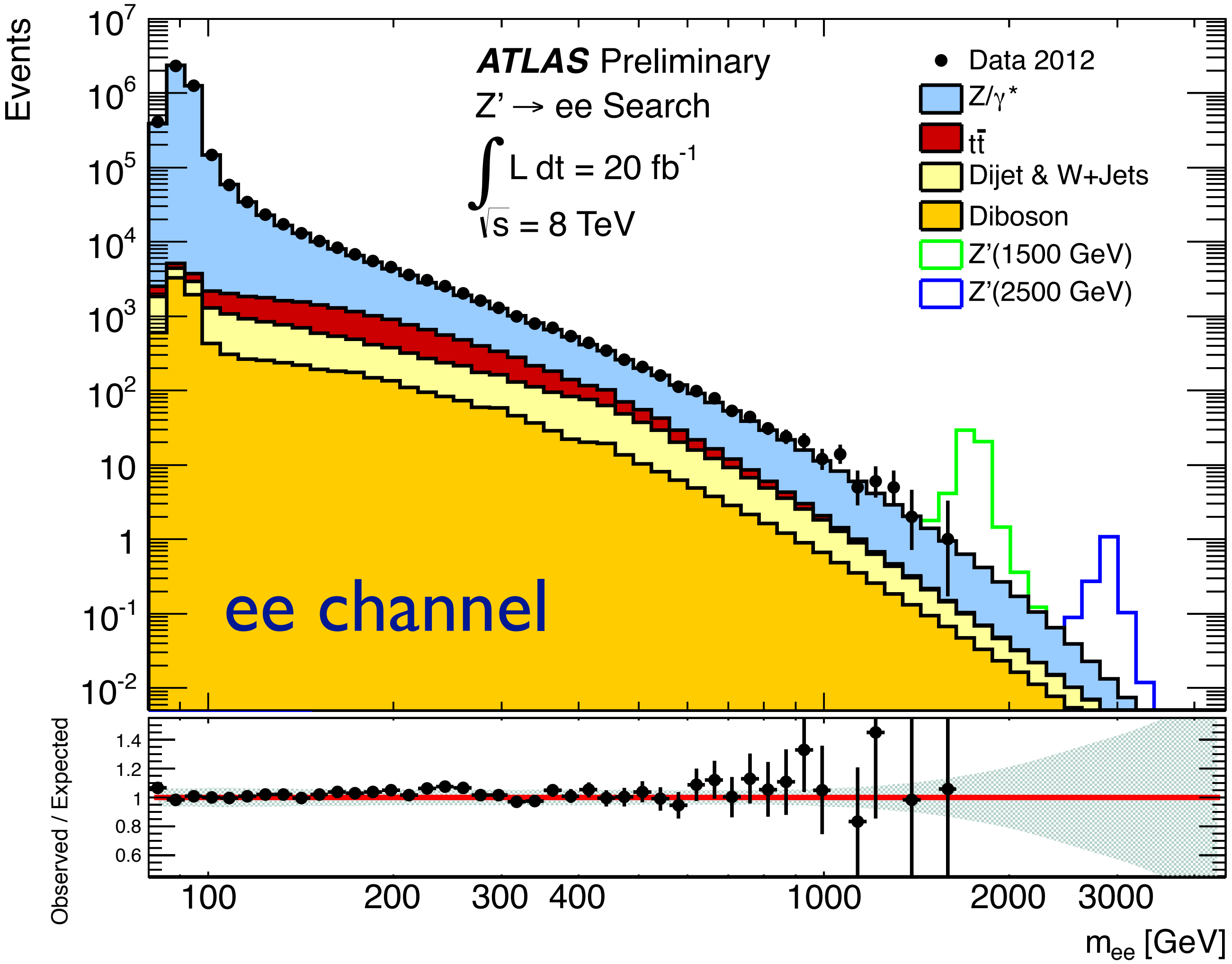
- Extension to SM gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - → U(1)' : neutral (Z') gauge boson
  - → SU(2)' : charged (W') and neutral (Z') gauge bosons
- SM embedded within a larger gauge symmetry group: GUT-E6, SO(10), ...
  - → Charged (W') and neutral (Z') gauge bosons
  - → Leptoquarks - color triplet bosons

生成過程・終状態の再構成が比較的シンプル（e, μ, jet）

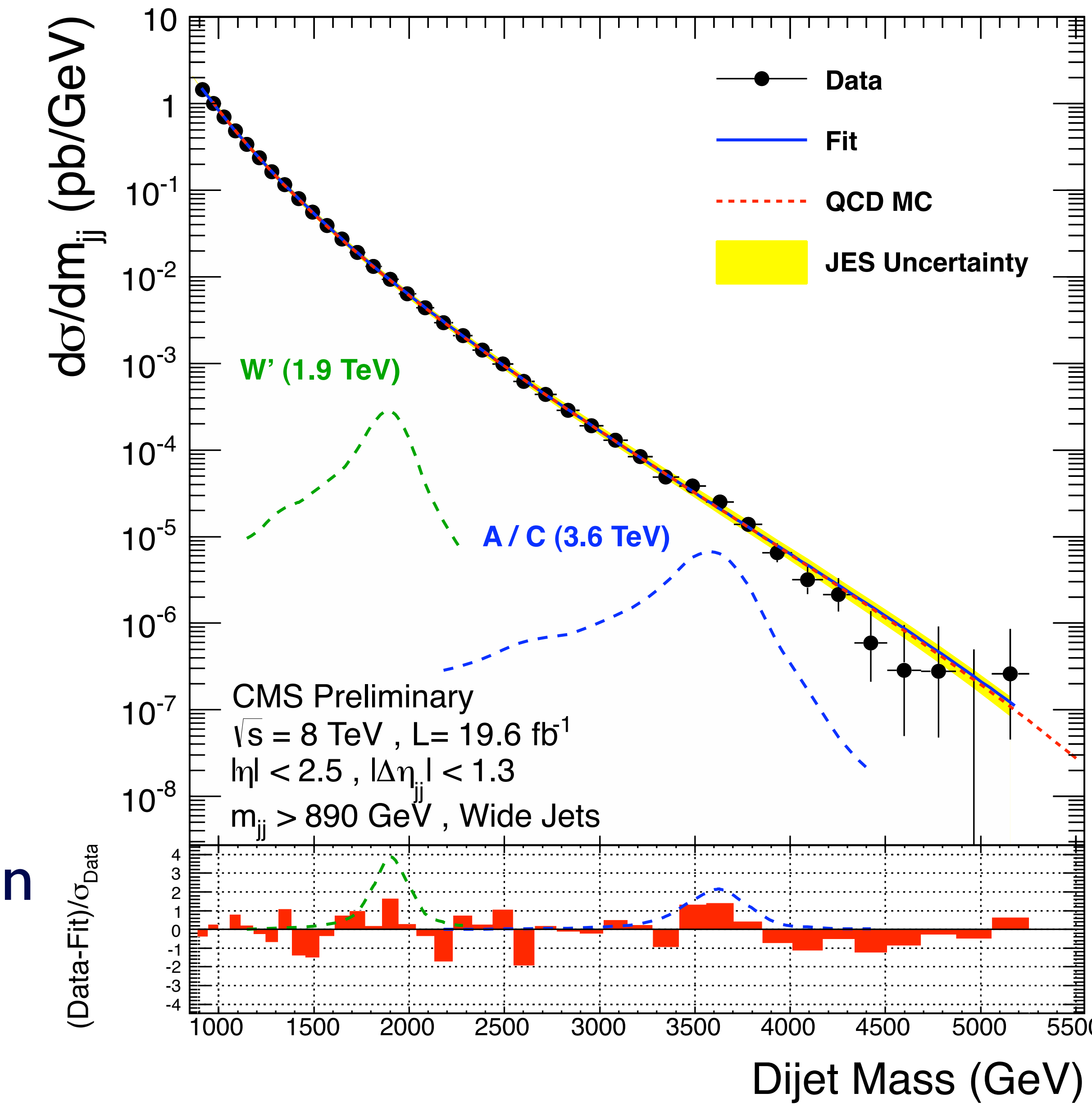
TeVスケールの物理を直接探索できる!!

Dilepton/Dijet : Now

≥2 isolated electrons E_T>40, 30 GeV



- ≥2 R=0.5 jets p_T >30 GeV
- "Fat jets" (all jets merged to closest leading jets if they are within ΔR<1.1)
- $|y^{j1,2}| < 2.5$, $|y^{j1}-y^{j2}| < 1.3$, $m_{jj} > 890$ GeV



Drell-Yan background estimated with
- POWHEG(NLO) for shape
- NNLO pQCD + NLO EW for cross section

➜ Scaled data at Z-peak (80<M_{ll}<100 GeV)

有意な超過は無し

Dilepton/Dijet : Prospect

$$\mathcal{L}_{Z'} \sim g_{Z'} Z'_\mu \left(\bar{q}_i \gamma^\mu \frac{1-\gamma_5}{2} q^i \right)$$

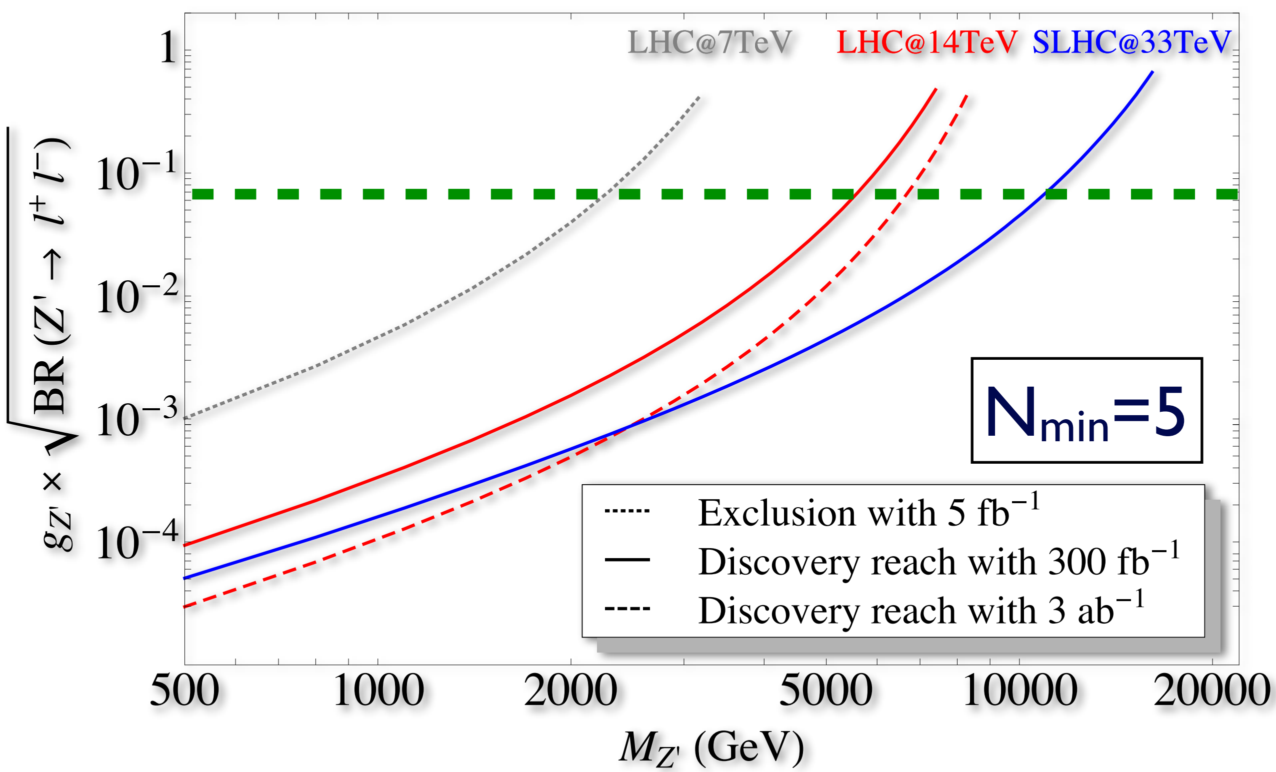
Assume universal left-handed coupling to up and down quarks

LHC2TSP workshop

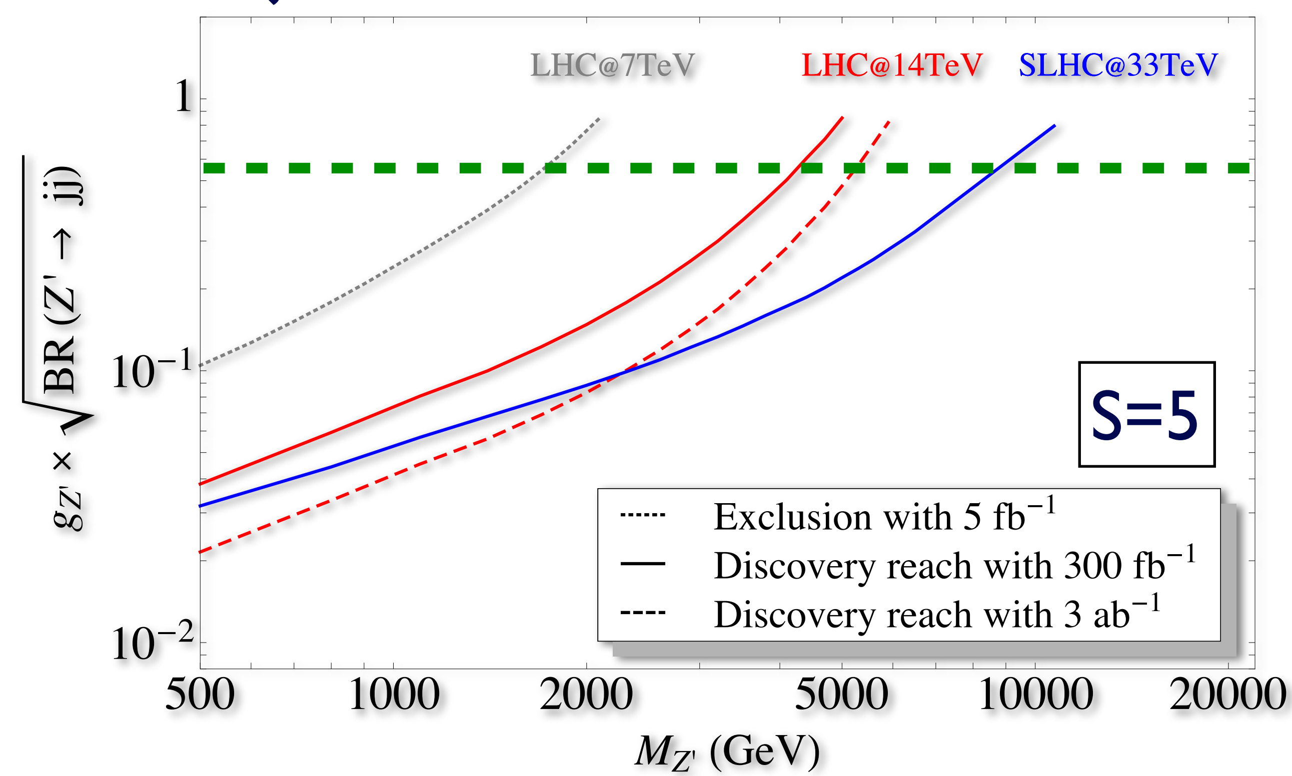
$$g_{Z'}\sqrt{\mathrm{BR}(Z' \to l^+ l^-)} = \left(\frac{N_{\min}}{\sigma(q\bar{q} \to Z')|_{g_{Z'}=1}\, A\epsilon L} \right)^{1/2}$$

$$g_{Z'}\sqrt{\mathrm{BR}(Z' \to l^+ l^-)} = \left(\frac{S\sqrt{N_{\mathrm{BG}}}}{\sigma(q\bar{q} \to Z')|_{g_{Z'}=1}\, A\epsilon L} \right)^{1/2}$$

Dilepton



Dijet



Z'$_{SSM}$ exclusion sensitivity

- 7TeV (5 fb^{-1}) : 2.2 TeV

→ Discovery sensitivity

14TeV (300 fb^{-1}) : ~5.5 TeV

W'$_{SSM}$ exclusion sensitivity

- 7TeV (5 fb^{-1}) : 1.7 TeV

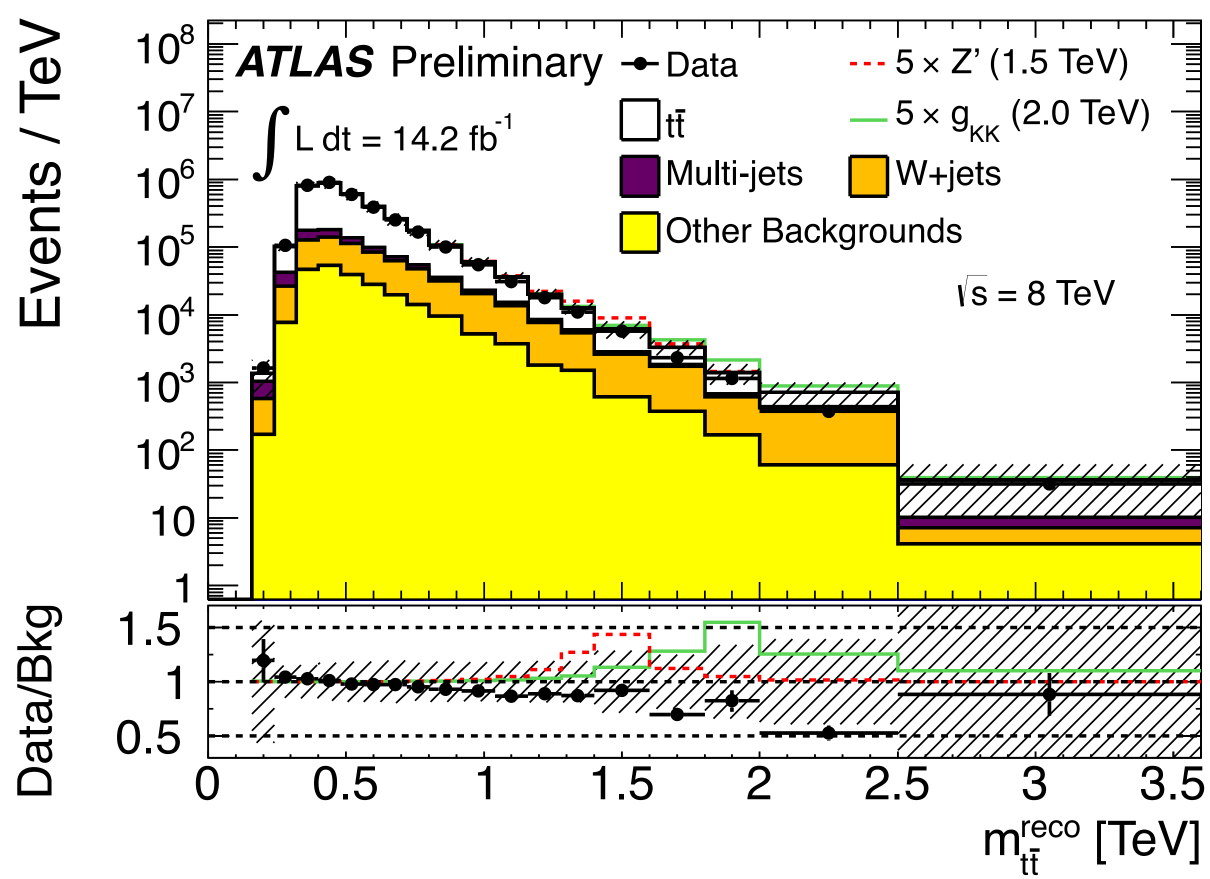
→ Discovery sensitivity

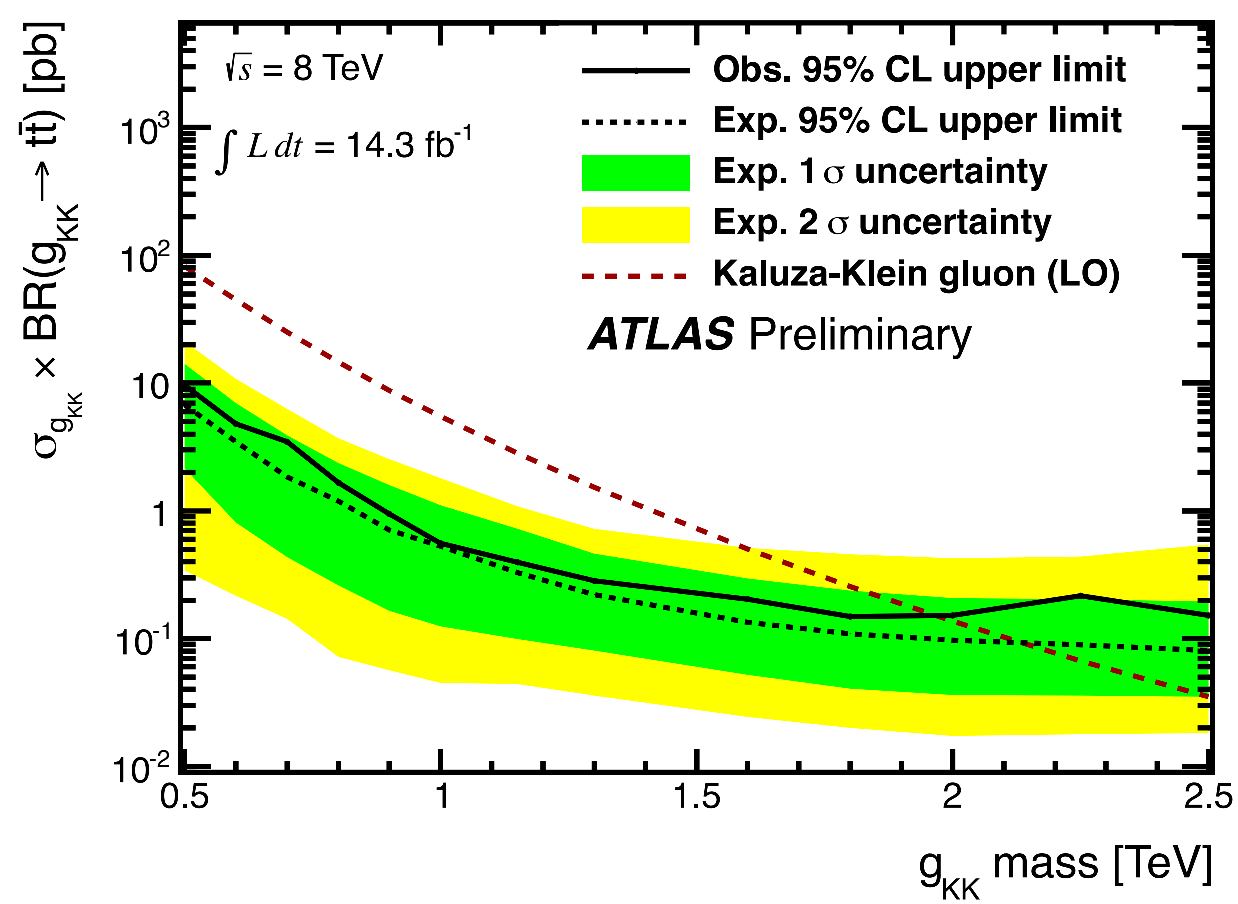
14TeV (300 fb^{-1}) : ~4.0 TeV

Ditop Signature

	ADD			RS1		Bulk RS		UED	Techni color	New Fermion	New Boson
	G	s-ch	t-ch	G	g	G	g				
Ditop				○?		●	●				○

- Large top-quark mass (Yukawa) implying connection to new physics
  - Top A_{FB} observed at Tevatron?
- Expected to be prominent signature in realistic Randall-Sundrum scenario
  - 8 TeV $t\bar{t}$ resonance searches start probing KK mass scale ≥ 2.0-2.5 TeV
  - Entering into regime predicted from precision EW measurements





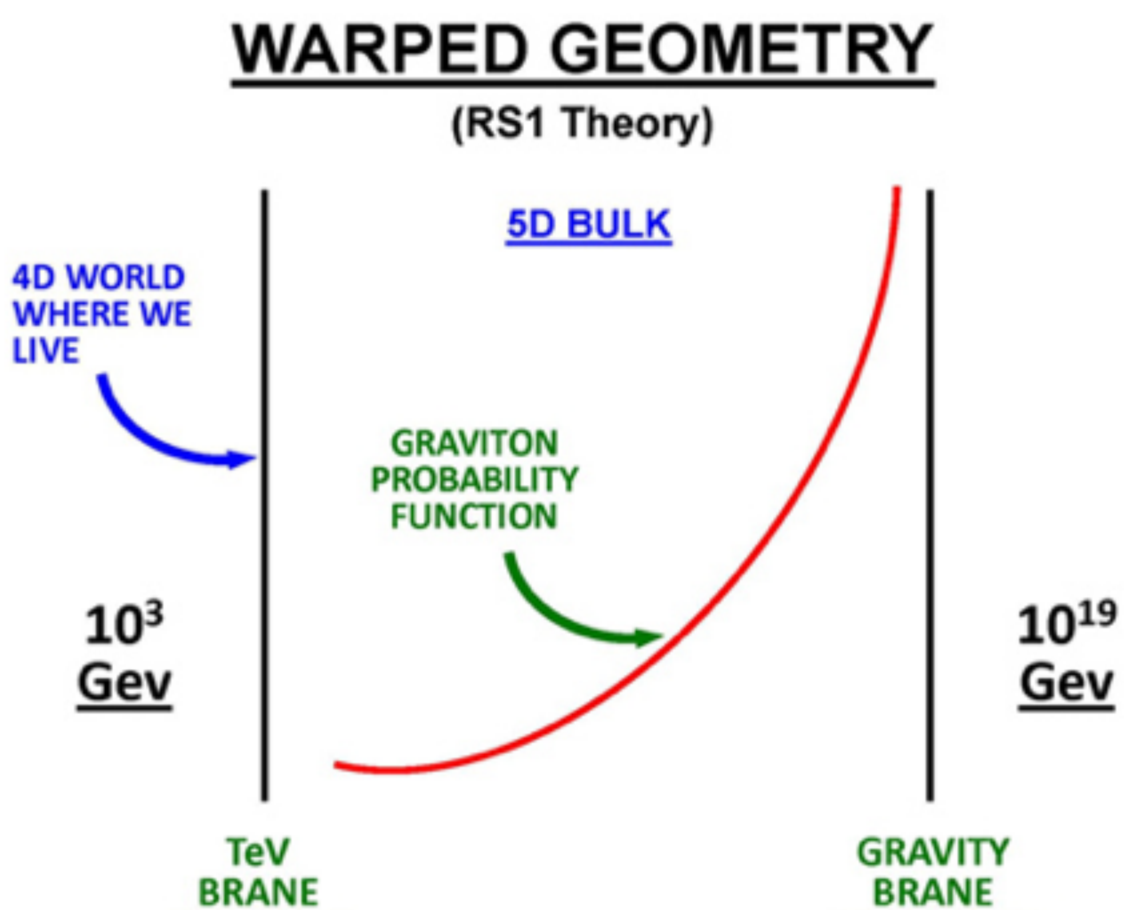
→ 解析の詳細は長谷川さんのトーク

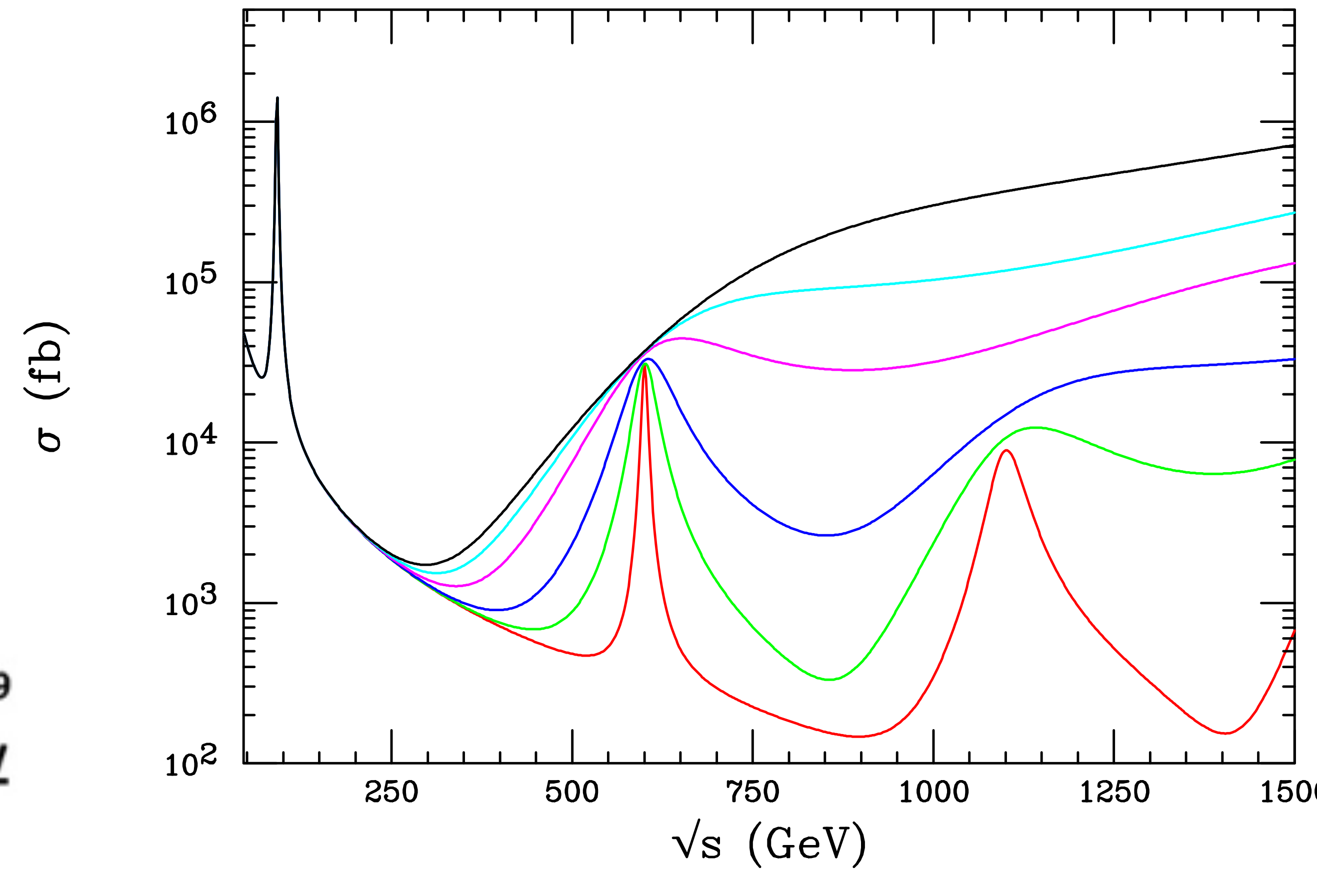
Warped Extra Dimensions

Randall, Sundrum

Original RS *~ golden signal ~*

- 5D universe bounded by two branes
- All SM particles localized on TeV-brane
- 5th dimension highly curved with a warp factor = $\exp(-kr\pi)$
- Planck mass "warped" down to EW mass at TeV-brane if kr≈12
  → Solve hierarchy problem





Main LHC signal : G→ll, G→γγ

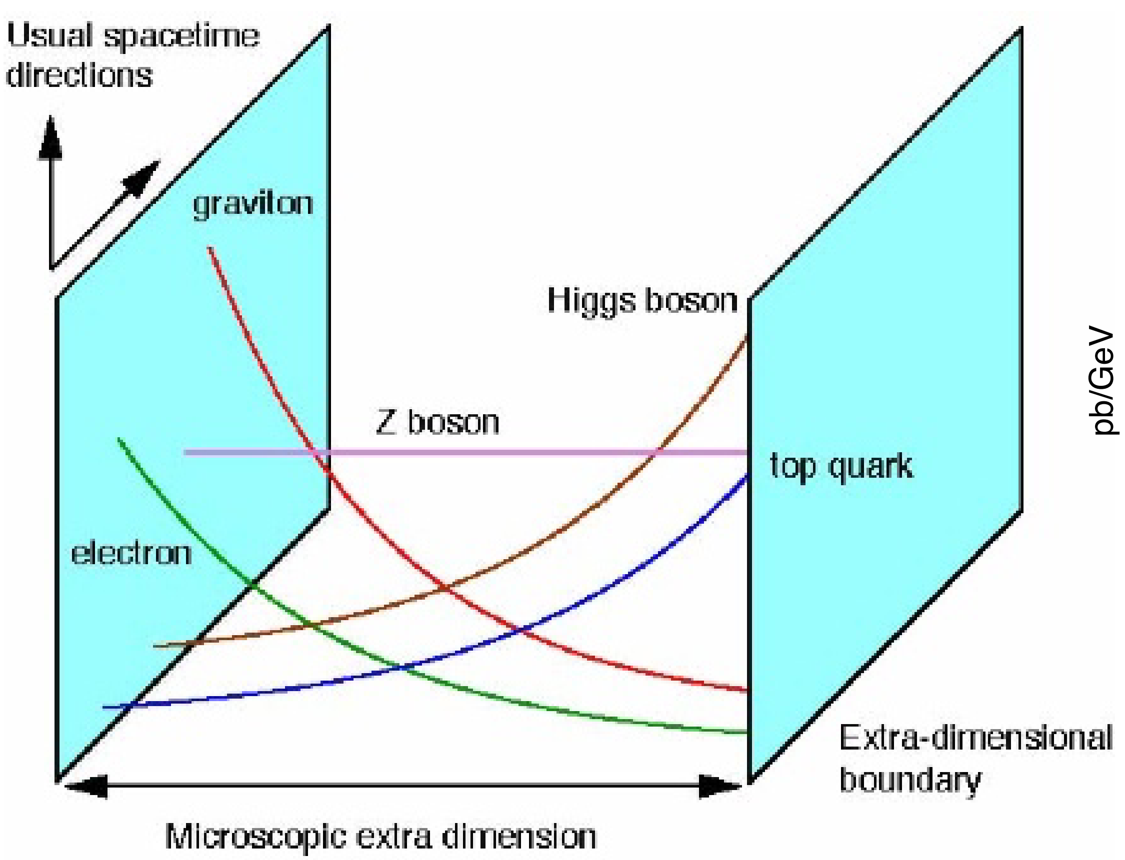
➠ dilepton/diphoton resonance

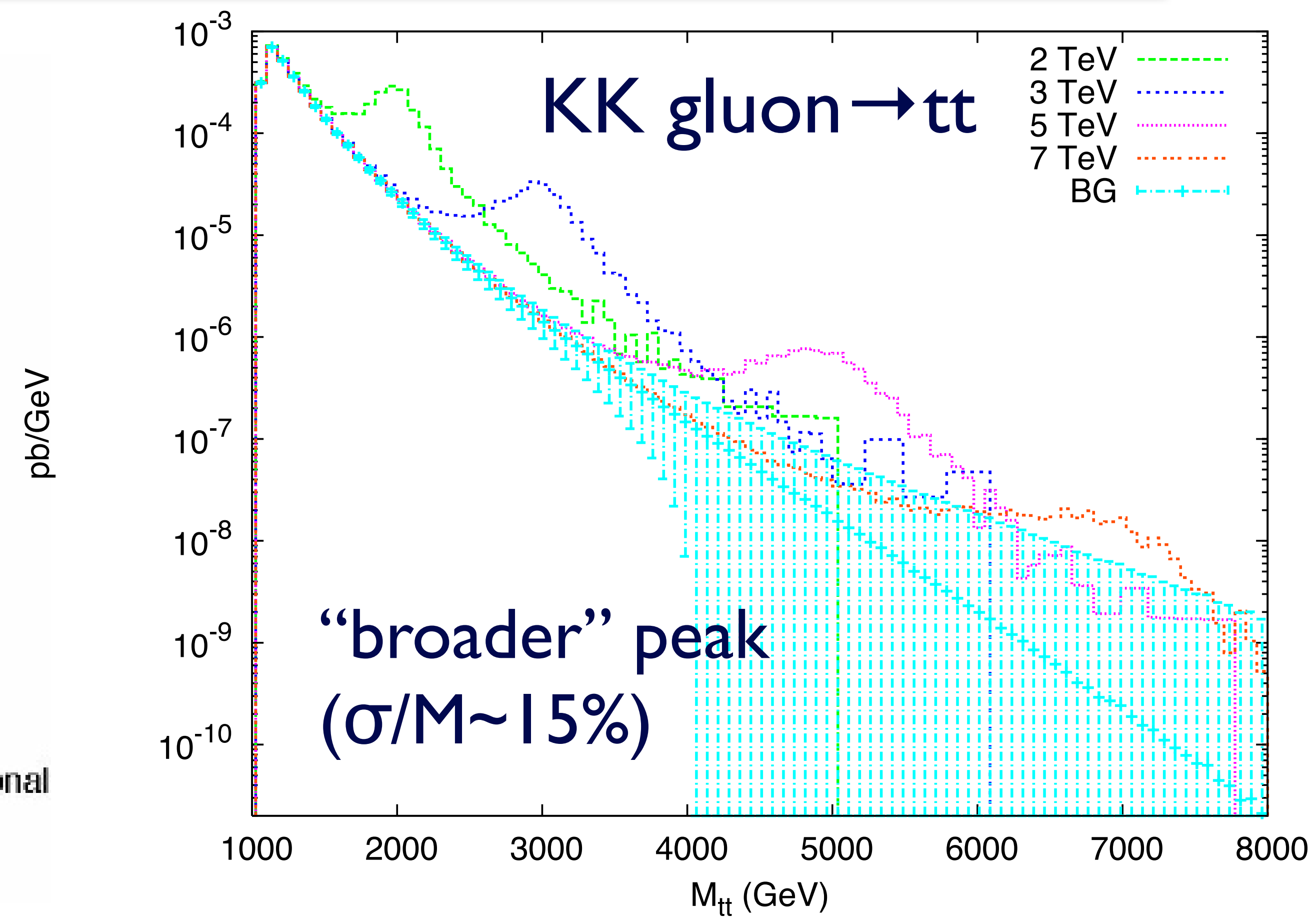
Bulk Rundall-Sundrum

Chang, Hisano, Nakano, Okada, Yamaguchi, ...

Bulk RS *~ more challenging ~*

- 5D universe bounded by two branes
- All SM particles in the bulk of extra dimension
- Higgs and heavier particles localized near TeV-brane (for hierarchy)
- Lighter particles near Planck-brane → weak coupling (smaller σ)
  - ➠ dilepton/diphoton signature not possible



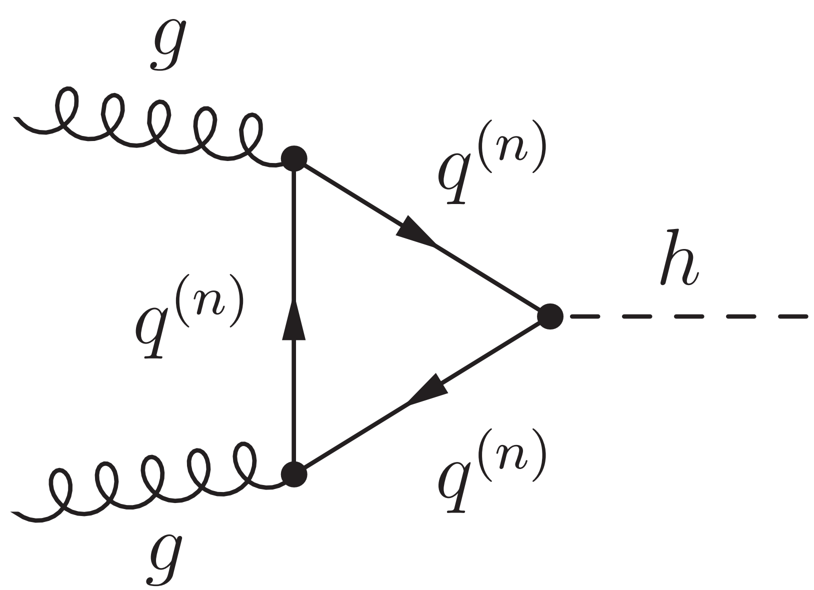


Main LHC signal : g→tt, G→tt, WW, ZZ

➠ **tt, WW, ZZ resonance**

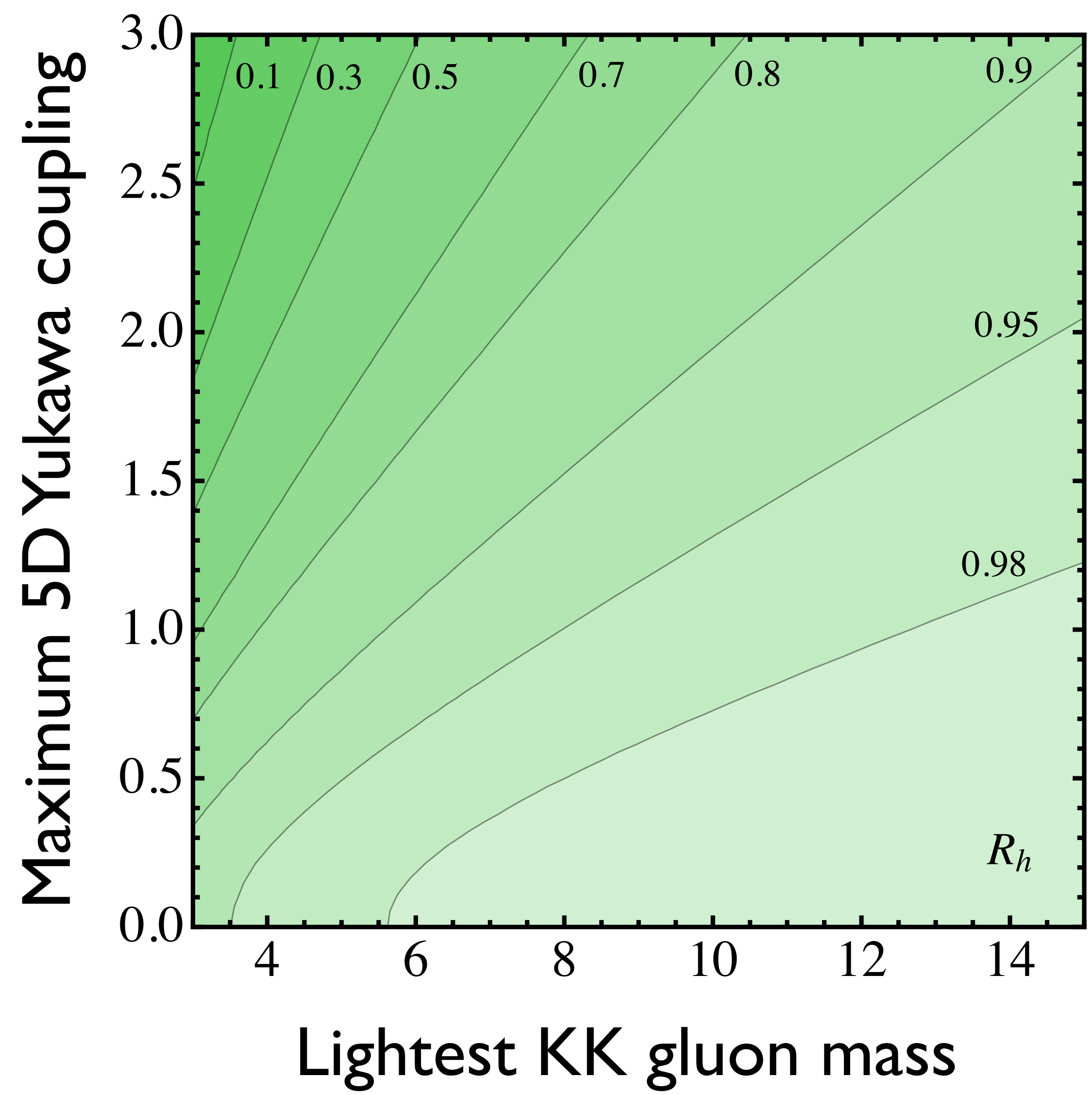
Bulk RS with 126 GeV Higgs

Minimal RS model (Bulk fermion fields with localized Higgs on TeV-brane)



arXiv:1204.0008

$$R_h = \frac{\sigma_{\mathrm{RS}}(gg \to h)}{\sigma_{\mathrm{SM}}(gg \to h)}$$



Bulk KK fields can contribute to gg→h loops

- *KK towers of all light quarks contribute*
  - → *destructive effect for brane Higgs*
  - → *constructive effect for bulk Higgs*

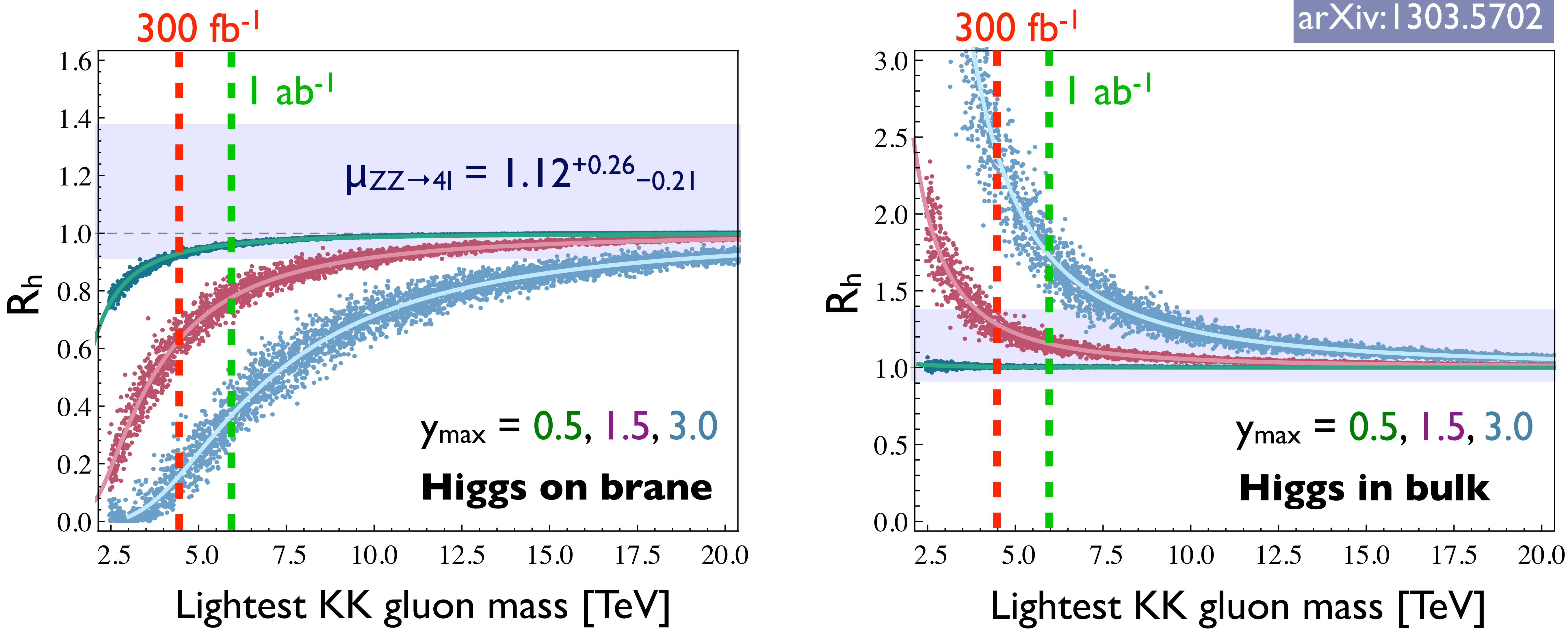
SM quark couplings to Higgs also modified

- *Top Yukawa reduced with respect to SM*

Bulk RS : Prospect

14TeV $t\bar{t}$ search sensitivity ATL-PHYS-PUB-2013-003

arXiv:1303.5702



Large 5D coupling regime significantly constrained to large KK mass scale (≳10 TeV)

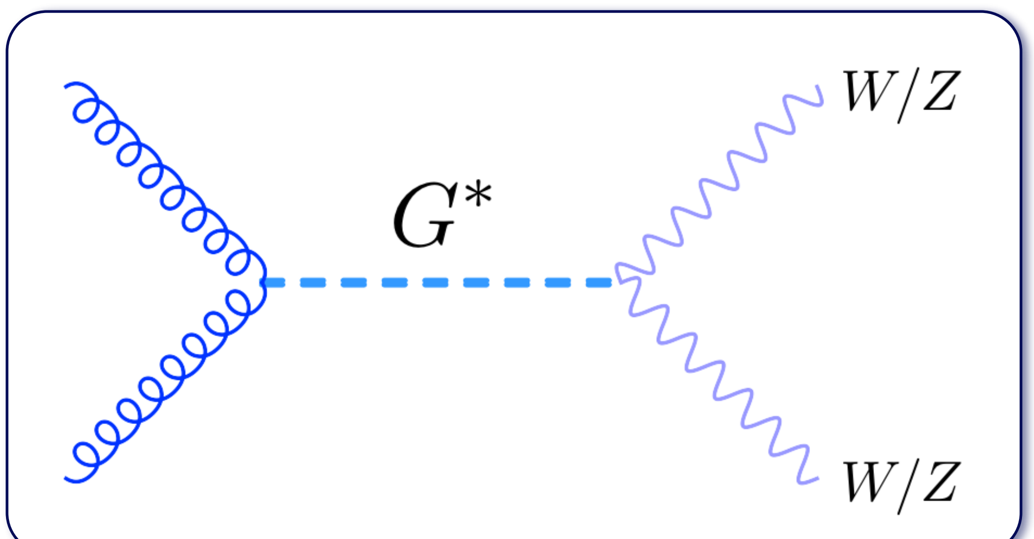
SM-likeになるほど直接探索は難しそう。。。

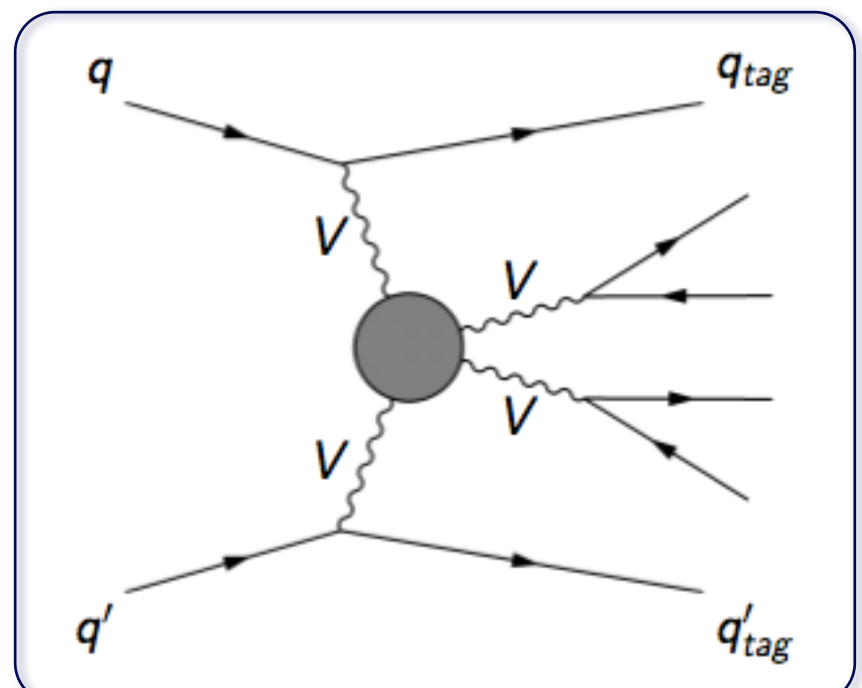
KK stateが非常に重くなると...
- Contact interactionになる？
- Non-resonant tt/VV excessのように見える？

Diboson

	ADD			RS1		Bulk RS		UED	Techni color	New Fermion	New Boson
	G	s-ch	t-ch	G	g	G	g				
Diboson						●			●		○

- Diboson final states predicted by Extra dimensions, Technicolor, Little Higgs, ...
- Triple/quartic gauge coupling : indirect probe to new physics
- (Non-)resonant VV→VV scattering : connection to EWSB and Higgs
- Mainly consider relatively *narrow*, high-mass resonances (Γ/M<~5%)
  - ➔ *Reconstructed resonance mass resolution > Γ/M (except ZZ→4l)*





Technicolor

Original Technicolor

- Scaled up version of QCD : $\Lambda_{\rm TC} \sim \sqrt{\frac{3}{N_{\rm TC}}} \frac{F_\pi^{\rm TC}}{F_\pi} \Lambda_{\rm QCD} \quad (F_\pi^{\rm TC} = v \simeq 246 \text{ GeV})$
- Chiral symmetry breaking by condensates $\bar{q}_R q_L$ (technipions)
- Already disfavored by precision EW measurements long time ago...

Extended Technicolor

- Additional gauge interactions connecting color to technicolor
- Larger group at ETC scale breaks at different TC scales → generate fermion masses

Λ_{TC} ~ 100 GeV, Λ_{ETC} ~ TeV to give quark masses ~ 0.1-1 GeV

Low-scale Technicolor (LSTC)

- Technicolorの典型的ベンチマークとしてよく使われてきた
- SM Higgsの観測と折り合いが悪い。。。

  H→ZZ, WWを説明できない (Higgs Imposter = 0- state only)

Walking Technicolor

Walking Technicolor

- Λ_{ETC}~10 (1)TeV → $m_{q,l}$~0.1(1) GeV
- Slow running of TC coupling enhances condensates at ETC scale
  → Possible to explain heavy quark masses

“Natural”なTCスケール：Λ=4πv ～ TeV

→ Walking TCで126GeV Higgsを生成することは可能

arXiv:1211.1083

Observed Higgs mass

$$M_H^2 = (M_H^{\rm TC})^2 + 3\kappa^2\left[-4r_t^2 m_t^2 + 2s_\pi\left(m_W^2 + \frac{m_Z^2}{2}\right)\right] + \cdots$$

“Bare” composite Higgs mass

Radiative correction from top quark (r_t=1 for SM)

$(F_\pi^{\rm TC} = v \simeq 246\ {\rm GeV})$

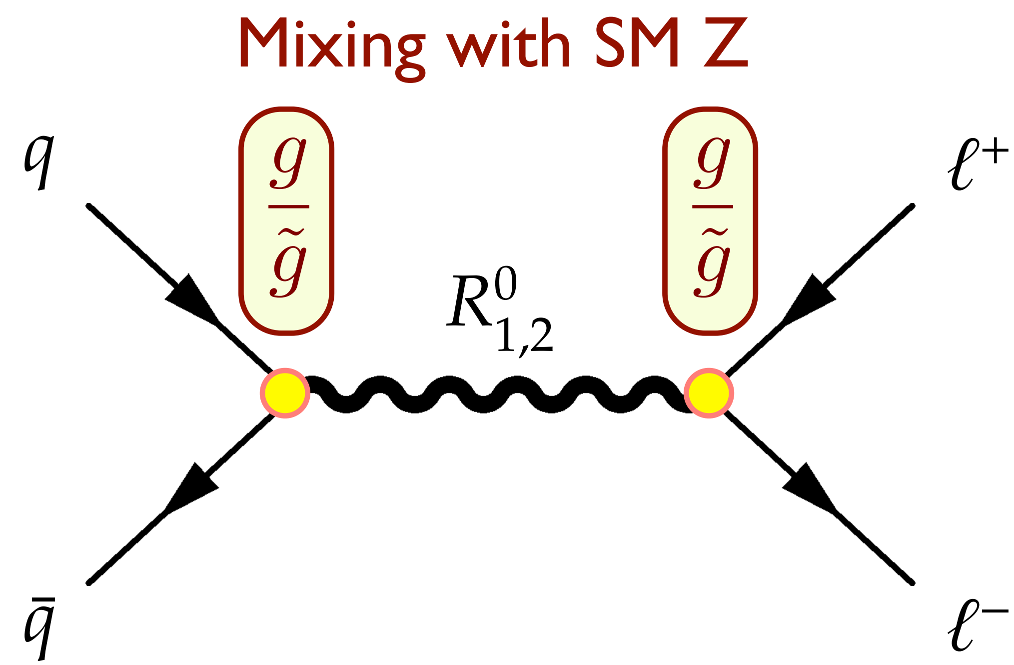
模型パラメータ

- vector, axial-vector mass : M_V, M_A
- spin-1 resonance coupling : $\tilde{g}$
- Higgs mass : M_H

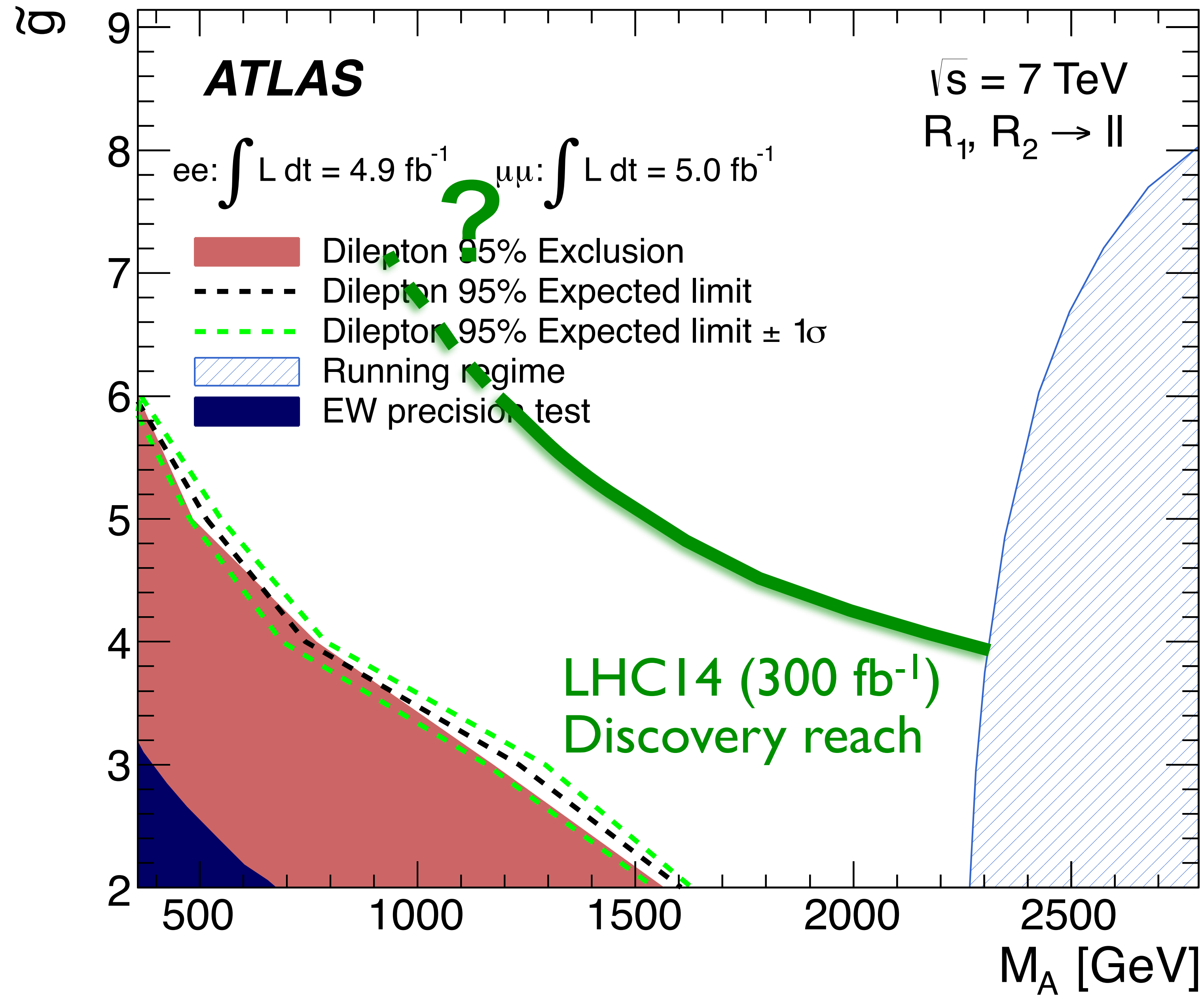
→ どのパラメータ領域が生きているか？

Walking TC : Now and Prospect (I)

arXiv:1209.2535



→ x-section suppressed at large $\tilde{g}$



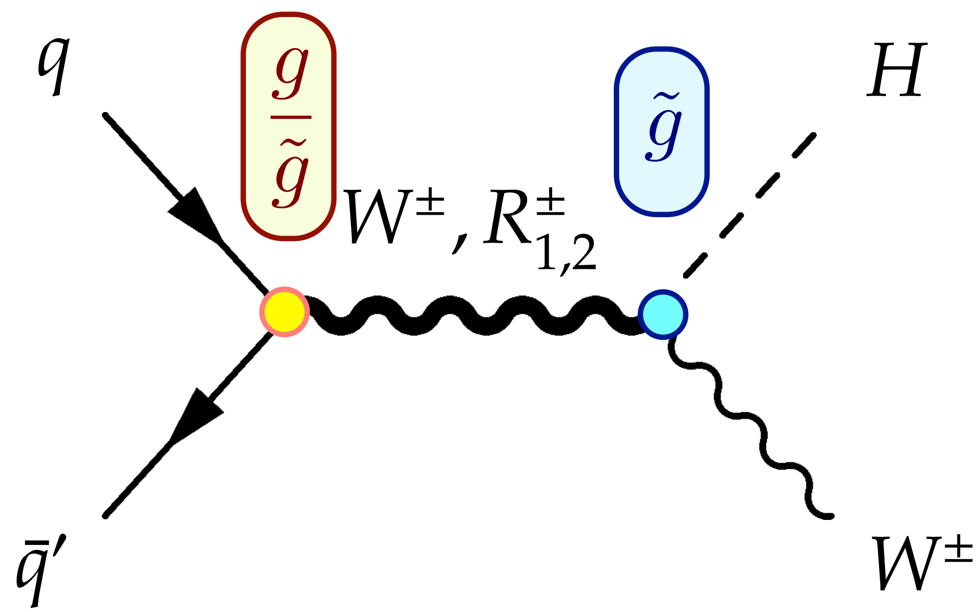
7 TeV dilepton analysis sensitivity

- 2 leptons p_T>25GeV, |η|<2.47(2.4) for electron(muon)
- Leading electron (both muons) required to be isolated

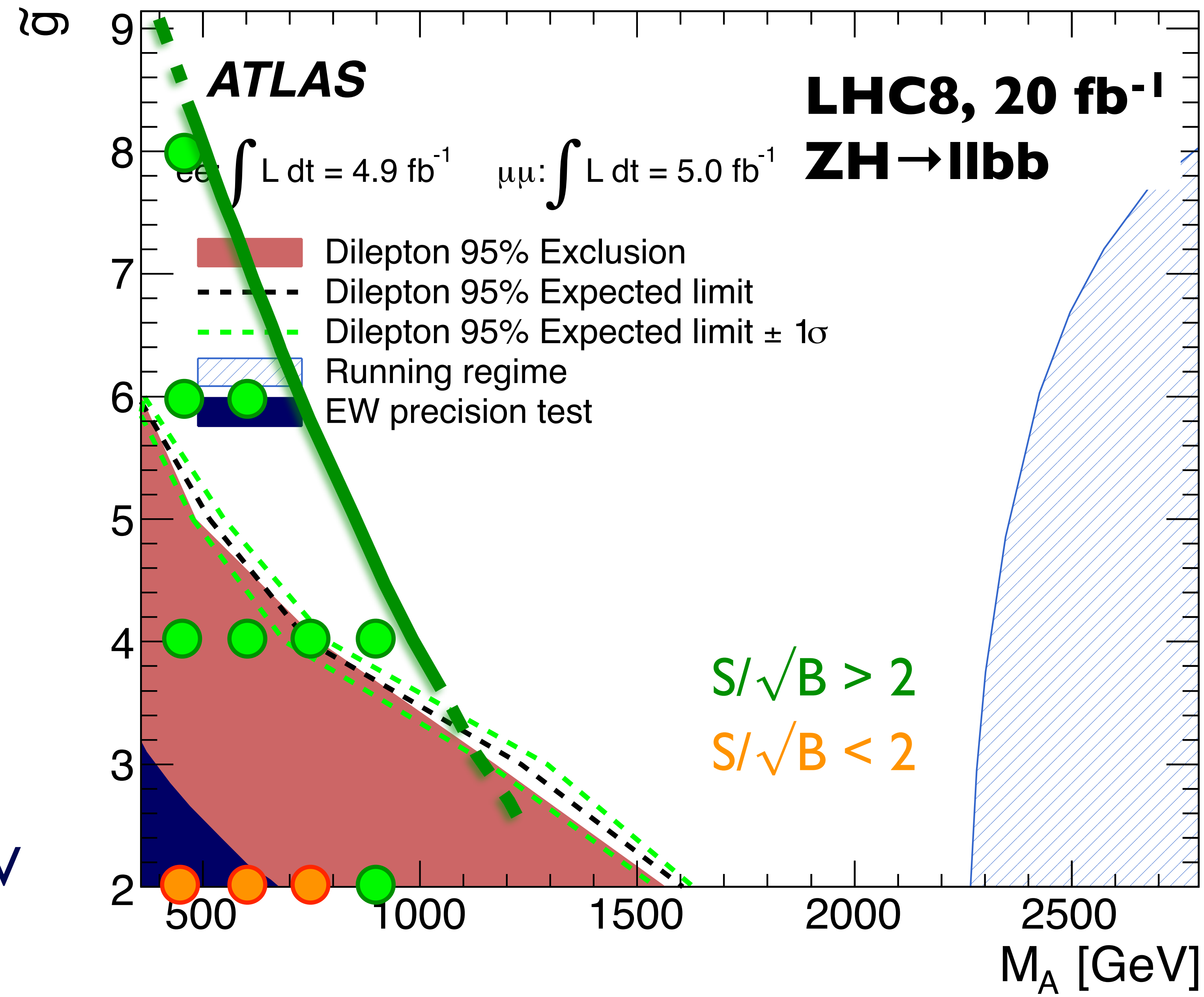
LHC14 sensitivity estimated from Z'→ll sensitivities at 7 and 14 TeV

- Not clear in large $\tilde{g}$ region (→resonance gets wider)

Walking TC : Prospect (II)



→ Not suppressed at RWH vertex



SM ZH→llbb解析の感度予想

Slightly optimized selection for R→ZH

- $Z \to ll$ (M_{ll}=83-99GeV), E_T^{Miss}<60GeV
- 2 b-tag (no ΔR_{jj} cut)
- $|M_{jj} - M_H|$<20GeV
- p_T^{jet}>45GeV, $\Delta\Phi_{jj} < \pi/2$, $\Delta\Phi_{ll} < \pi/2$

➔ Large $\tilde{g}$ではdileptonより感度は高い

Dileptonと相補的に広いパラメータ領域をカバー出来るかもしれない

Vector Boson Scattering

Longitudinal gauge boson scattering
➔ EWSBの直接検証

arXiv:0806.4145

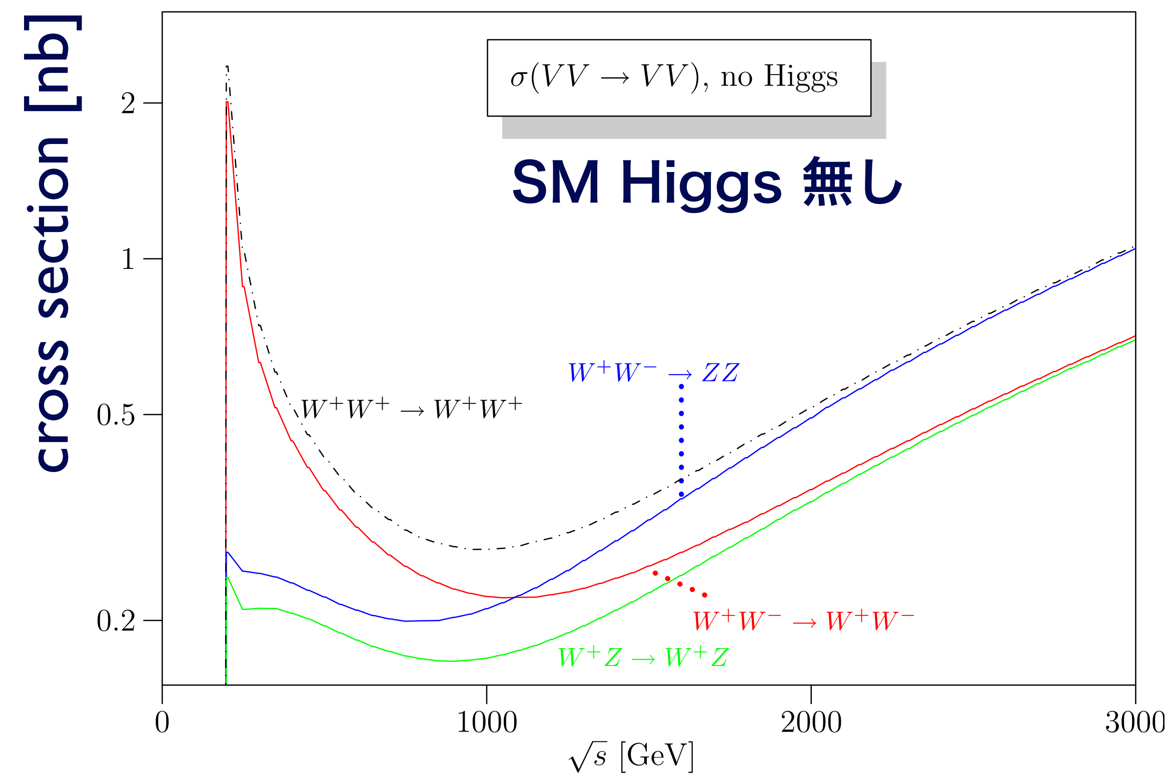
- $V_LV_L \to V_LV_L$ scattering w/o SM Higgs will violate unitarity above $\sqrt{s} \approx 1.2$ TeV ➡
- Unitarity can be restored with a specific coupling to VV if only one resonance
  例）**SM Higgs**

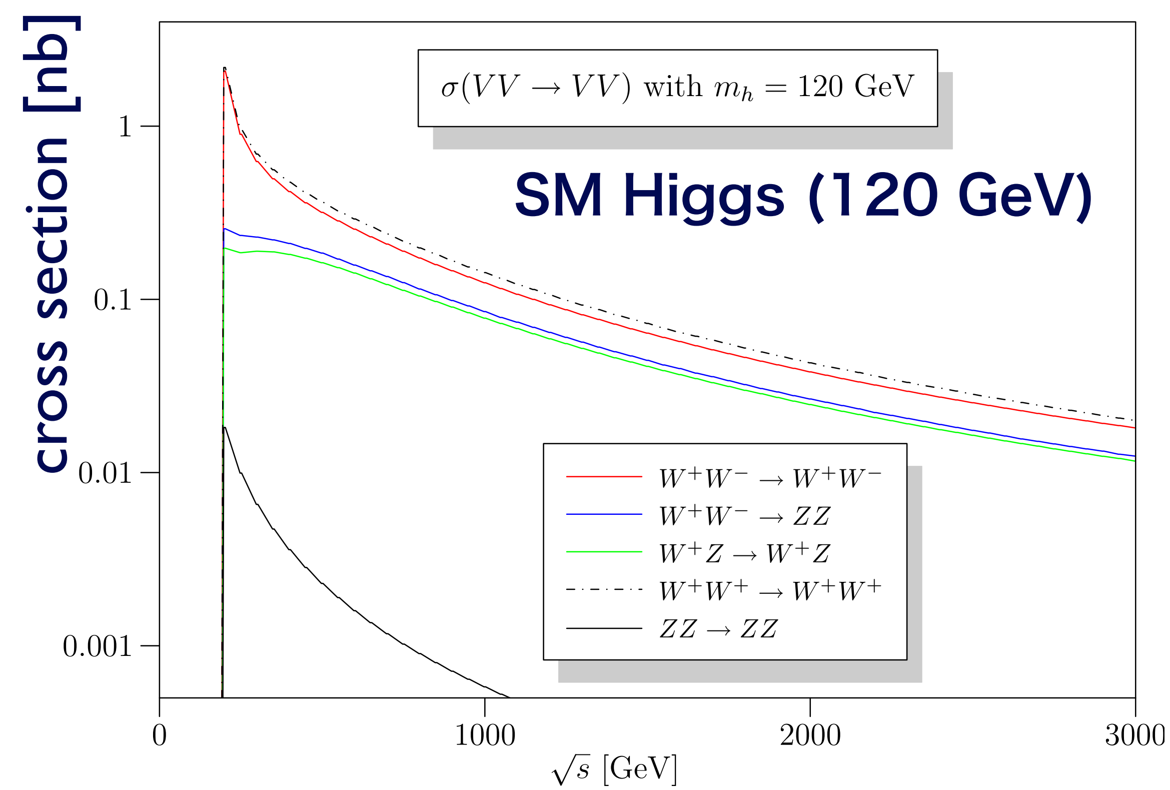
$$A(W_L^+W_L^- \to W_L^+W_L^-) \approx \frac{1}{v^2}\left(s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right)$$

- … or with a unique combination of couplings and resonances
  例）**Technicolor, 2HDM, …**

$$\sum_i g^2_{X_iWW} = g^2_{H_{SM}WW} = \left(\frac{2M_W^2}{v}\right)^2$$

$\sigma_{VV \to VV}$の$\sqrt{s}$依存性 (≳1 TeV)を14TeVで検証できるか？





VBS : Prospect

14 TeV, 3000 fb^{-1}でのW^+W^-→ZZに対する感度

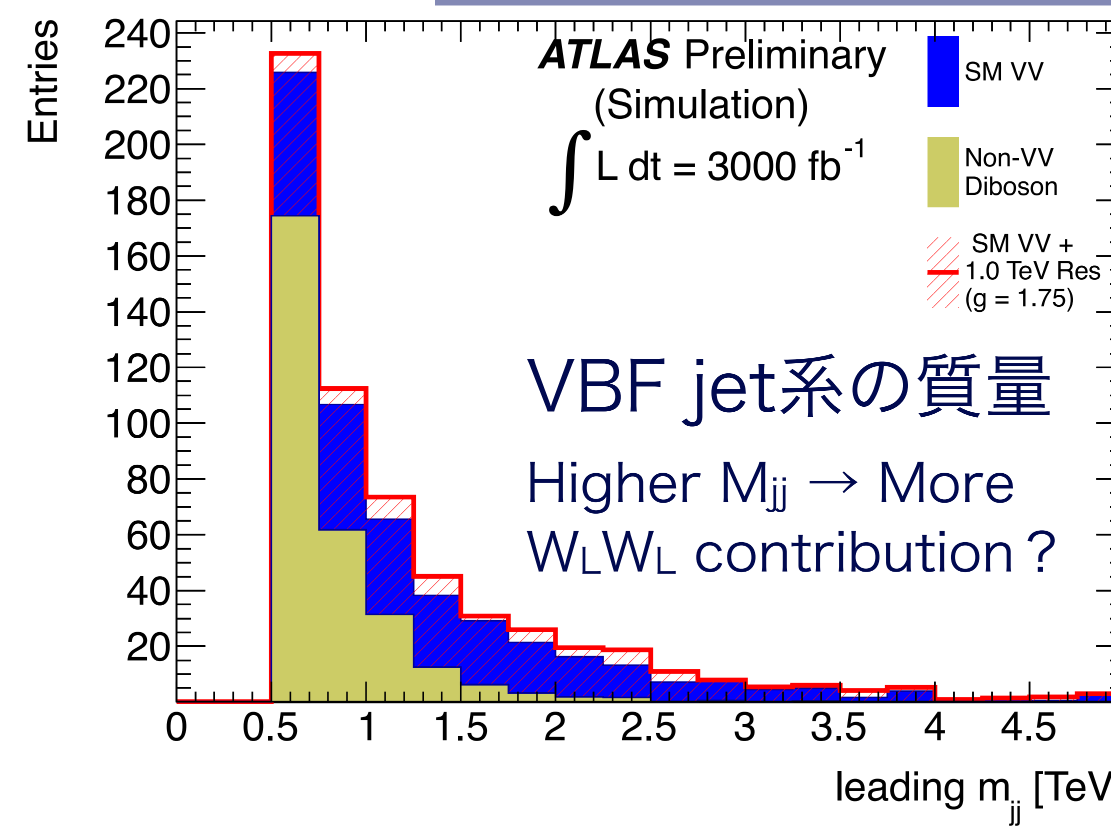
ATL-PHYS-PUB-2012-005

SM Higgs (126 GeV) included in WW→ZZ

- 2 OS-SF paris of 4-leptons
- VBF jets : ≥2 jets with M_{jj} > 1 TeV
  (More SM VV events at higher M_{jj})

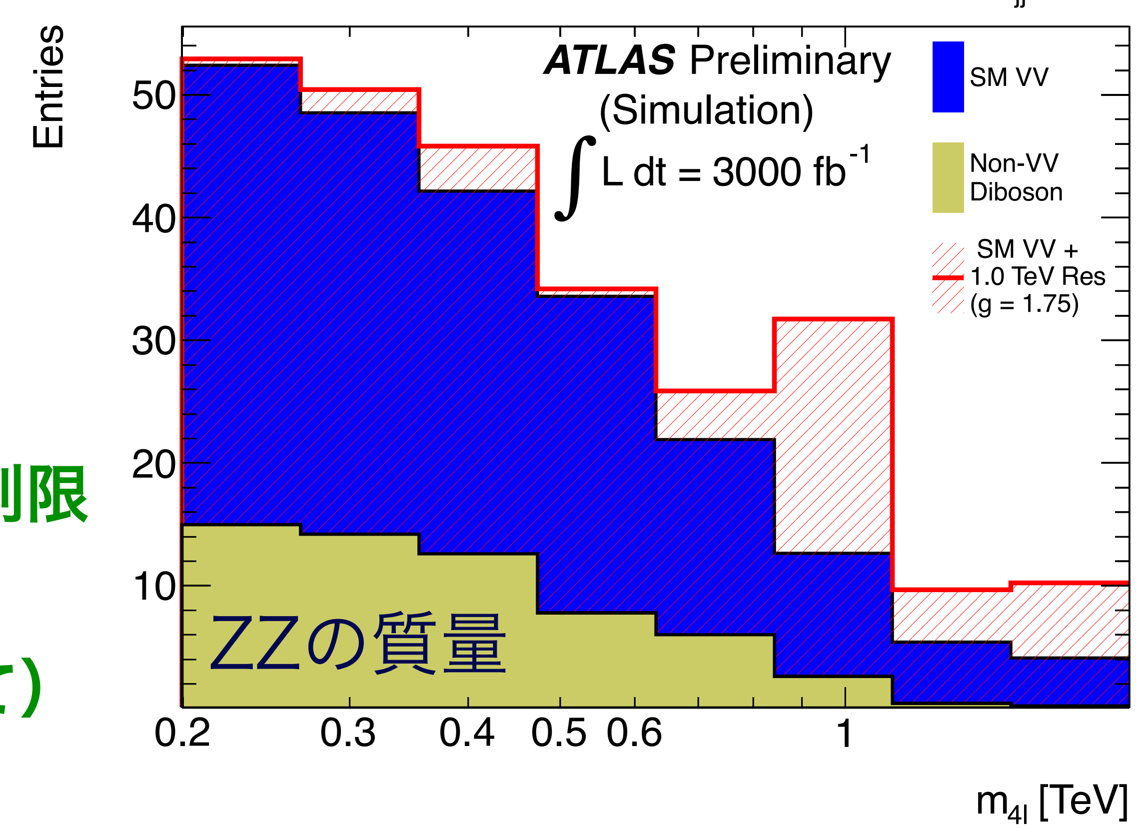
Resonanceの発見感度

model	300 fb^{-1}	3000 fb^{-1}
$m_{\text{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\text{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ



2015-17年 (~100 fb^{-1}) で出来ること?

- **$\sigma_{VV}/\sigma_{VV}^{SM}$の測定** at $\sqrt{s}$(VV)≥1 TeV
- 126GeV Higgsが非SM結合を持つと想定
  → **Unitarity結合を仮定したResonanceの質量制限**
- 126GeV HiggsがSM結合を持つと想定
  → **VV resonance結合の制限（質量の関数として）**

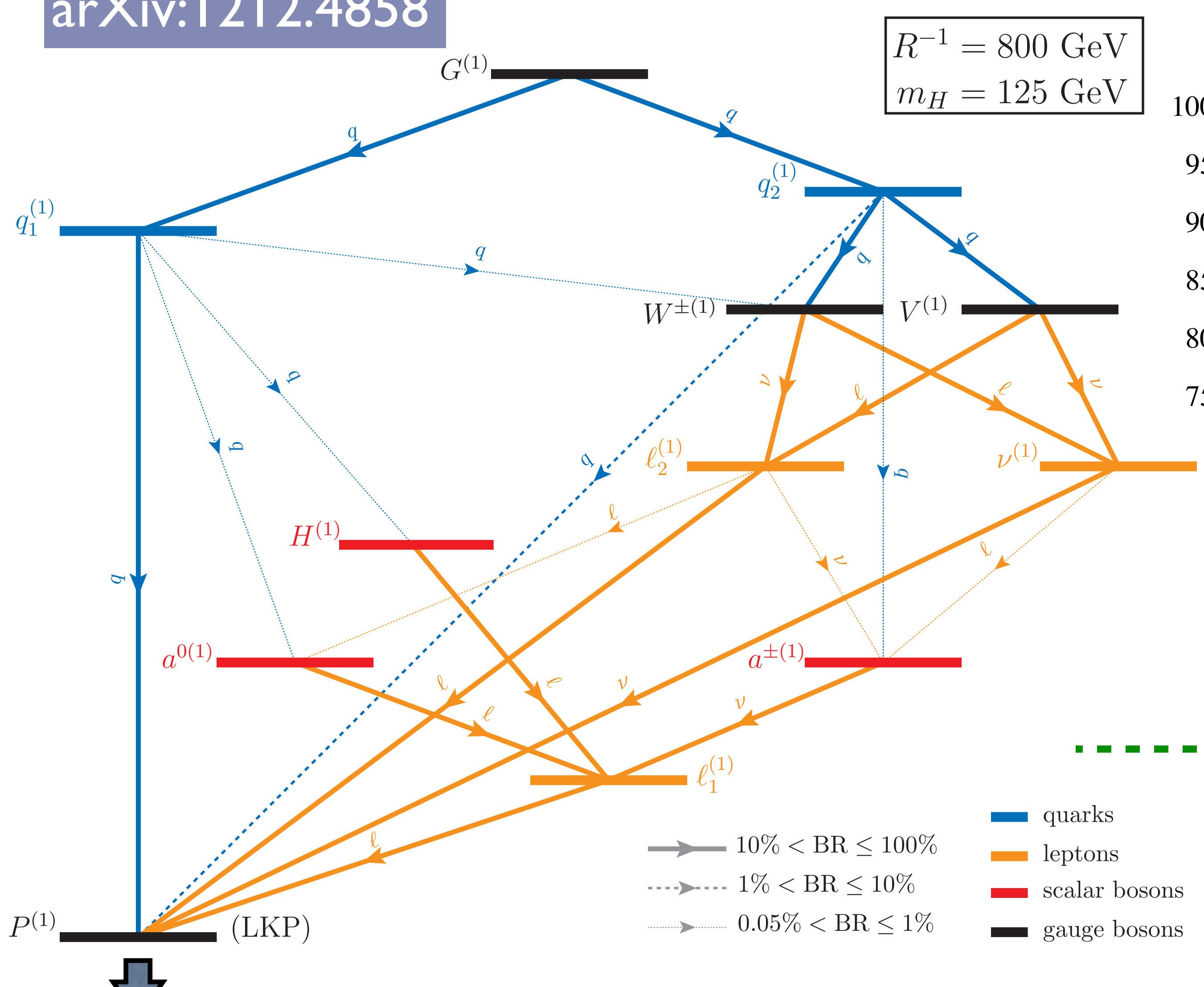


Universal Extra Dimensions

UED (Appelquist, Cheng, Dobrescu)

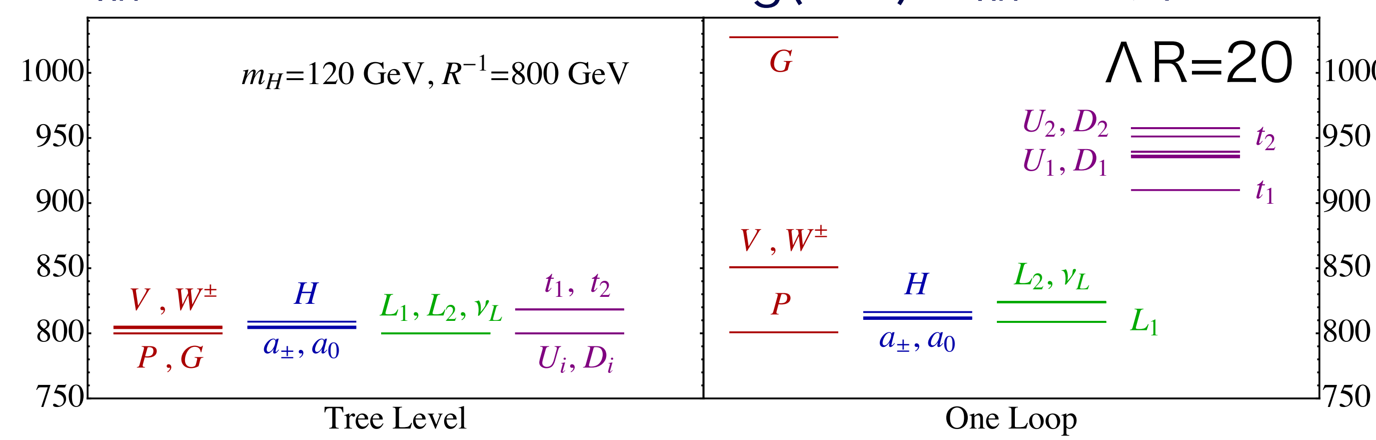
- R^{-1}~TeV sized flat extra dimension (4 + extra 1-dim = Minimal UED)
- Effective field theory with cut-off scale Λ
- Infinite number of KK towers to SM particles : $m_n^2 \approx m_{SM}^2 + (n/R)^2$
- KK parity conserved → lightest KK particle (LKP) = DM candidate

arXiv:1212.4858



Missing E_T

縮退している　　log(ΛR)で縮退が解ける

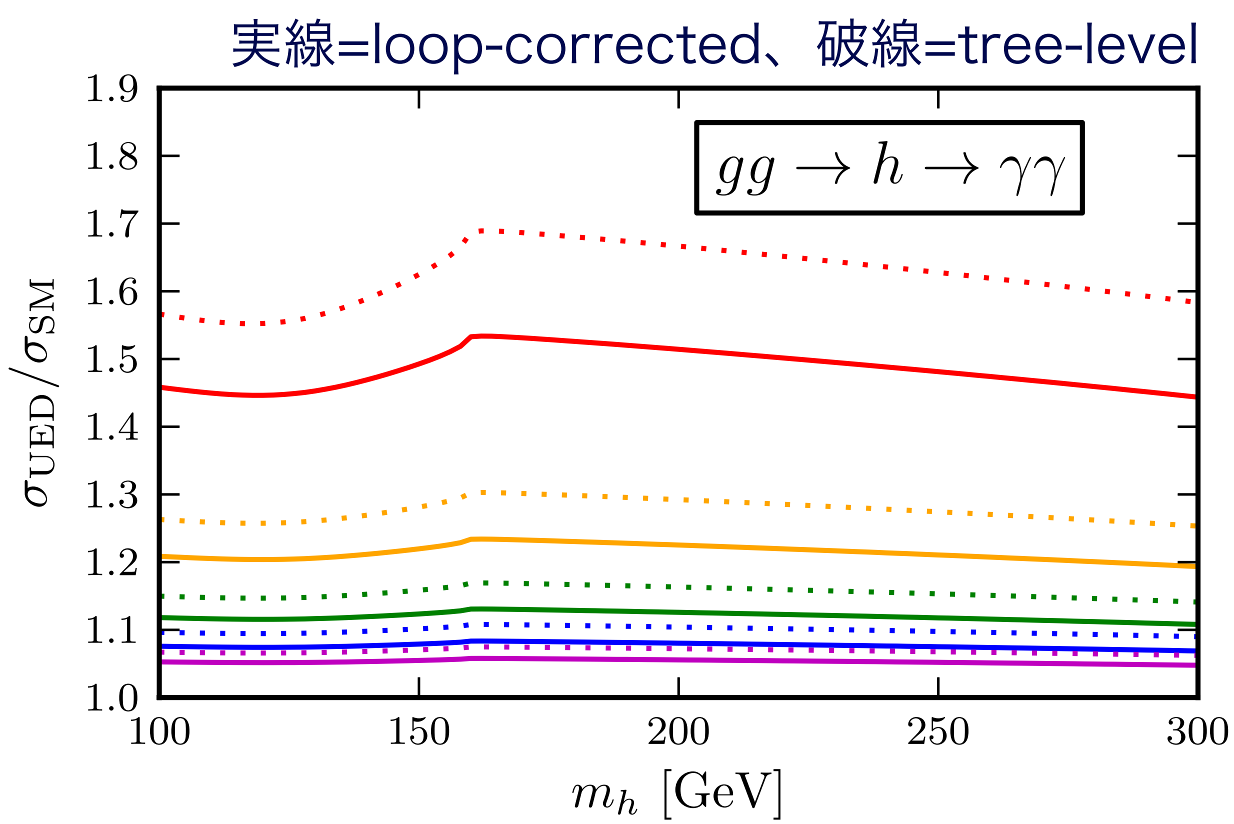


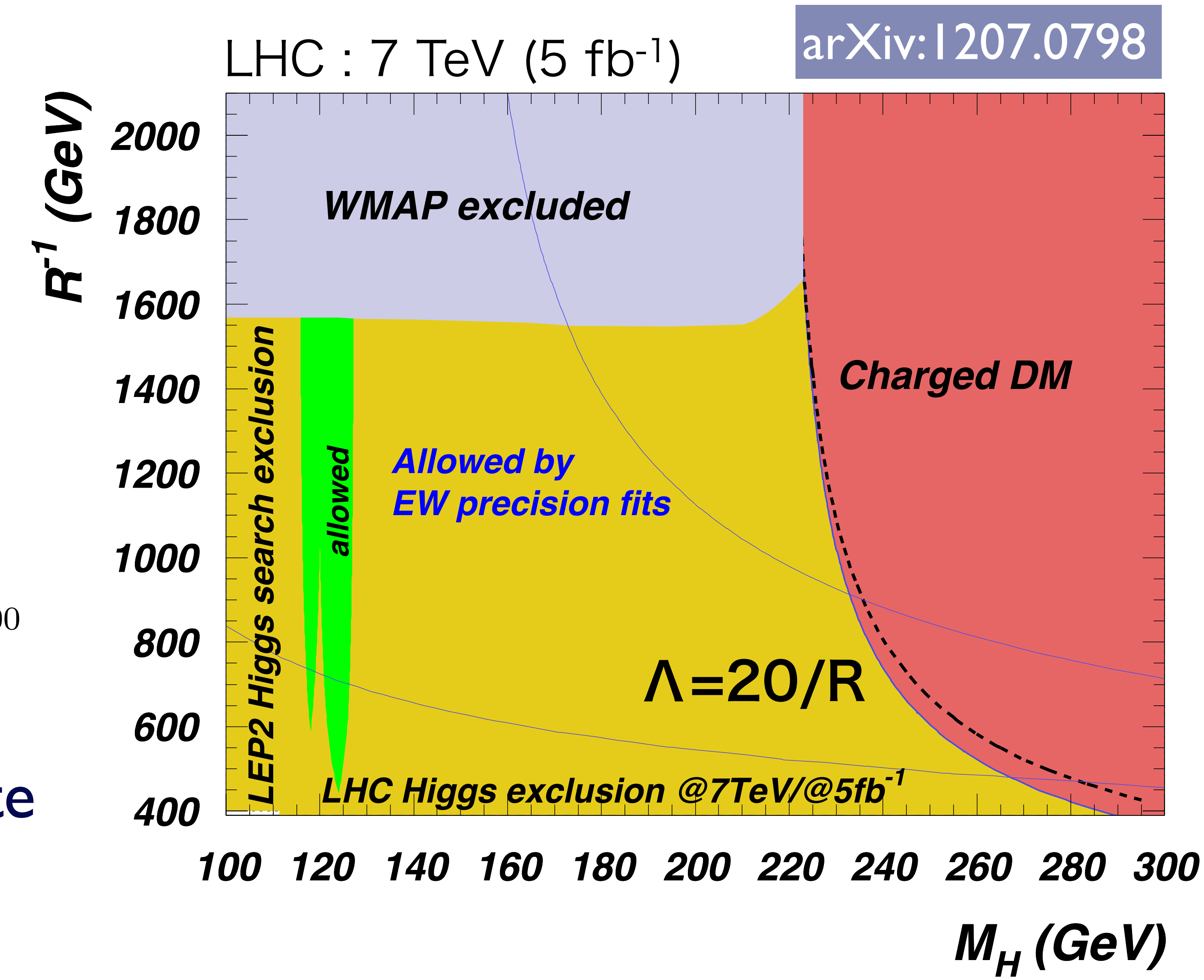
- KK gluon→KK photonへカスケード崩壊

→ 生成粒子のスペクトラムがソフト

- KK photonの質量 〜 R^{-1}
- Lepton崩壊経由の割合が高い可能性
  - KK W/ZがKK quarkより軽い
  - KK W/Z→SM W/Z崩壊はsuppressされる

mUED with 126 GeV Higgs





KK fermions (mainly top) contribute to $gg \to h$ loops

➔ Enhance $\sigma_{gg\to h}$ relative to SM

Both KK W and KK top contribute to $h \to \gamma\gamma$ loops

- Large *negative* KK top effect

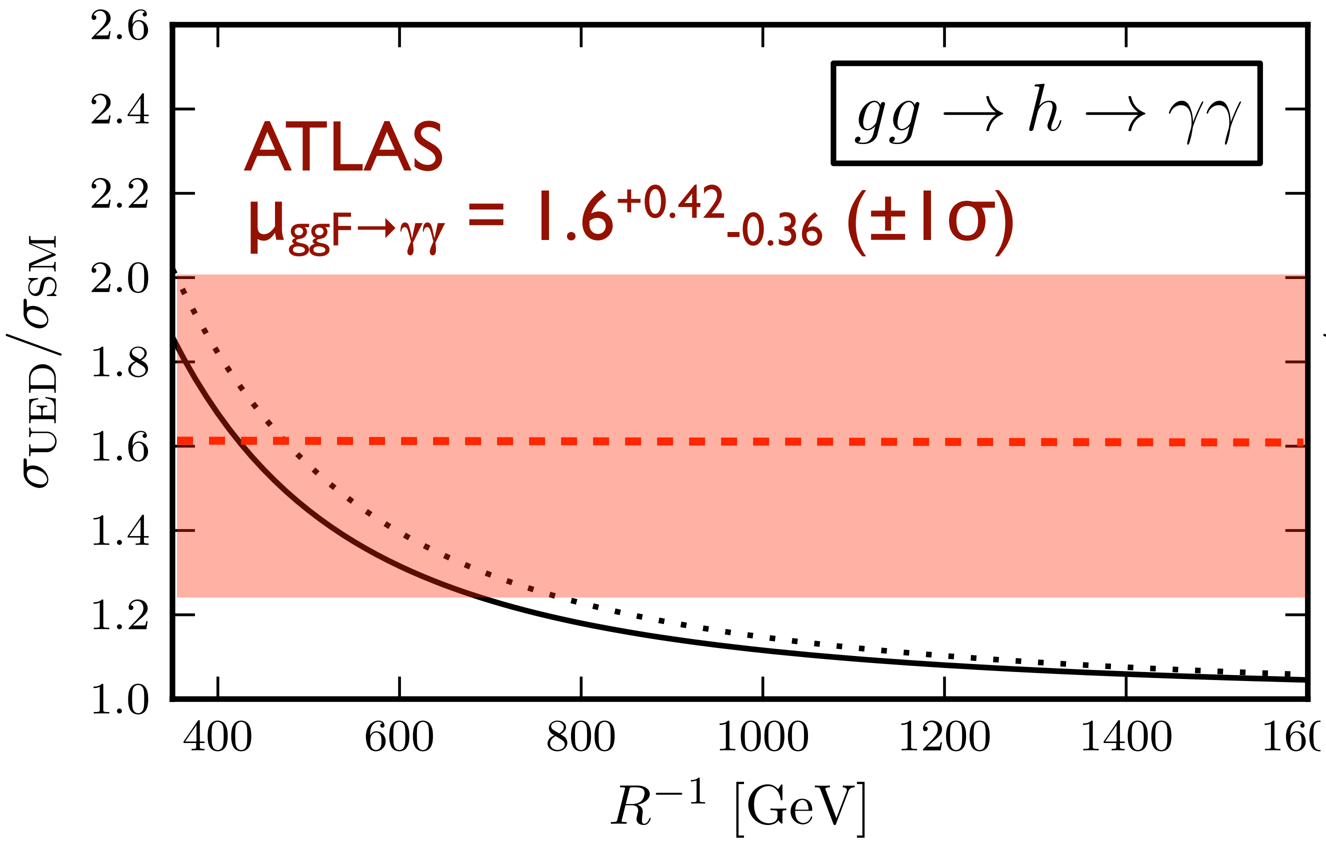
➔ $h \to \gamma\gamma$ suppressed relative to SM

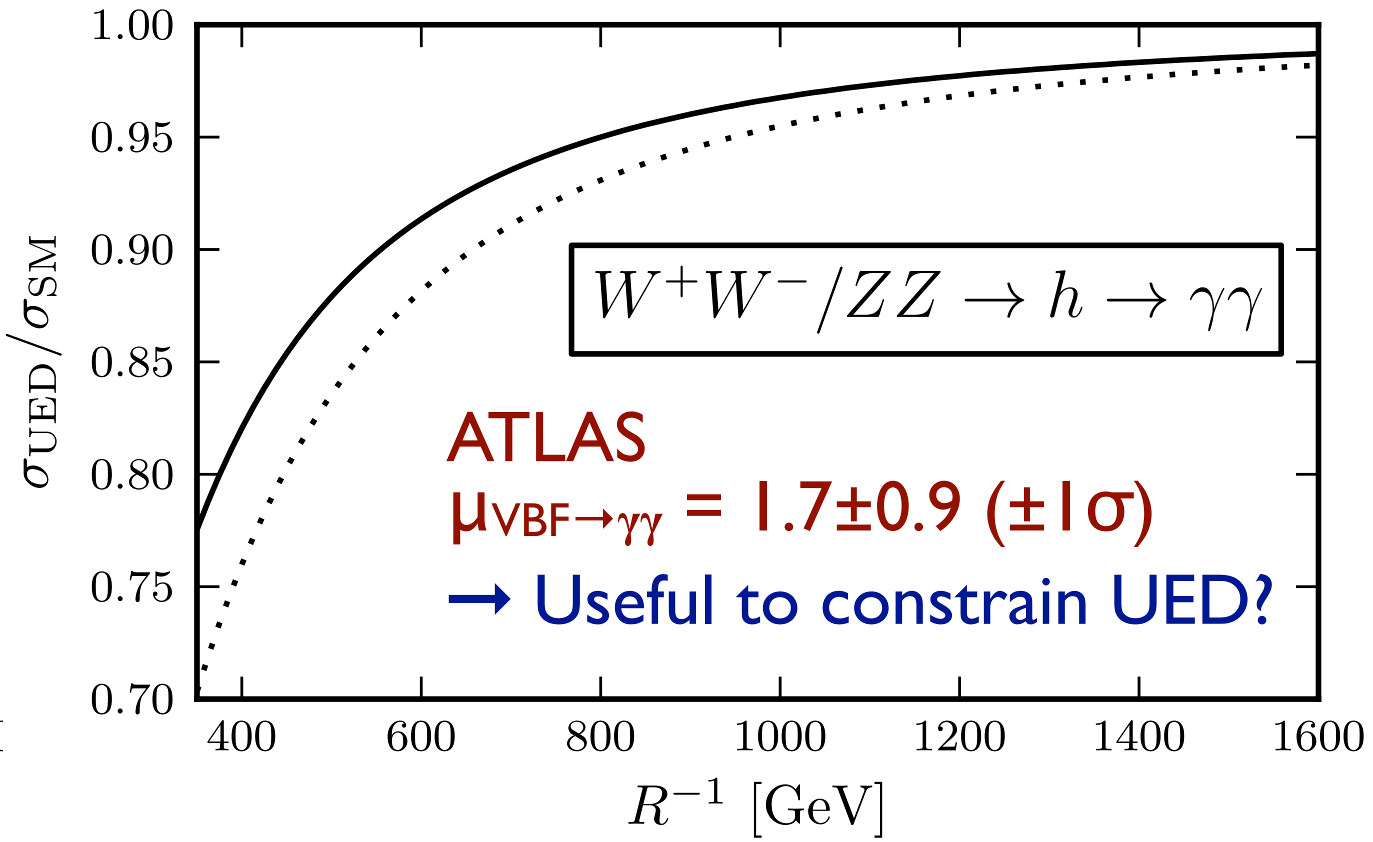
許容されるパラメータ領域

- 測定されたHiggs質量領域に限定される
- R^{-1} vs Λで許容領域を書くべき？（基研研究会）

➔ 結局は大きいR^{-1}（高いKK質量領域）を探索できるかが鍵

mUED : Constraint by μ_H





KK particle contributions to $gg \to h$ and $h \to \gamma\gamma$ loops become smaller with increasing KK particle masses

➔ Smaller effect at larger R^{-1} : ~10(15)% effect on $\mu_{\gamma\gamma}$ (μ_{WW}) at R^{-1}=1 TeV

300-3000 fb^{-1}では$\mu_{ggF\to\gamma\gamma}$($\mu_{VBF\to\gamma\gamma}$)の精度は5-10%(10-30%)程度で決まる

mUED : Direct Search Prospect

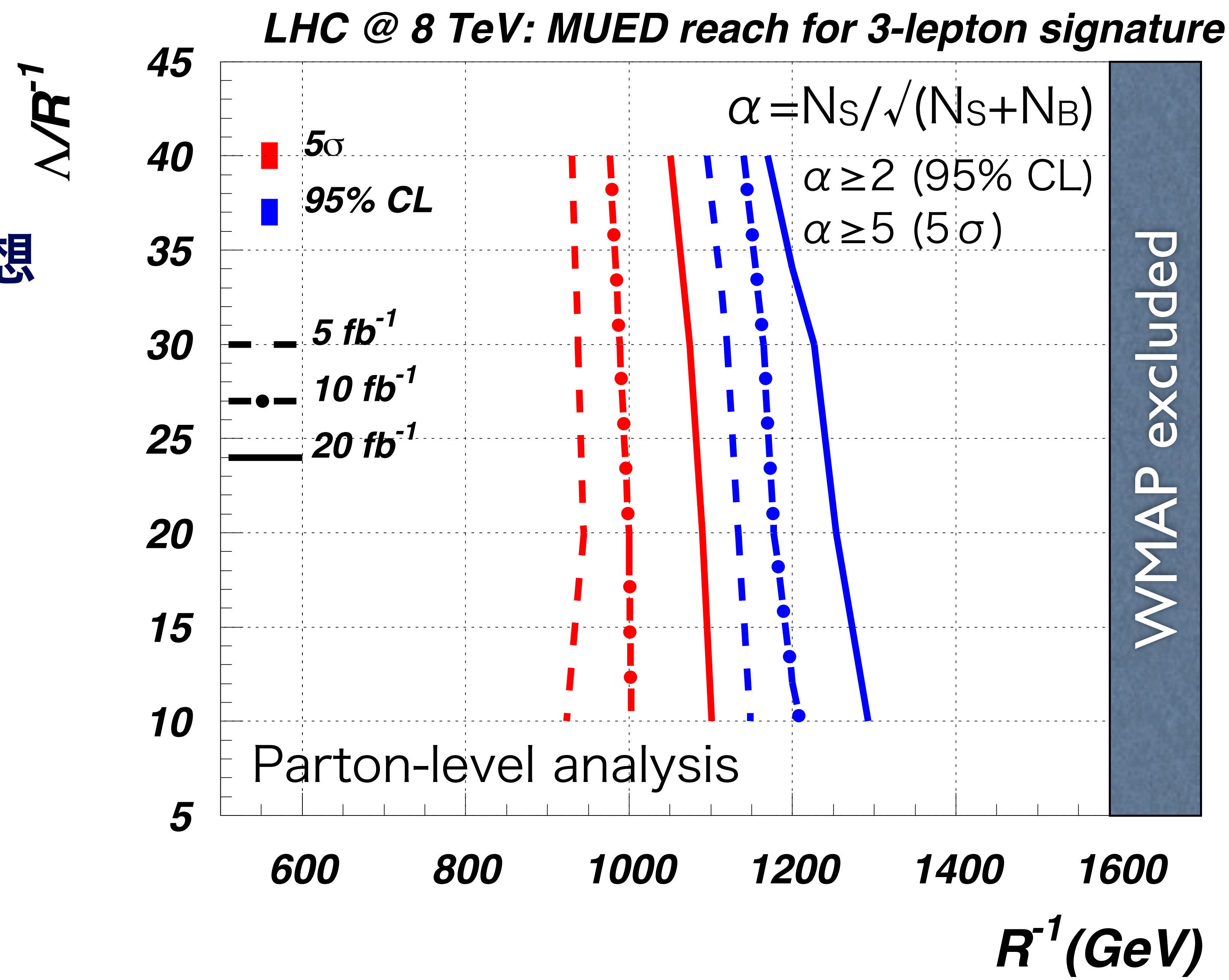
arXiv:1212.4858

Multilepton探索での感度予想

- ≥ 3 leptons (e, μ) $p_T > 10$ GeV
- $p_T^{lepton1(2,3)} < 100(70,50)$ GeV
- $E_T^{Miss} > 50$ GeV
- Z-veto: $|M_{ll} - M_Z| > 10$ GeV
- $M_{eff} = \sum_{lepton,jet} p_T + E_T^{miss} > R^{-1}/5$

主なバックグラウンドは

WZ, ttV, VVV



8TeVの解析は進行中

（ΛR<10の領域は理論的に有効？）

Summary

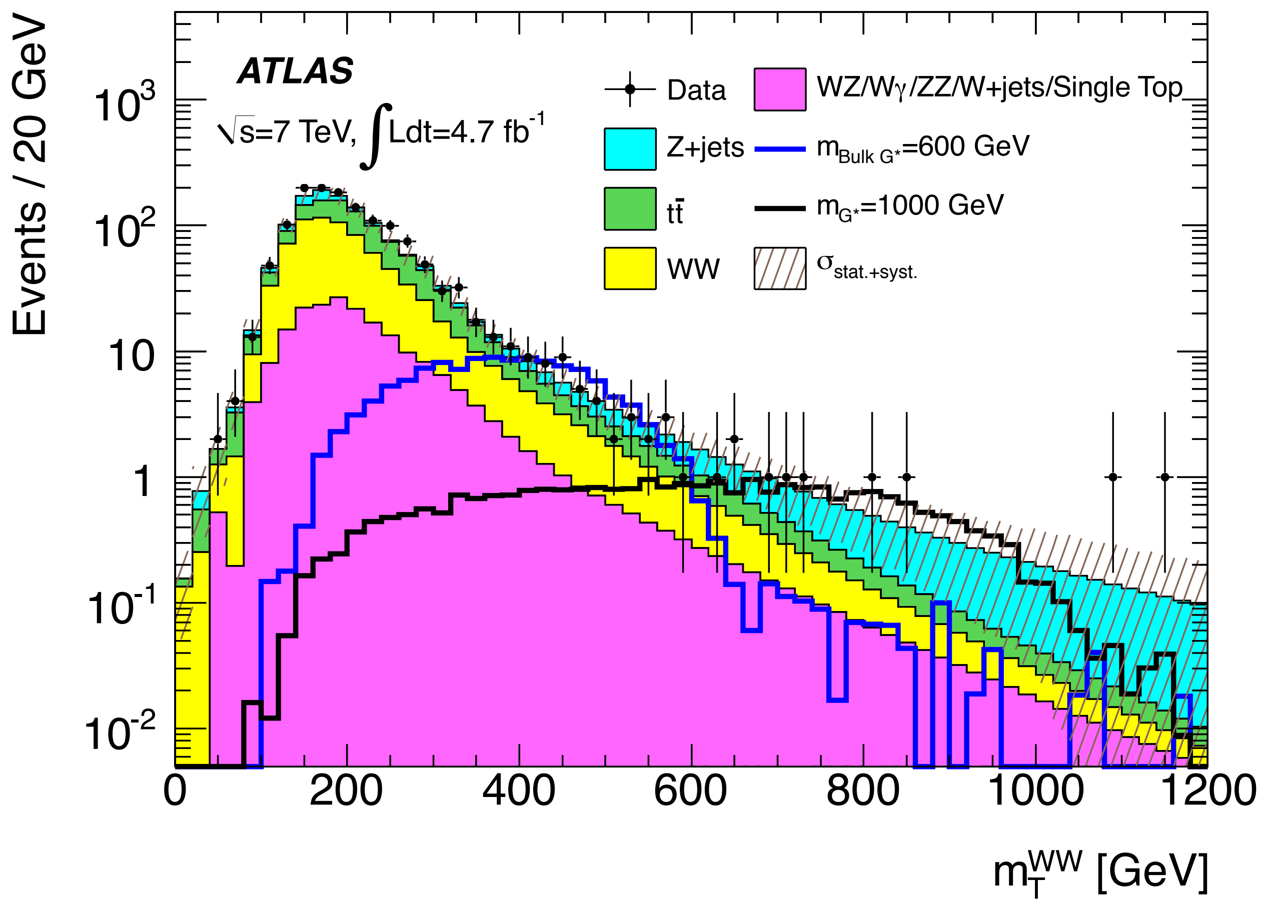
- ヒッグスの性質測定から余剰次元模型へ制限を課すことができる
- KK gluonの直接探索はRS模型で期待される領域へ到達しつつある
  - より重いKK stateへの感度？non-resonant excess?
- mUED
  - 8 TeV 3-lepton解析でどこまで行けるか？
- Walking Technicolor
  - DileptonとVHチャンネルで広いパラメータ領域をカバーできる可能性
- VV散乱
  - 14 TeV Run2でSM過程の測定、resonanceへの制限

Backup

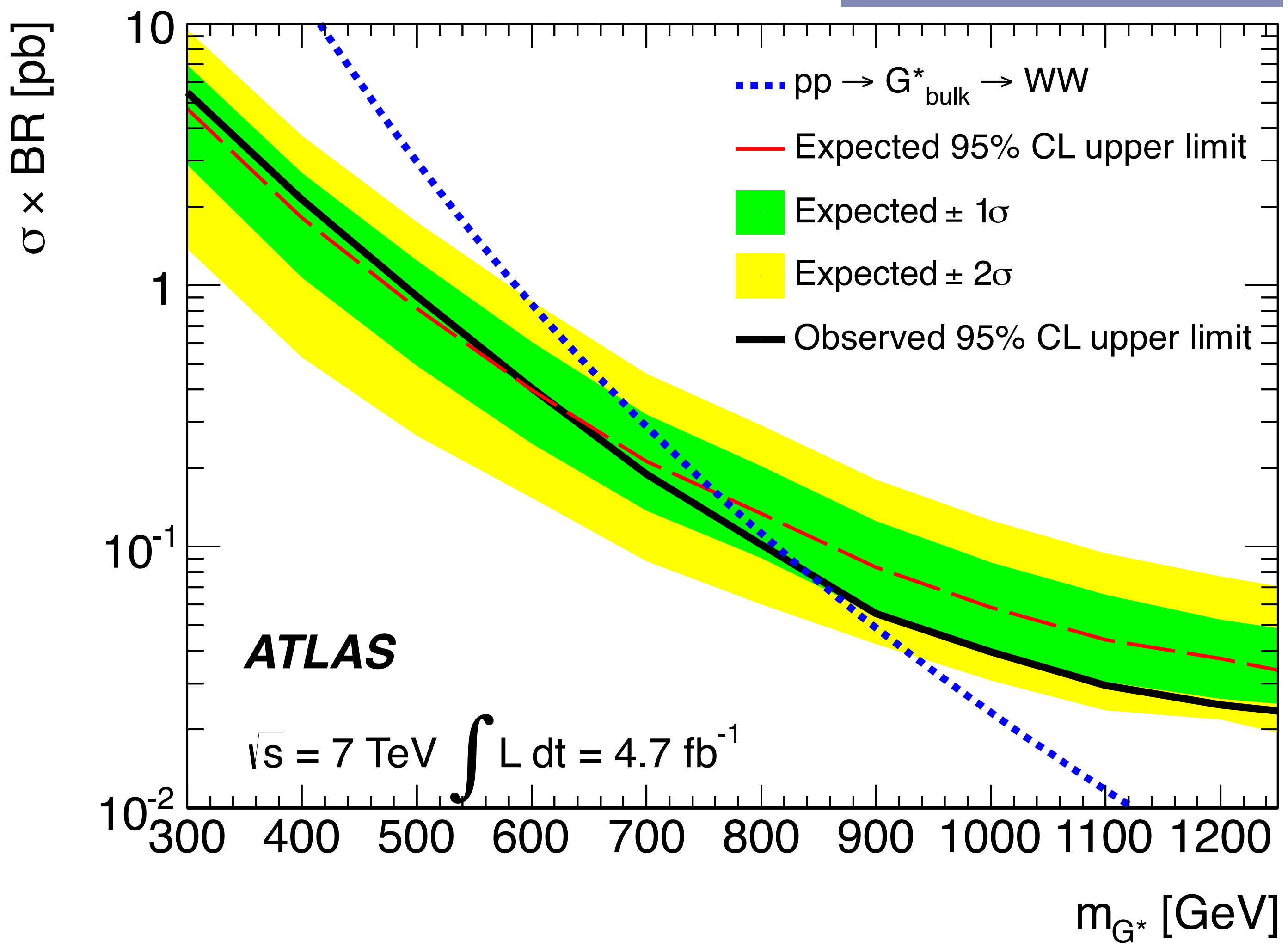
High-Mass WW → lνlν

arXiv : 1208.2880

2 OS leptons p_T > 25 GeV
M_{ll} > 106 GeV
E_T^{miss} > 30(60,65) GeV for ee(eμ,μμ)
no b-jet p_T>20 GeV



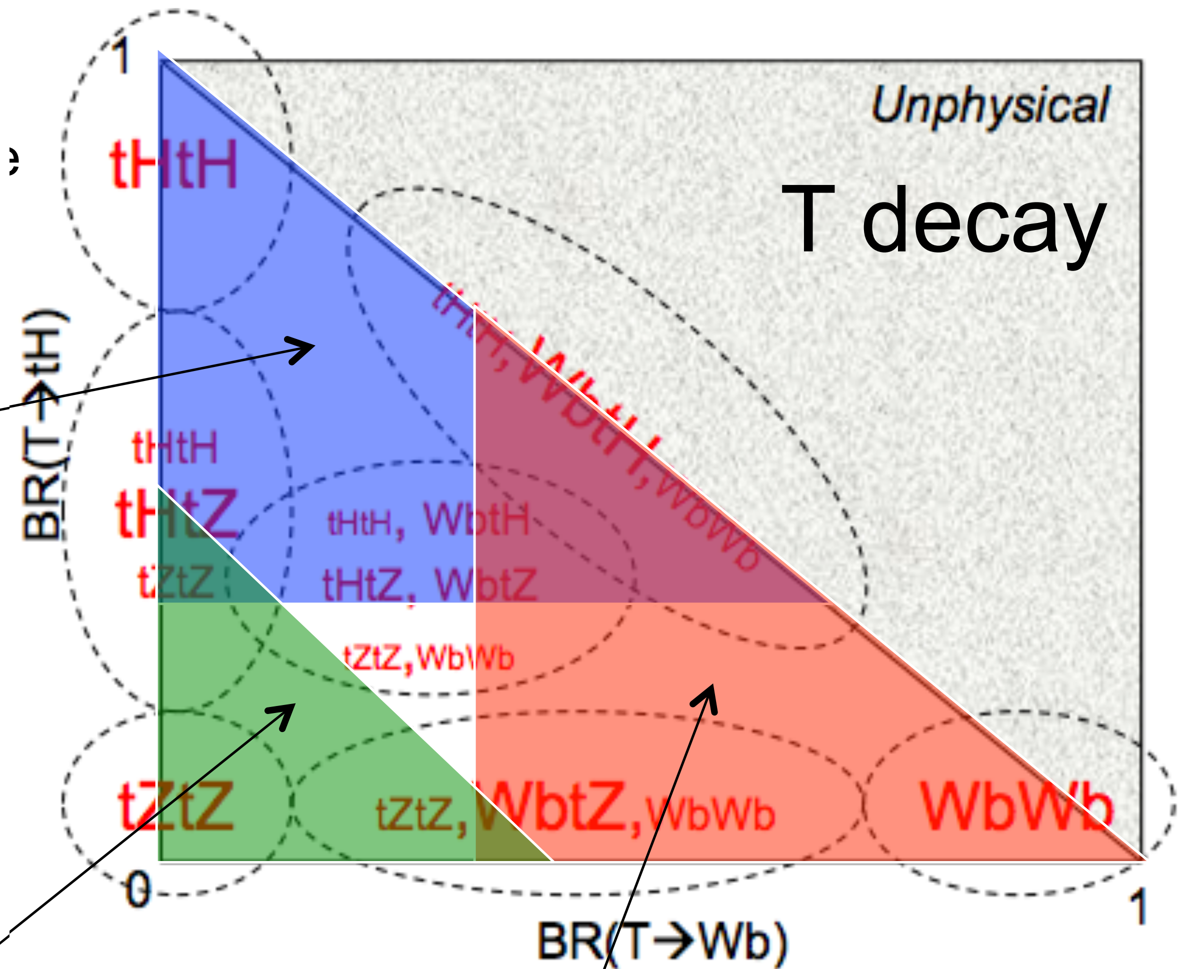
Also sensitive to SM Higgs-like wide resonance



Bulk RS gravitonへの制限
- M(graviton) > 0.84 TeV

Vector-like Quarks

Lepton+Jets channel



Sub-analysis #2 (a-la ttH-like):

- N_{jets}: 6, 7, ≥8 ➔ 3 bins
- $N_{b\text{-tags}}$: 3, ≥4 ➔ 2 bins

Total: 6 bins

➔ Mass reconstruction hard. Use H_T.

Sub-analysis #3 (a-la b'b'→WtWt):

- N_{jets}: 6, 7, ≥8 ➔ 3 bins
- $N_{b\text{-tags}}$: 1 or 2 ➔ 1 bins
- N_{Vhad}: 0, 1, ≥2 ➔ 3 bins

Total: 9 bins

➔ Mass reconstruction hard.
Counting experiment.

Sub-analysis #1 (a-la t't'→WbWb):

- N_{jets}: ≥4 ➔ 1 bins
- $N_{b\text{-tags}}$: 1 or 2 ➔ 1 bins
- N_{Vhad}: 1, ≥2 ➔ 2 bins

Total: 2 bins

➔ Mass reconstruction possible

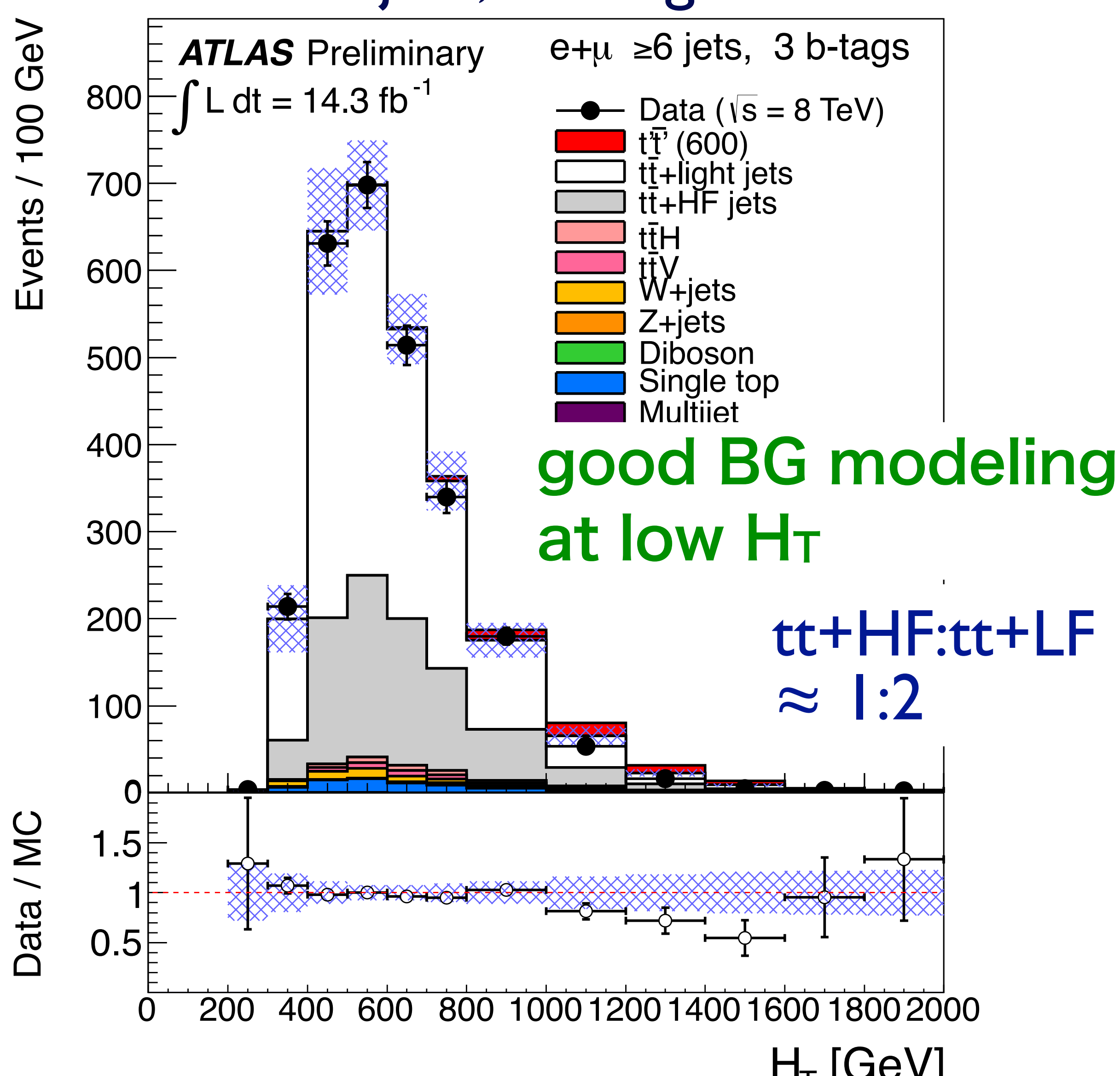
➔ 3つの解析でBR空間をカバー（model independent）

t't̄' → Ht + X (I)

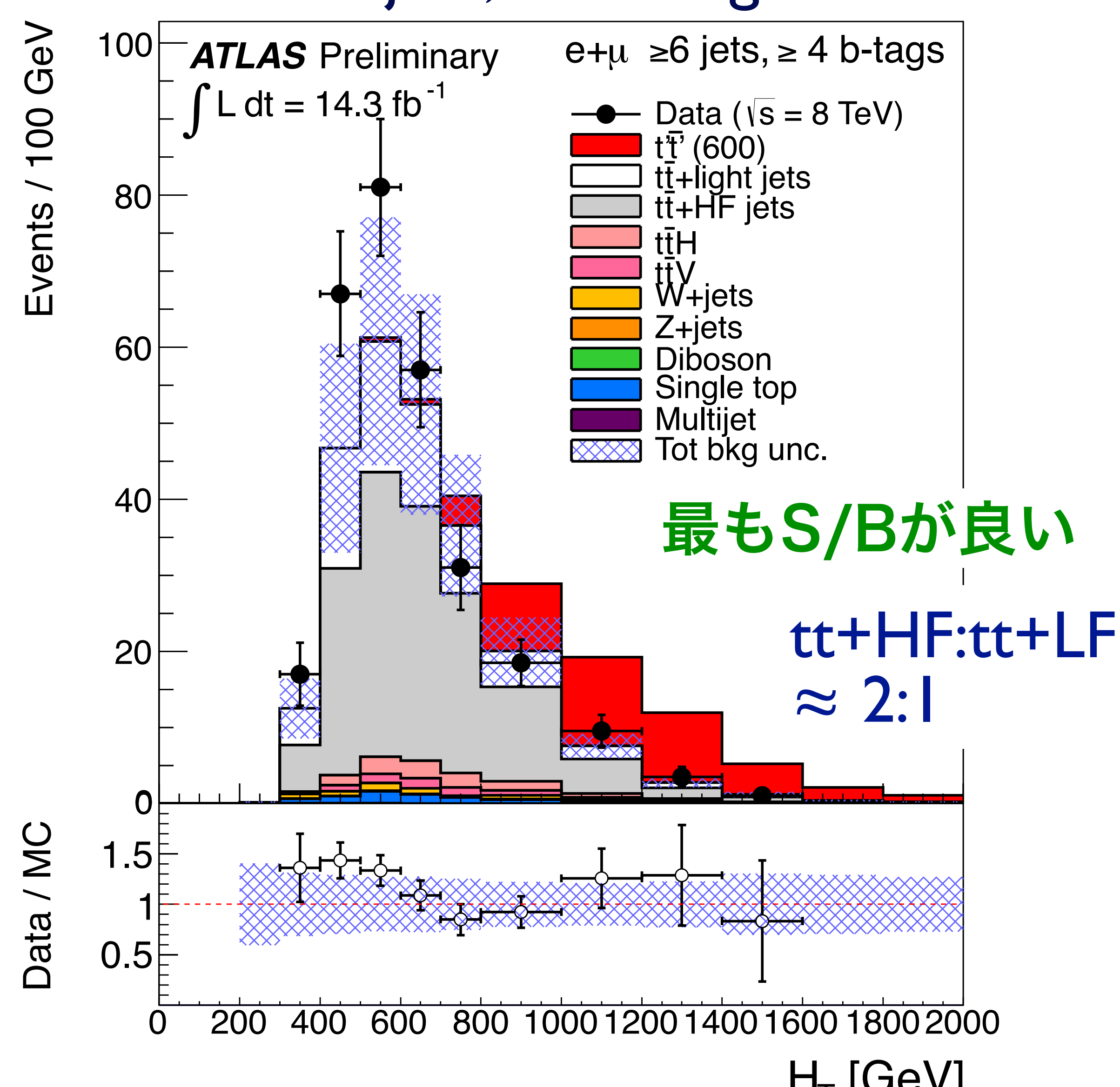
Analysis strategy
- Built on ttH(→bb) analysis
- large N_{jet}(≥ 6), large $N_{b\text{-}tag}$ (≥ 3)
- Use H_T as discriminant variable
- Orthogonal to Wb+X with event-veto

- tt+HF jets dominant BG (≥4 b-tags)
- tt+JF/HF jets normalizations determined by fits in CR (H_T<700 GeV)

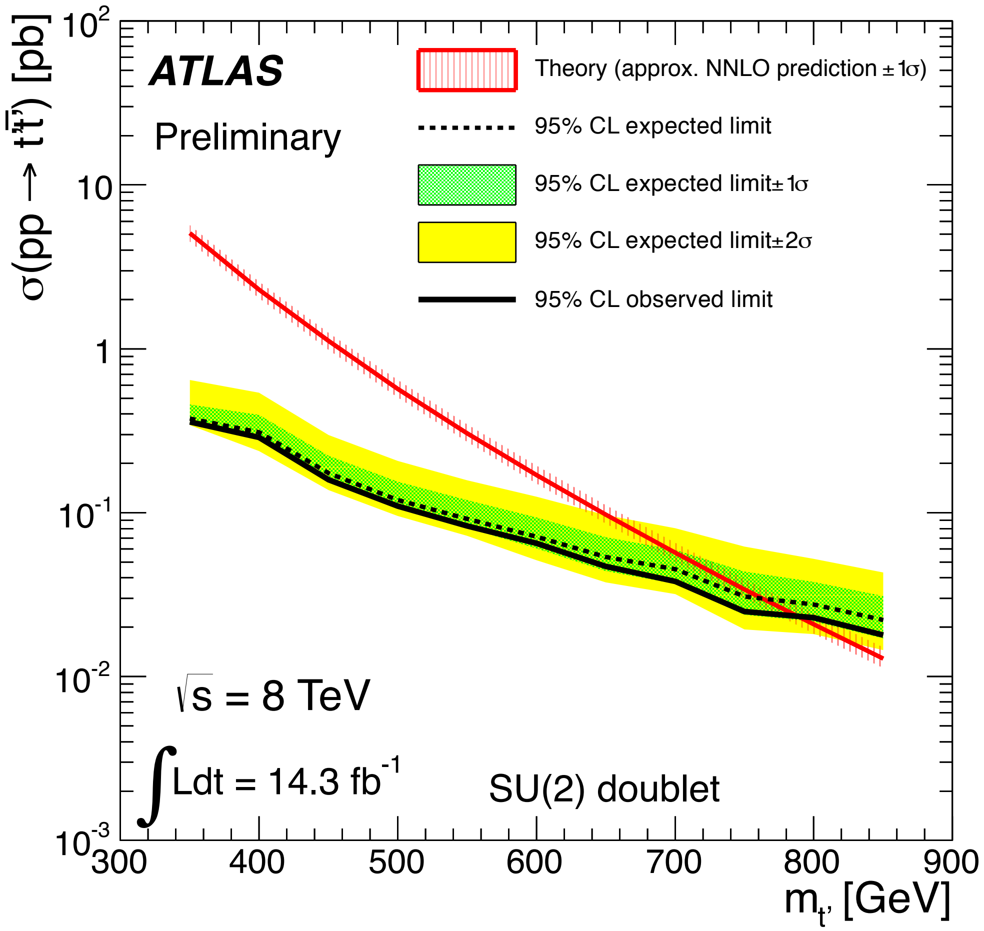
SR : ≥6 jets, 3 b-tags

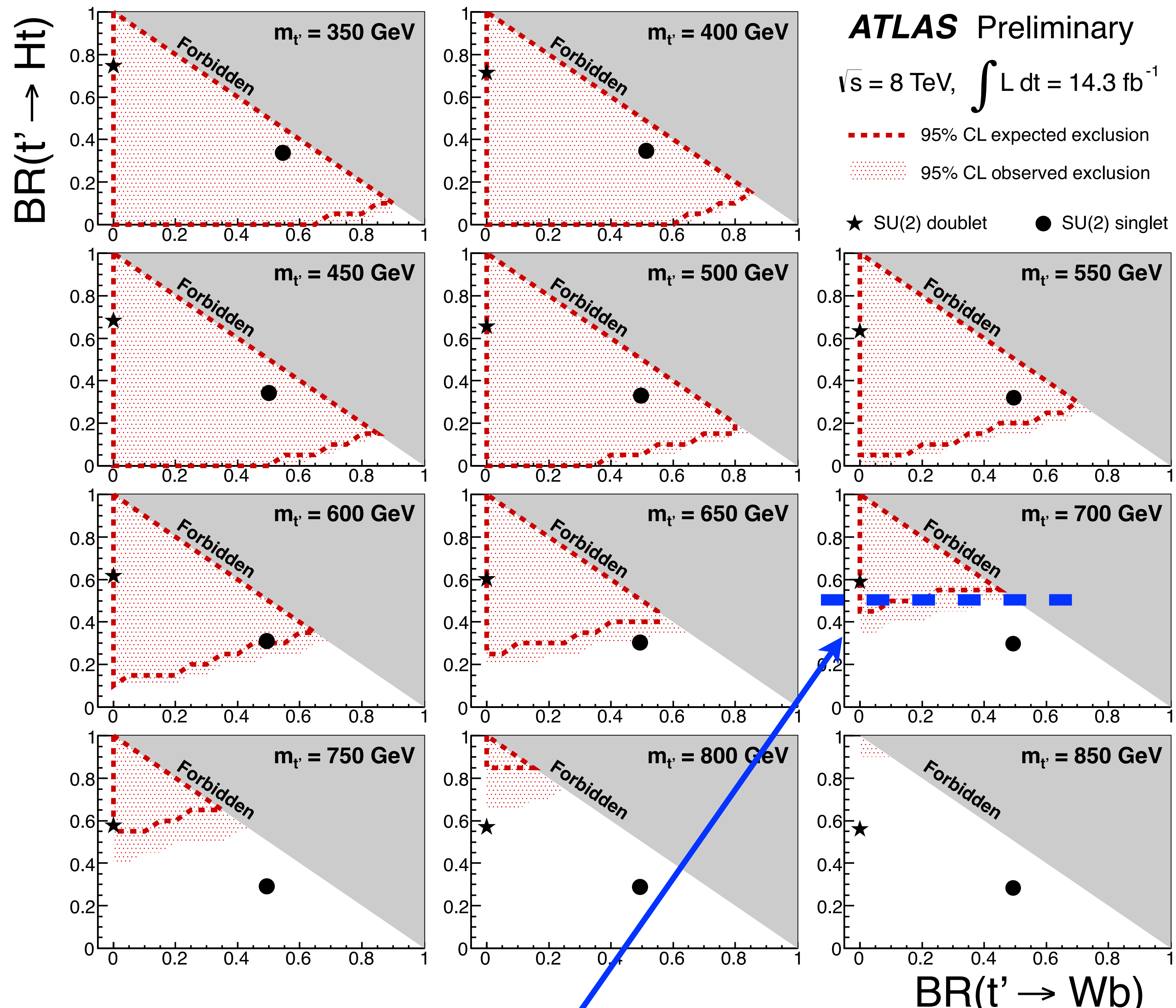


SR : ≥6 jets, ≥4 b-tags



$t'\bar{t}' \to Ht + X$ (II)





VLQへの制限

- $M(VLQ) > 790$ GeV
  SU(2) doublet

例）BR(t'→Ht)>0.5 excluded
for m_{VLQ}=700 GeV

$t'\bar{t}' \rightarrow Wb + X$ (I)

Analysis with “boosted” W-bosons

- A high pT isolated lepton with large E_T^{miss}
- $\geq$3 jets with $\geq$1 b-tag jet
- A high-p_T hadronic-W jet (merged or resolved)

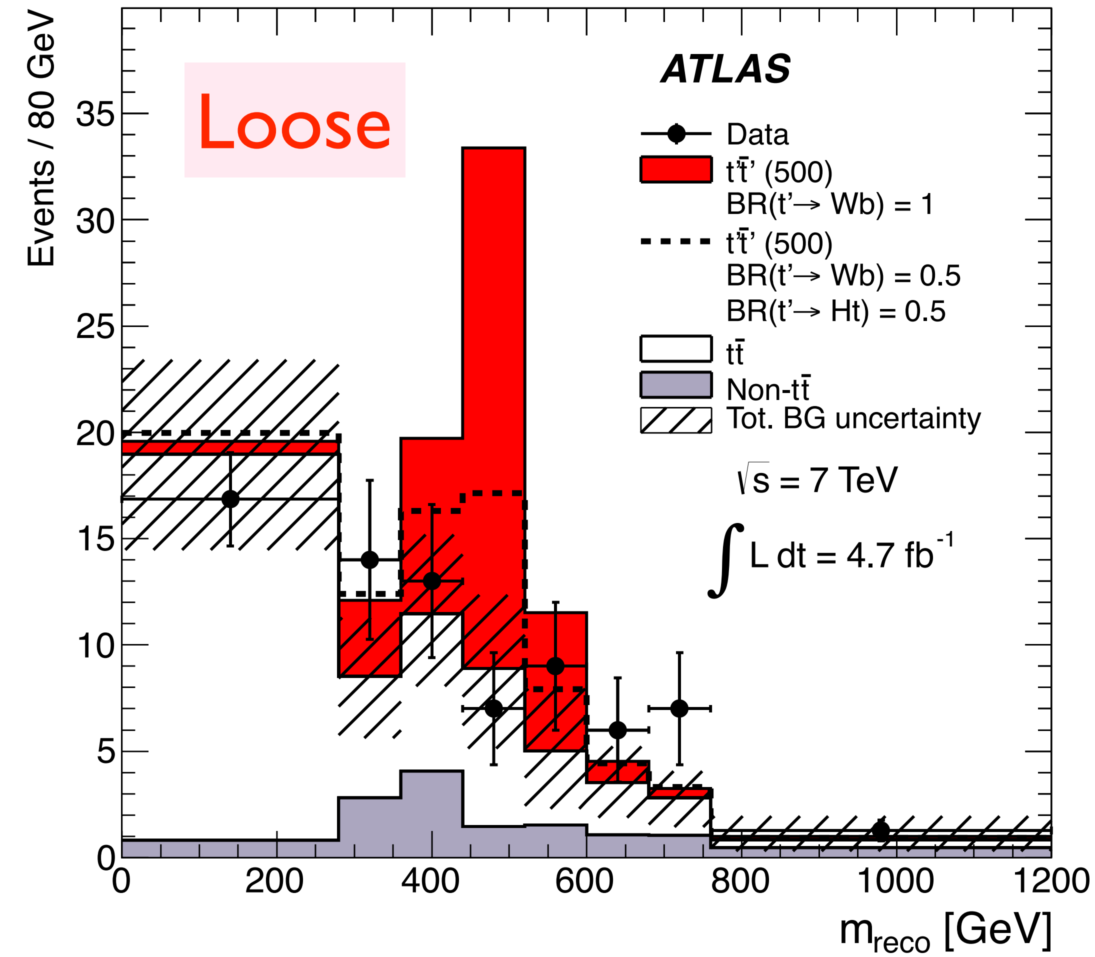
<u>Selection Cuts</u>

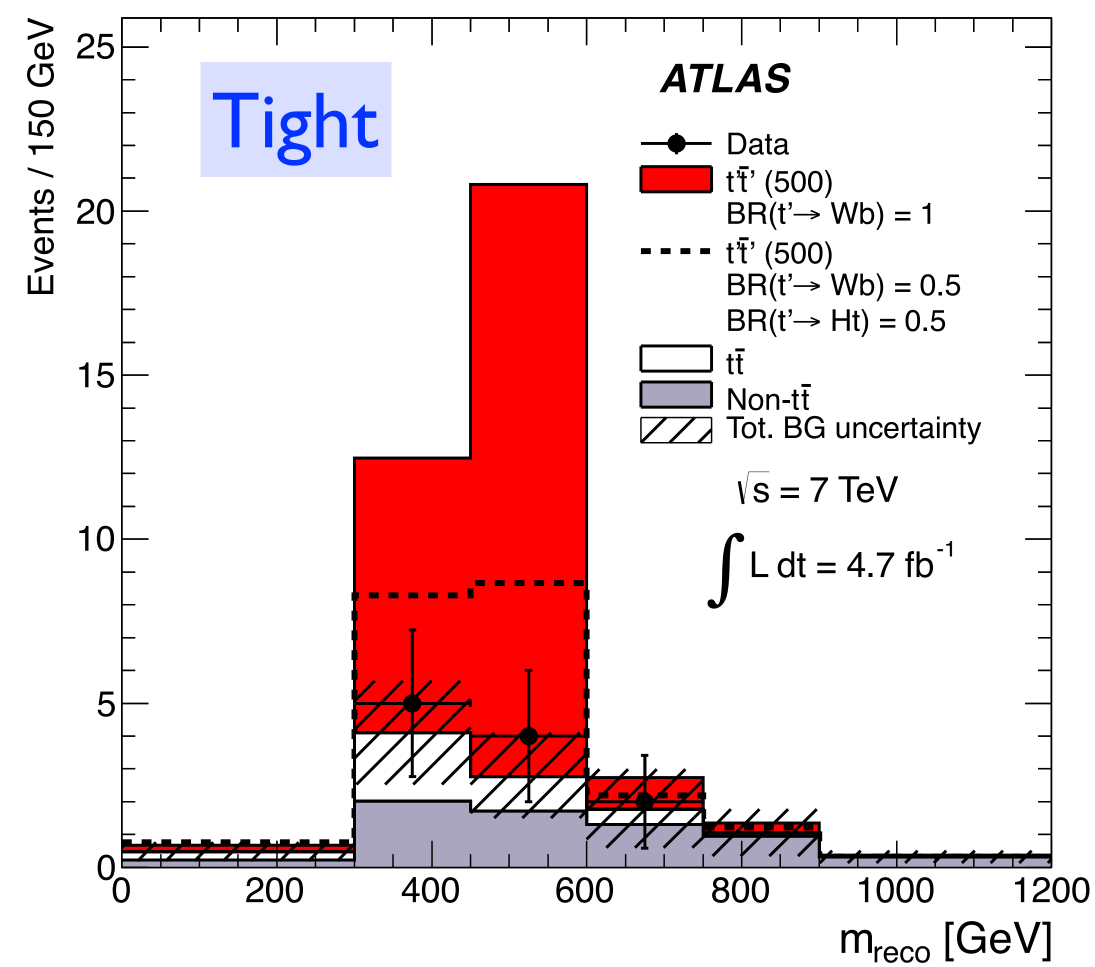
- Leptonic-W by solving p_Z^{ν} with W-mass
- Large scaler p_T sum of lepton, jets and E_T^{miss}
- Two jets with highest b-tag weight : p_T >160 and >60 GeV
- ΔR(lepton, ν) < 1.4

→ Loose selection

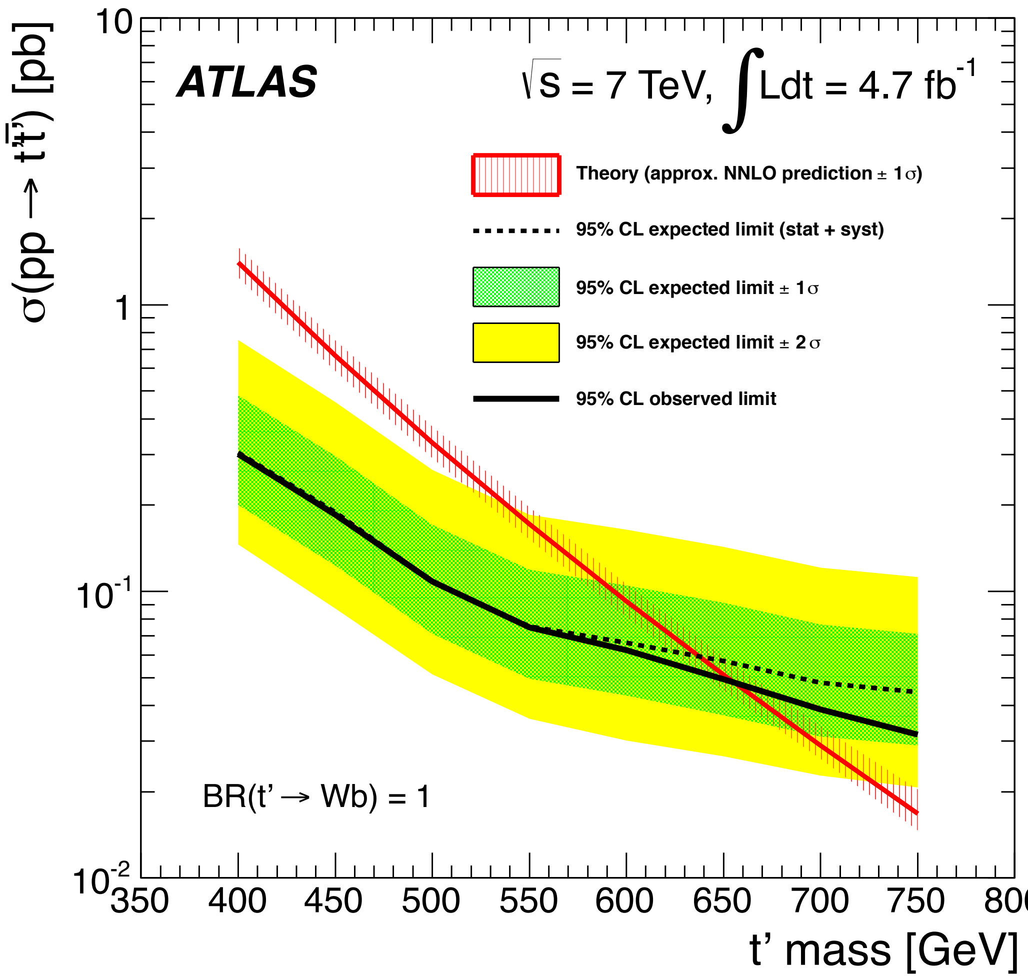
- min($\Delta R(W^{had}$, b_1 or b_2)) > 1.4
- min(ΔR(lepton, b_1 or b_2)) > 1.4

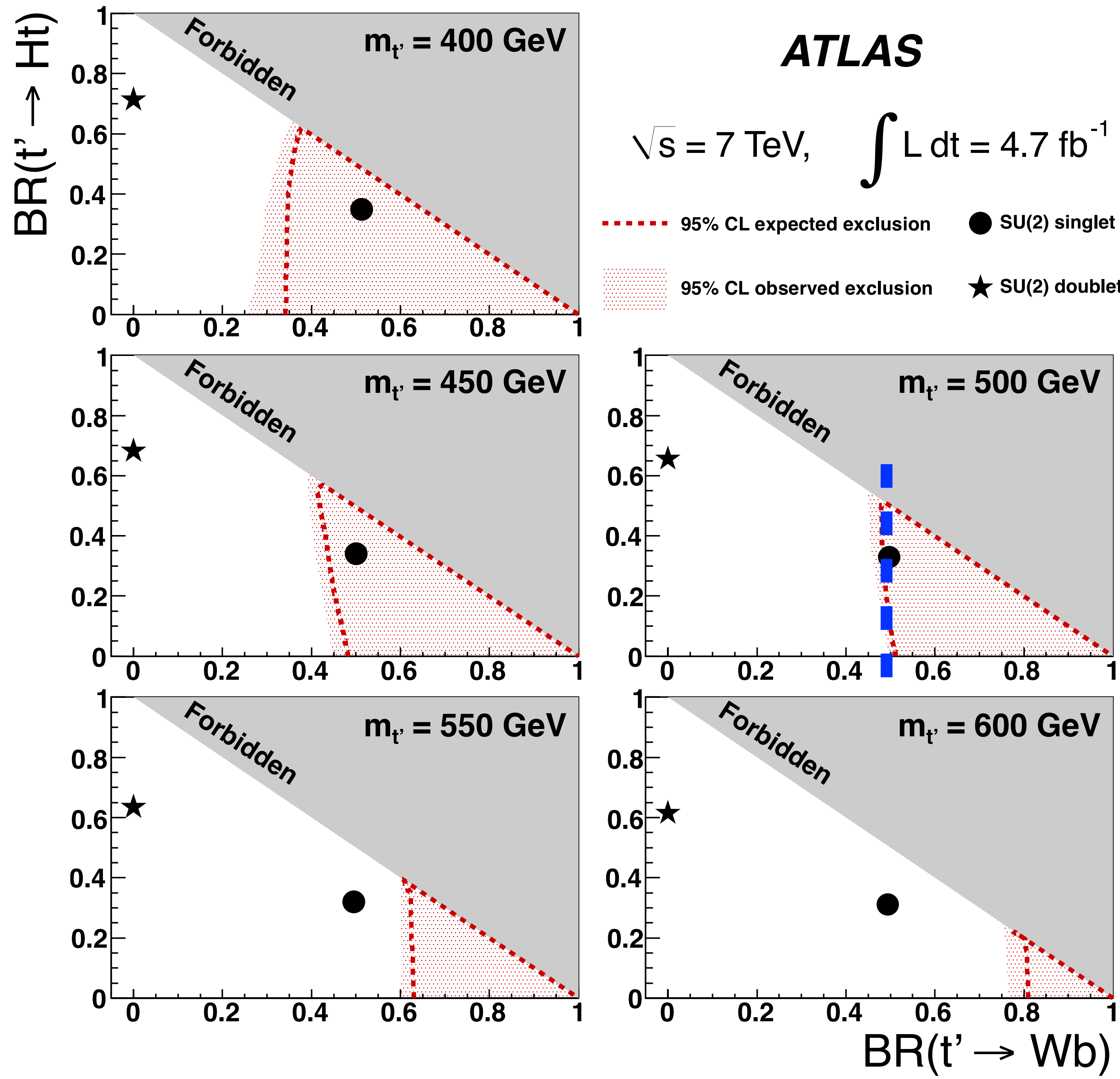
→ Tight selection





$t'\bar{t}' \rightarrow Wb + X$ (II)





VLQへの制限

- M(VLQ) > 650 GeV

  BR(t'→Wb) = 1

BR(t'→Wb)>0.5 excluded
for m_{VLQ}=500 GeV

*Only a selection of the available mass limits on new states or phenomena shown