SEARCH FOR 4^{TH} GENERATION QUARKS AT CMS

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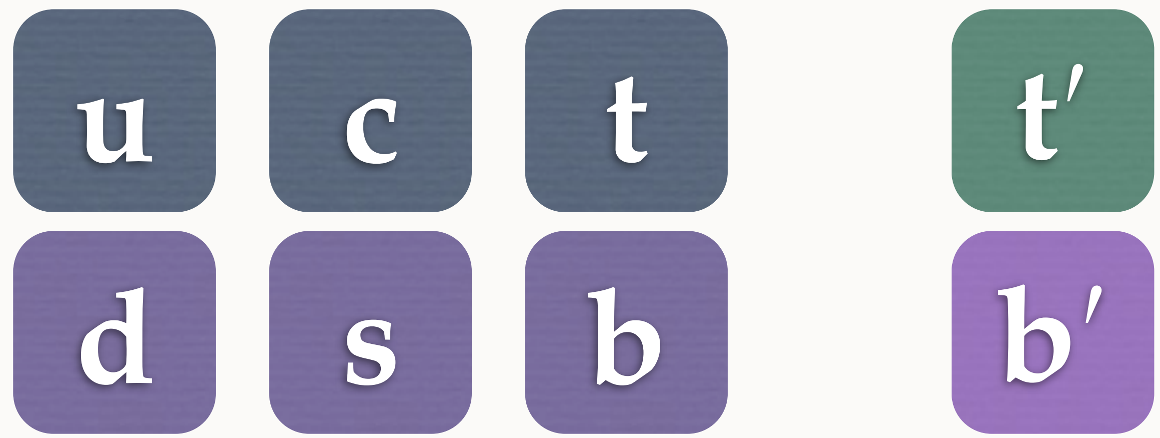
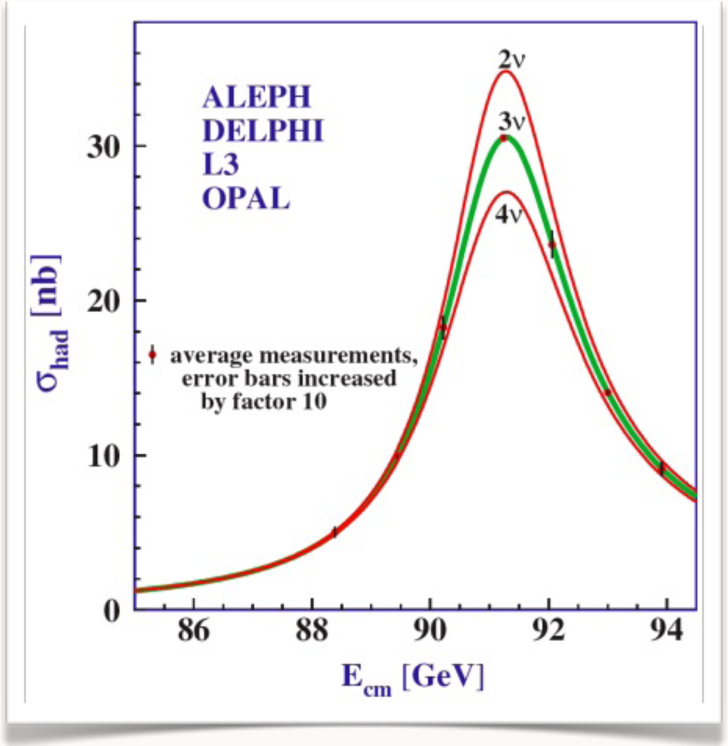
4TH GENERATIONS: WHY? WHY NOT?

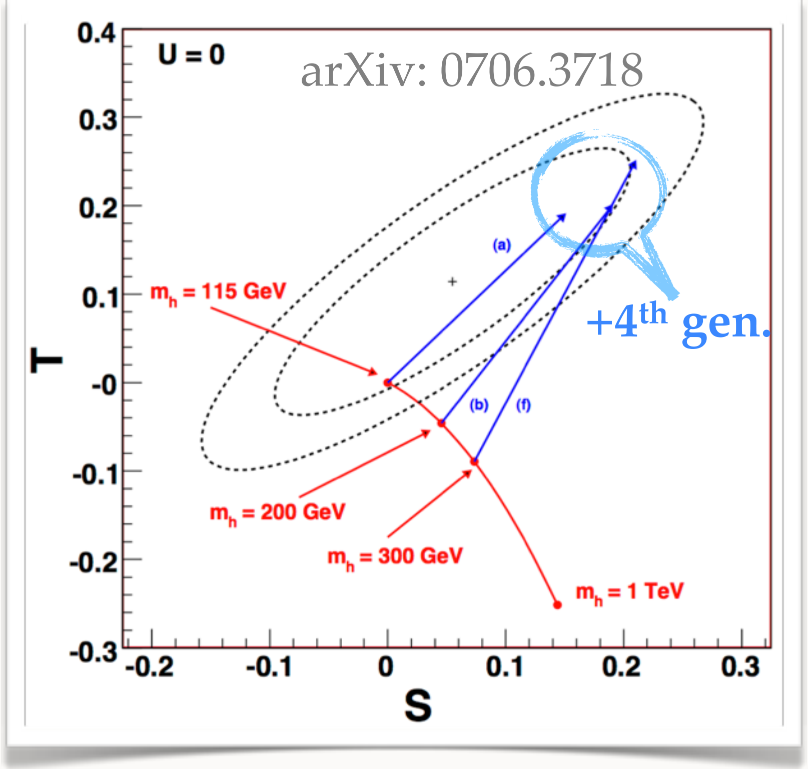


- The possibility of 4th generation is not really excluded by the current experimental data.
- Small mass splitting between the 4th generation quarks is preferred: $|M_{t'}-M_{b'}|<M_W$.
- Flavor physics data and the tests for unitarity triangle provide some information regarding the “CKM4” matrix, but it is only weakly constrained due to the uncertainties.

4TH GENERATIONS: WHY? WHY NOT?

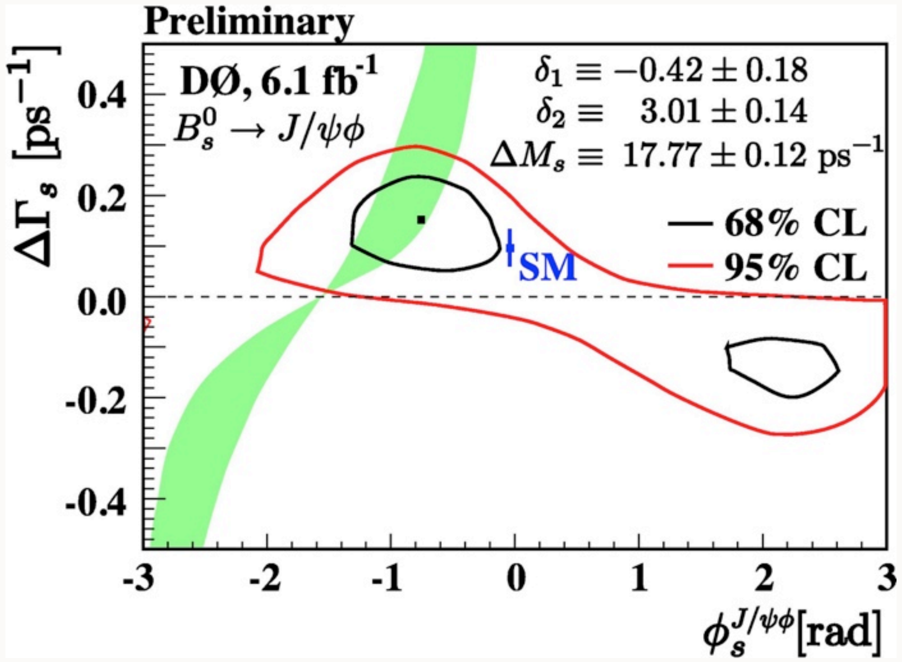
- The direct measurement of invisible Z width from LEP: $N\nu = 2.92 \pm 0.05$, but it does not guarantee that N(gen) = 3 exactly, e.g. heavy neutrino with mass > 0.5 M_Z.

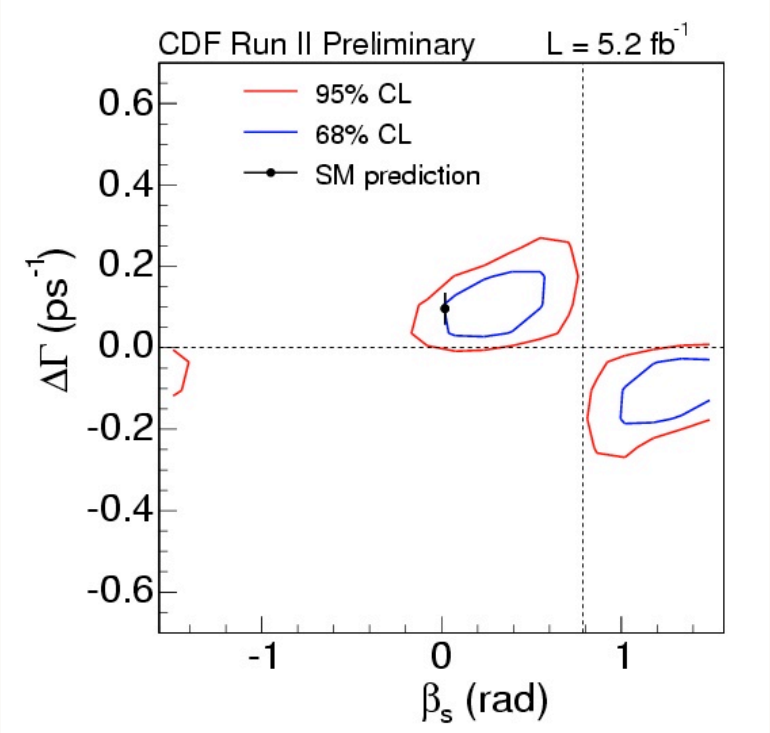




- The electroweak fits constrain the available phase space allowed for the 4^{th} generations.
- Large impact on the Higgs sector: Heavy Higgs (up to 500 GeV) is allowed.

4TH GENERATIONS: WHY? WHY NOT?





SM: sin2Φ_{Bs}~0 ➠ add ~500 GeV *t′*: sin2Φ_{Bs}~-0.33

References:
Hou et. al. arXiv: 1004.2186

- Adding 4th generation quarks will pull down the sin2Φ_{Bs} value from the 3 generation SM. Agreement with data is improved, but the tension is reduced since recent Tevatron updates.
- Wait for the results from LHCb to verify it.

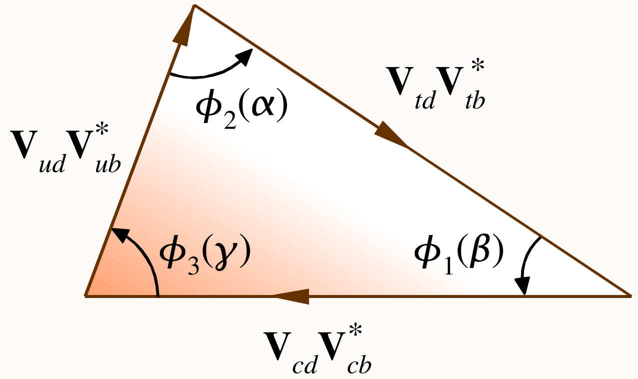
A BIG MOTIVATION: BAU

Ingredients of CPV in the Standard Model:

#1: At least THREE generations;

#2: Non-trivial *CP* phase; Non-trivial unitarity triangle.

#3: Non-degenerate like-charge quarks.



Jarlskog Invariant

proportional to quarks masses and triangle area A:

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

The SM contributes only

$J/T^{12} \sim 10^{-20}$

$$\frac{n(B)}{n(\gamma)} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

(WMAP)

"Something" is definitely necessary to enlarge the asymmetry by $O(10^{10})$!

A BIG MOTIVATION: BAU

If we simply shift the invariant by one generation:

$$\begin{bmatrix} u & c & t \\ d & s & b \end{bmatrix} \begin{matrix} t' \\ b' \end{matrix} \rightarrow \begin{matrix} u \\ d \end{matrix} \begin{bmatrix} c & t & t' \\ s & b & b' \end{bmatrix}$$

$$J' = (m_{t'}^2 - m_c^2)(m_{t'}^2 - m_t^2)(m_t^2 - m_c^2)(m_{b'}^2 - m_s^2)(m_{b'}^2 - m_b^2)(m_b^2 - m_s^2)A'$$

$$\frac{J'}{J} \approx \frac{m_{t'}^2}{m_c^2}\left(\frac{m_{t'}^2}{m_t^2} - 1\right)\frac{m_{b'}^4}{m_b^2 m_s^2}\frac{A'}{A}$$

References:
Hou arXiv: 0803.1234

By inserting M(b′,t′) ~ 300~600 GeV/c^2, it already gives us a huge boost on *J*, of O(10^{13}~10^{15})

Replacing the unitary triangle contributes a factor of 30.

A low cost solution: only needs heavier quarks!

FOUR STATEMENTS ABOUT THE FOURTH GENERATION

Ref. Holdem *et al*. arXiv: 0904.4698

1) The 4th generation is not excluded by EW precision data;
2) SM4 addresses some of the currently open questions;
3) SM4 can accommodate emerging possible hints of new physics;

4) LHC has the potential to discover or fully exclude SM4!

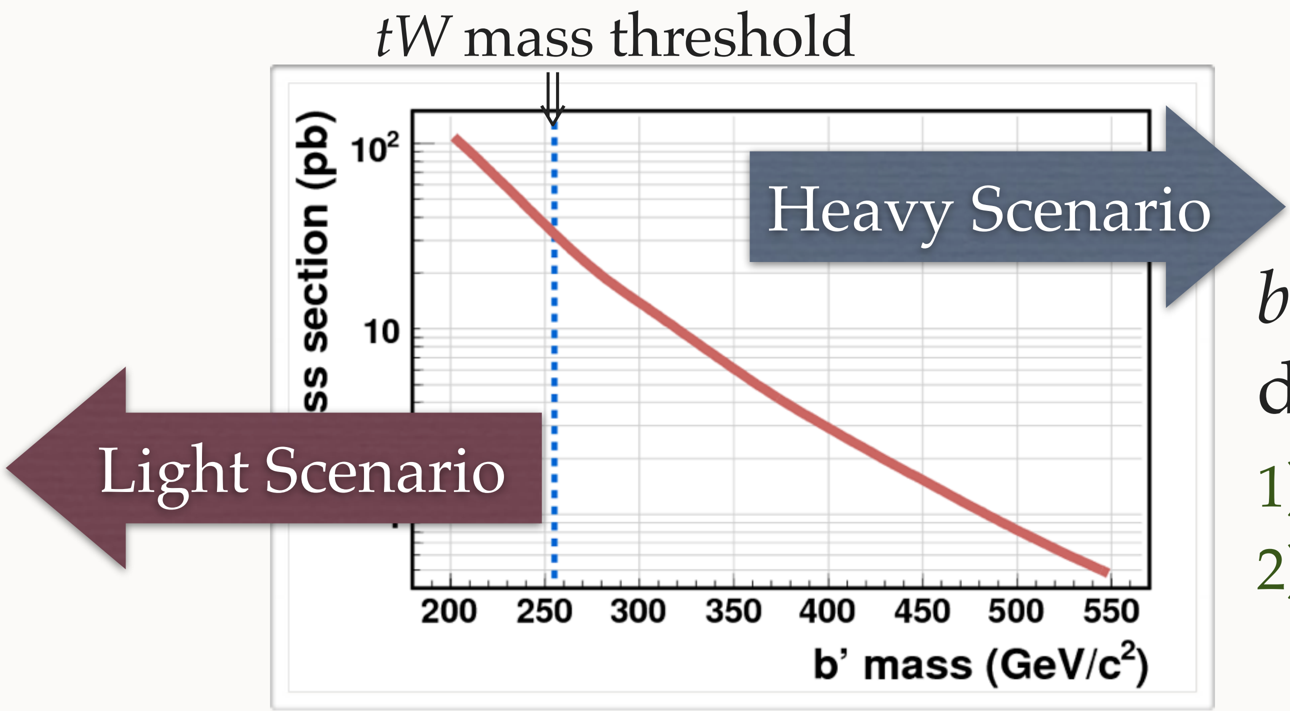
THE DECAY PATTERN

t′ Mostly ***t′→bW*** (simply a heaver top quark) or ***t′→b′W***

b′ Depends on the mass hypothesis of ***b′***:

Rich Signatures

1) Larger X-sec;
2) For sizable $|V_{cb'}|$
   b′→cW >> t(*)W(*)
3) Suppressed $|V_{cb'}|$
   b′→cW << t(*)W(*)
4) FCNC:
   b′→bZ, bH



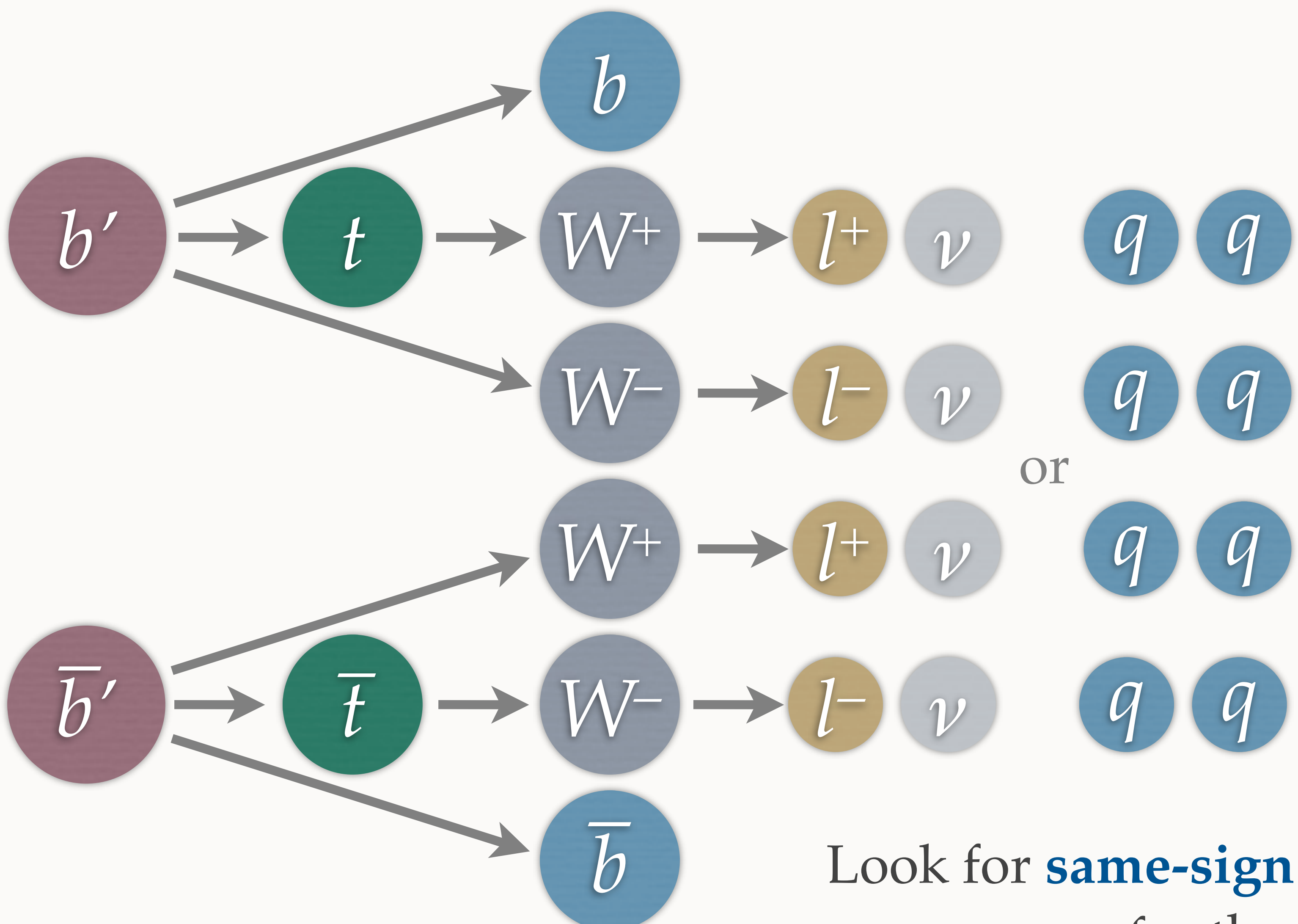
b′→tW dominance

1) Lower X-sec;
2) Larger mass coverage.

Today we only focus on the "heavy scenario", ***b′→tW*** decays.

SIGNATURE OF HEAVY $b'b' \rightarrow tWtW$

The full decay chain: $b'b' \rightarrow tWtW \rightarrow bbW^+W^-W^+W^-$ (4 *W*-bosons + 2 *b*-jets)



Possible final states:

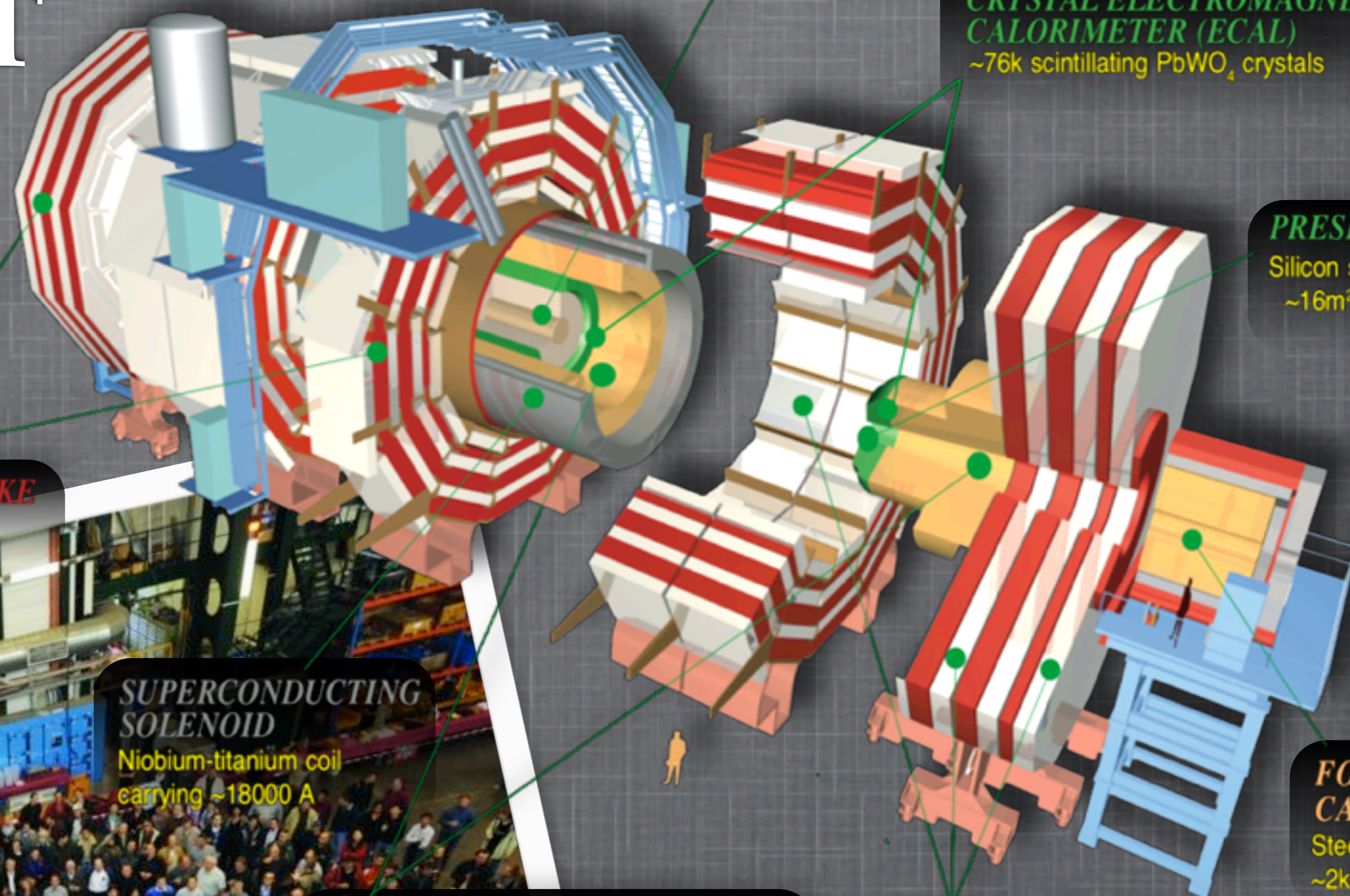
L: Lepton, **J**: Jet,
MET: Missing Energy

0L+10J
1L+8J+MET
2L+6J+MET ←
3L+4J+MET ←
4L+2J+MET

5 possibilities in total

Look for **same-sign dileptons** and **trileptons** for the first probing of the signal

CMS
EXPERIMENT



3170 scientists and engineers
from 169 institutes in 39 countries.

From Taiwan:
NTU and NCU

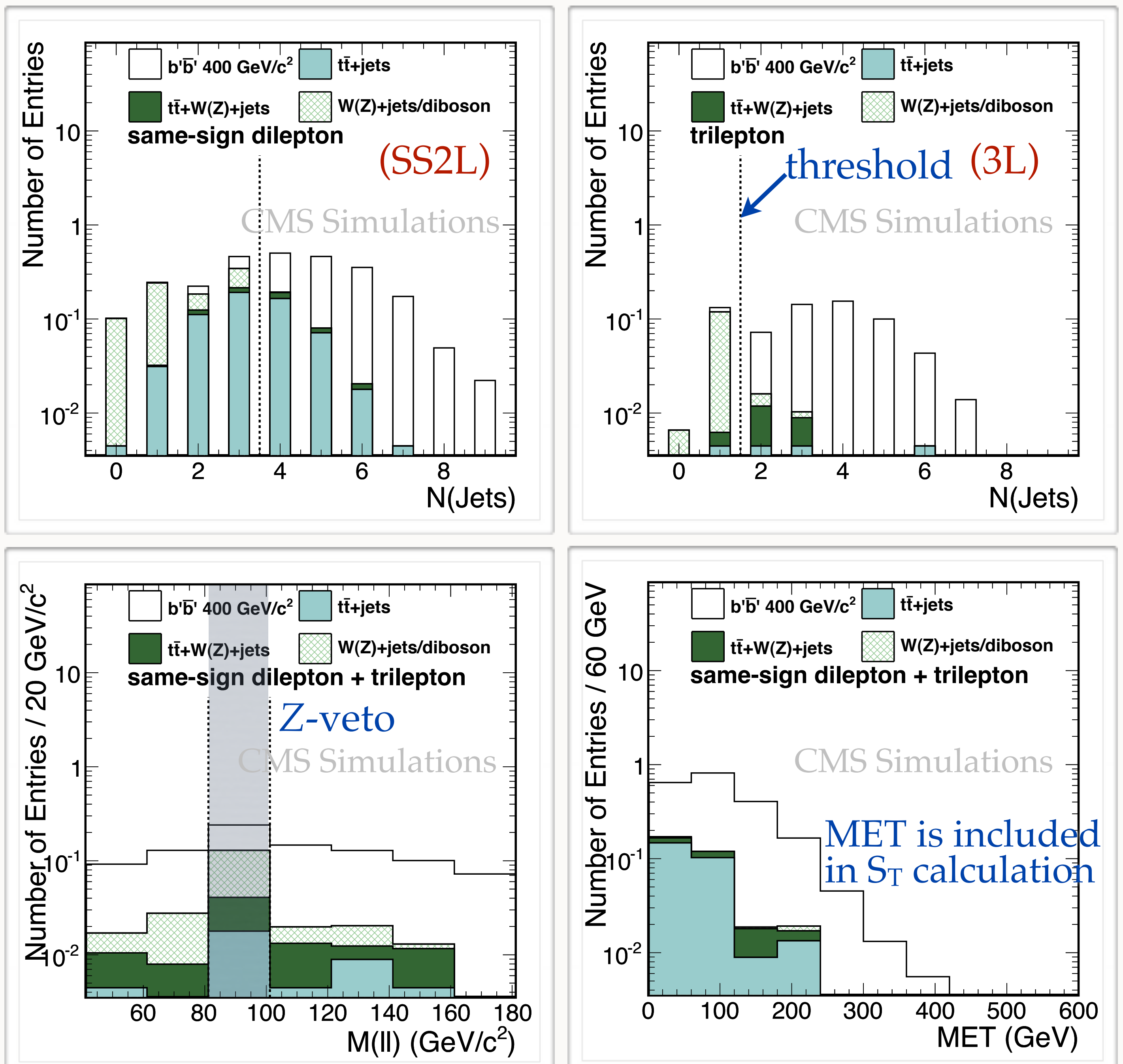
ANALYSIS OF HEAVY $b'b' \to tWtW$

Ref. CMS PAS EXO-10-018

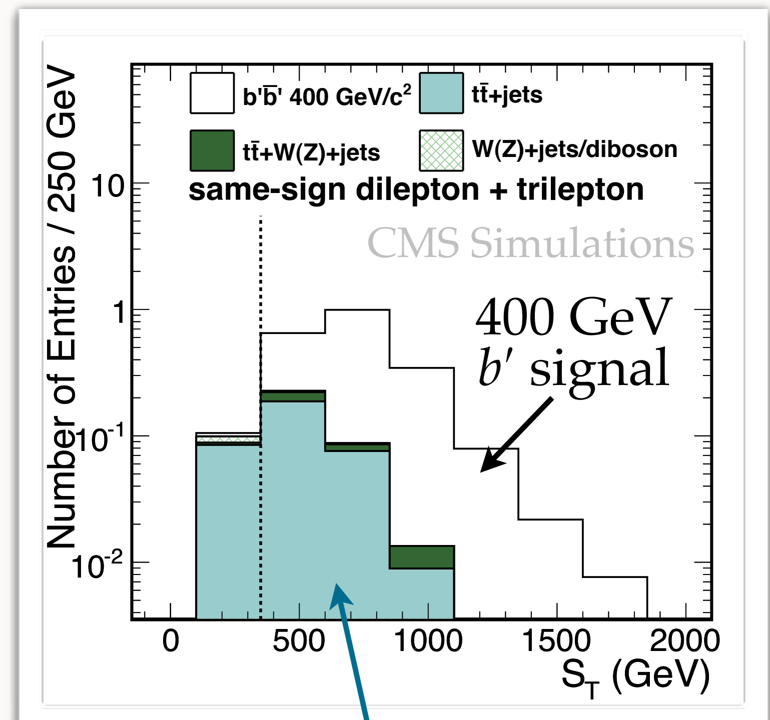
- **Data set analyzed:**
  34 pb^{-1} at 7 TeV recorded by the CMS detector.
- **Trigger:** double electron trigger or single muon trigger.
- **Lepton selections:**
  - ➡ **Muons:** cut-based ID, isolated from other activities, $p_T > 20$ GeV/c.
  - ➡ **Electrons:** cut-based ID, isolated from other activities, $p_T > 20$ GeV/c.

  Requiring exact 2L with the same charge, or 3L in the final state.
- **Jet selections:** Anti-K_T algorithm $R = 0.5$ with particle flow candidates.
  - ➡ **Same-sign 2L:** at least 4 or more jets $p_T > 25$ GeV/c.
  - ➡ **3L:** at least 2 or more jets $p_T > 25$ GeV/c.
- **Other requirements:**
  - ➡ A Z-boson veto: $|M(\ell\ell)\text{-}M_Z| > 10$ GeV/c^2.
  - ➡ Objects isolation: $\Delta R(e,\mu) > 0.1$ and $\Delta R(\text{jet},\ell) > 0.4$.
  - ➡ S_T [= MET + Σp_T(jets) + Σp_T (leptons)] > 350 GeV

RESULTING FIGURES
(MC Distributions)



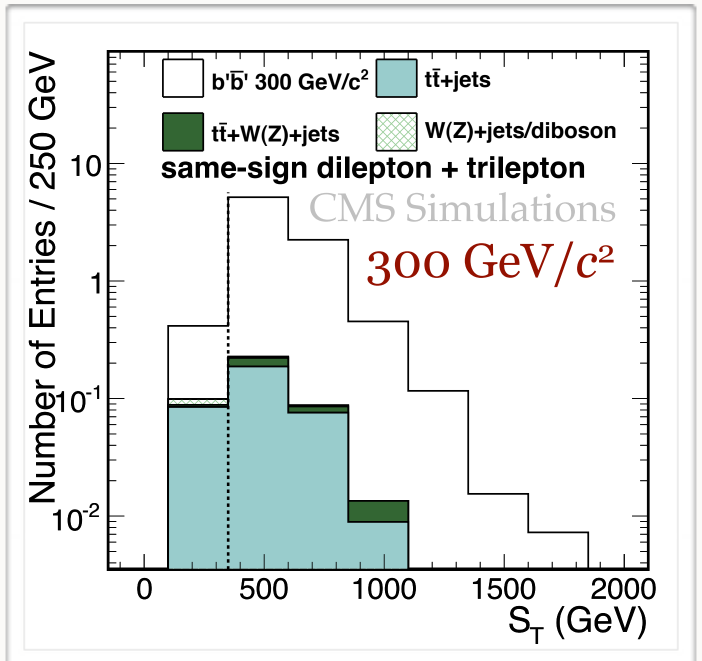
Signal Observable:
$S_T = \text{MET} + \Sigma p_T(\text{jet}) + \Sigma p_T(\text{lep})$

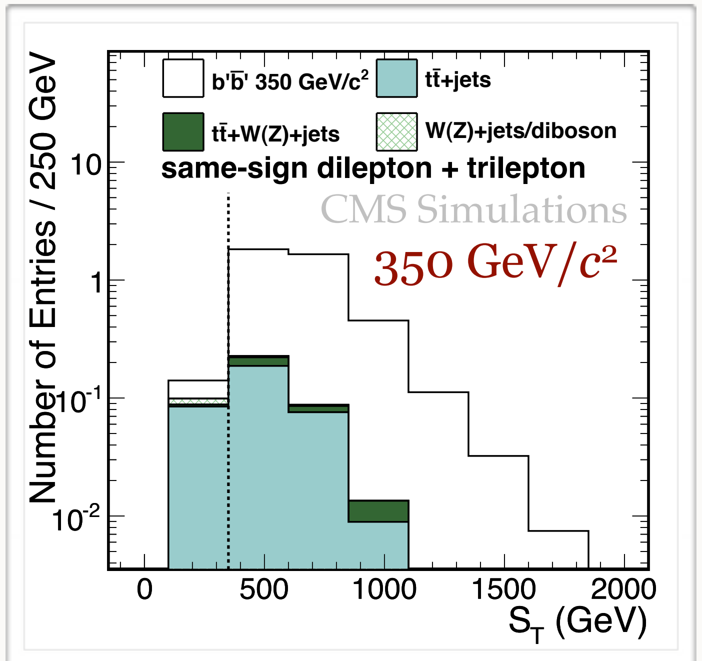


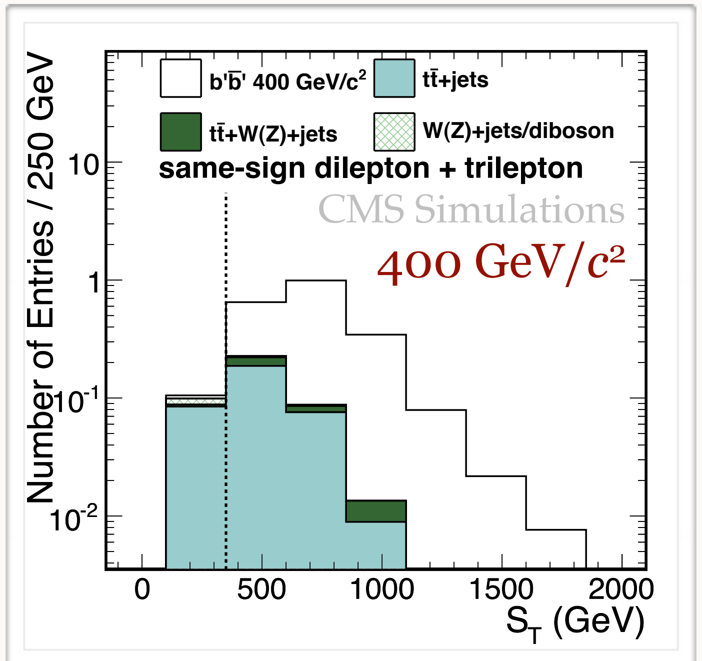
background, mainly *tt*+jets

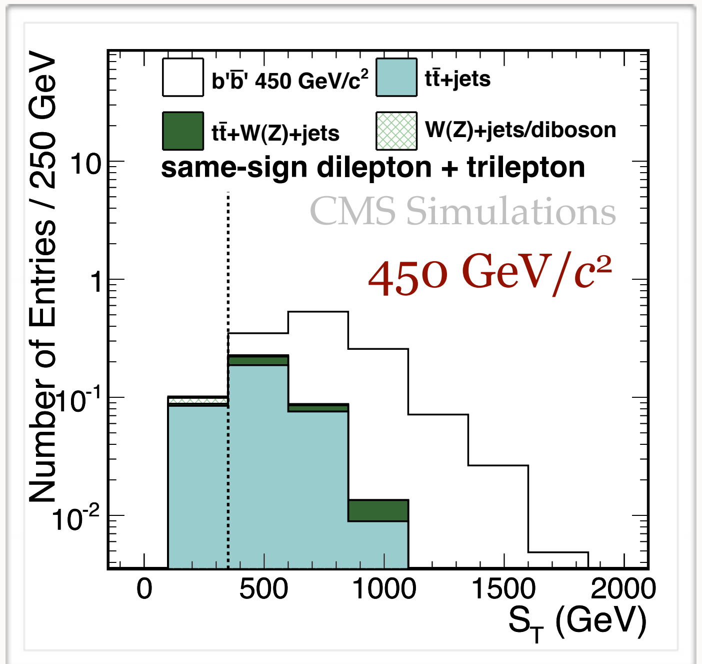
MC distributions are normalized to 34 pb⁻¹

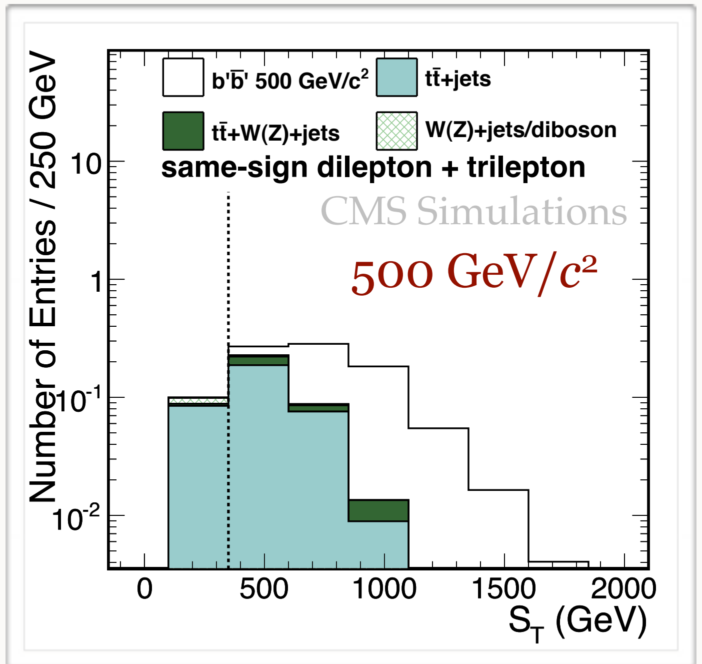
RESULTING FIGURES
(MC Distributions)











b' mass (GeV/c²)	300	350	400	450	500
N_S	7.7	3.8	1.8	0.91	0.49
N_B	0.33 [background sum]				

EXPECTED YIELDS

b' Signal

b' mass (GeV/c^2)	Cross section (pb)	Yield	S/N
300	7.29 (NLO)	7.7	23
350	2.94 (NLO)	3.8	12
400	1.30 (NLO)	1.8	5.5
450	0.617 (NLO)	0.91	2.8
500	0.310 (NLO)	0.49	0.9

- S/N is high, up to 300~400 GeV/c^2 b' masses.
- Background is dominated by the tt+jets events.

Background Sources

Process	Cross section (pb)	Yield
tt+jets	194 (CMS)	0.27
$tt+W$ (+j)	0.144 (LO)	0.033
$tt+Z$(+j)	0.094 (LO)	0.016
W+jets	29850 (CMS)	<0.11
Z+jets	2919 (CMS)	<0.09
WW	43 (NLO)	<0.012
WZ	18 (NLO)	<0.005
ZZ	5.9 (NLO)	0.006
Same-sign $WW+jj$	0.15 (LO)	0.002
MC background expectation	-	**0.33**

QCD contributions are estimated to be small (<0.09)

BACKGROUND ESTIMATION WITH DATA

Background Types

- Find a sign-flipped electron
- Find an extra (fake) lepton

Select

Opposite-sign dilepton events

Normalized by electron charged mis-identification rate; measured using Z→ee data.

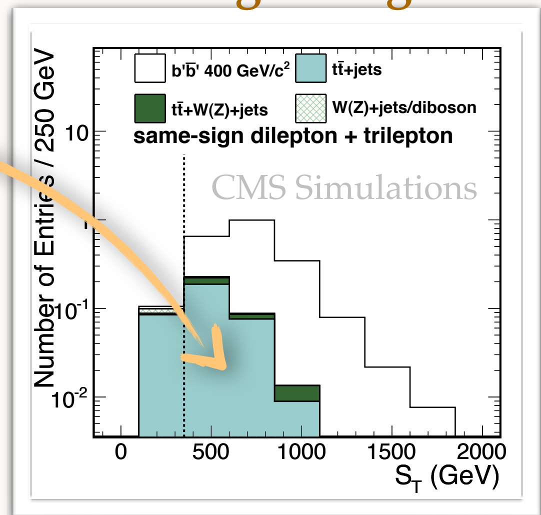
Select

Same-sign dilepton events with loosened lepton criteria

N_B

Normalized by lepton loose-to-tight ratio measured from data.

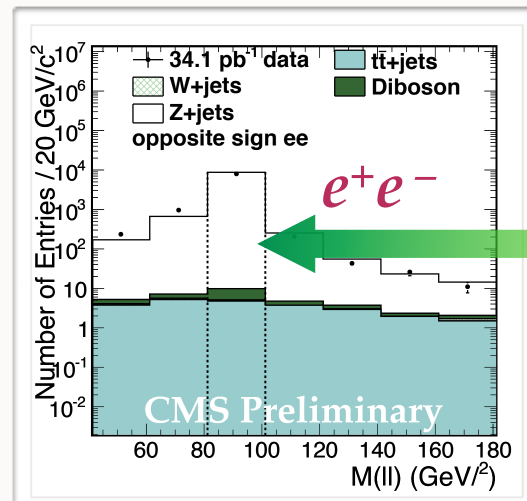
Signal region

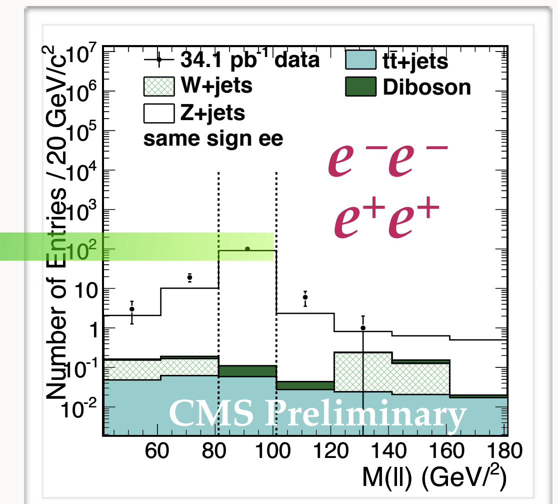


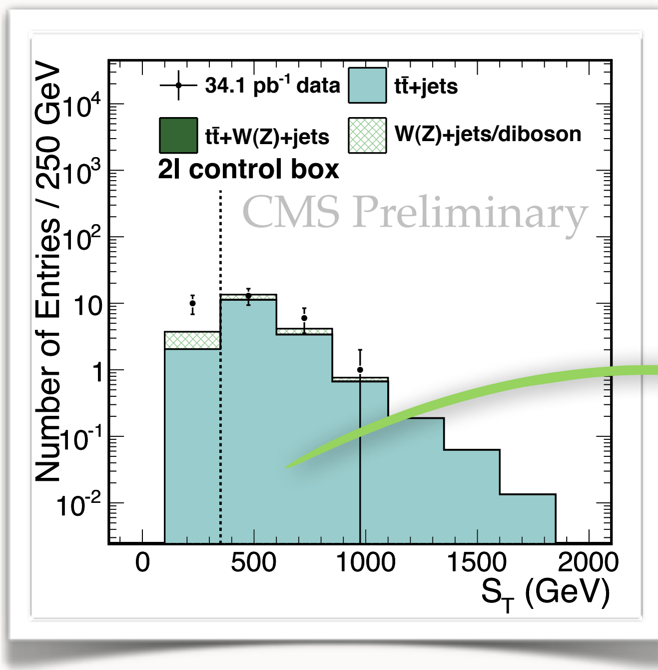
Use a data-driven based estimation instead of the MC expected value (ie. the 0.33 events)

BACKGROUND ESTIMATION WITH DATA

Opposite-sign dilepton events (and preserve all other crieria)



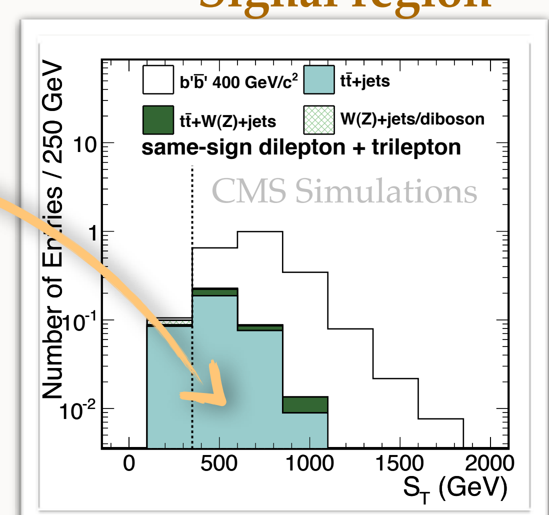




× *electron charged mis-ID rate*

N_B

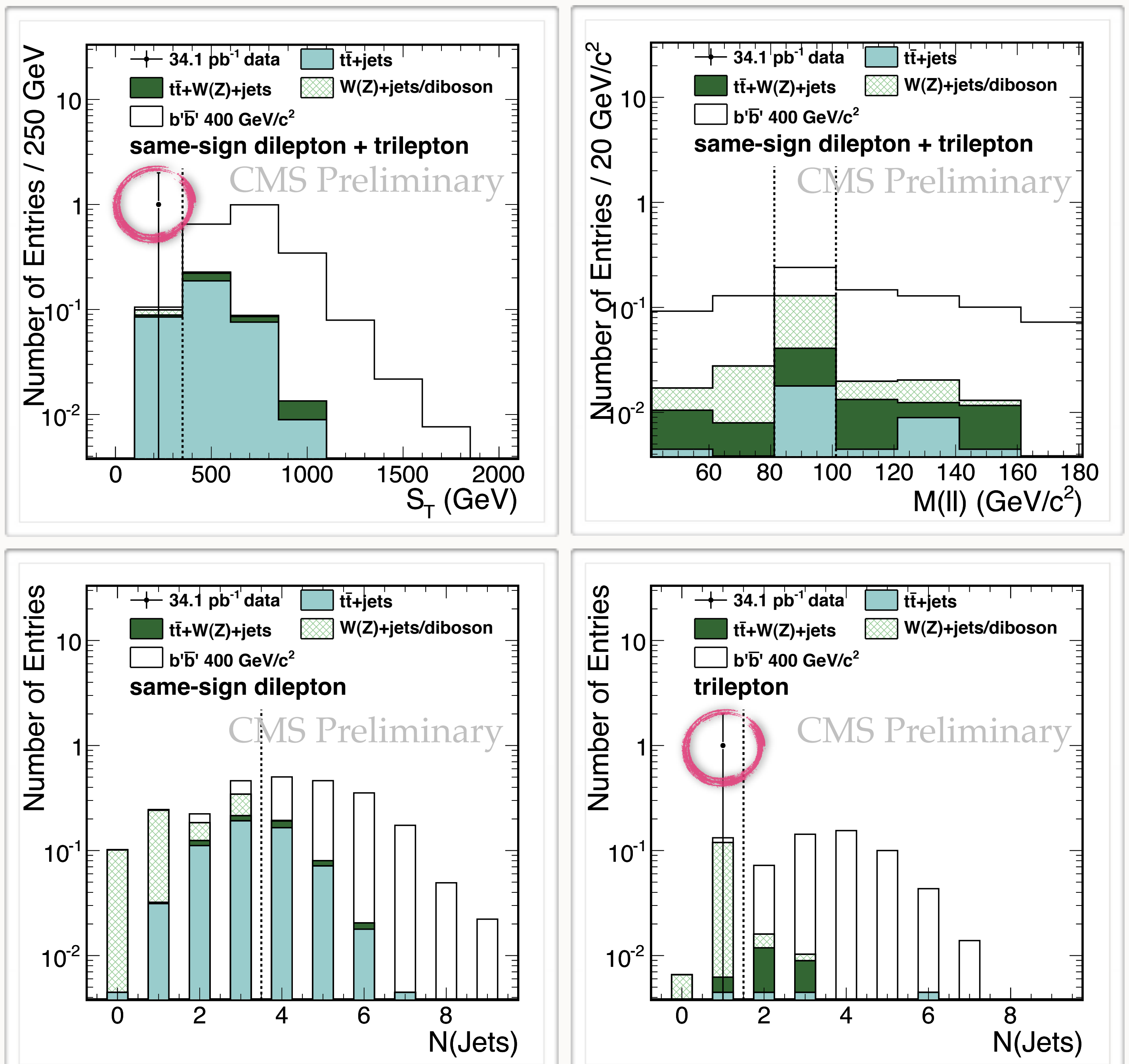
Signal region



- This estimation has little dependency on luminosity and background cross section.
- Systematic uncertainty from a MC closure test.

DATA RESULTS

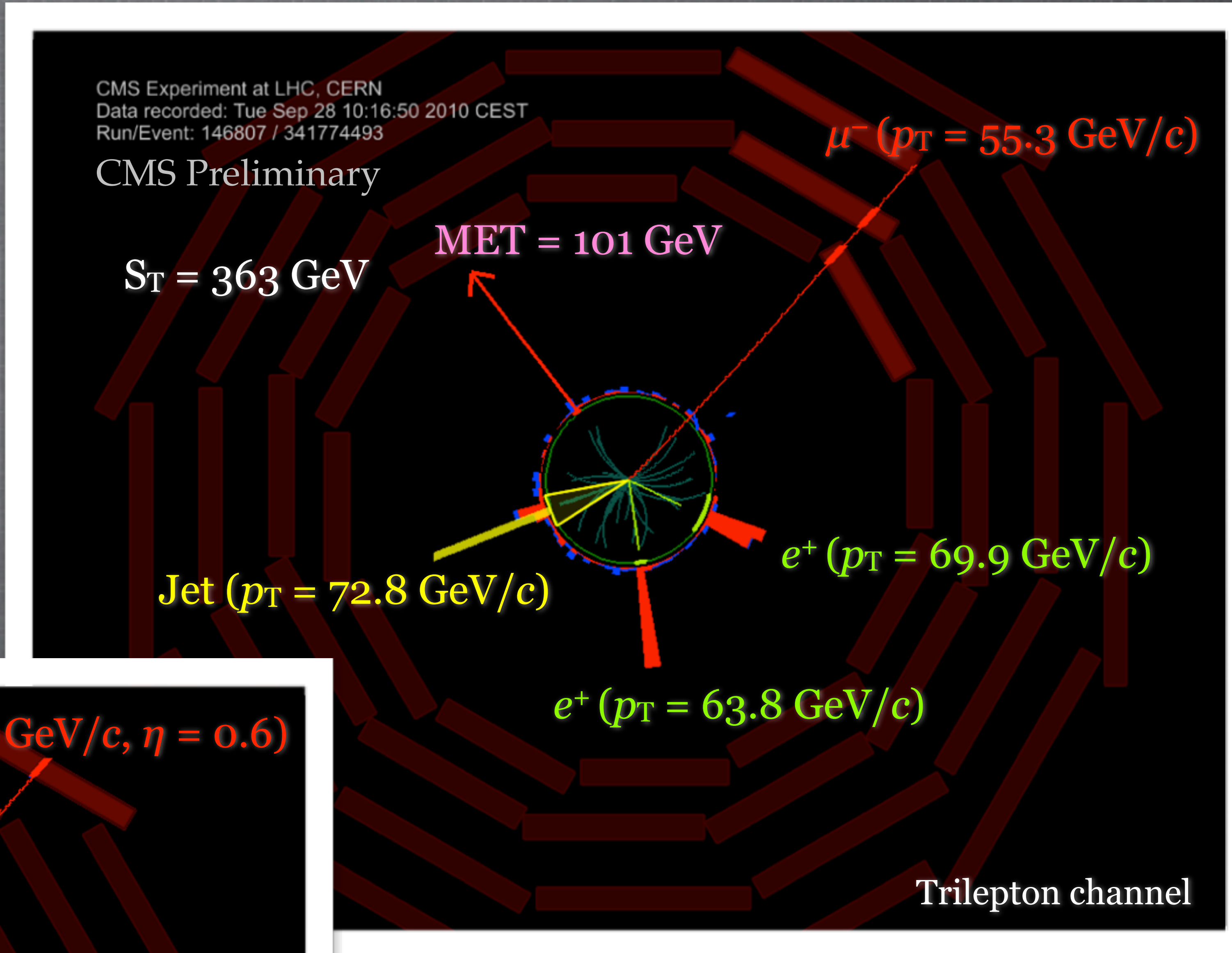
Only two events failed with the last step selection

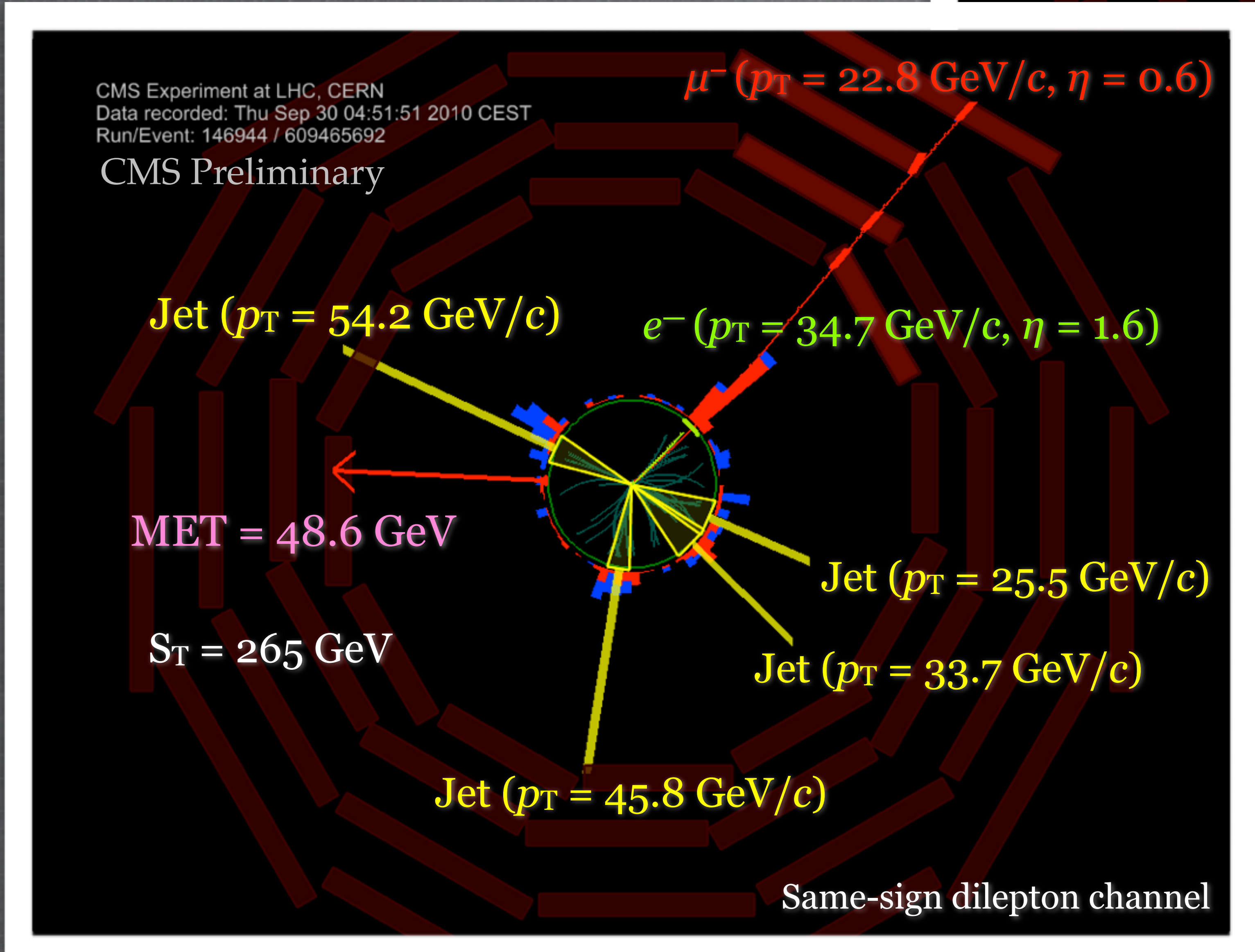


Zero event found in the signal region

	Yields
$b'(400\ \mathrm{GeV}/c^2)$	1.8
MC expected background	0.33
Data (34 pb^{-1})	0
Estimated background (data-driven)	0.32 ± 0.21

Full systematic uncertainties included

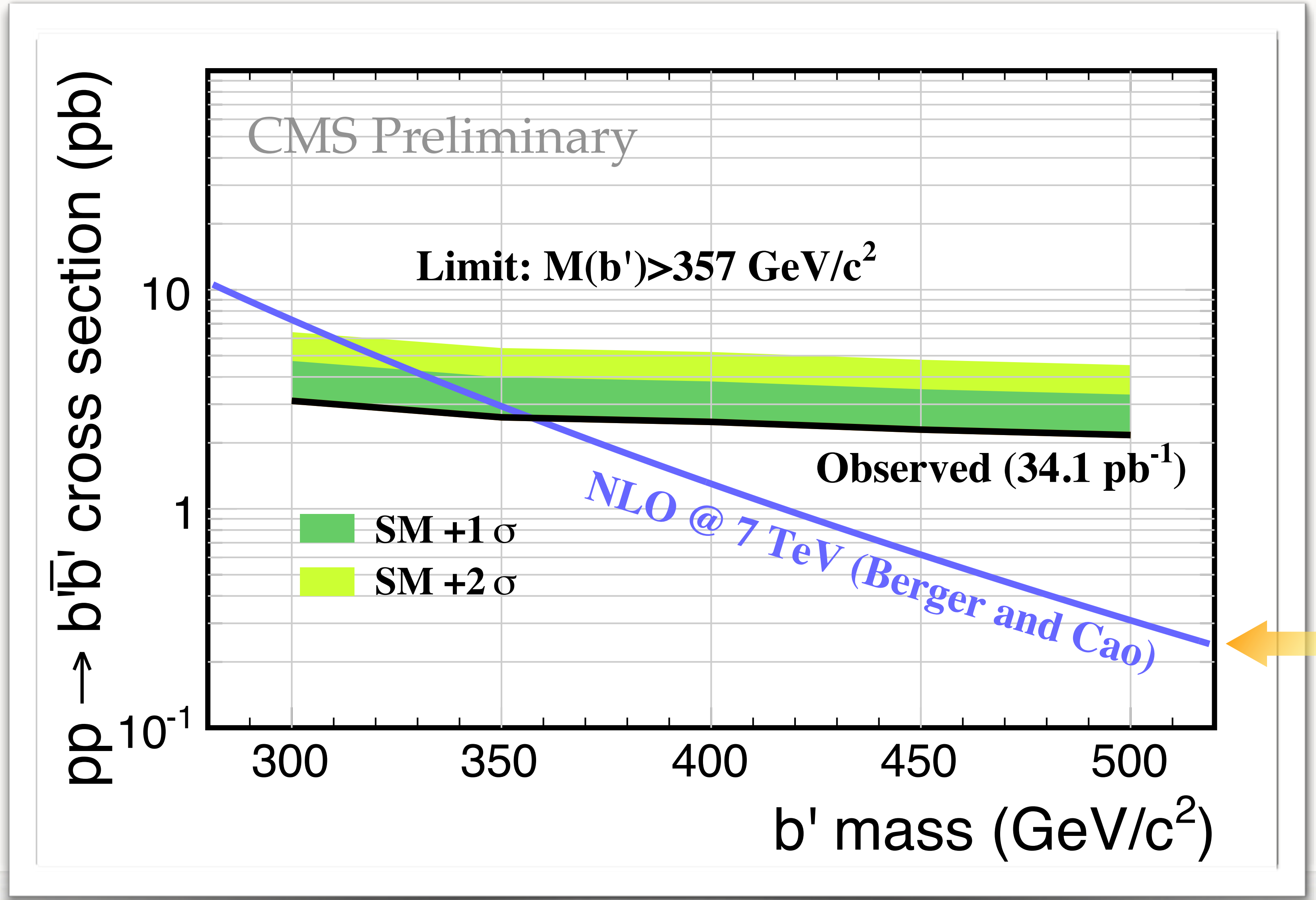




Two interesting events,
but failed with the last step selection

EXCLUSION LIMITS

- No signal observed in data: we set the exclusion limit at 95% C.L.
- We use a Bayesian limit for null hypothesis tests, with all the systematic uncertainties included:



Observed limit is consistent with the (median) expected limit

b′ production cross section as a function of its mass.

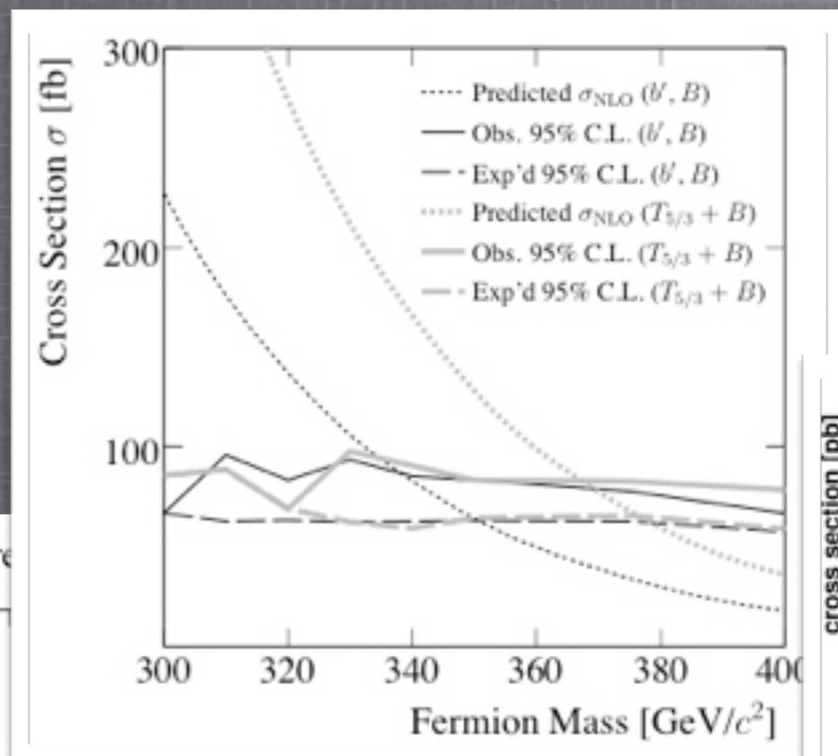
SUMMARY

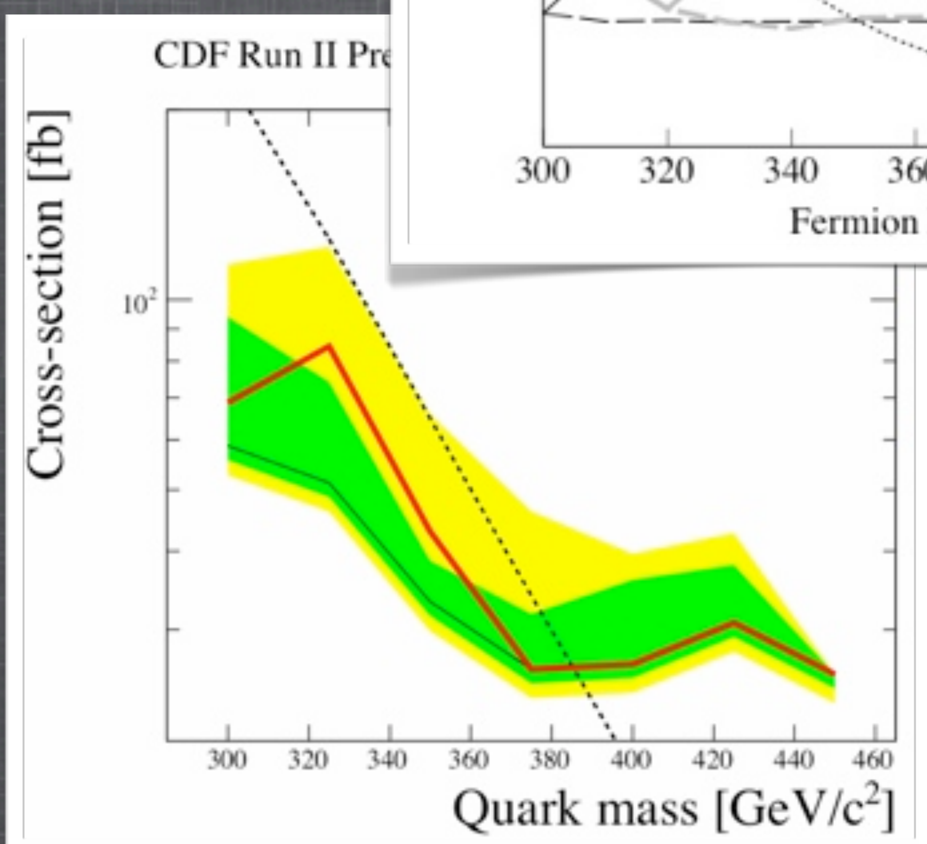
- We report the search of heavy bottom-like 4th generation quark in *tW* final state at 7 TeV LHC pp collisions.
- The analysis with 34.1 pb^{-1} CMS data is presented:
  - The expected signal yield for b′ (300~500 GeV/c^2) is 7.7~0.5 events with this data set.
  - No event found in the signal region.
  - A limit for $b' \to tW$ signal is set: M(b')>357 GeV/c^2 at 95% C.L., comparing to the NLO production cross sections.
- This result extends the current CDF published limit based on an analysis of the same decay signature.
  [M(b')>338 GeV/c2, PRL 104, 091801 (2010)]

BACKUP SLIDES

TEVATRON LIMITS

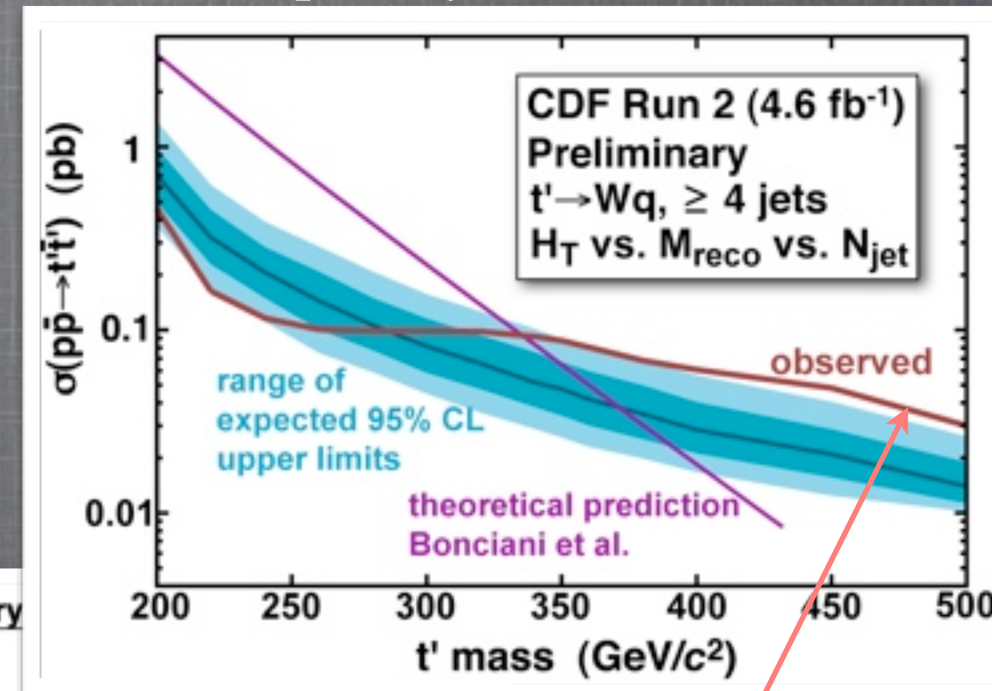
CDF b′ same-sign dilepton

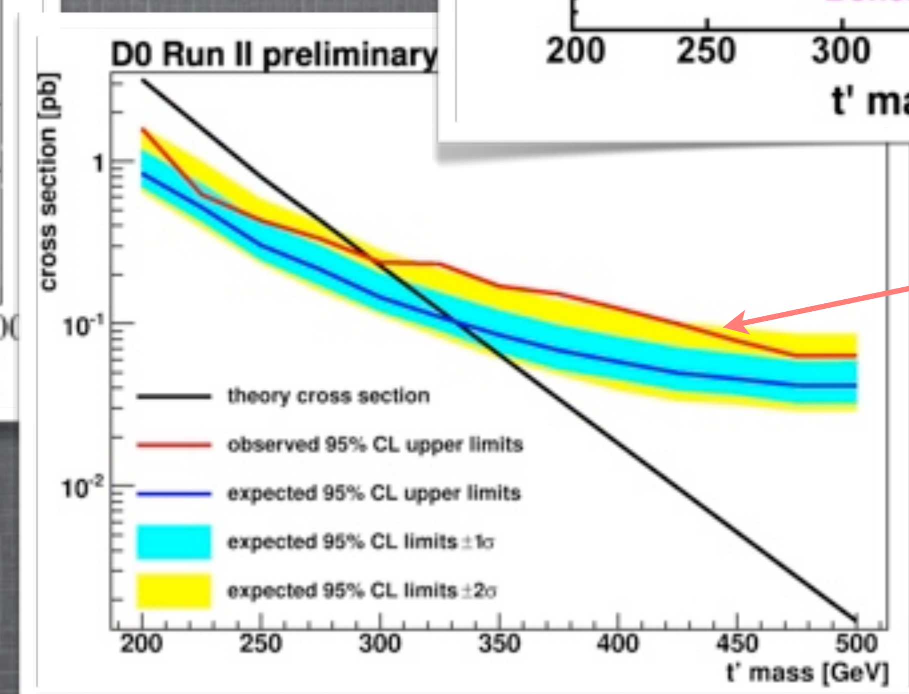




CDF b′ lepton+ jets

CDF t′ lepton+jets





D0 t′ lepton+jets

Observed limit is slightly above the expected limit for t′ data.

Tevatron limits on 4th generations:
b′ lepton+jets: M(b′) >385 GeV
b′ same-sign dilepton: M(b′) >338 GeV
t′ lepton+jets: M(t′) >335 GeV (CDF) / >296 GeV (D0)

SYSTEMATIC UNCERTAINTIES

Signal Efficiencies: $\Delta\varepsilon/\varepsilon$

Source	Input	M(b′) =300	M(b′) =350	M(b′) =400	M(b′) =450	M(b′) =500
JES	JME-10-010	2.1%	1.8%	1.1%	1.3%	1.1%
JE resolution	10% of p_T	0.3%	0.6%	0.2%	0.1%	0.4%
MET	±1σ	1.2%	0.5%	0.2%	0.1%	0.1%
Leptons	e: 5.8%, μ: 5.4%	13%	13%	13%	13%	13%
Pile-up jets	0 PU vs 5 PU	1.2%	1.2%	1.1%	1.1%	1.0%
PDF	CTEQ6 uncertainty sets	15%	17%	20%	21%	21%
MC Statistics	-	3.0%	2.7%	2.7%	2.5%	2.4%
Sum		**20%**	**22%**	**24%**	**24%**	**24%**

Background Estimation:

Source	Input	ΔB/B
Luminosity	±11%	0%
Method error	-	56%
background cross sections	tt ±39%, etc.	5.7%
QCD	±100%	29%
JES	JME-10-010	1.0%
JE resolution	10% of p_T	1.5%
MET	±1σ	5.6%
Leptons	e: 5.8%, μ: 5.4%	1.5%
pile-ups	0 PU vs 5 PU	<0.1%
PDF	CTEQ6 uncertainty sets	2.1%
Control reg. statistics	-	13%
Sum		**65%**