Search for BSM particles coupling to 3rd generation Fermions in CMS

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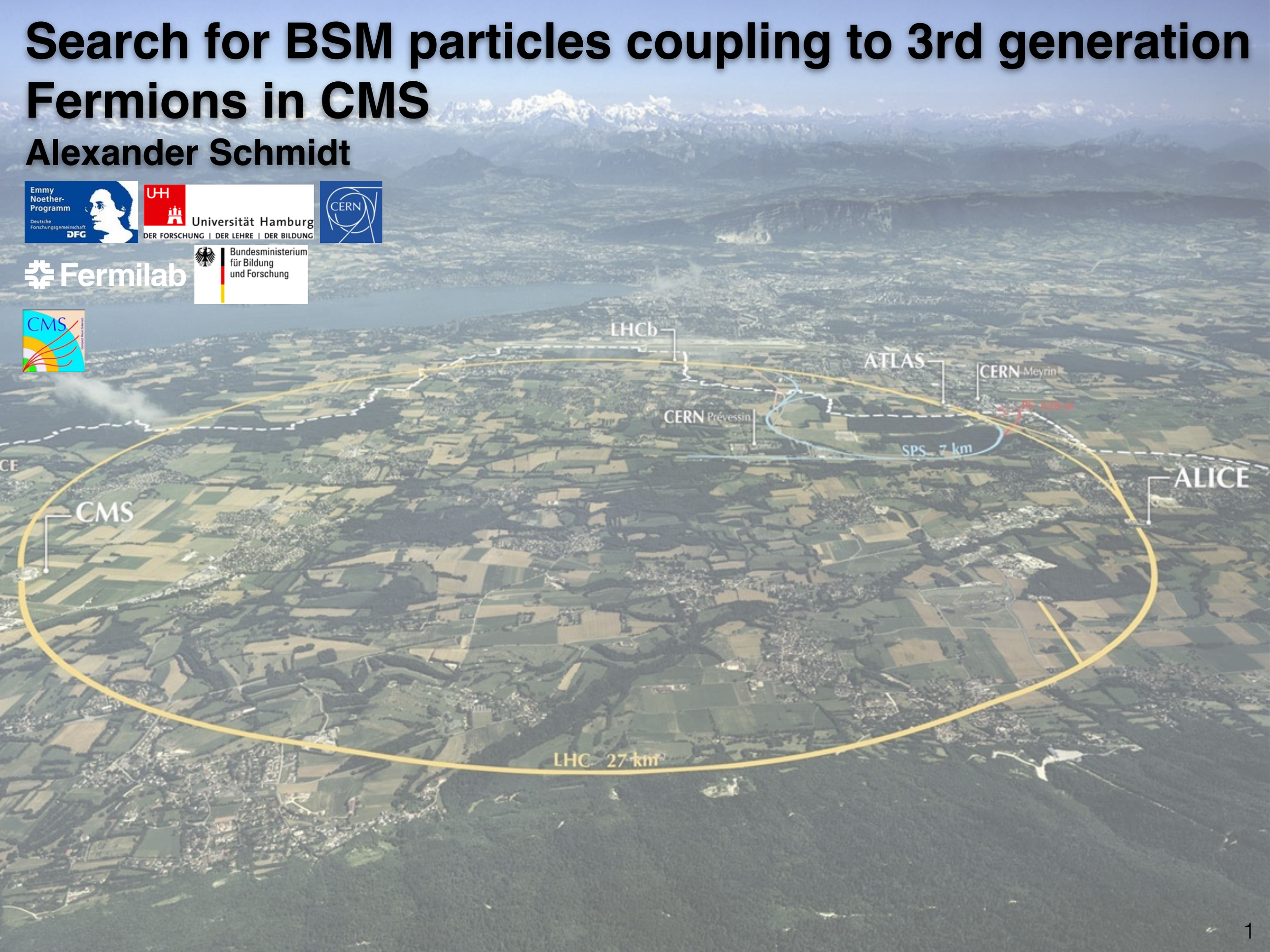
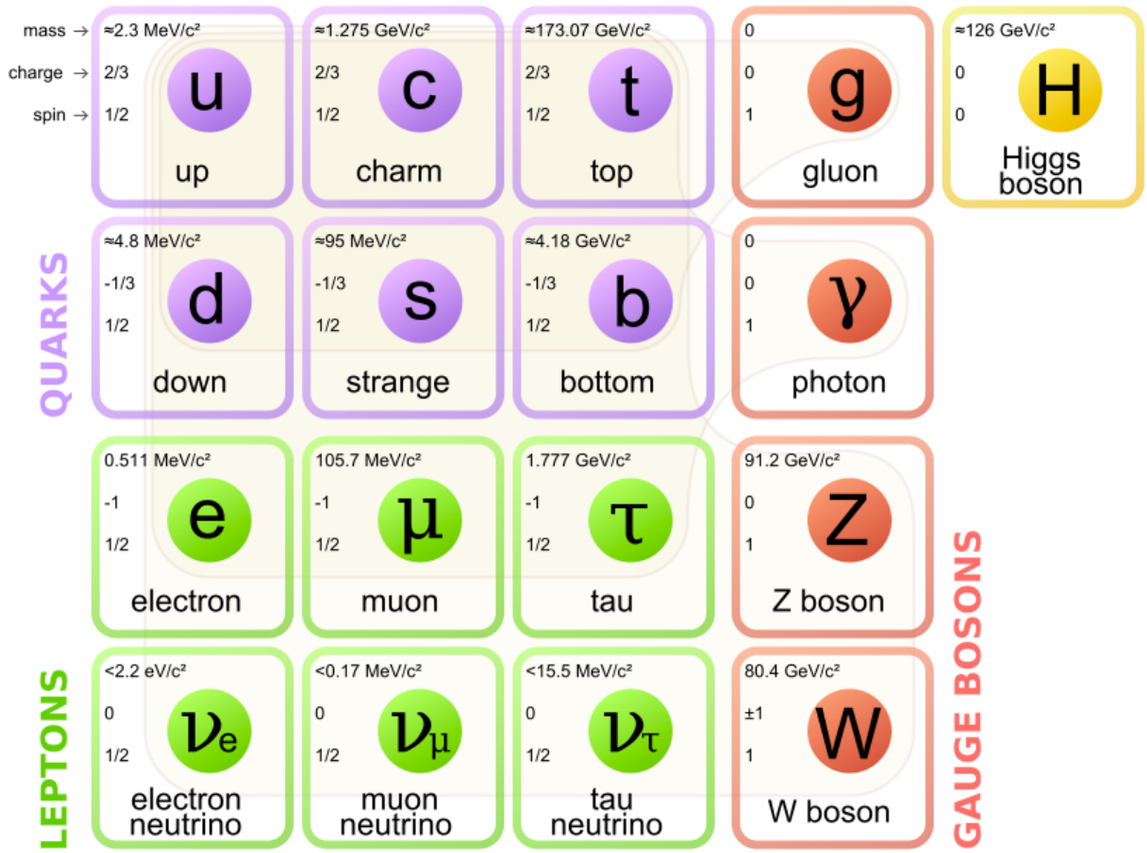
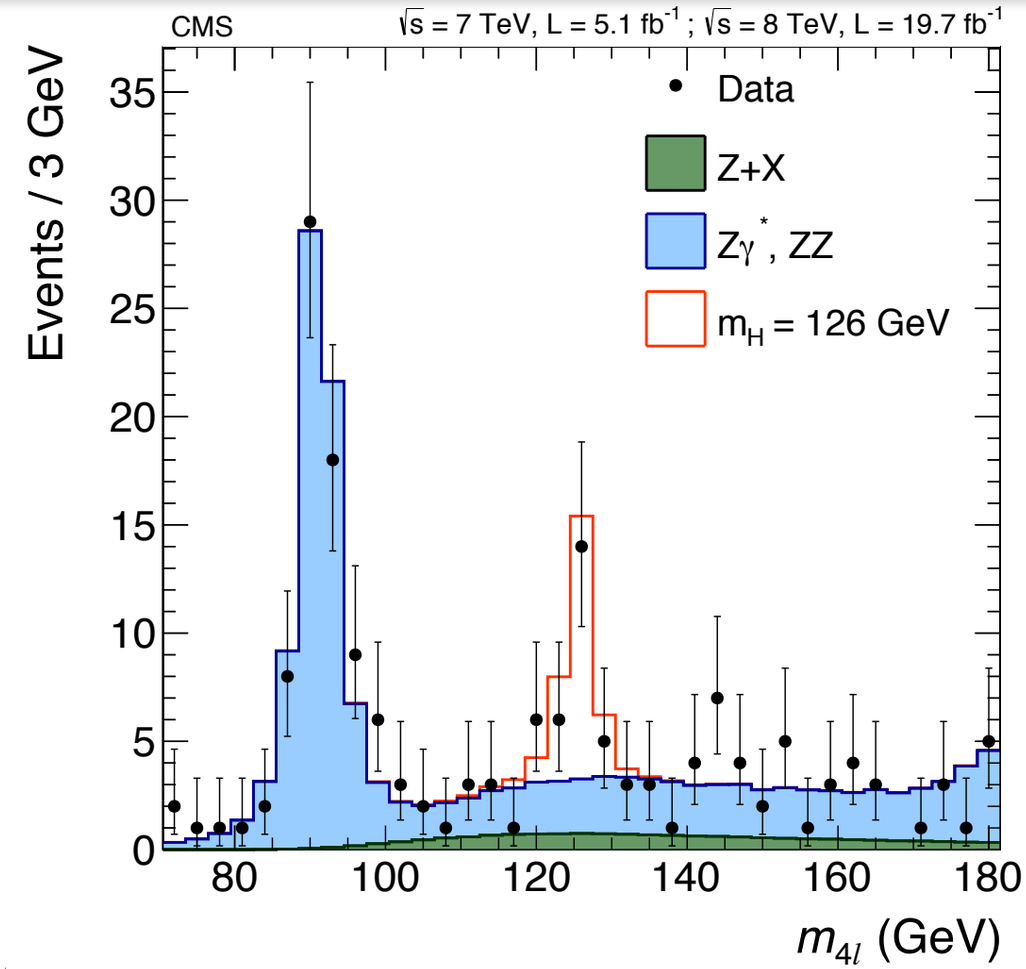
CMS



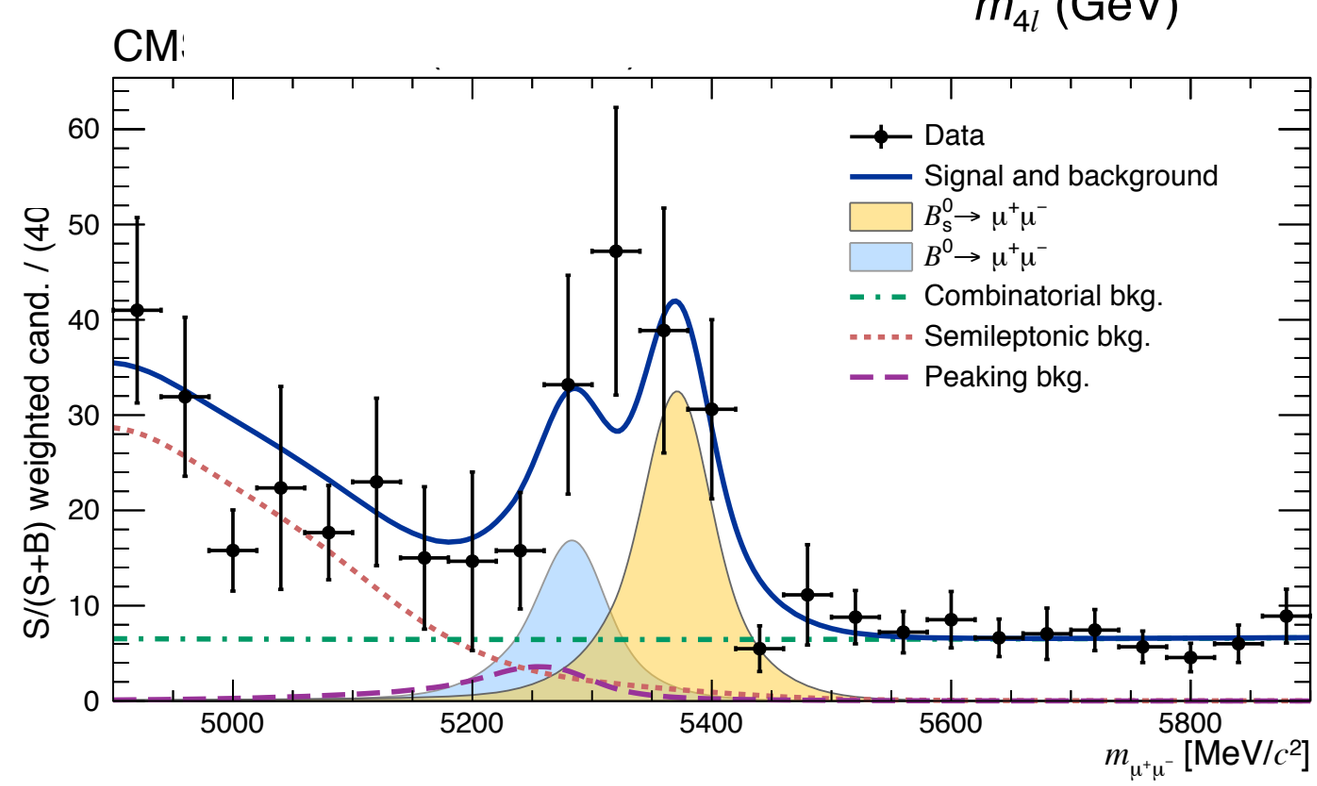
result of LHC run I: the standard model

- confirmation of the SM BEH mechanism

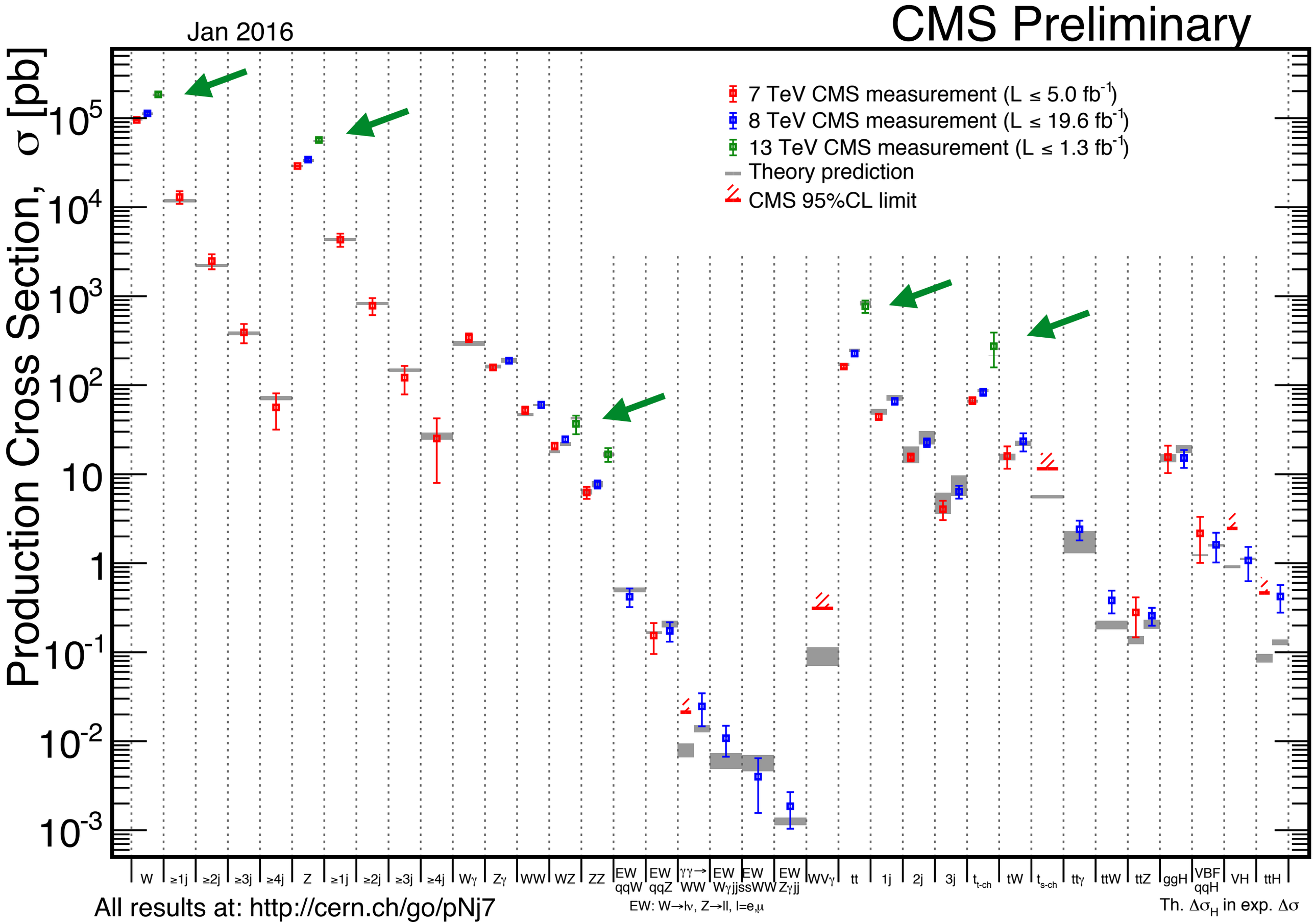




- B_s meson decay $\mathcal{B}(B_s \to \mu\mu)$
  predicted 3.66 x 10^{-9}
  measured 2.8 ± 0.7 x 10^{-9}

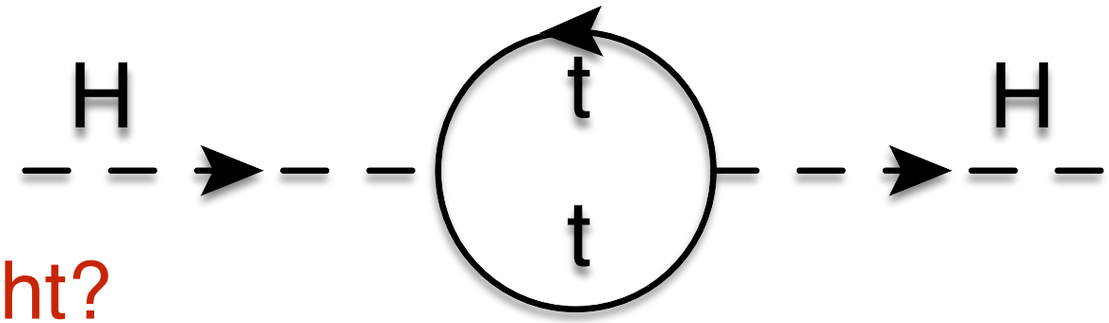


- countless other SM precision tests



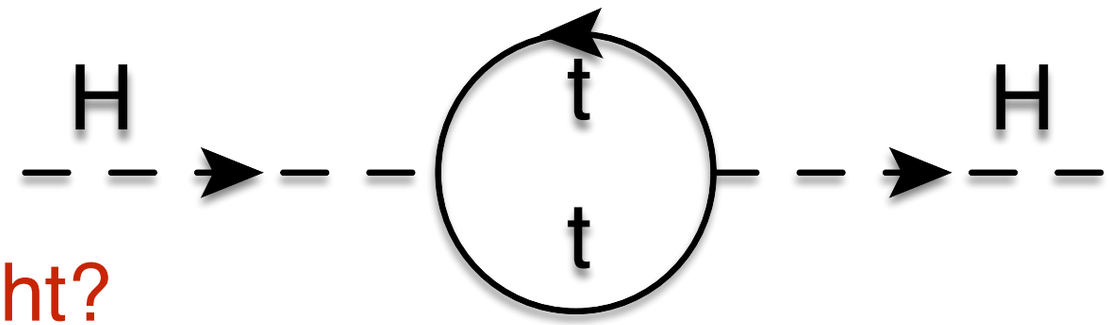
All results at: http://cern.ch/go/pNj7

the problems of the SM



- hierarchy problem
  - why is the Higgs boson so light?
  - why is gravity so weak?

the problems of the SM



- hierarchy problem
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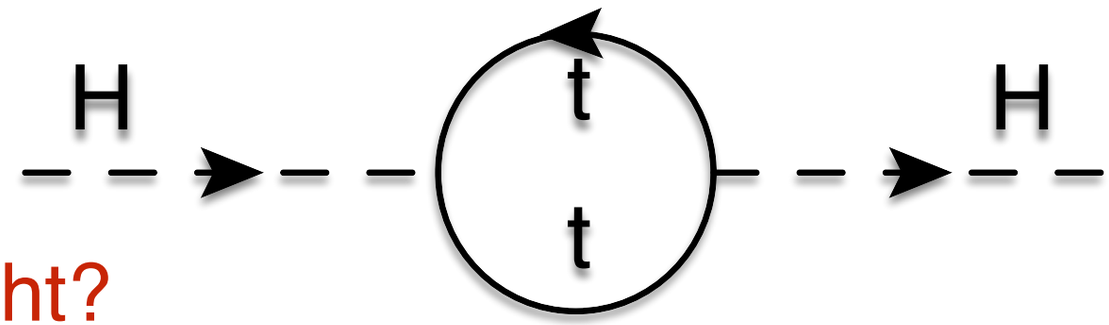
- dark matter, dark energy
  - the SM explains only 5% of the energy in the universe
- matter-antimatter asymmetry
  - the SM predicts that matter and antimatter are created (almost) equally
- several others
  - strong CP problem, number of SM parameters, neutrino masses

the problems of the SM



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➡we expect answers from the LHC at 13 TeV

beyond the standard model models

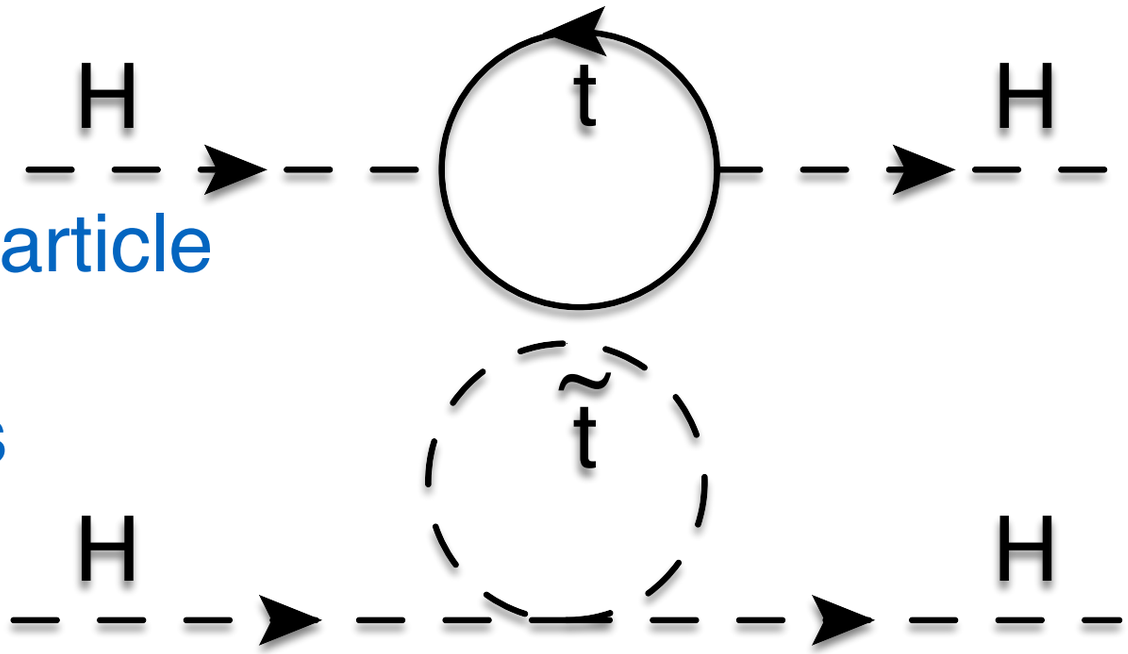
SUSY

non-SUSY BSM

beyond the standard model models

SUSY

- add superpartner for each SM particle
- solves hierarchy problem
- provides dark matter candidates
- gauge coupling unification
- not covered in this talk



non-SUSY BSM

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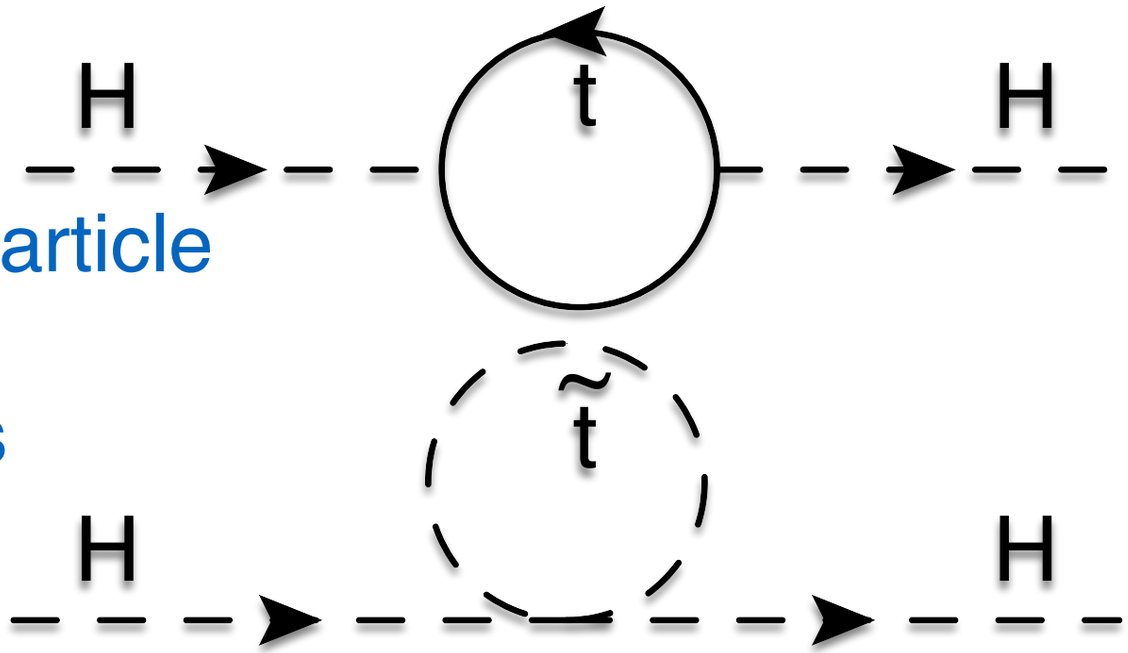
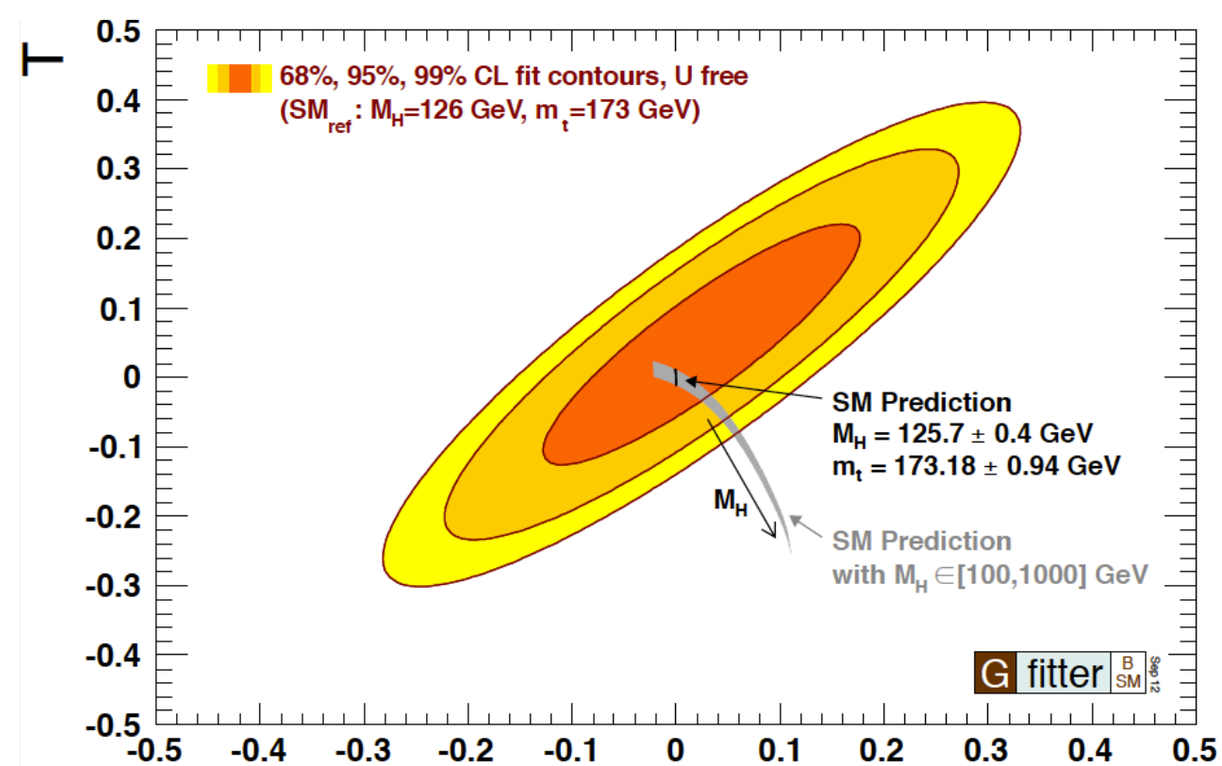


non-SUSY BSM

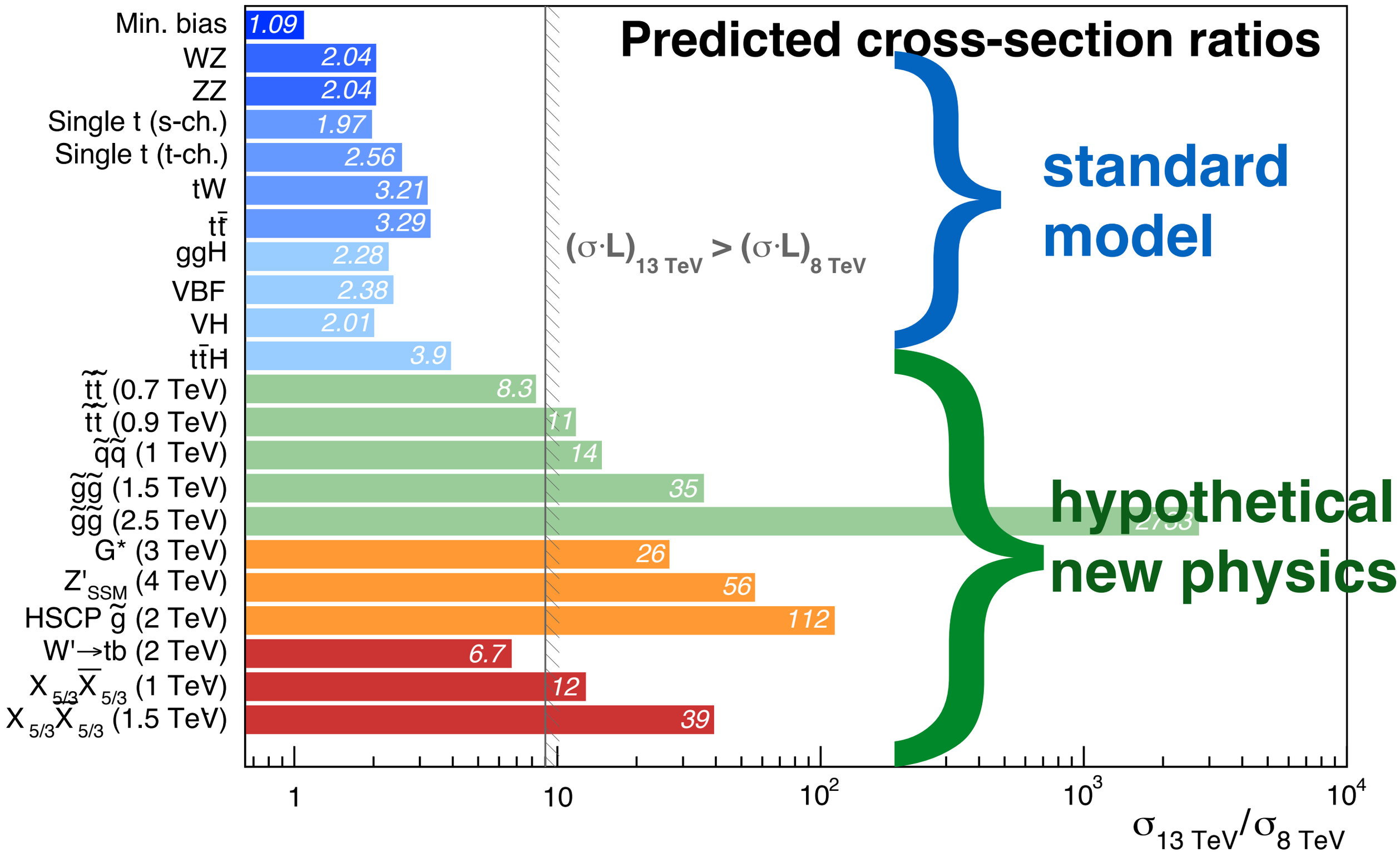
- similar motivations as SUSY
- examples:
  - extra dimensions: warped extra dimension models where fermions propagate in the bulk
  - Composite Higgs: Heavy Vector Triplet model, with new W'±, Z' states
  - contributions to S and T parameters must be small

[Gfitter group, EPJC 72, 2205 (2012)]



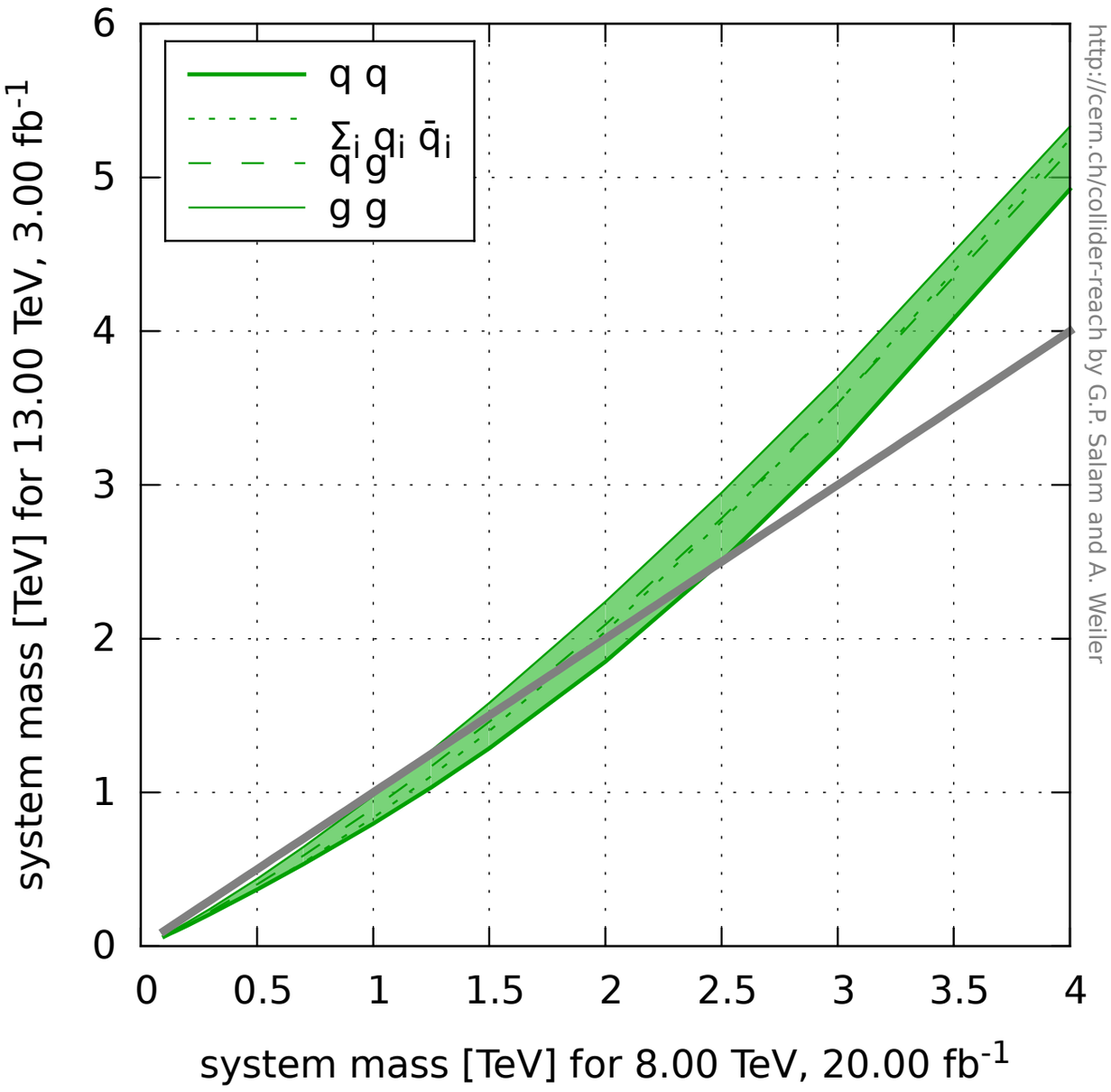
→high resonance masses

higher energy: huge boost



collider reach

parton luminosity scaling:



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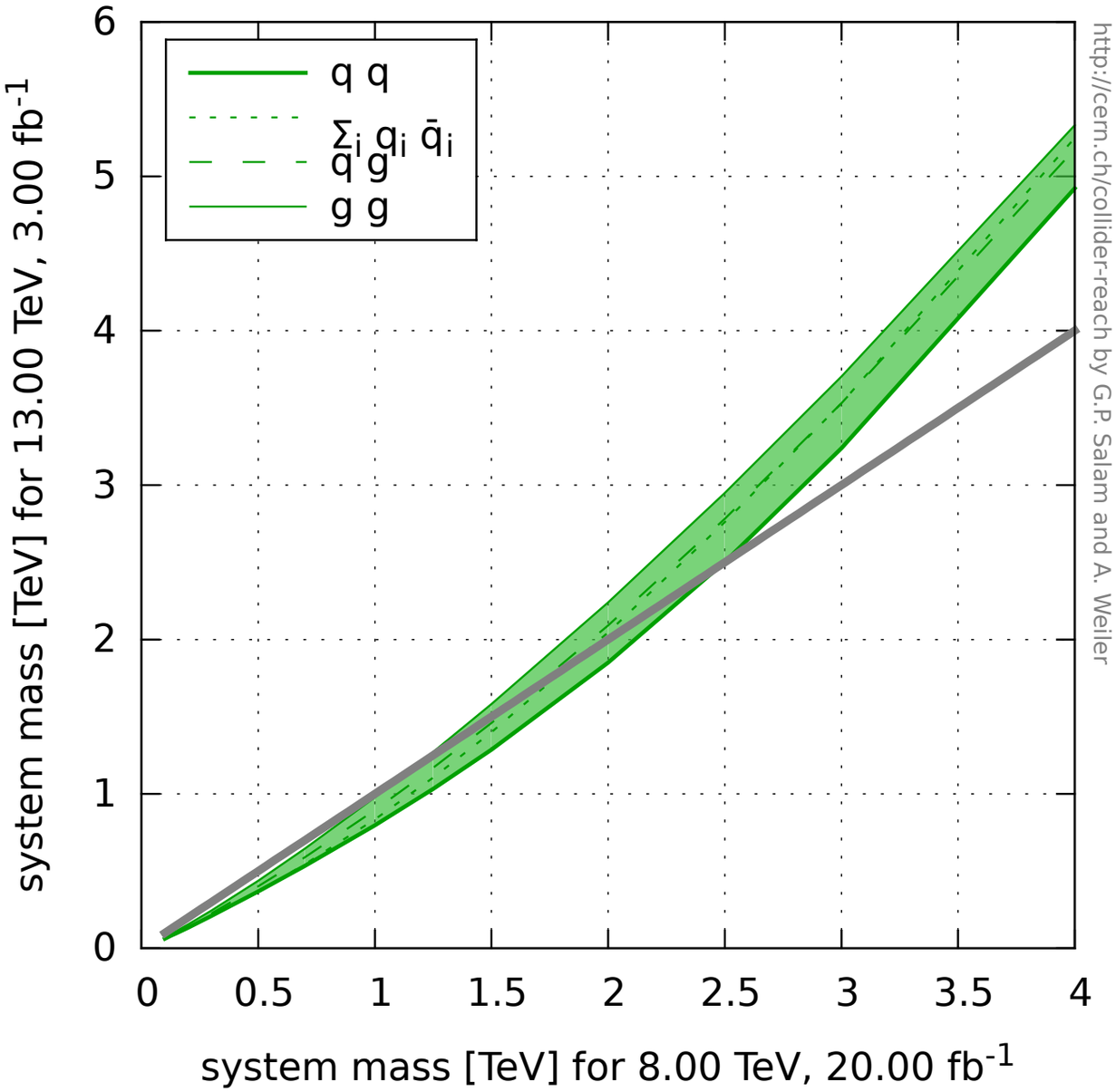
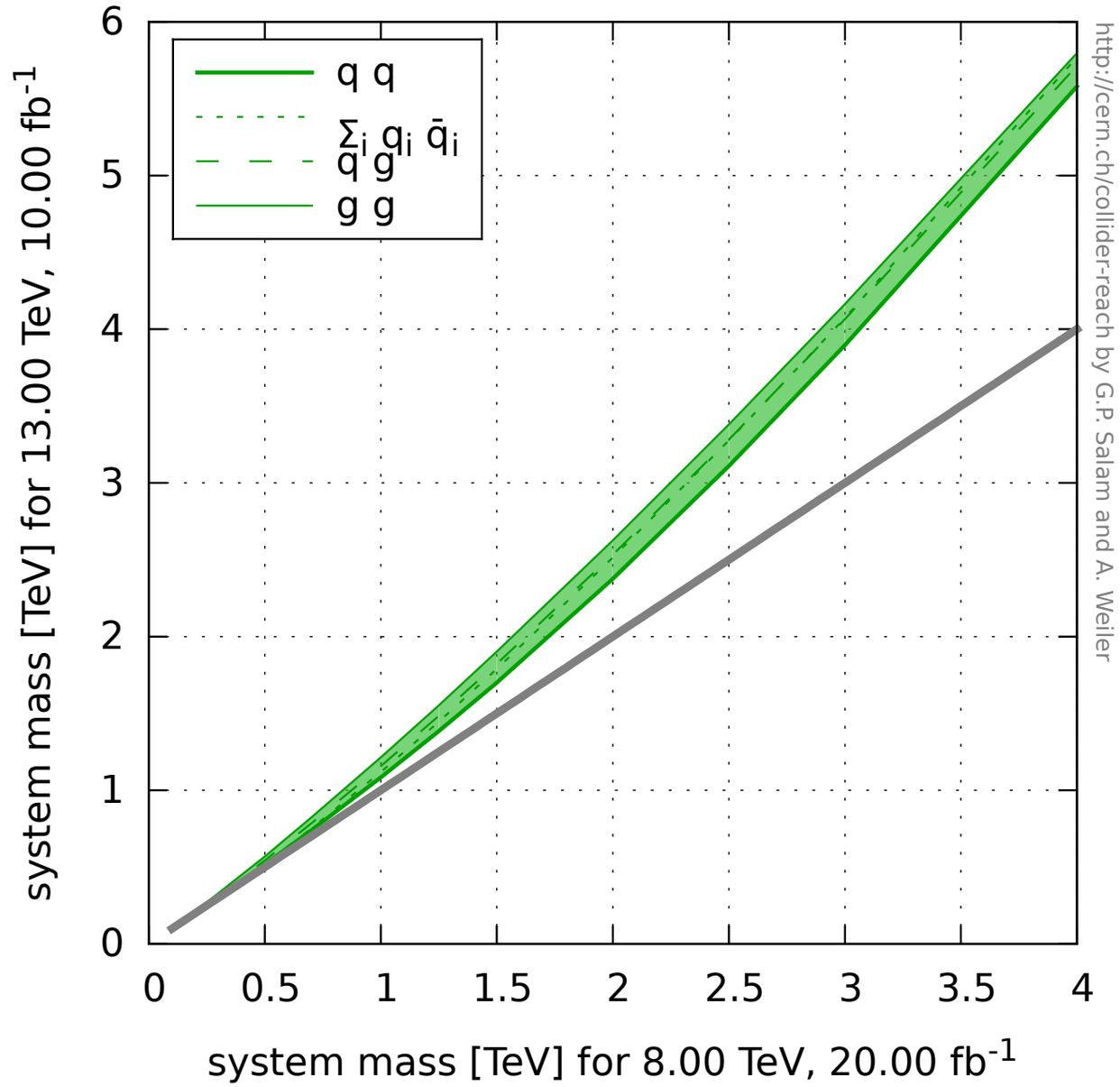
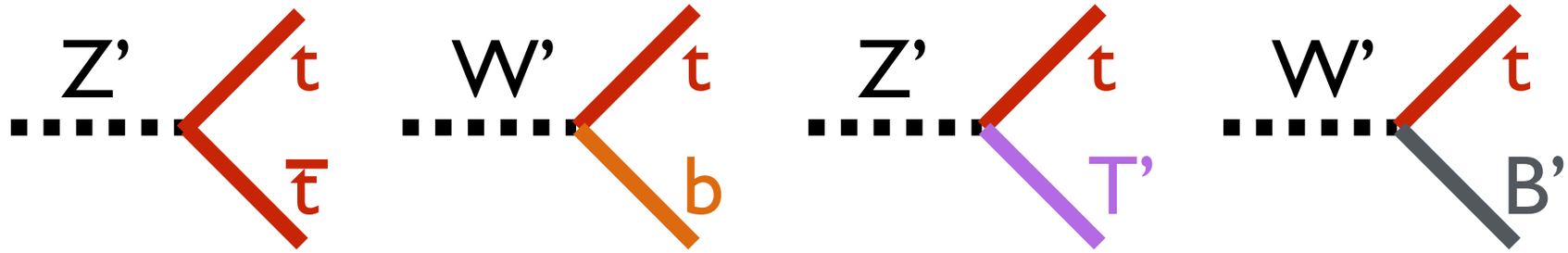




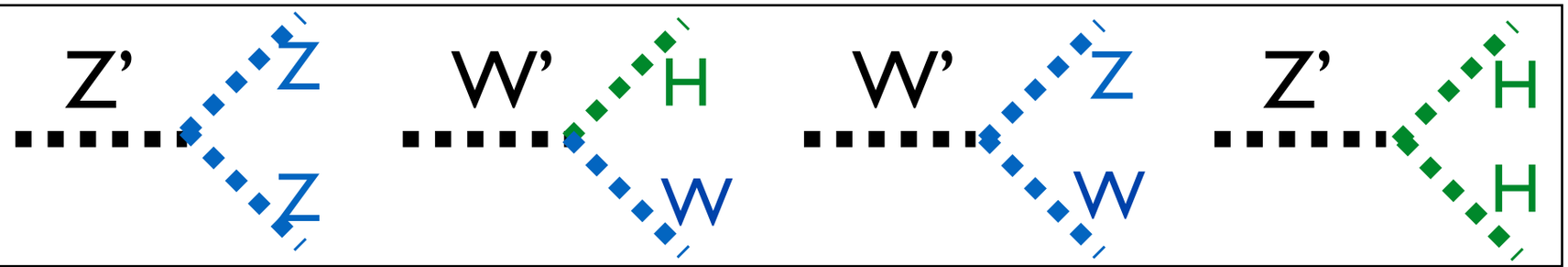
- we do better at high masses

typical signatures

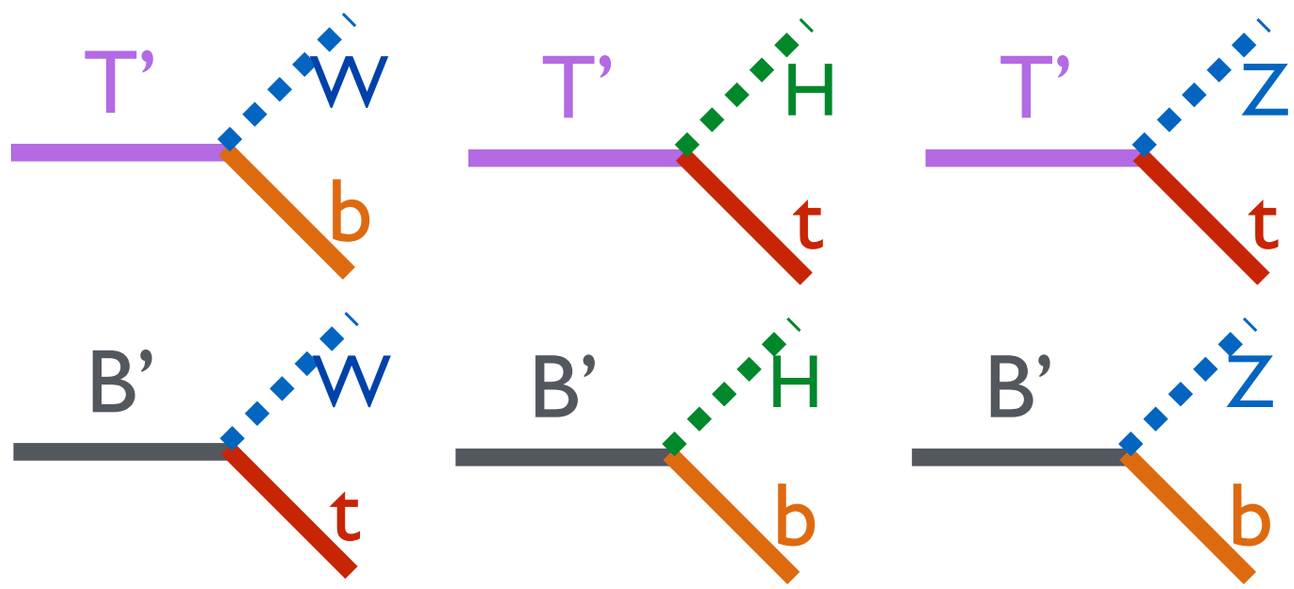
fermion resonances



diboson resonances



vector-like quarks

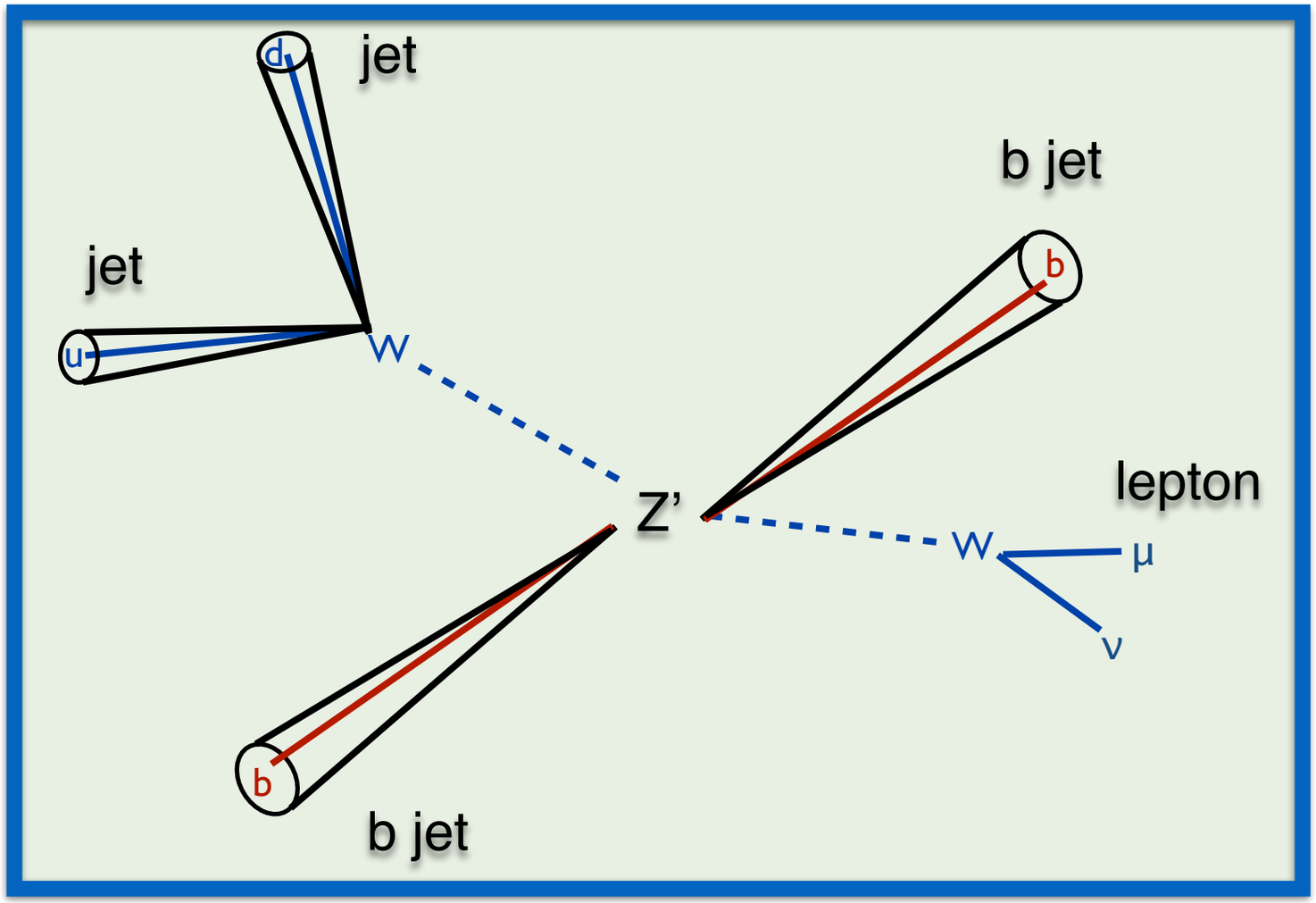


excited quarks, leptoquarks

topology of a tt resonance

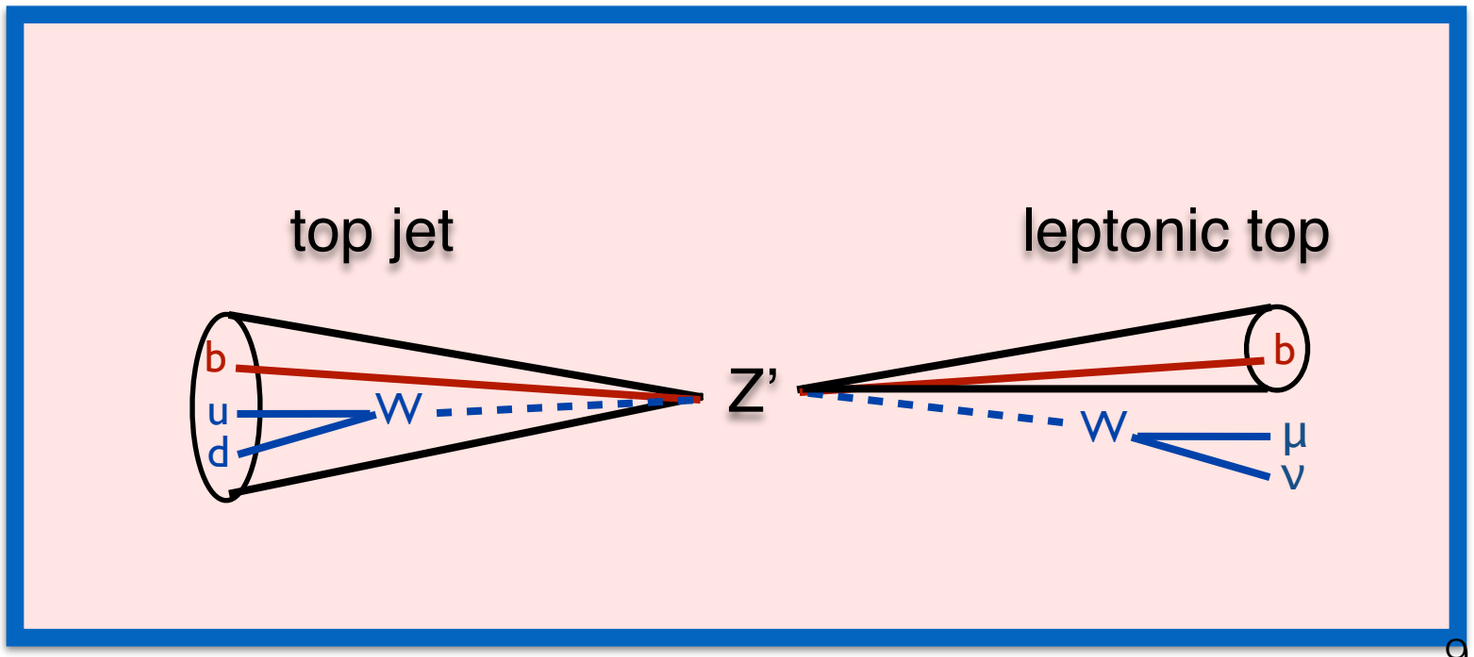
light resonances (M ~ 500 GeV):

- "classical" event topology

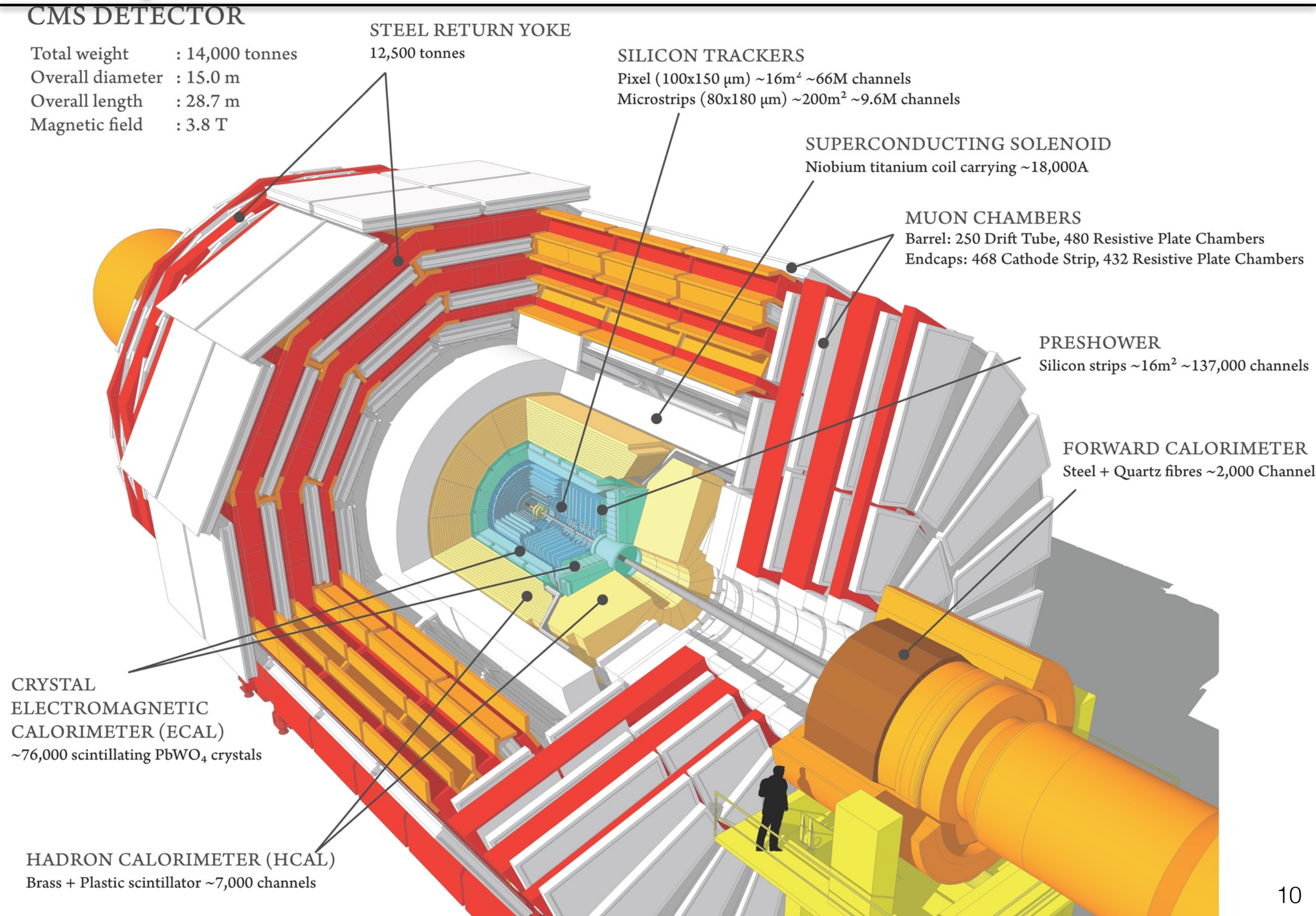


heavy resonances (M ~2 TeV):

- decay products p_T~1TeV
- large γ factor (>5 -10)
- jets overlap and merge
- special reconstruction techniques needed !



Compact Muon Solenoid



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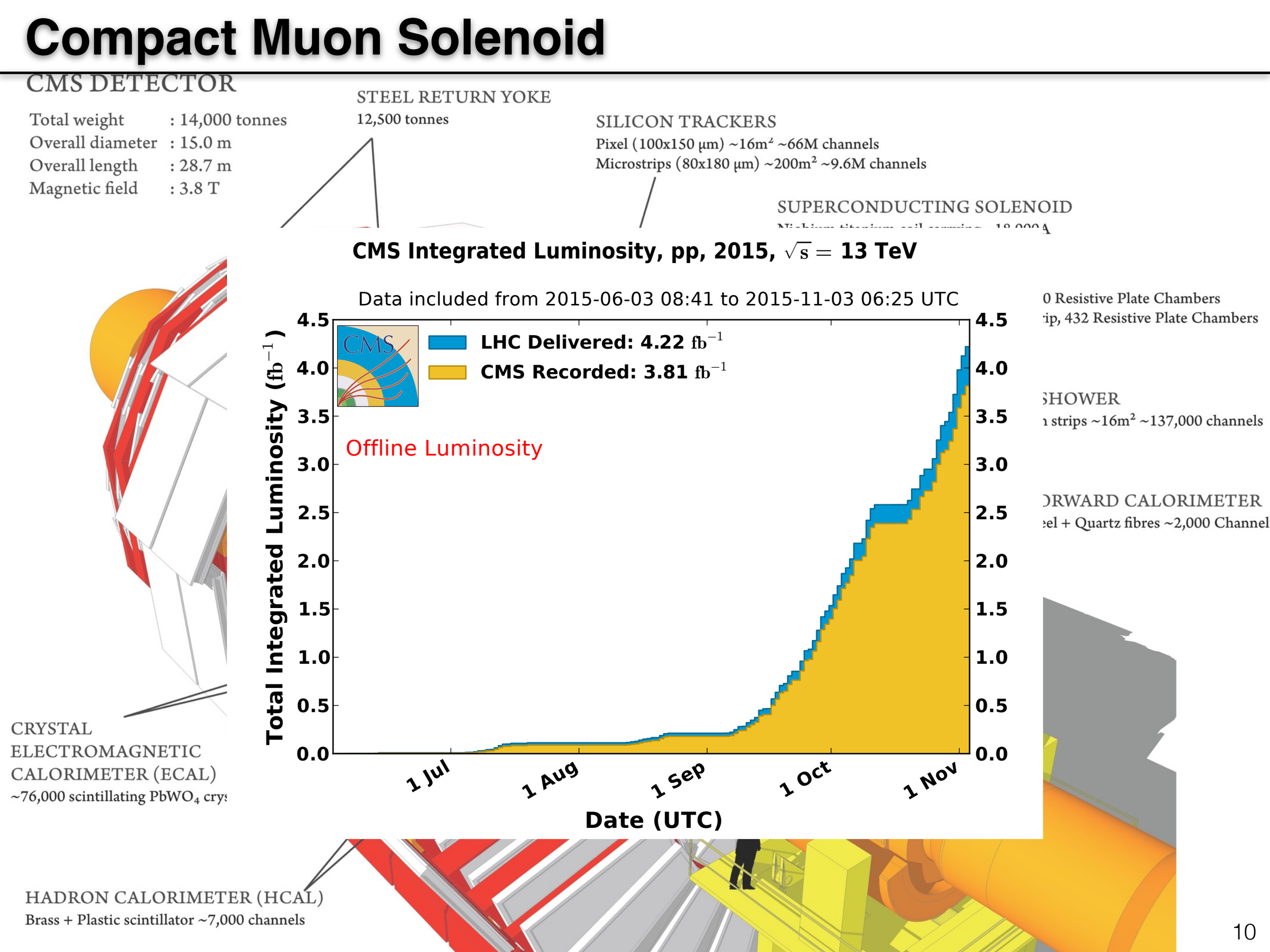
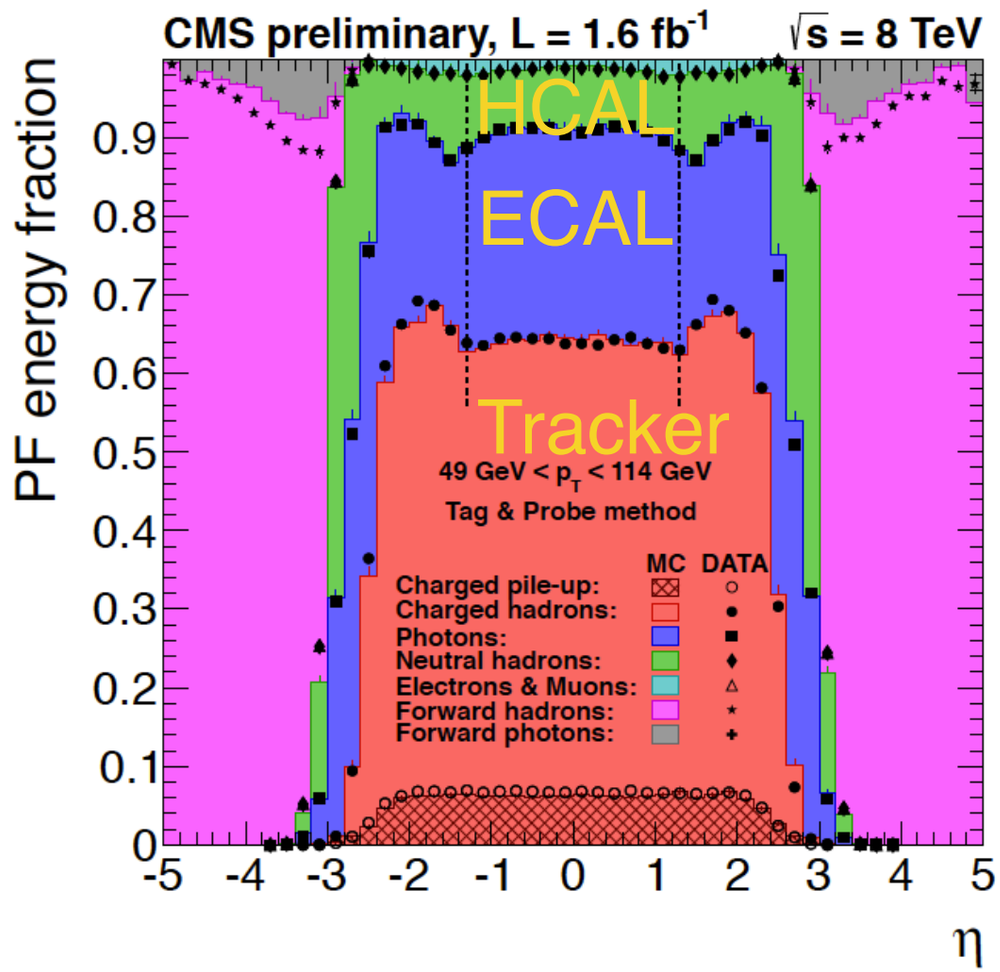


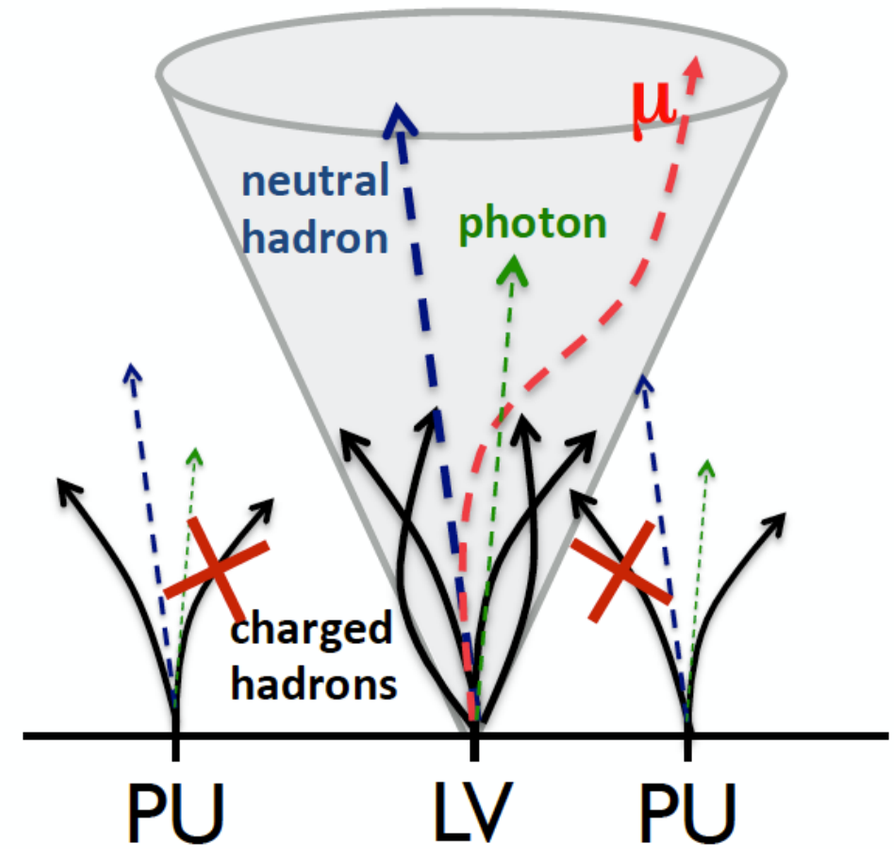
particle flow event reconstruction

[CMS DP-2012/012]

- jet composition:



- charged hadron subtraction:



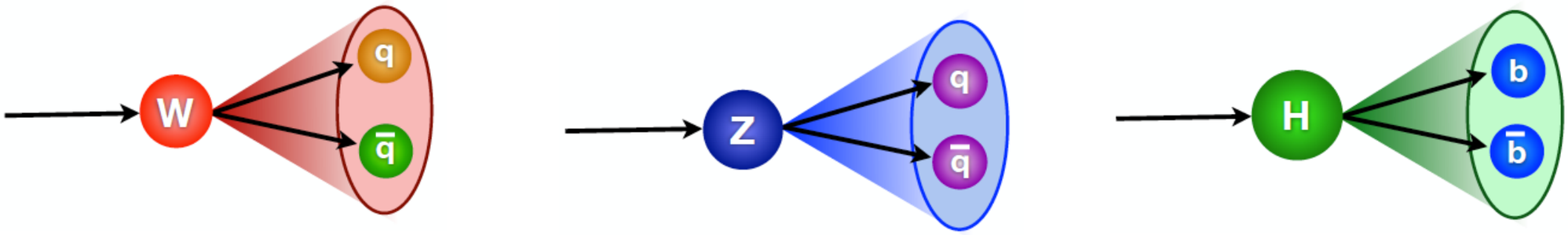
- **PF combines information from all subdetectors to optimise resolution:**

Detector	p_T-resolution (range)	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

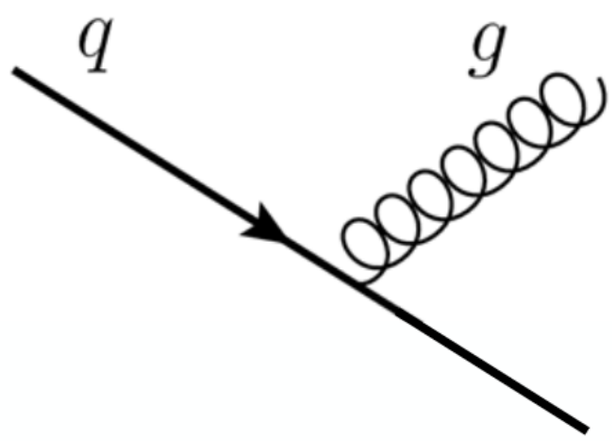
boosted bosons

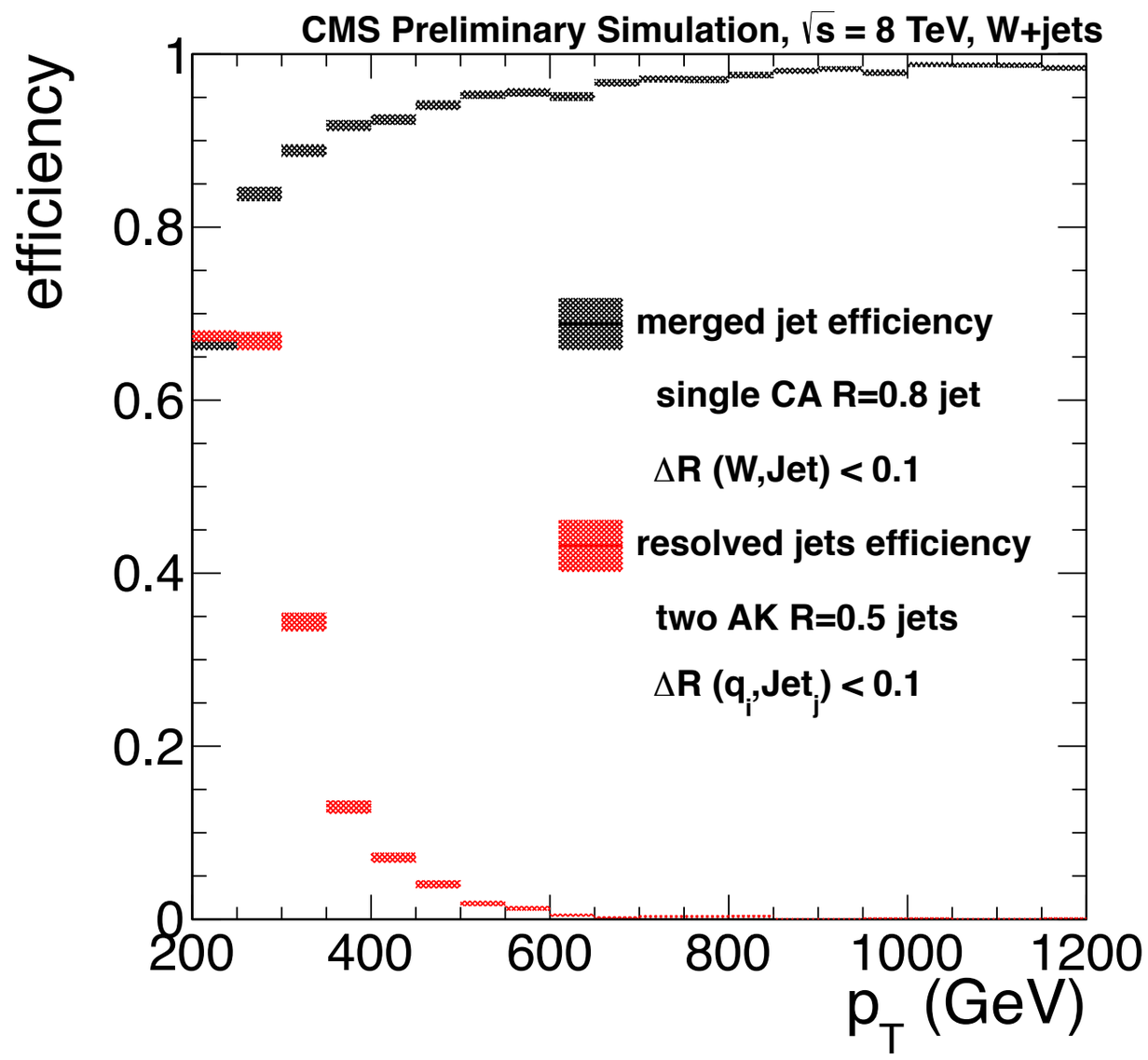
[CMS-PAS-JME-13-006]

2-body decay



- angular separation $\Delta R \approx 2M/p_T$
- efficiency for 2 jets drops with p_T
- how to distinguish from QCD:

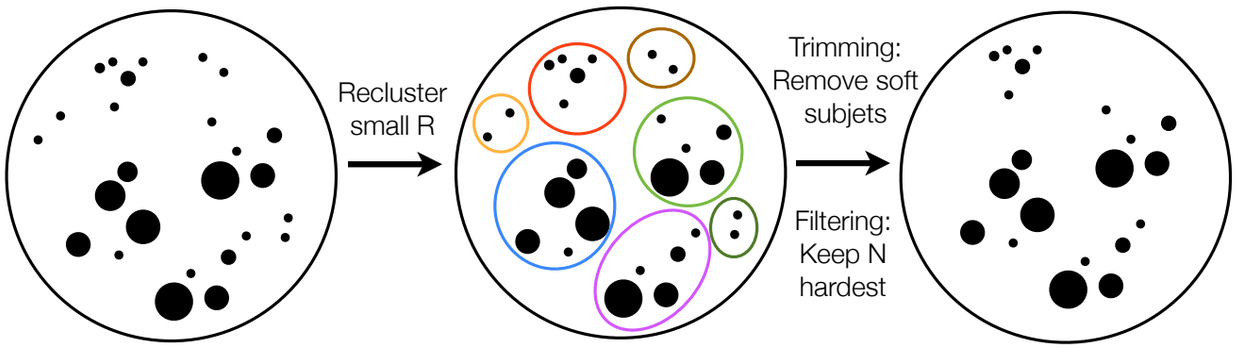




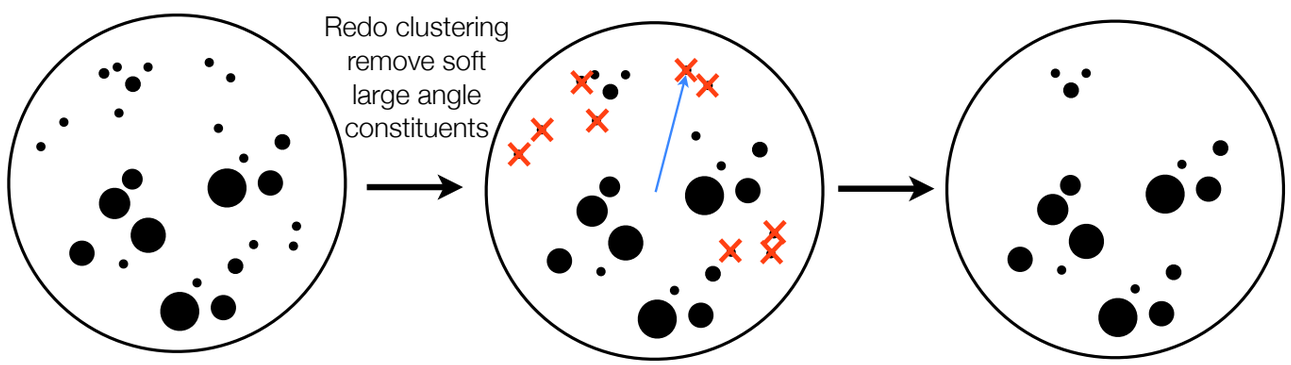
jet grooming

J. Dolen

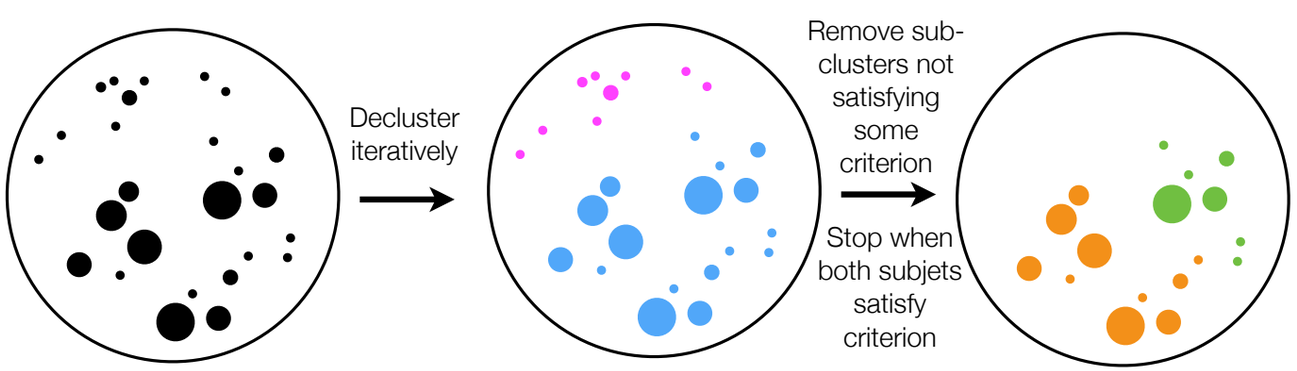
Trimming, Filtering - Recluster jet with smaller distance parameter. Condition based subjet removal.



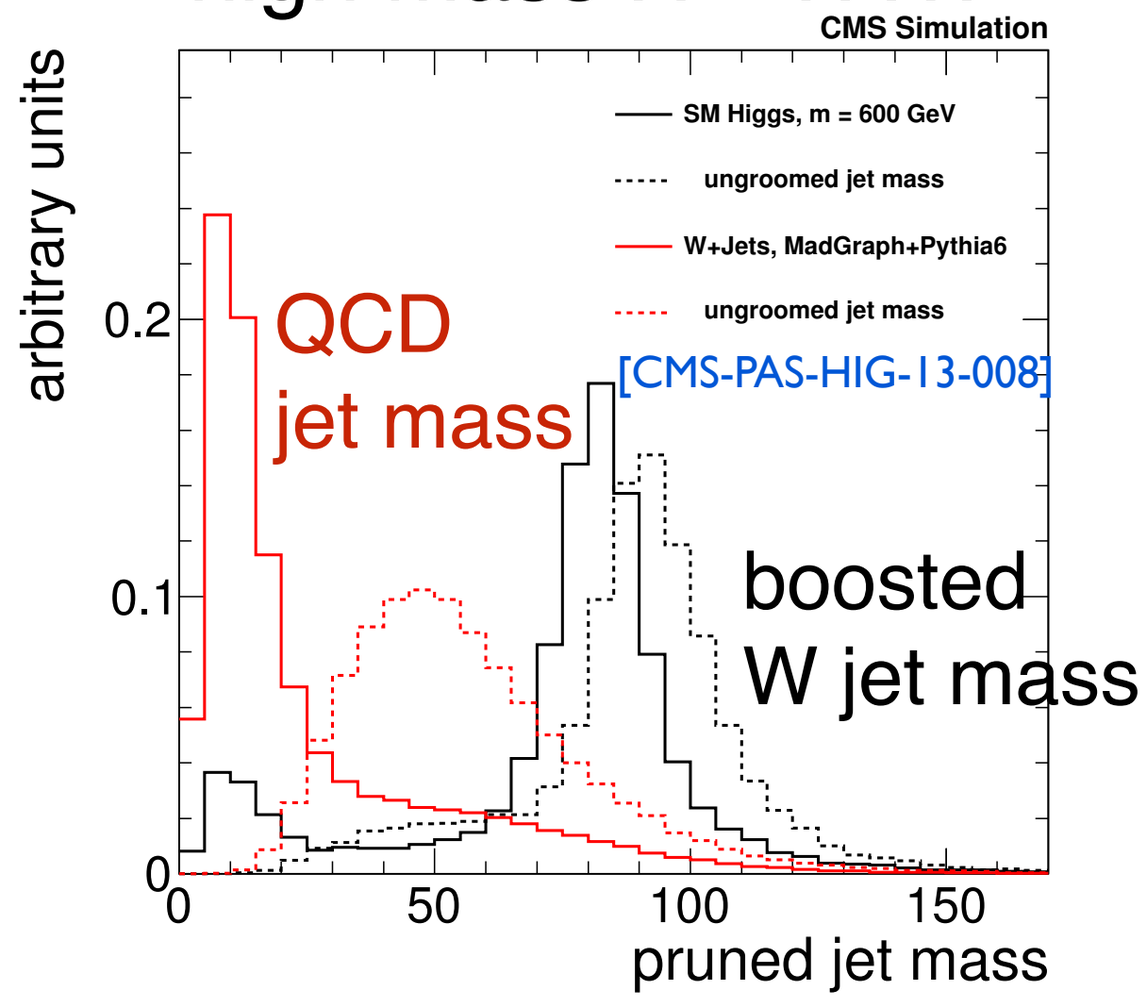
Pruning - Recluster jet. Remove soft large angle particles.



BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.



high mass H→WW:



- improves jet mass resolution
- reduces QCD jet mass

jet shapes

[CMS-PAS-JME-13-006]

energy patterns within a jet:

- characterise multi-prong properties
- many definitions and varieties

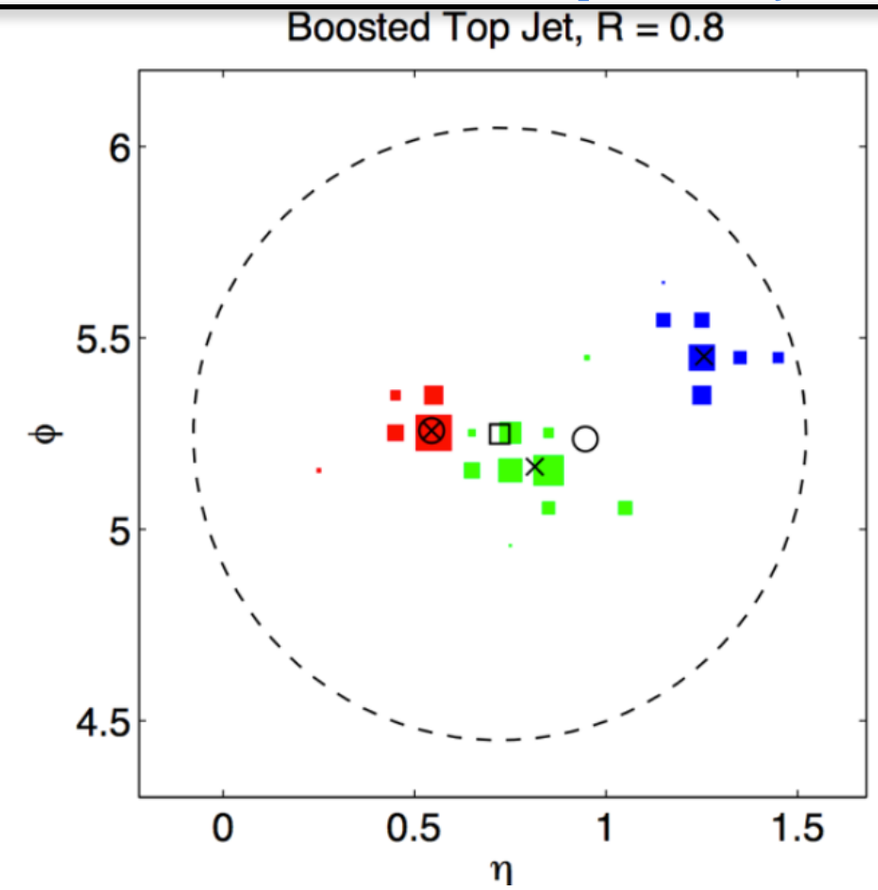
n-subjettiness:

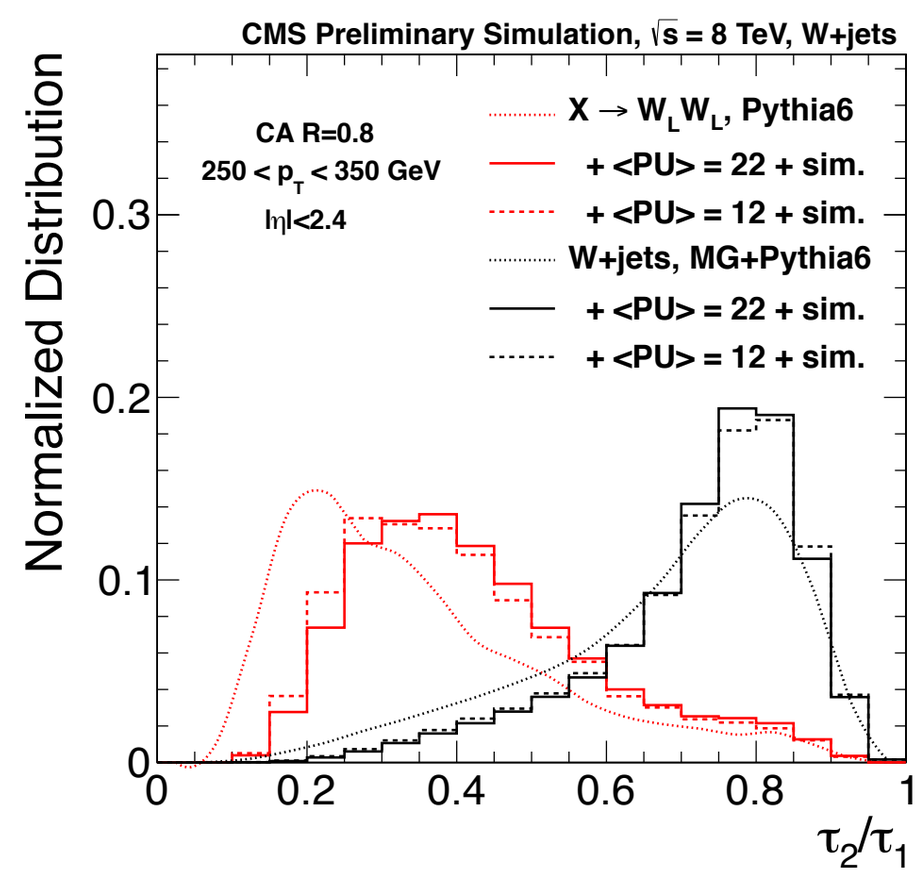
$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} R}$$

- how consistent is jet with having N subjets
- ratios discriminate hypotheses: τ_2/τ_1

many other on the market:

- energy correlation functions
- Q-jet volatility
- …





calibration with data

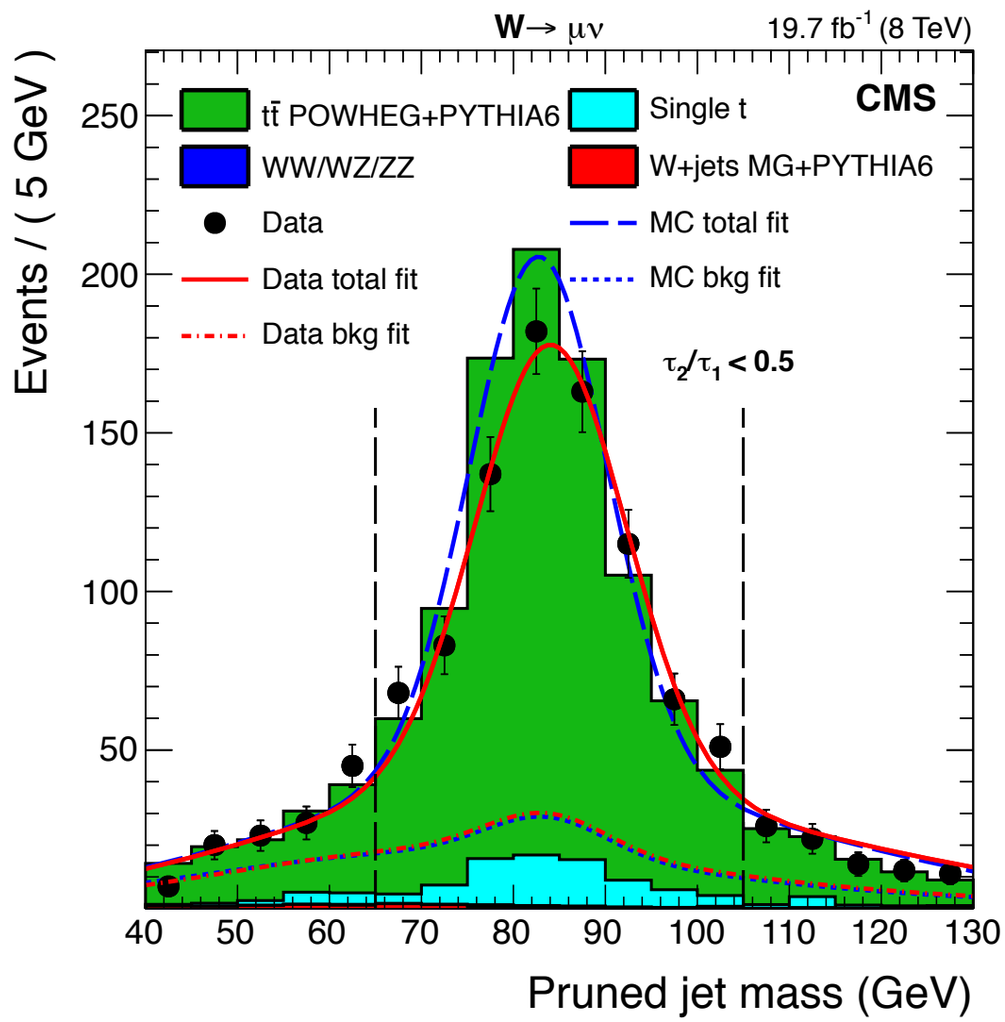
[CMS-PAS-JME-13-006]

efficiency:

- semi-leptonic tt sample
- hadronic W boson decay is probe

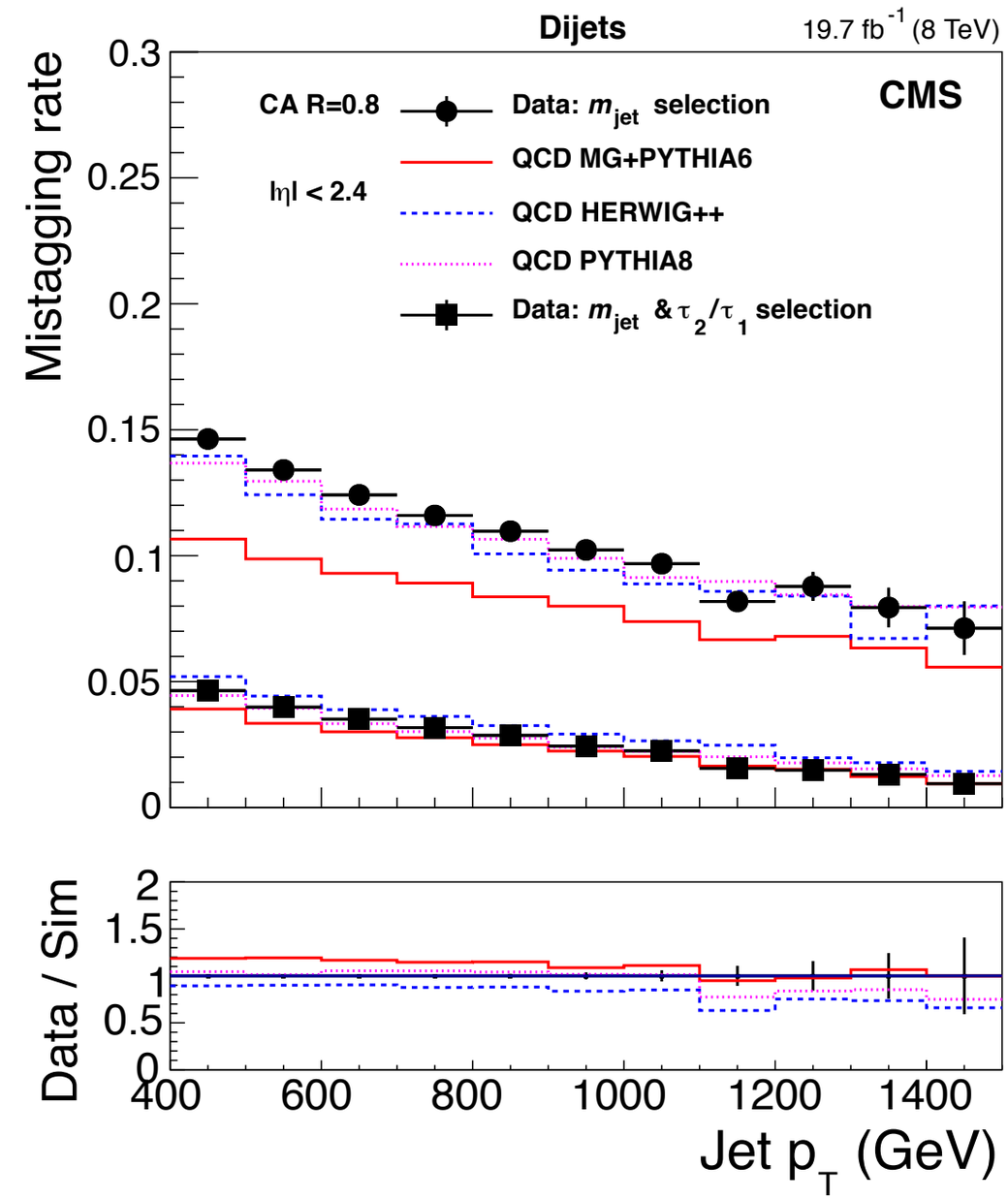
Table 1: Summary of the fitted W-mass peak fit parameters.

Parameter	Data	Simulation	Data/Simulation
$\langle m \rangle$	84.1 ± 0.4 GeV	82.7 ± 0.3 GeV	1.017 ± 0.006
σ	8.4 ± 0.6 GeV	7.6 ± 0.4 GeV	1.11 ± 0.09



fake rate:

- di-jet sample

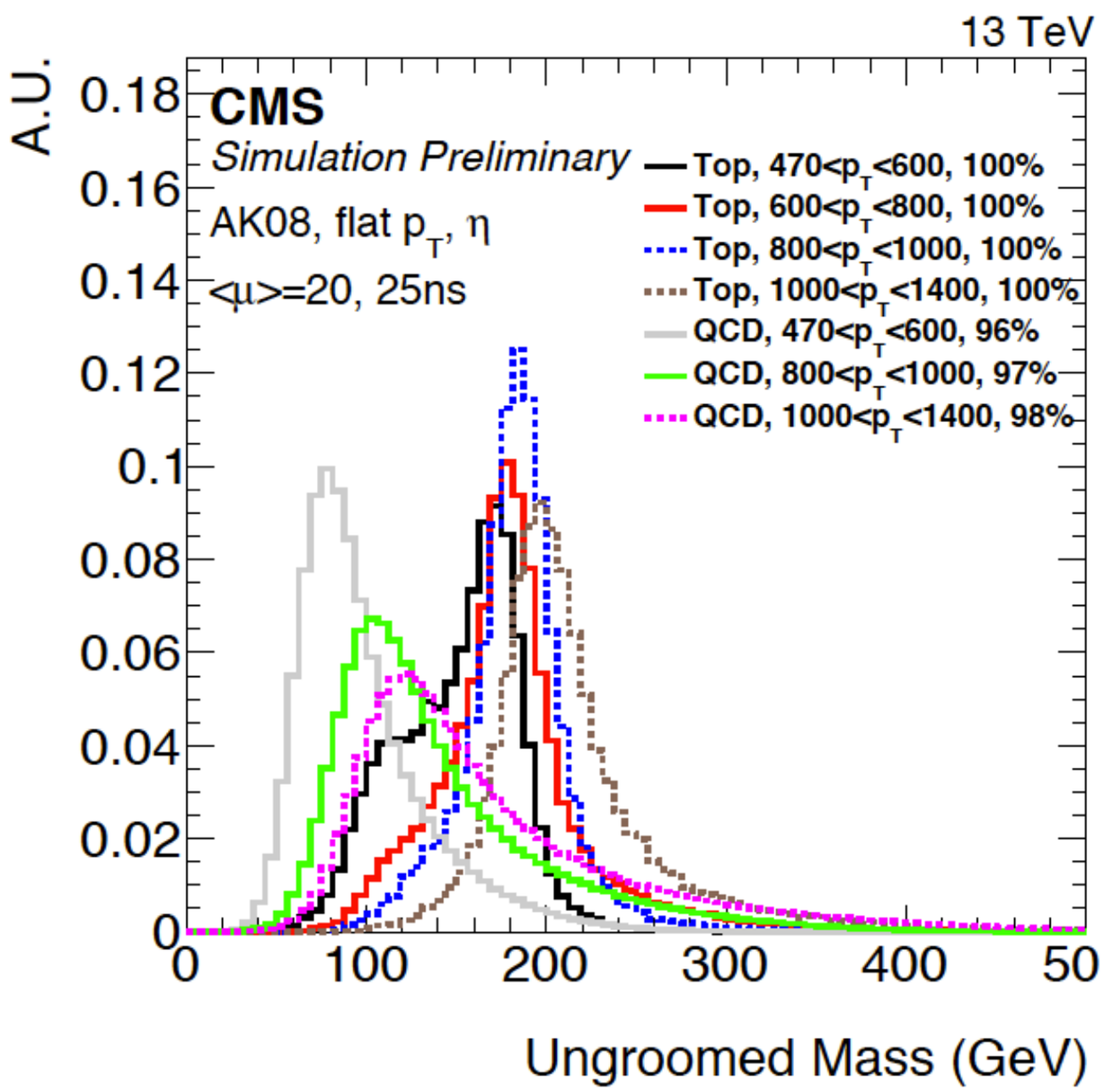


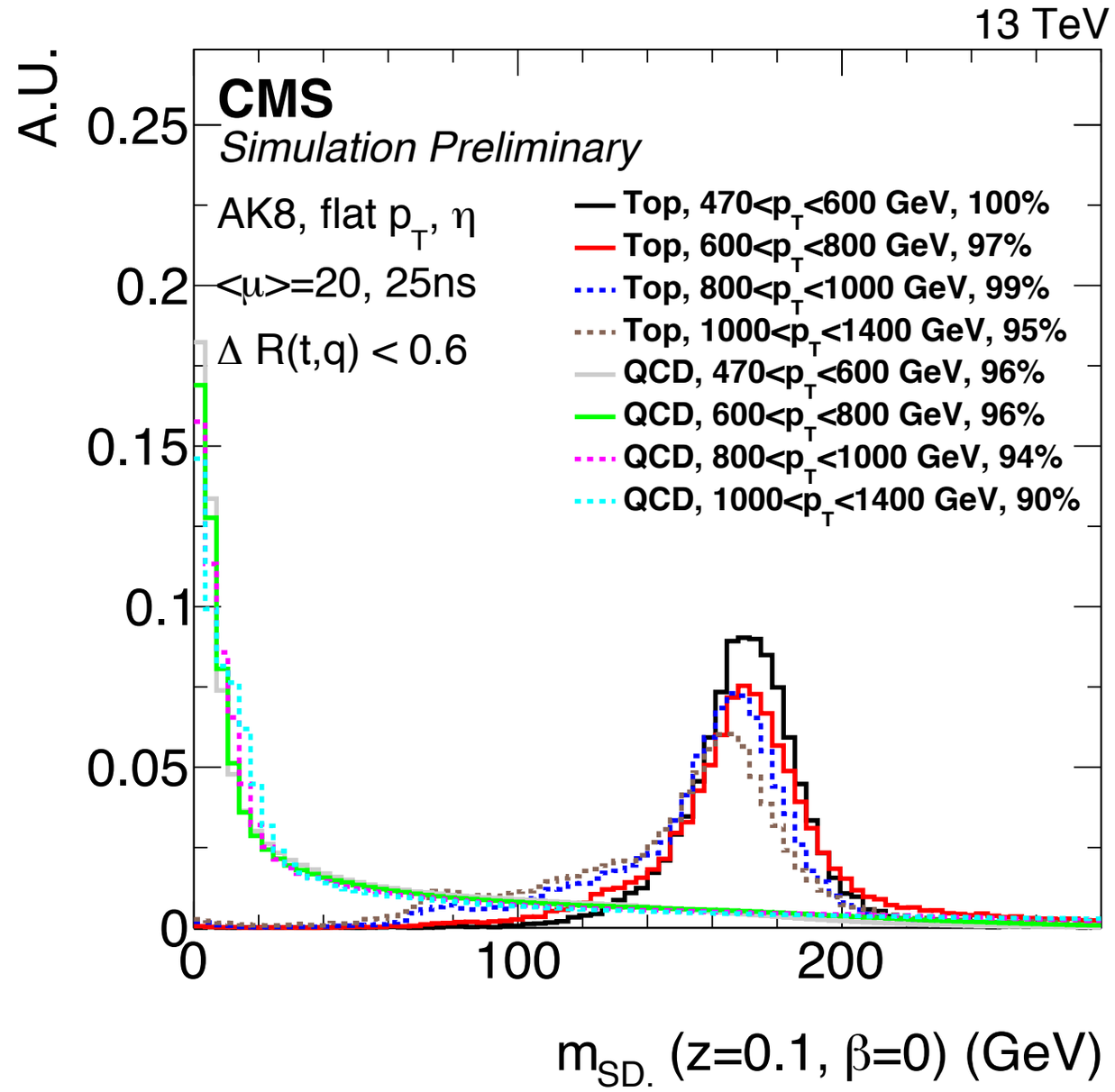
boosted t tagging

[CMS-PAS-JME-15-002]

similar approach as boson-tagging:

- try various grooming methods and jet shape variables
- scan their parameters, optimise



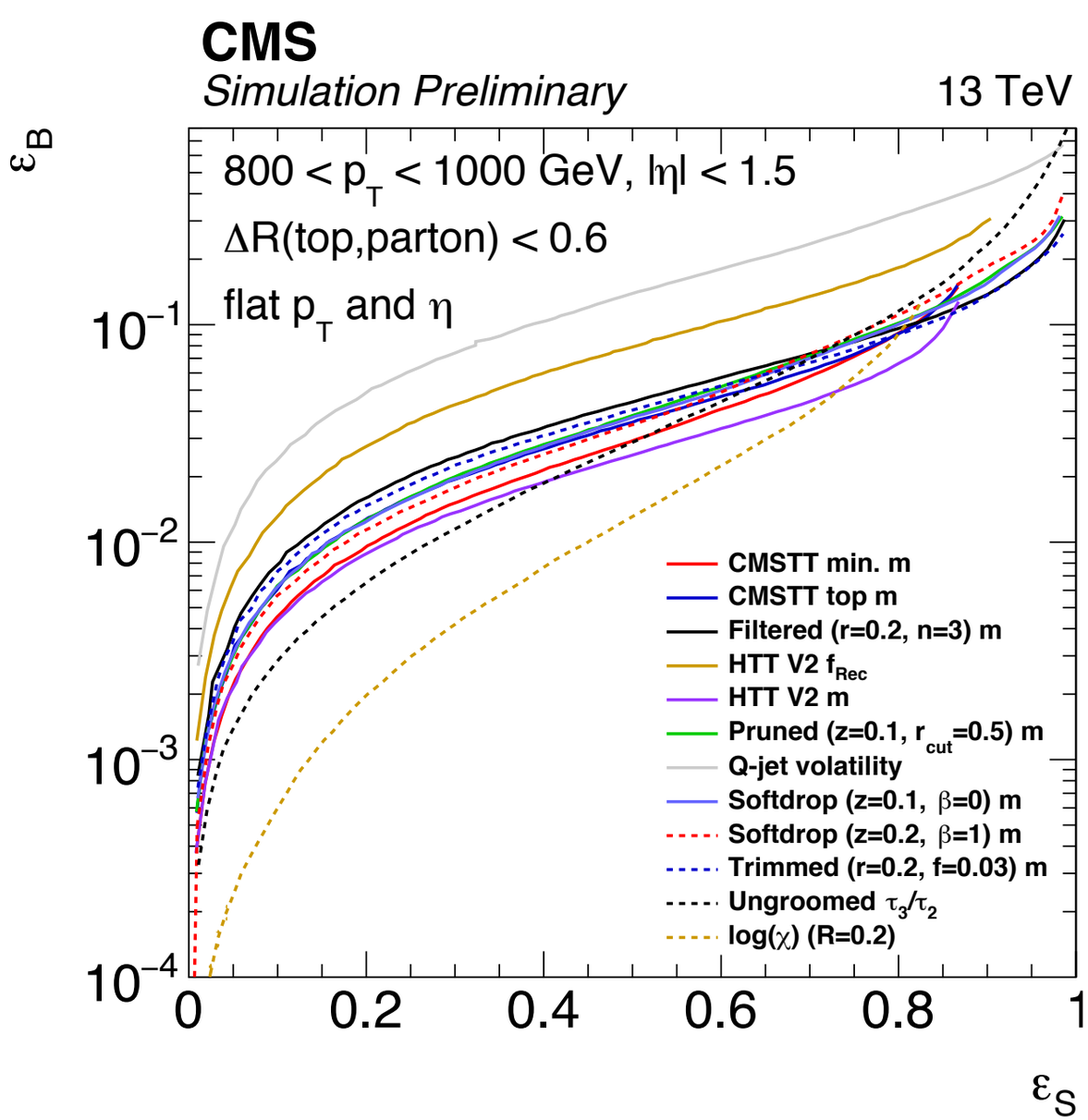


boosted t tagging

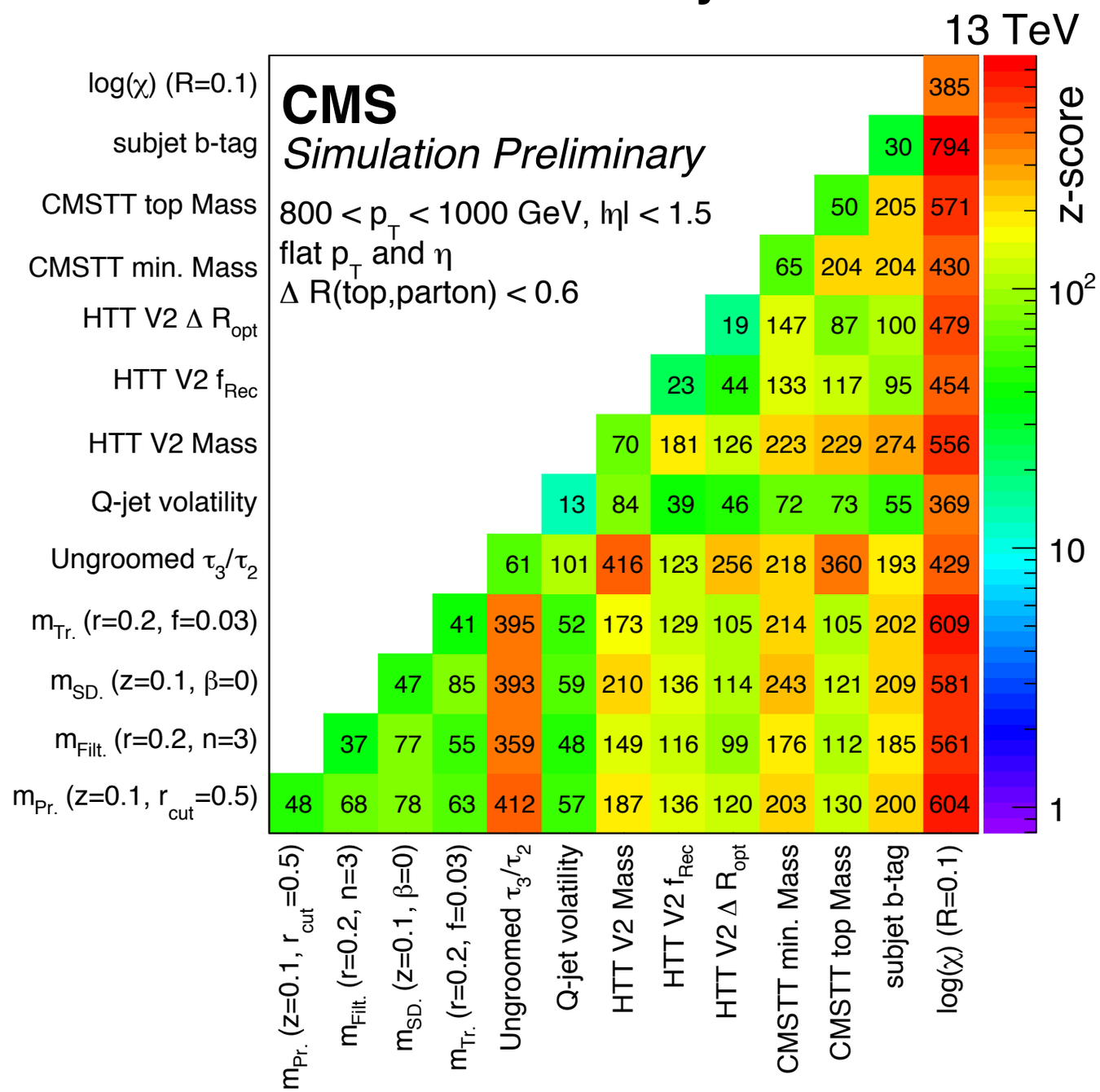
[CMS-PAS-JME-15-002]

performances:

- several variables scanned individually



- background rejection at 30% efficiency

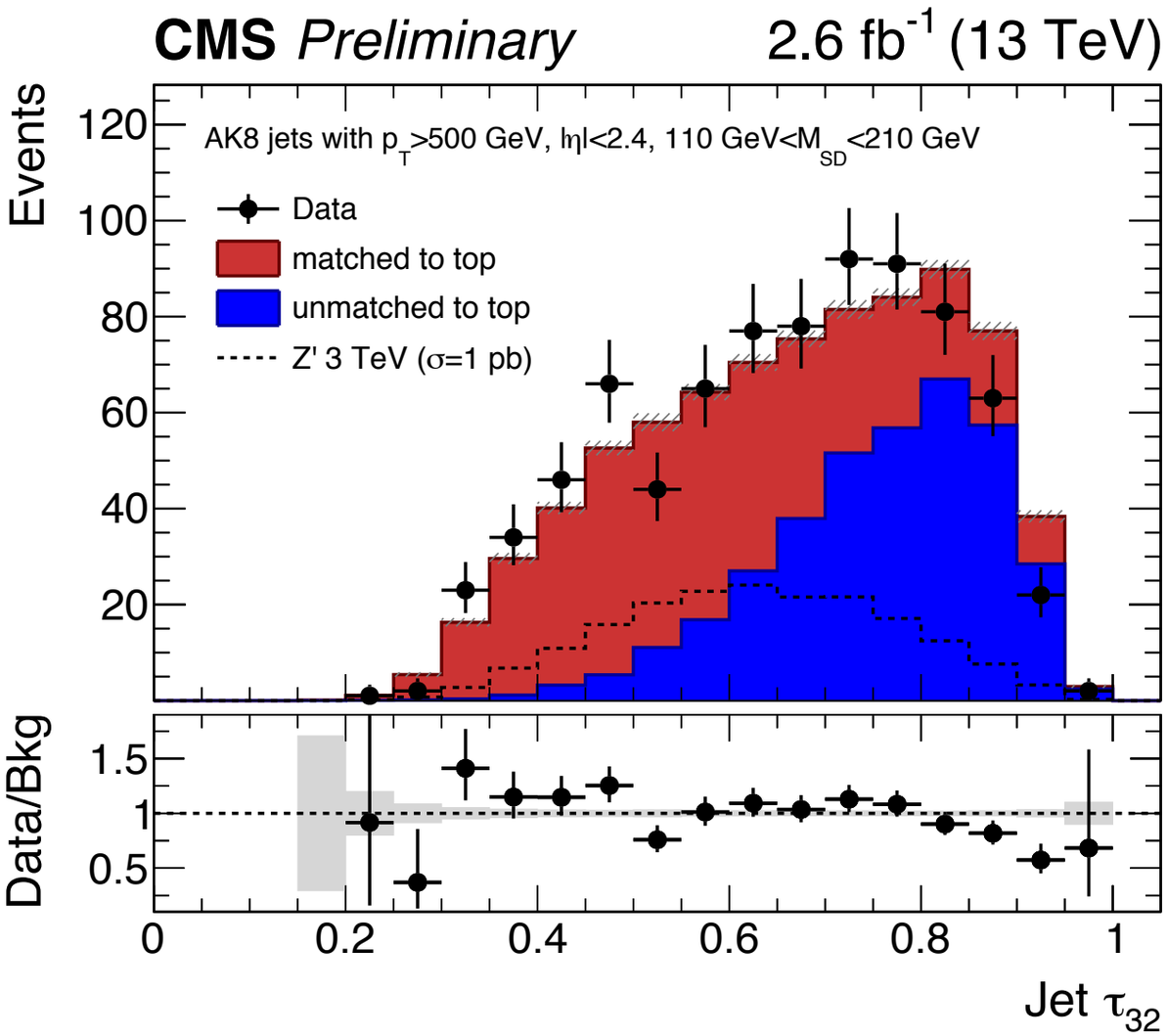


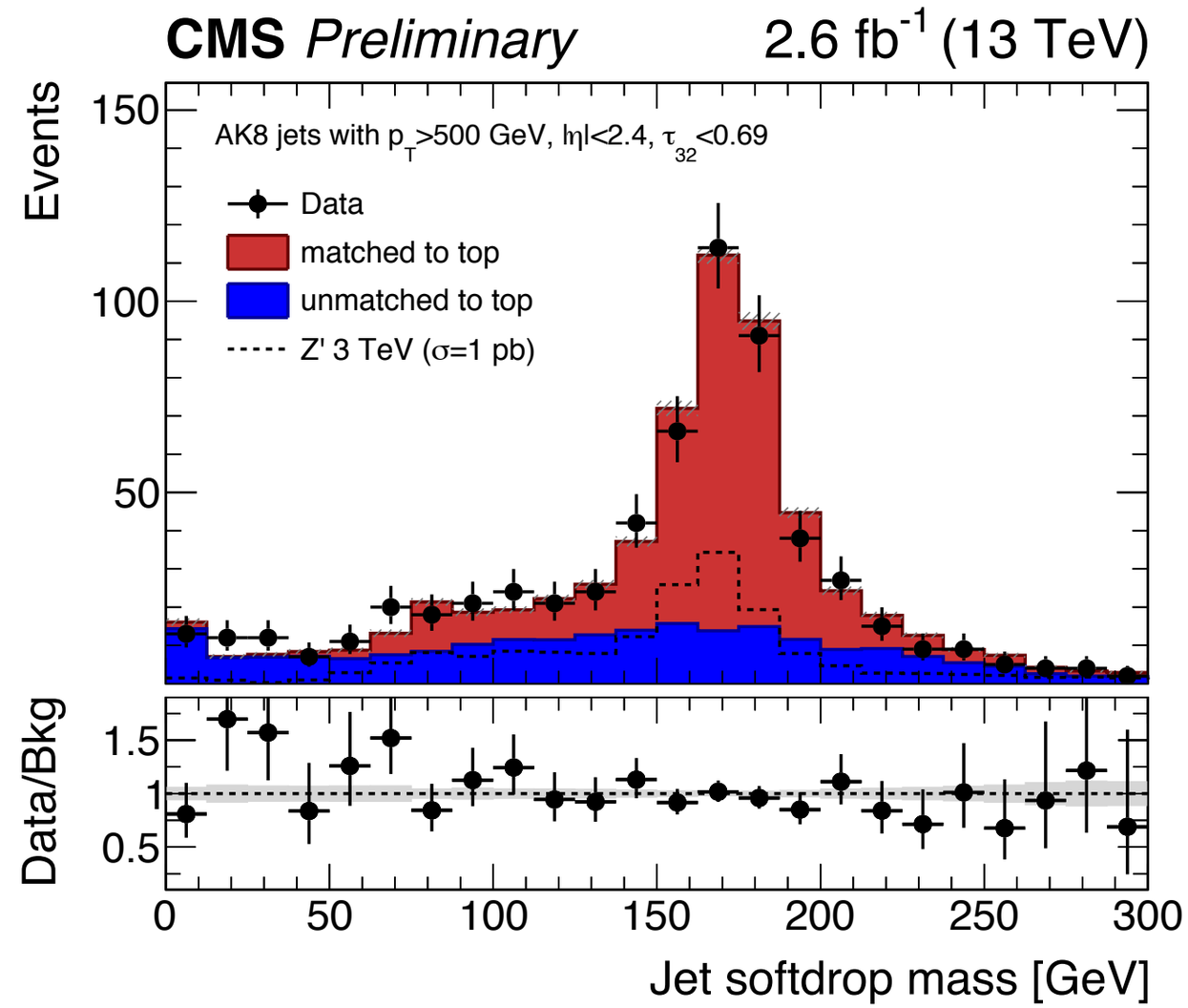
boosted t tagging

[CMS-PAS-B2G-15-002]

modeling of variables at 13 TeV:

- semi-leptonic top selection

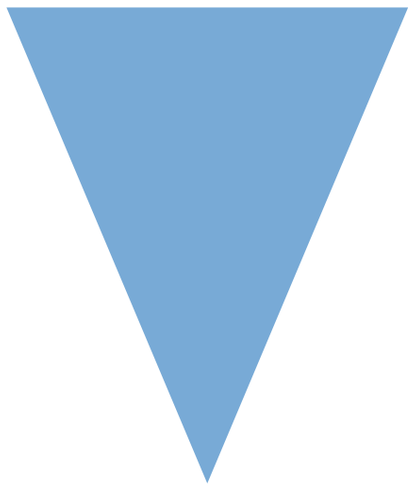




- after initial difficulties at the start of Run II, **things look very good now**

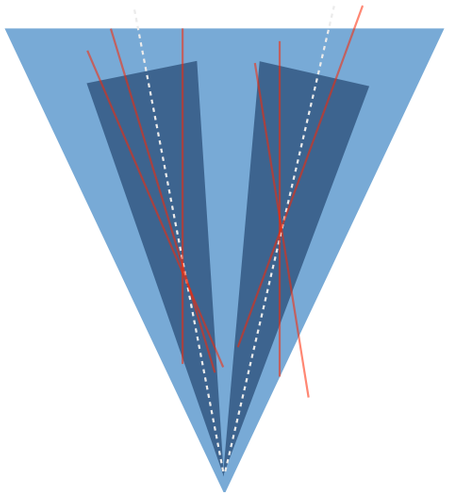
b-tagging in boosted topologies

several approaches:



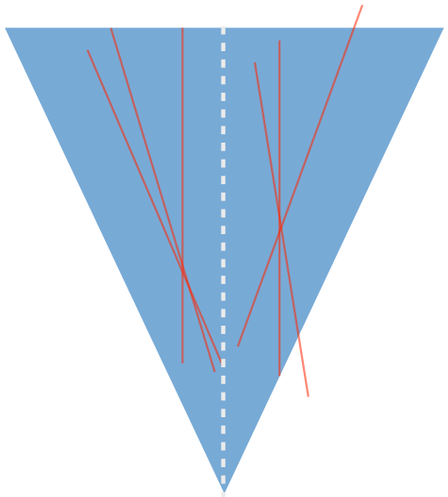
fat jet

- run standard b-tagging algorithm on wide jets
- not able to distinguish two from one b jets



subjets

- run standard b-tagging algorithm on subjets
- can distinguish two from one b jets

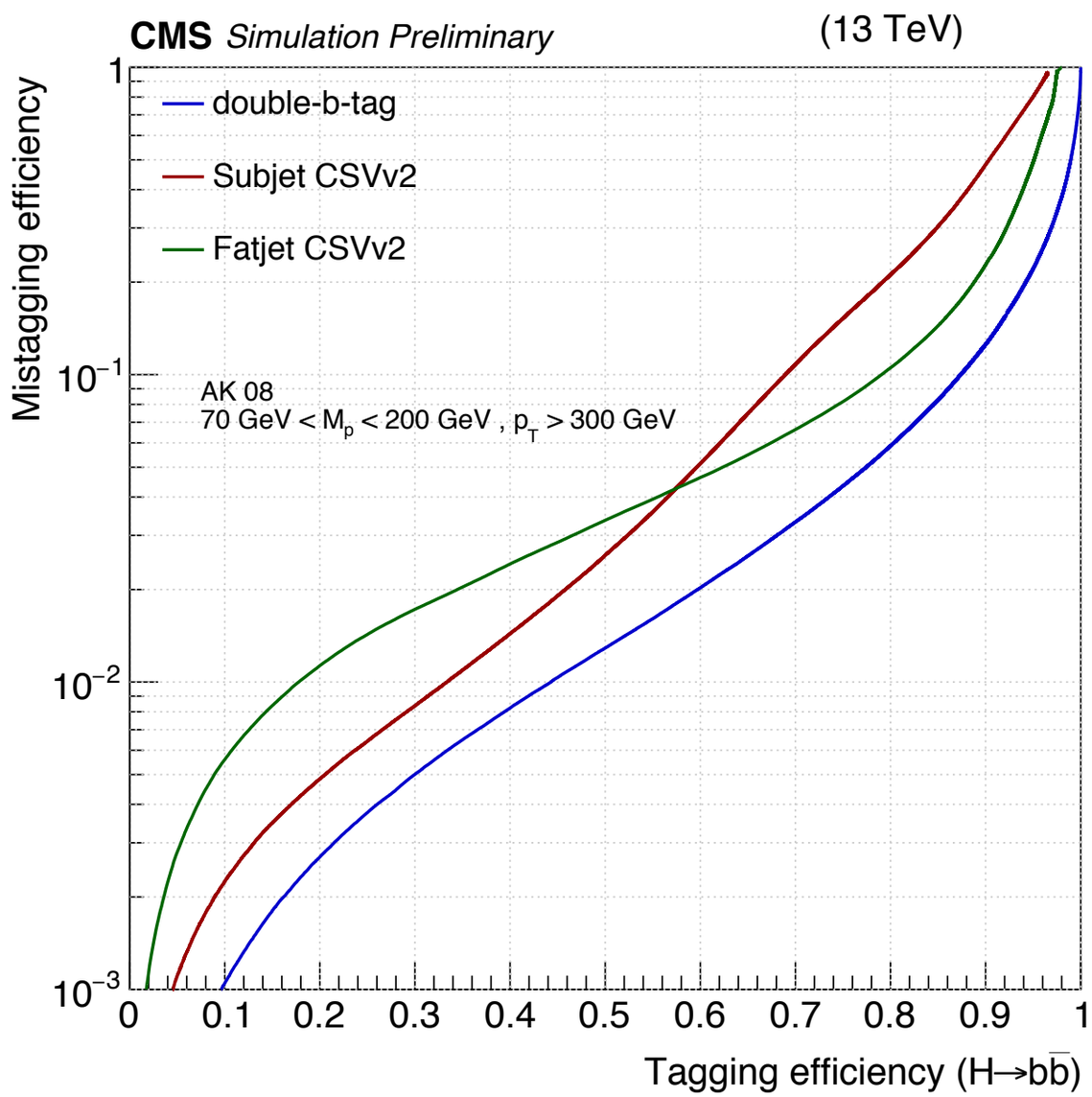


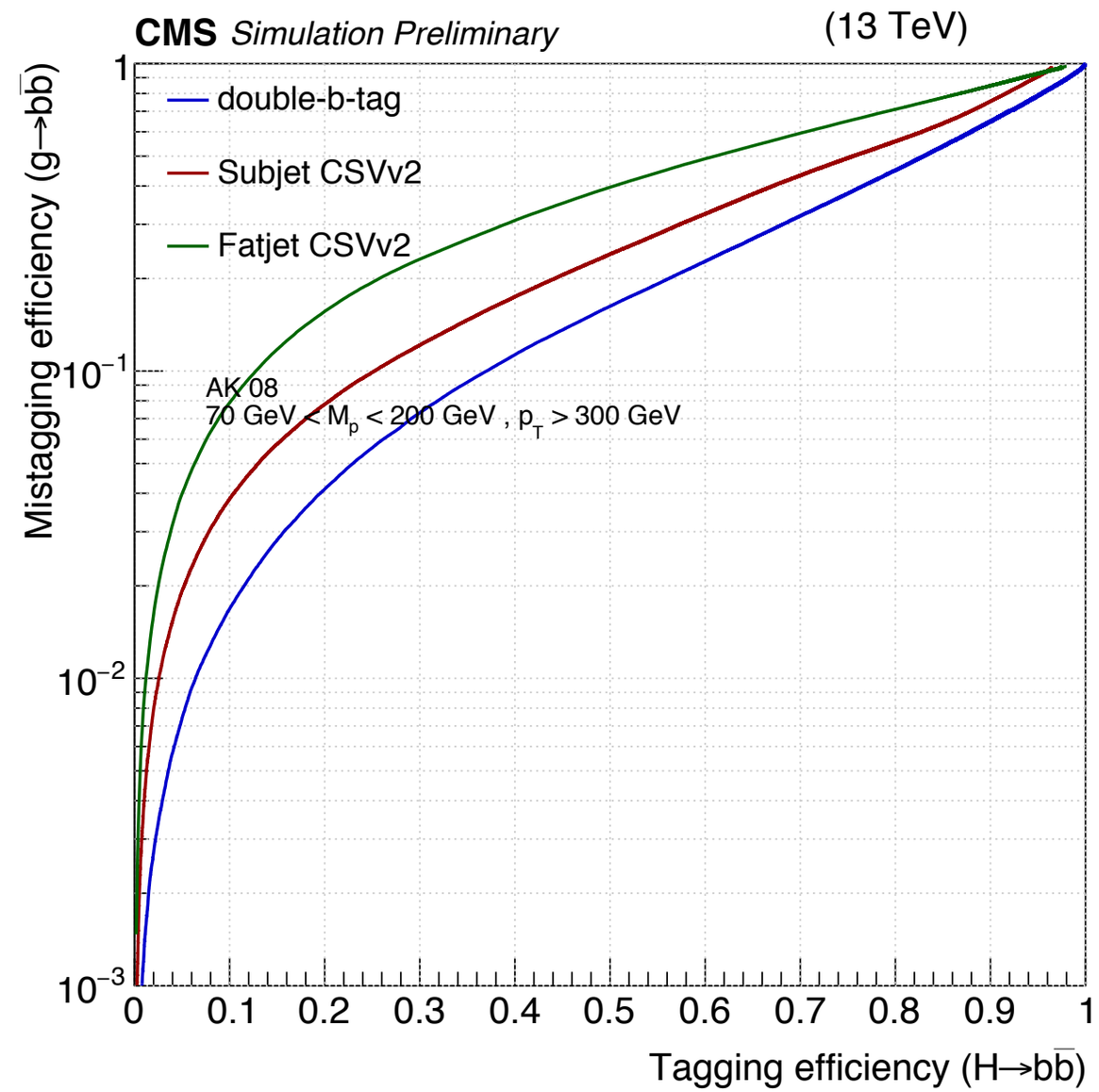
- dedicated double tagger
- specialised for boosted H→bb

b-tagging in boosted topologies

[CMS DP-2015/038]

performance of new H→bb tagger





challenge: how to calibrate a boosted H→bb tagger with data?

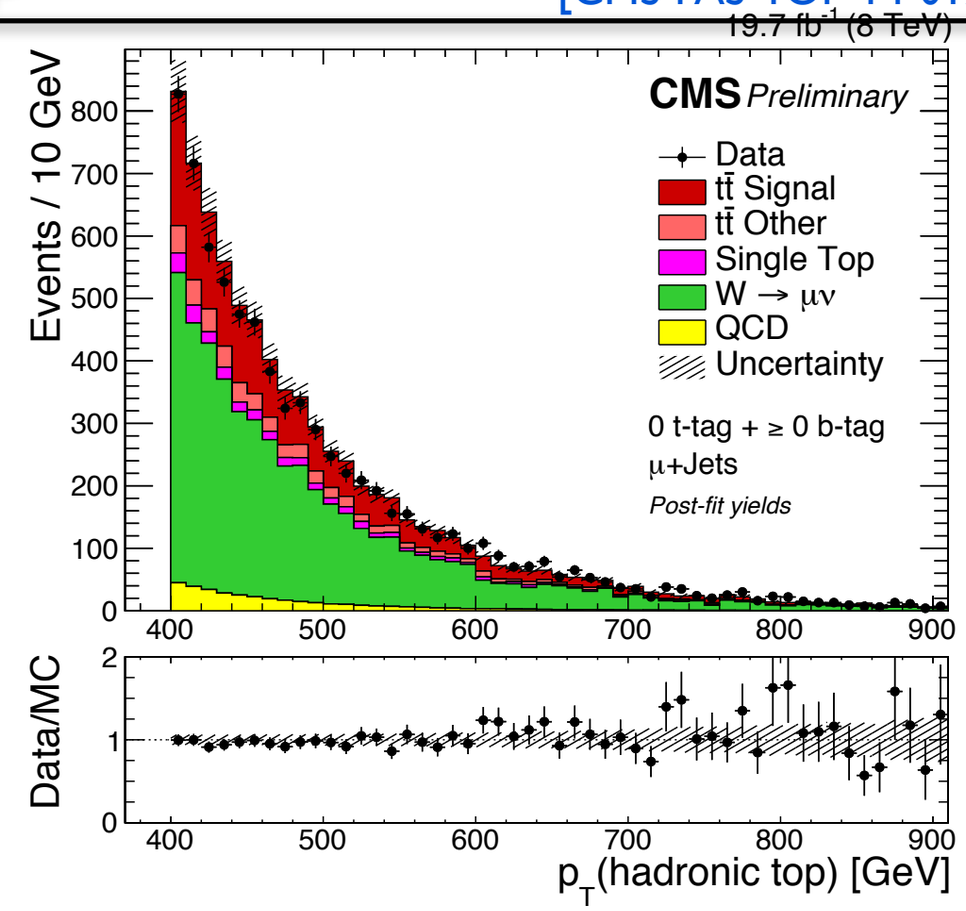
measurements with boosted top

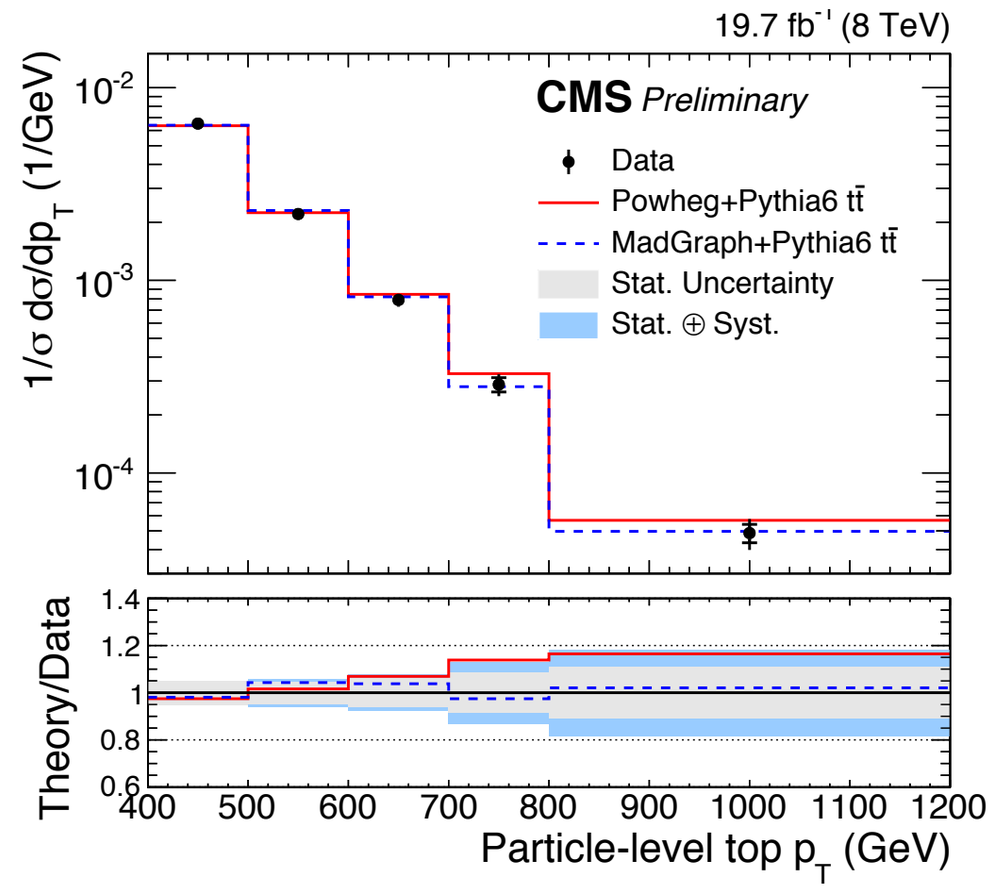
[CMS-PAS-TOP-14-012]

first cross-section measurement of boosted top quarks:

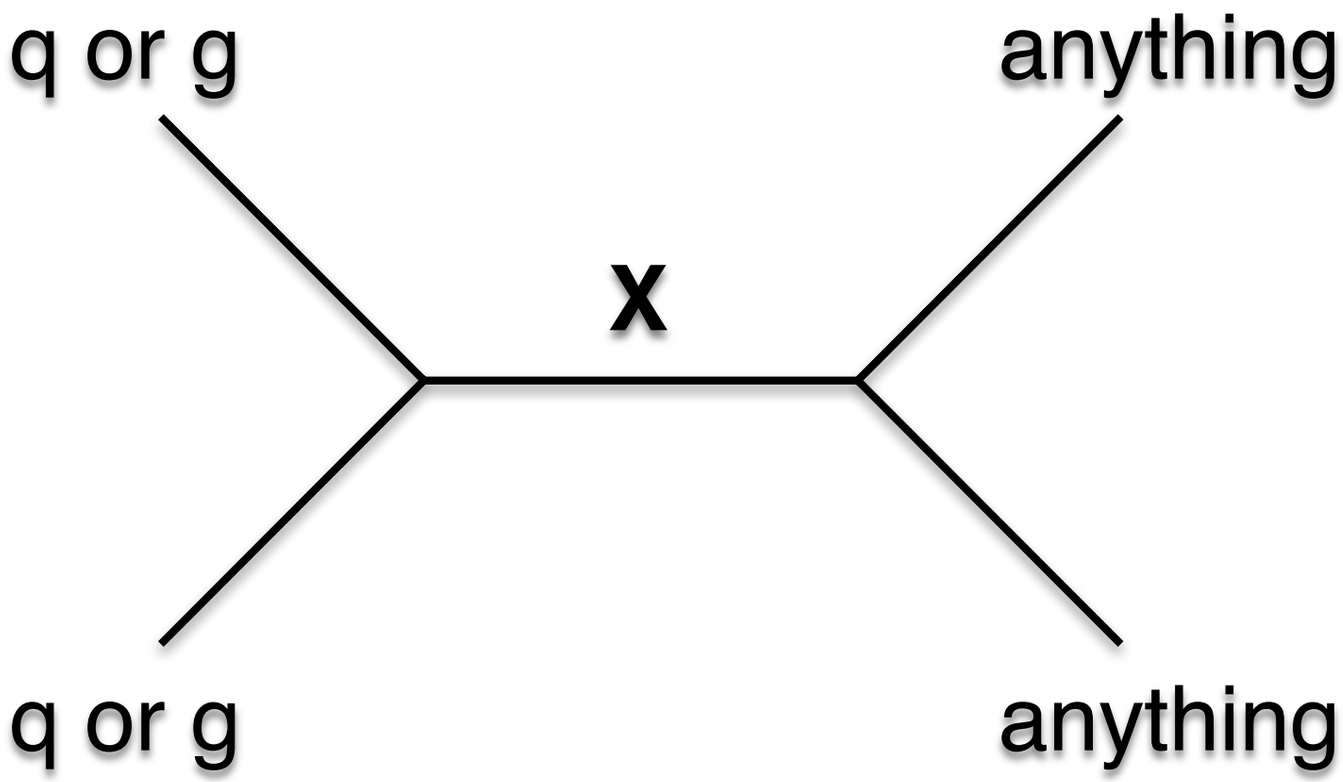
- semi-leptonic top quark events
- three categories:
  - 0 top-tag 0 b-tag (background)
  - 1 top-tag 0 b-tag
  - 1 top-tag 1 b-tag (signal)

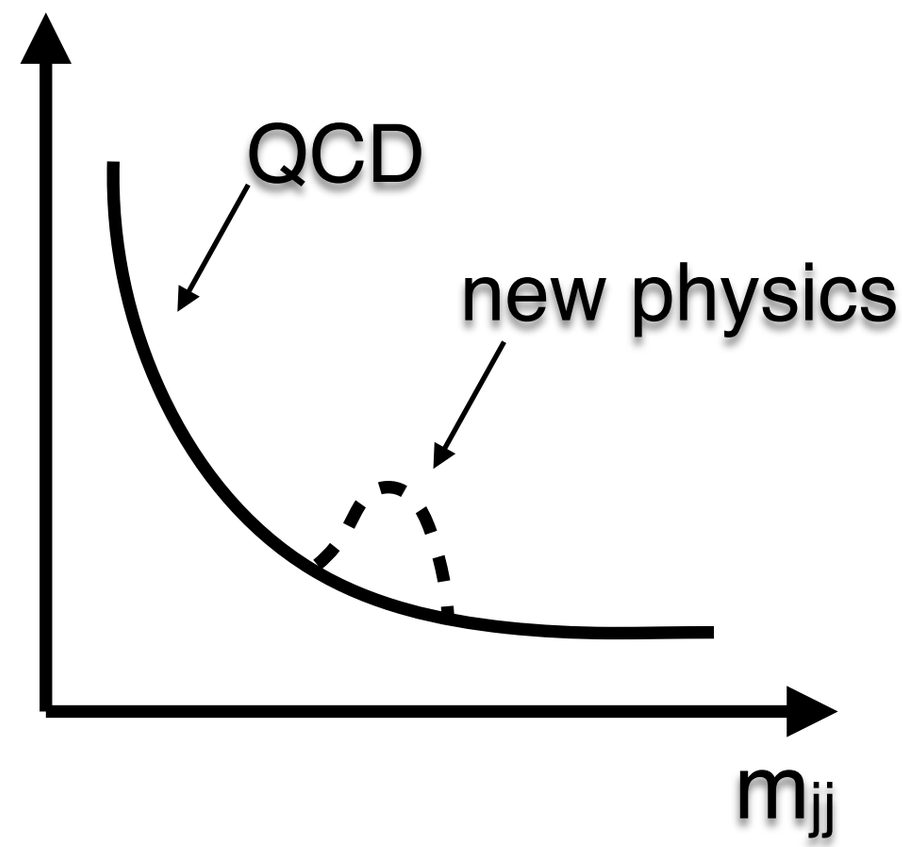
→boosted top algorithms useable in precision measurements





search for exotic resonances



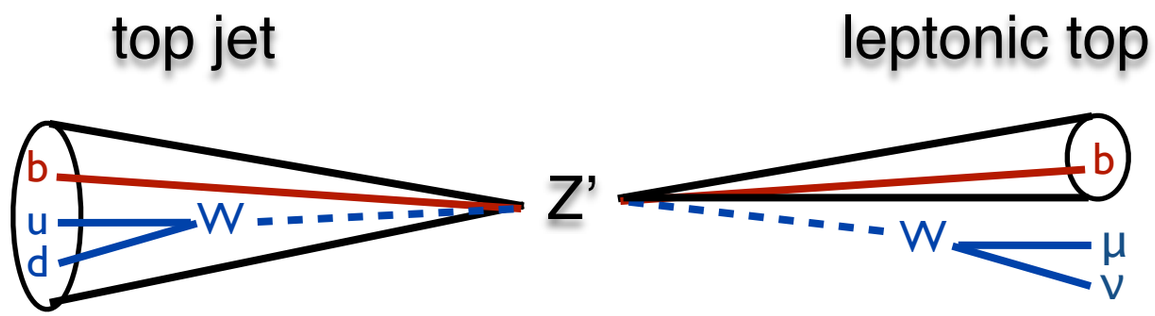


appear in many extensions of the standard model

tt resonances: semi-leptonic

[CMS-PAS-B2G-15-002]

- top tagging
- subjet b-tagging



- b-tagging
- **lepton isolation**

lepton isolation:

- mini-isolation:

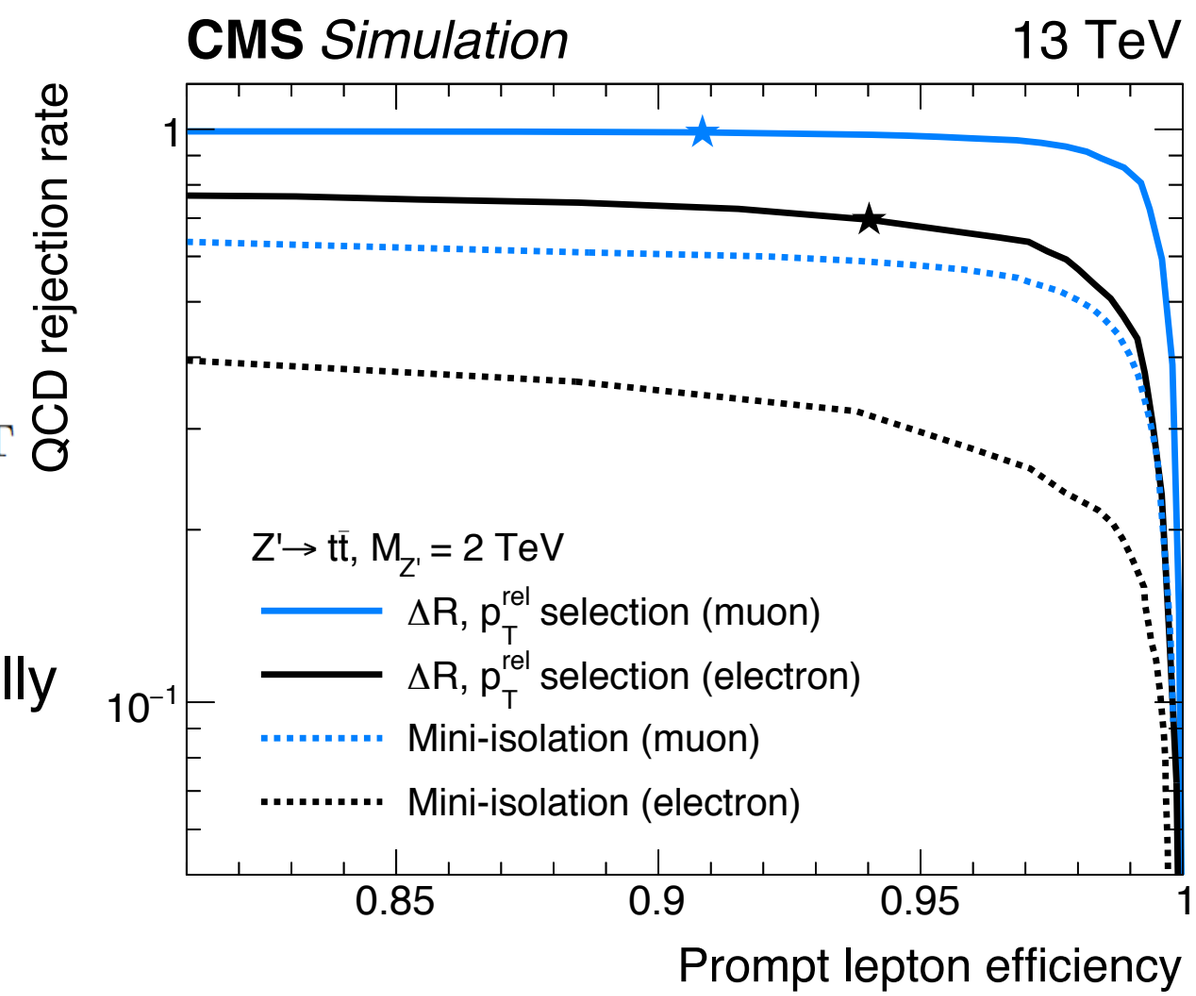
$$I^{\ell}_{\mathrm{mini}} = \sum_{\mathrm{tracks}} p_{\mathrm{T}}^{\mathrm{track}} \,, \quad \Delta R(\ell, \mathrm{track}) < K_{\mathrm{T}}/p^{\ell}_{\mathrm{T}}$$

$I^{\ell}_{\mathrm{mini}}/p^{\ell}_{\mathrm{T}} <$ desired value

chosen empirically

- 2D isolation:

$$\Delta R(\ell, j) > 0.4 \text{ or } p_T^{\mathrm{rel}}(\ell, j) > 20\,\mathrm{GeV}$$

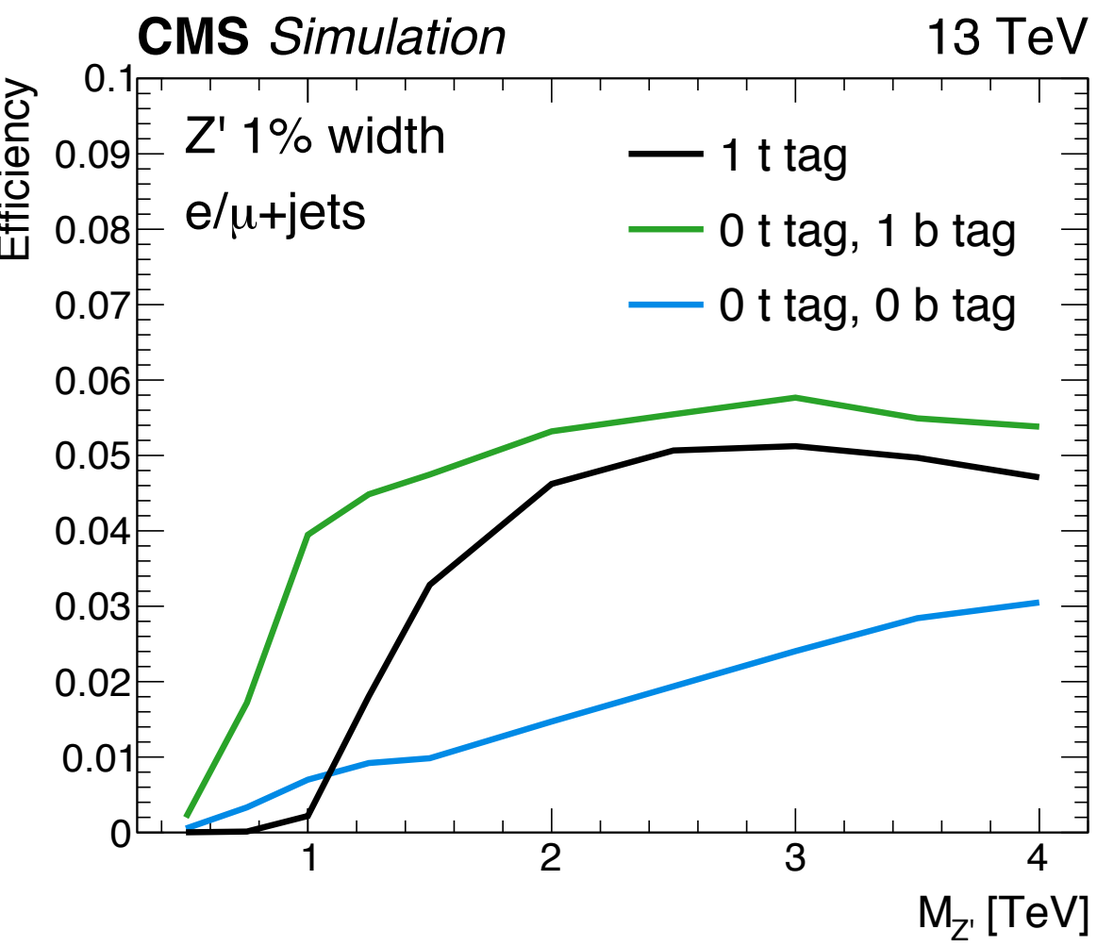


tt resonances

[CMS-PAS-B2G-15-002]

event categorisation:

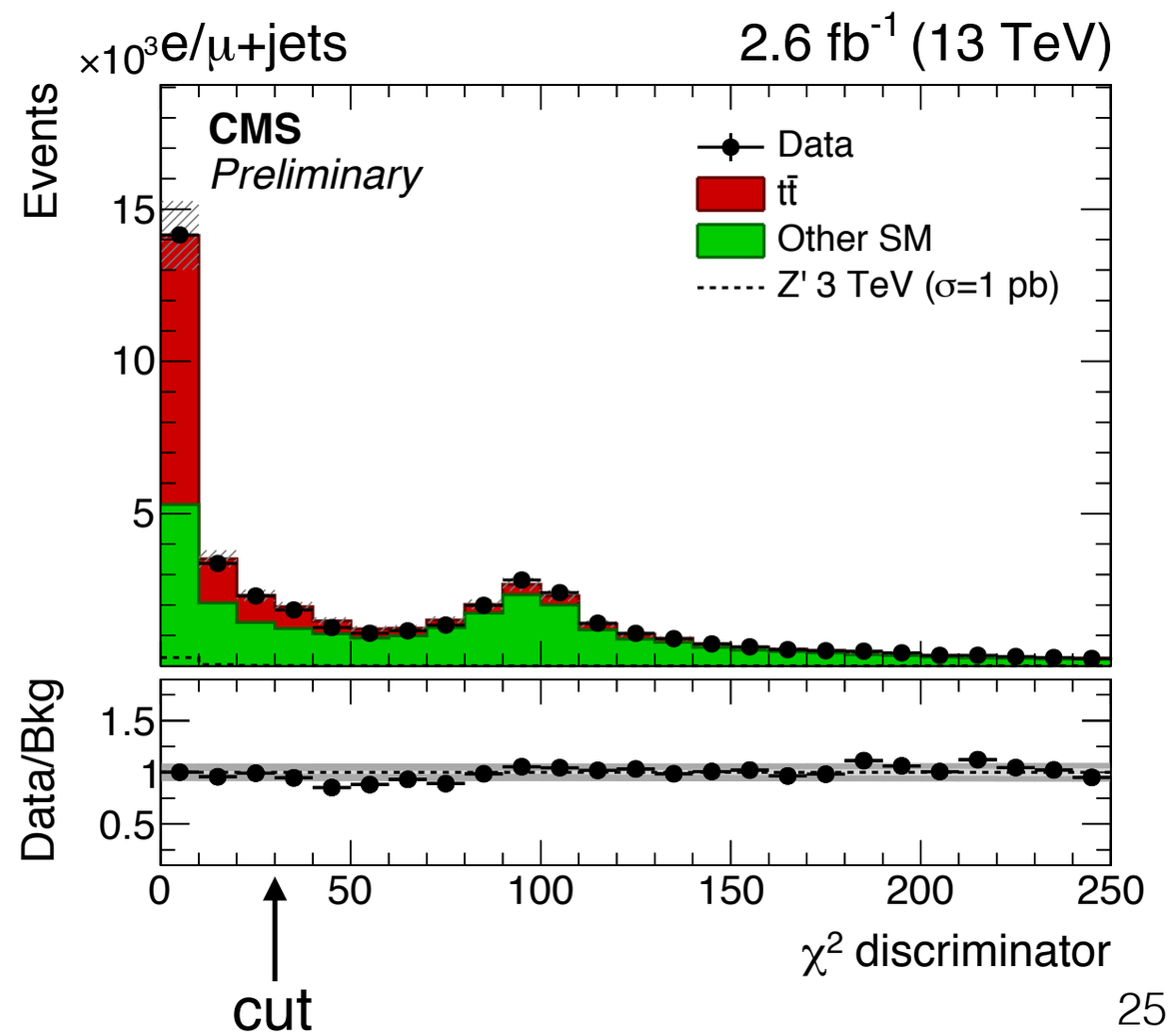
- t-tagging, b-tagging



event reconstruction:

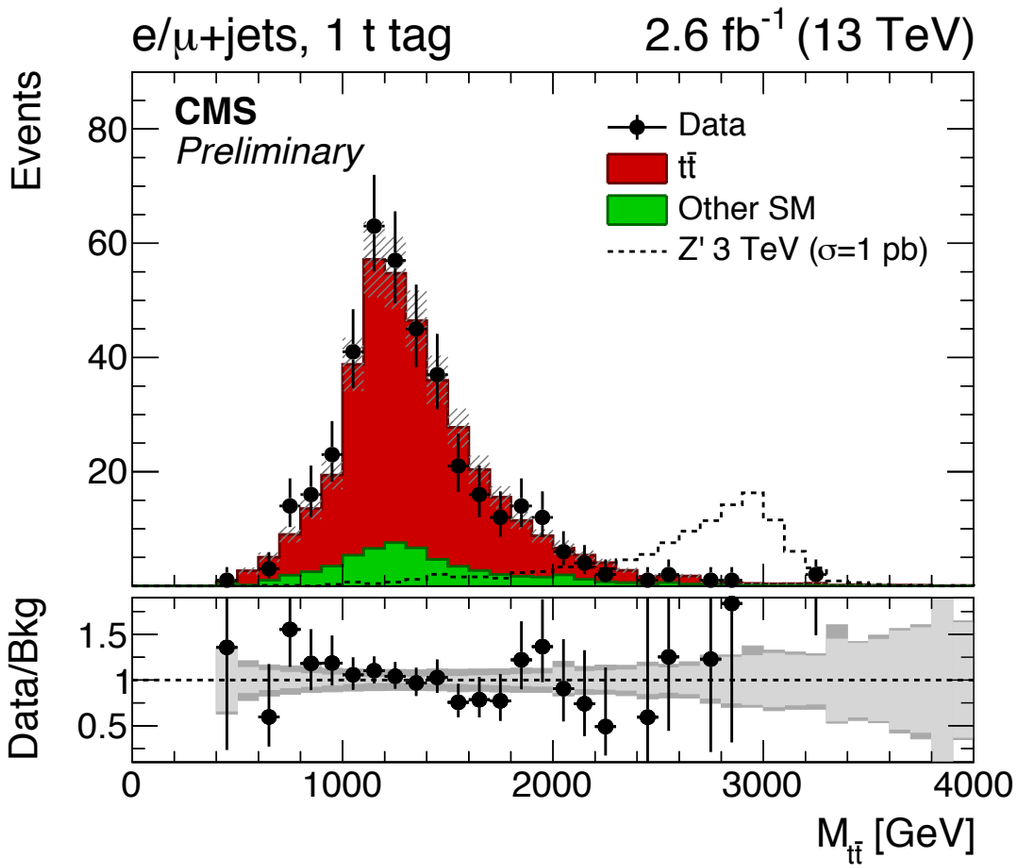
- chi² discriminator built from various hypotheses

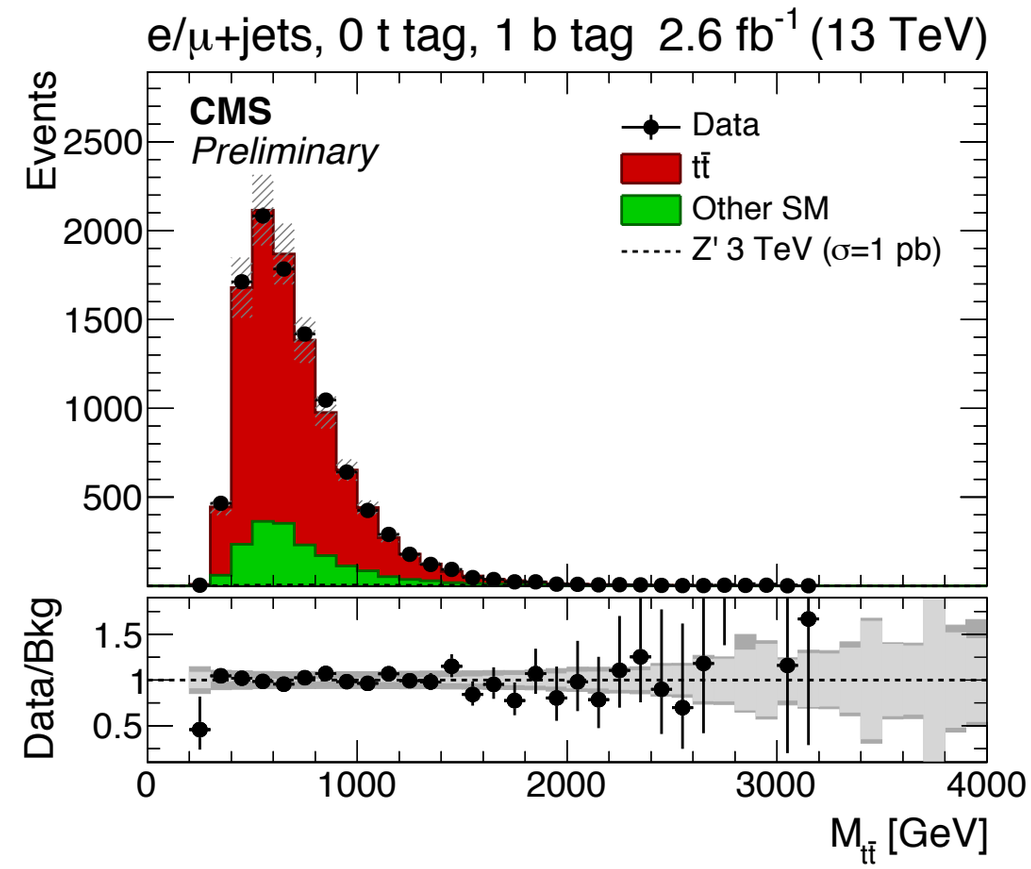
$$\chi^2 = \left(\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}}\right)^2 + \left(\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}}\right)^2$$

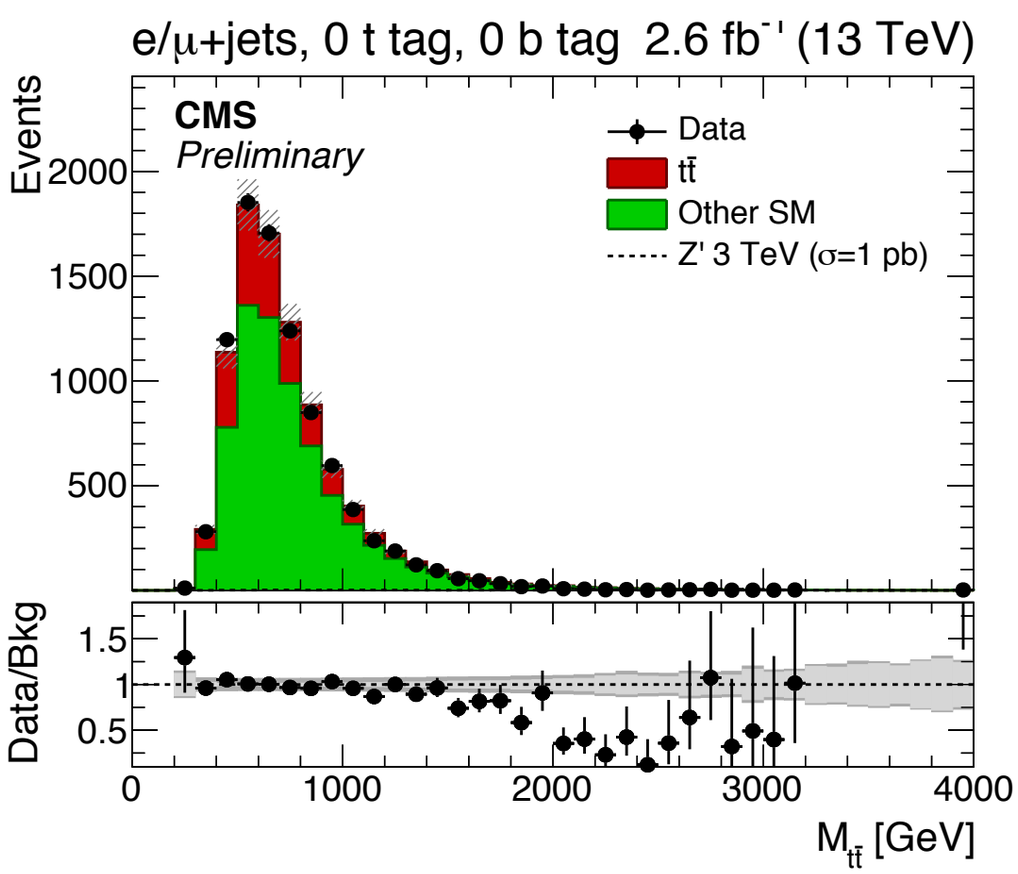


tt resonances

[CMS-PAS-B2G-15-002]





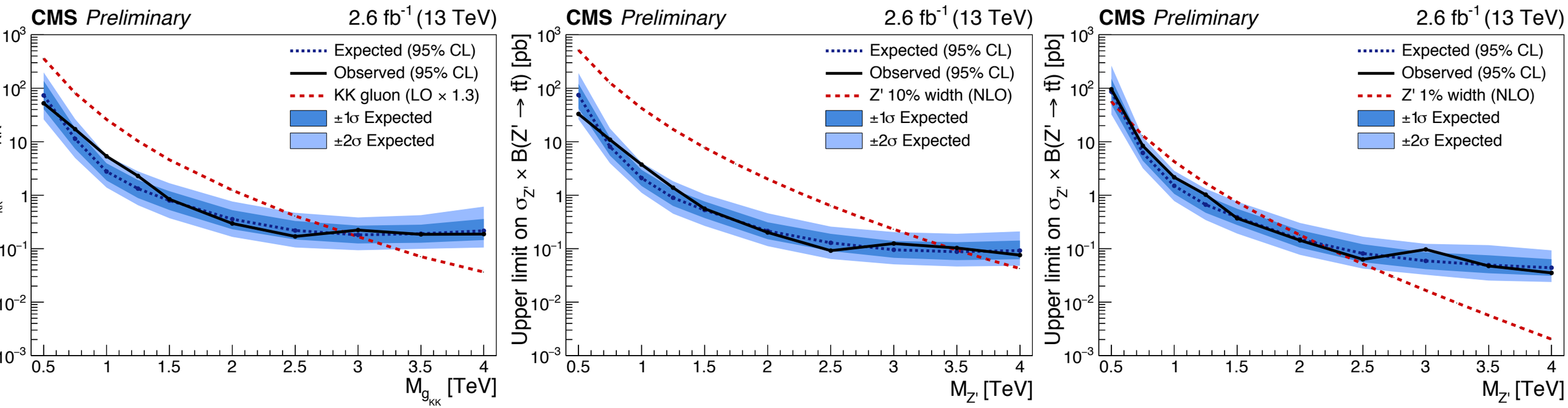


M_{tt} distributions

- background shapes from simulation (not possible to derive tt background from data)
- likelihood fit, free parameters: three background x-sections, t-tagging scale factor

tt resonances: semi-leptonic

[CMS-PAS-B2G-15-002]

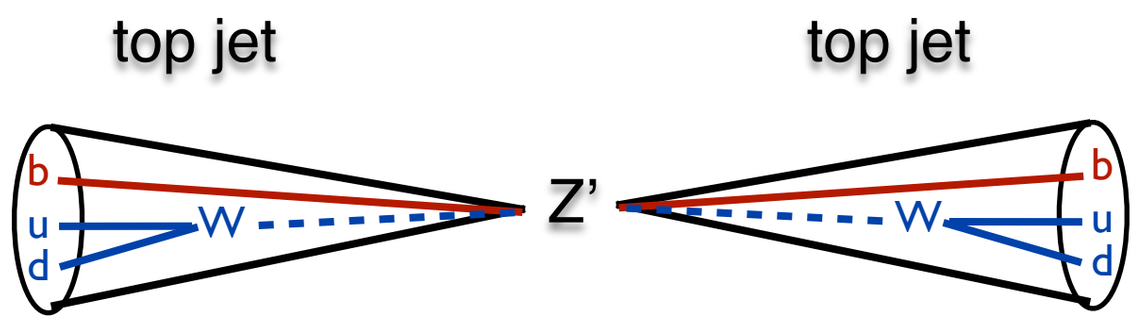


signal	excluded mass regions [TeV] μ + jets observed (expected)	e + jets observed (expected)	combination observed (expected)	8 TeV combination
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)	2.4 (2.4)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)	2.9 (2.8)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)	
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)	2.8 (2.7)

tt resonances: hadronic

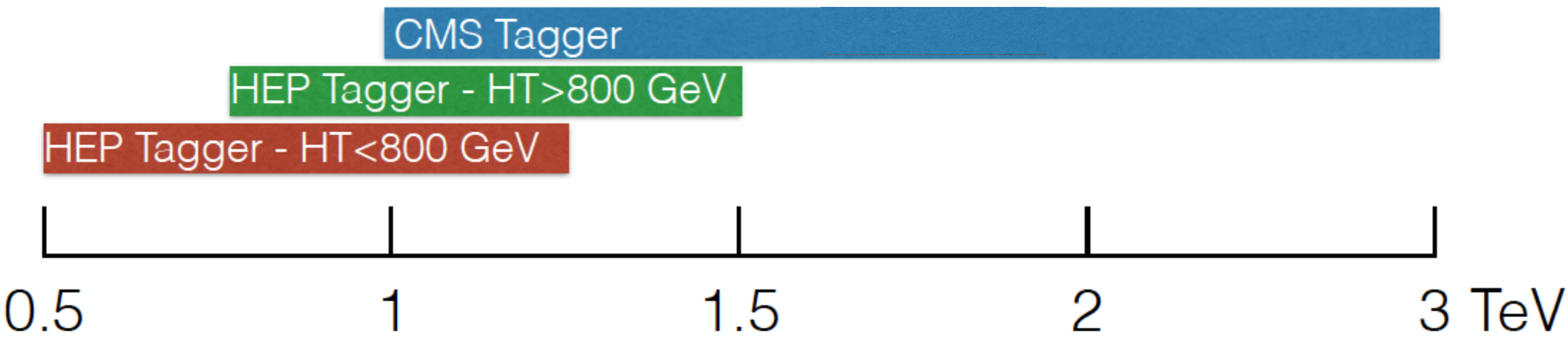
[Phys Rev D 93 (2015) 012001]

- top tagging
- subjet b-tagging



- 13 TeV analysis not yet ready

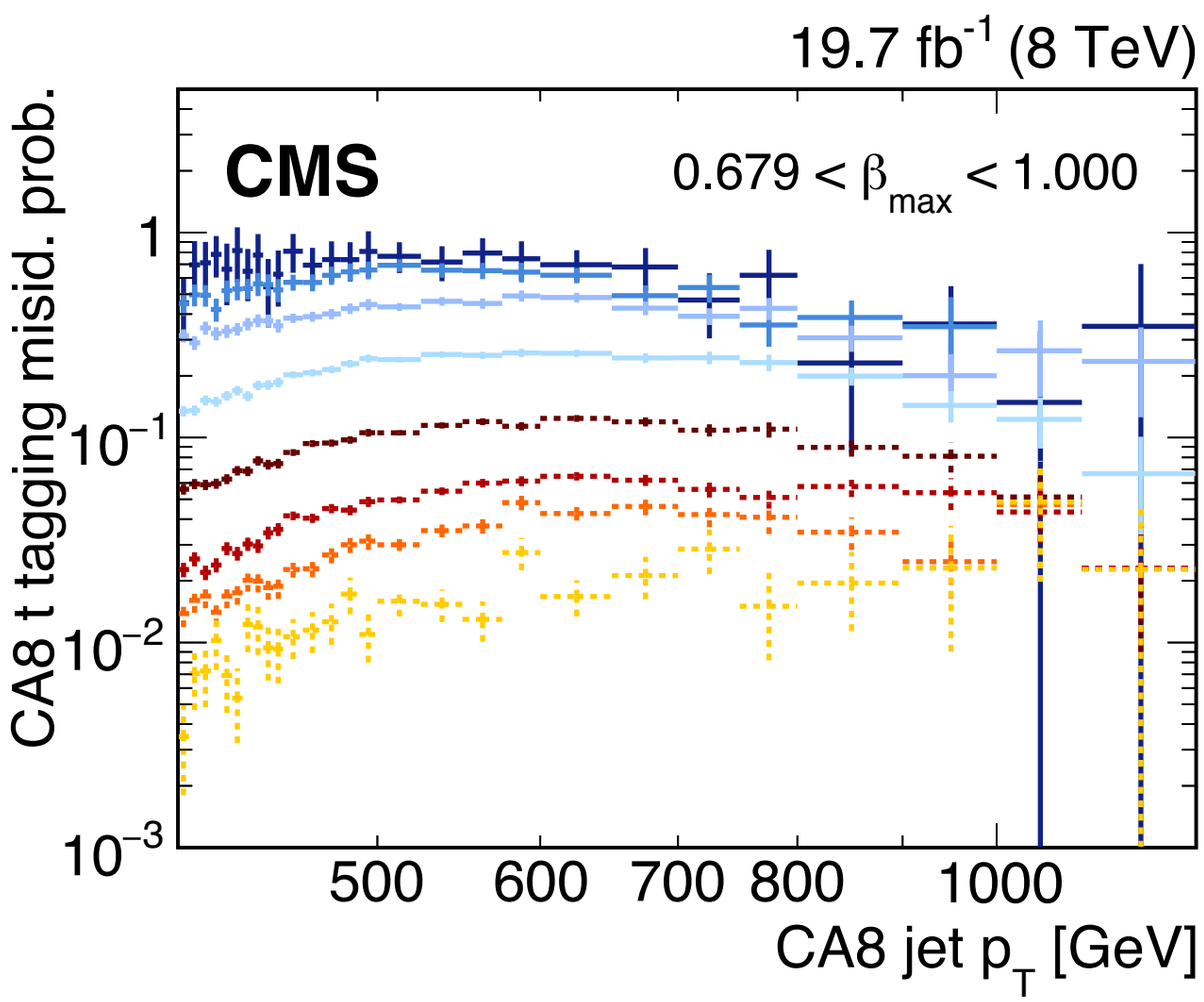
- 8 TeV used CA jets and different top-tagging approaches
  (CA8 CMSTopTagger and CA15 HEPTopTagger)

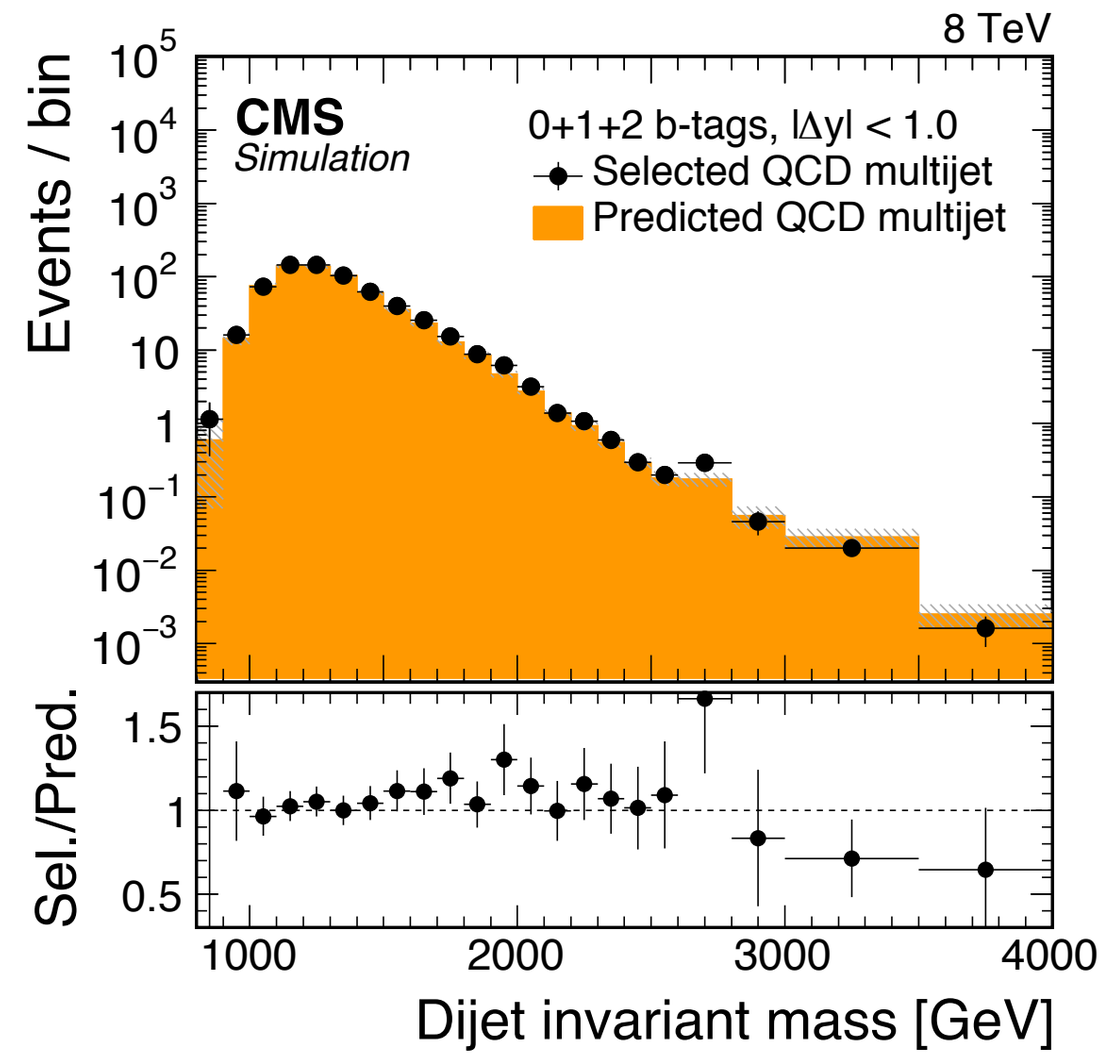


tt resonances: hadronic background estimation

[Phys Rev D 93, 012001]

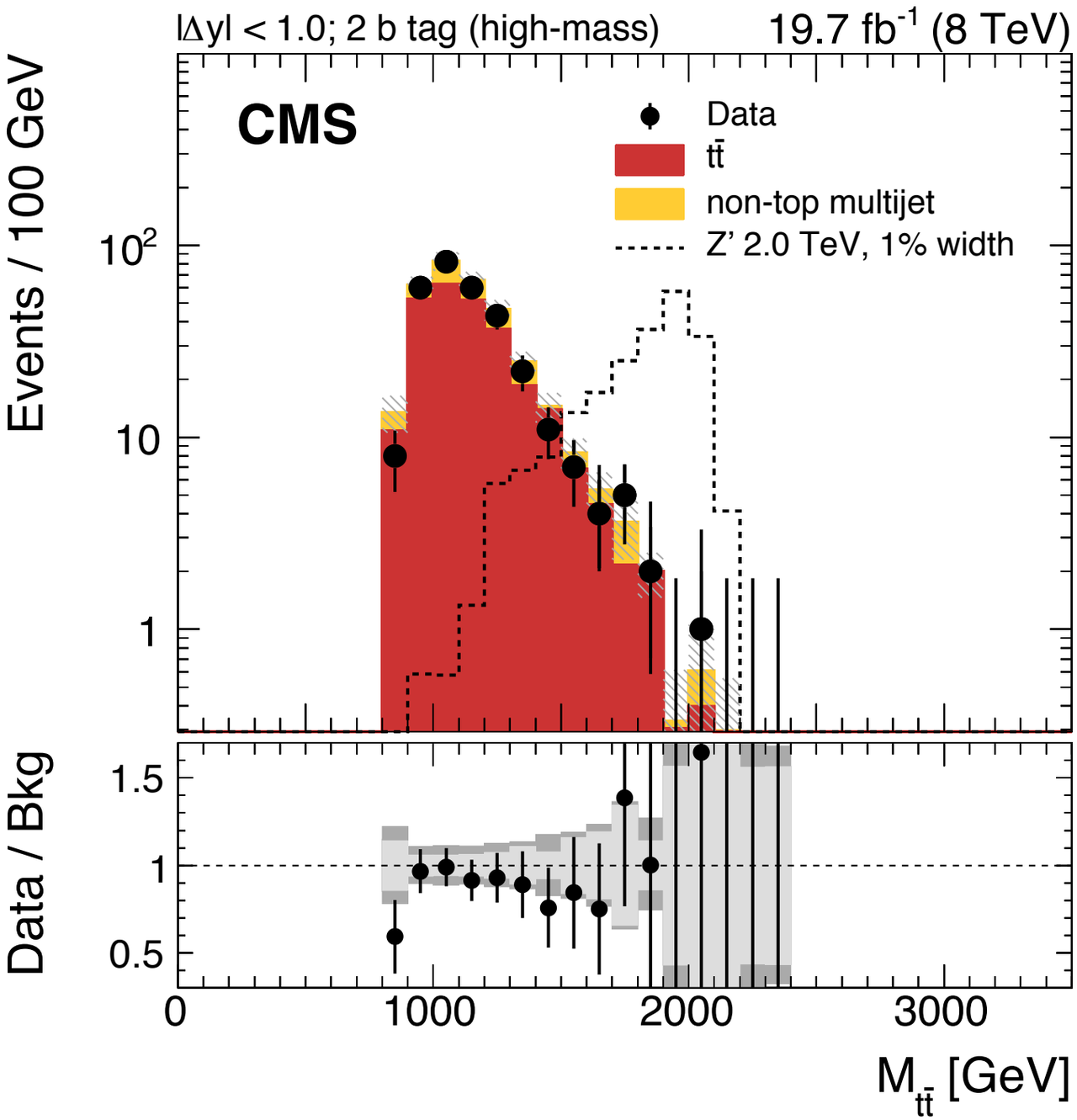
- invert substructure selection criterion on **one** jet
  →QCD enriched control region
- measure mistagging probability of **other** jet
- parameterised in bins of b-tag and τ_{32}
- apply mistag rate in single t-tagged sample to predict background in signal region

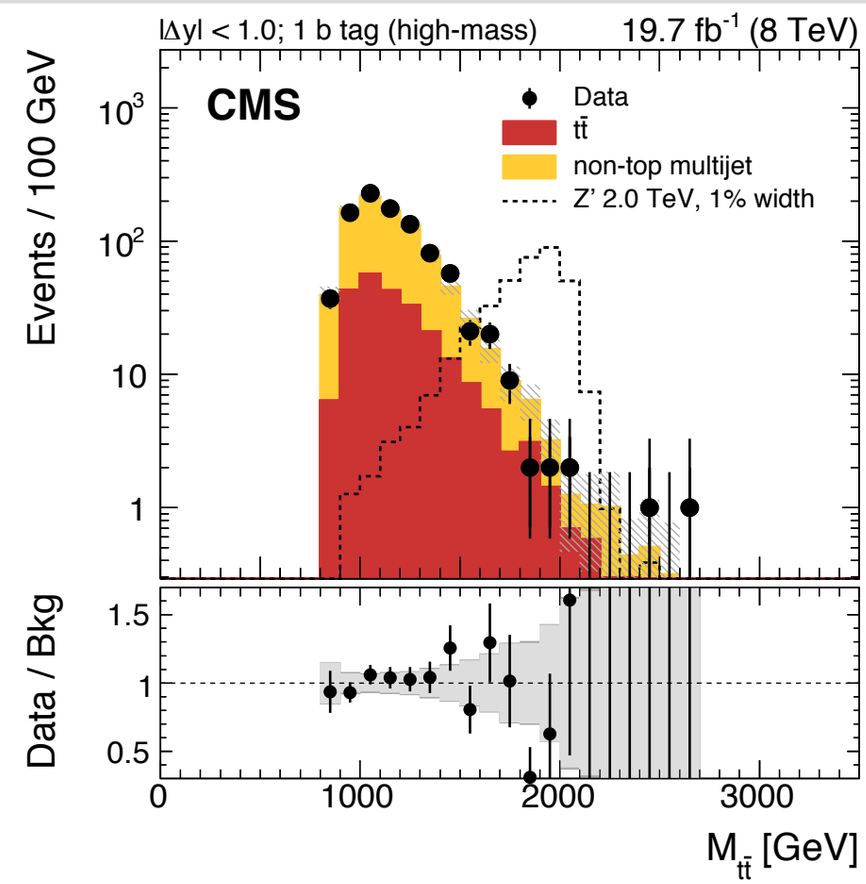


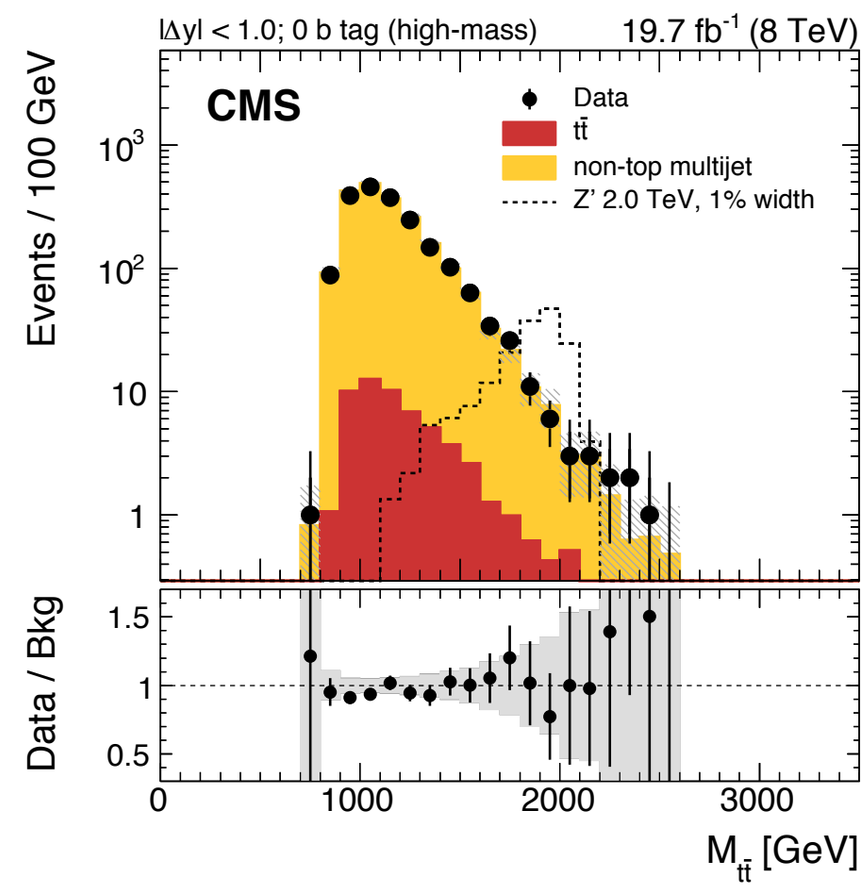


tt resonances: hadronic

[Phys Rev D 93, 012001]



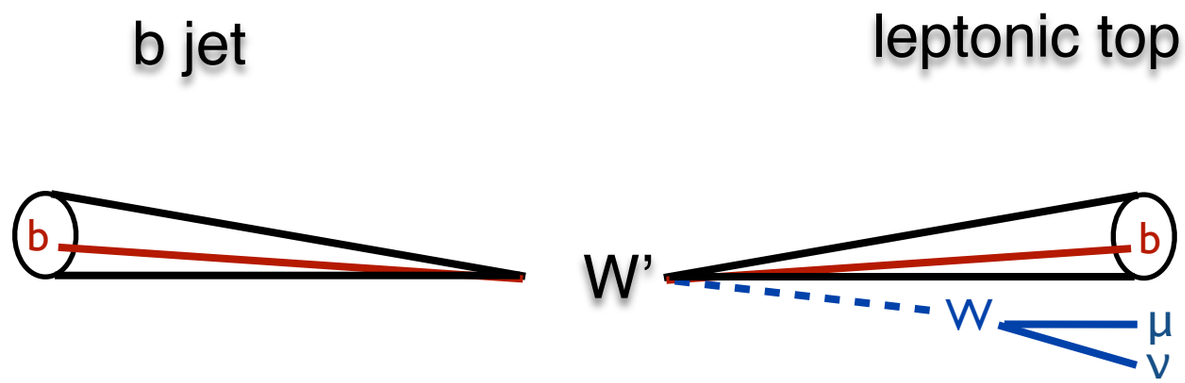




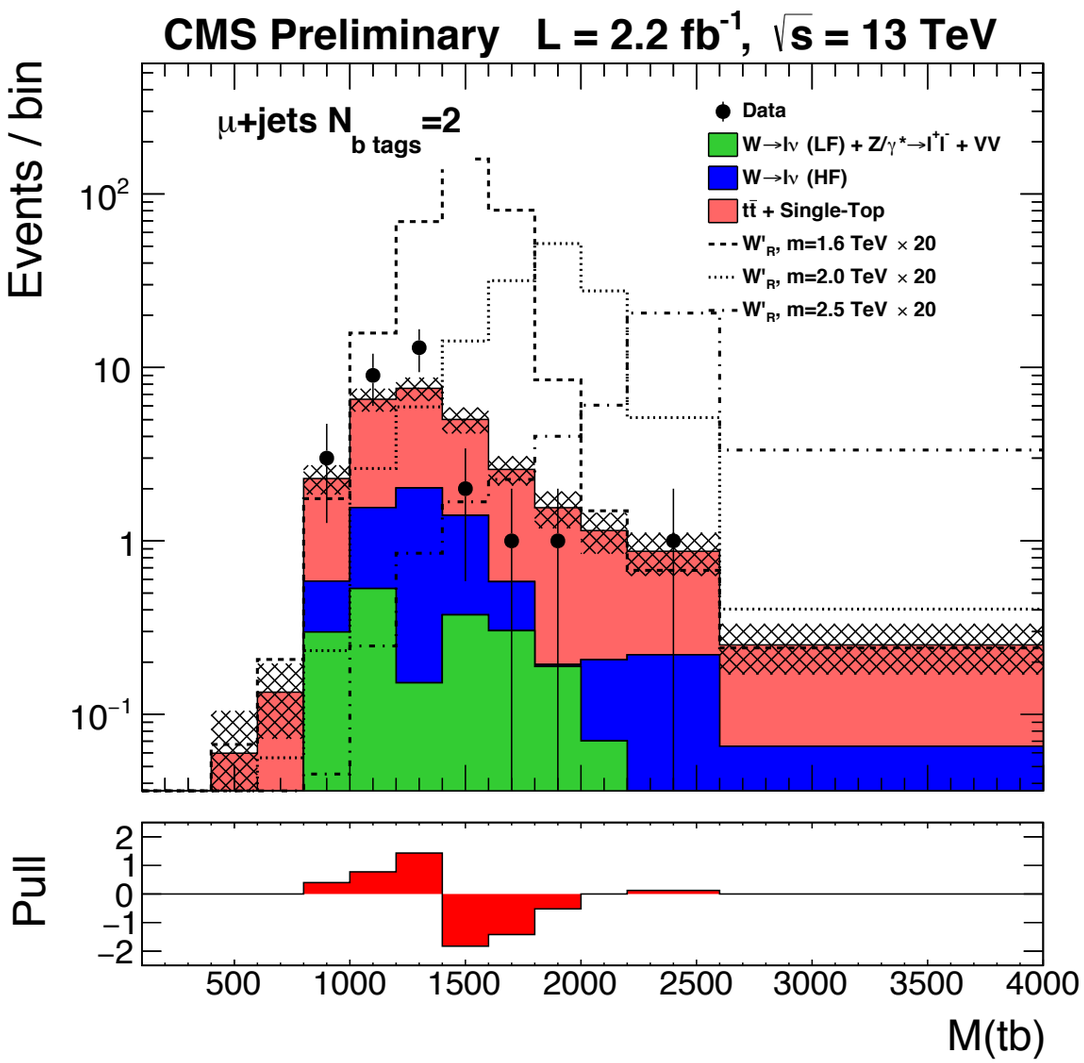
tb resonances: semi-leptonic

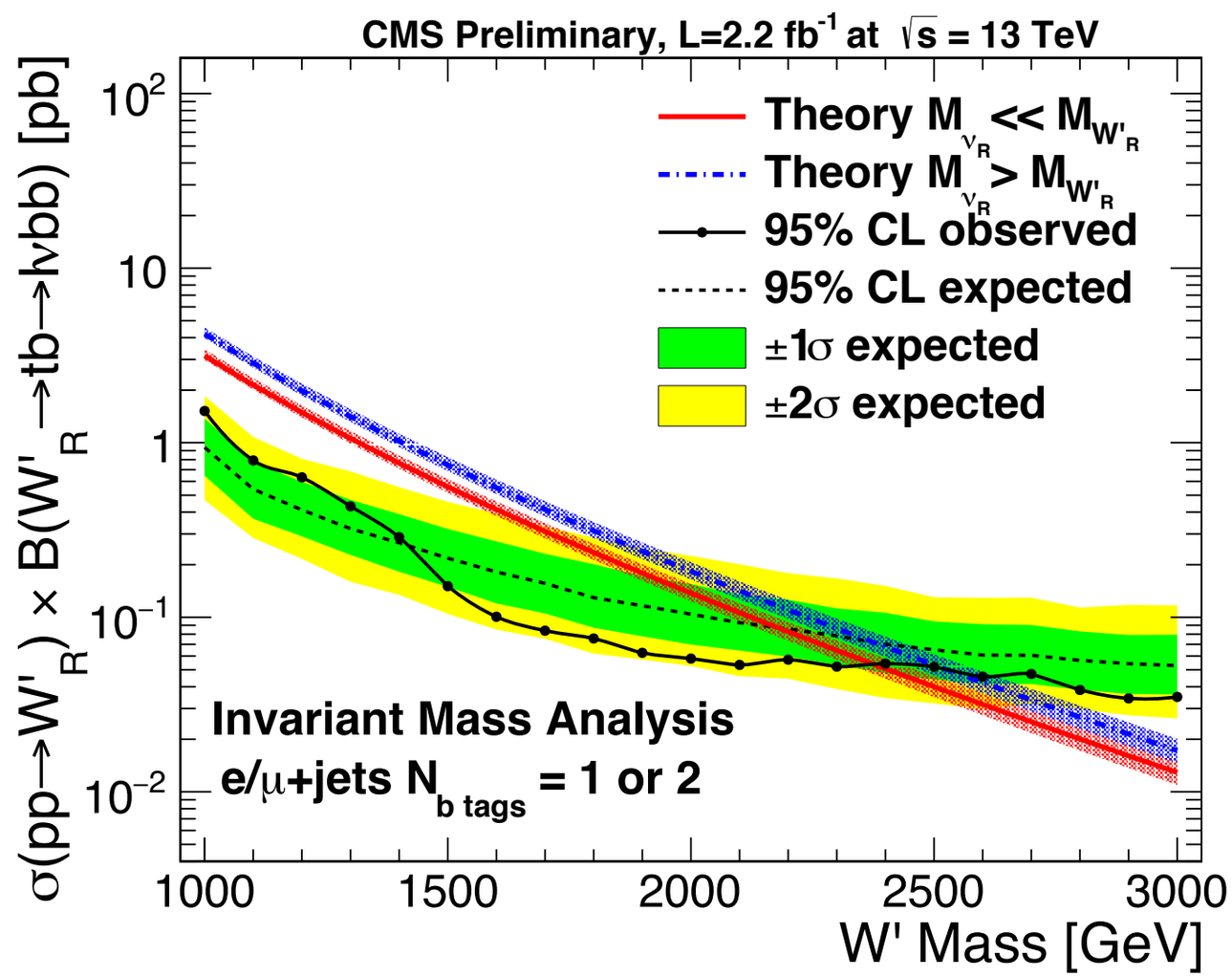
[CMS-PAS-B2G-15-004]

- b-tagging



- b-tagging
- missing energy
- lepton isolation





exceeds 8 TeV results already now

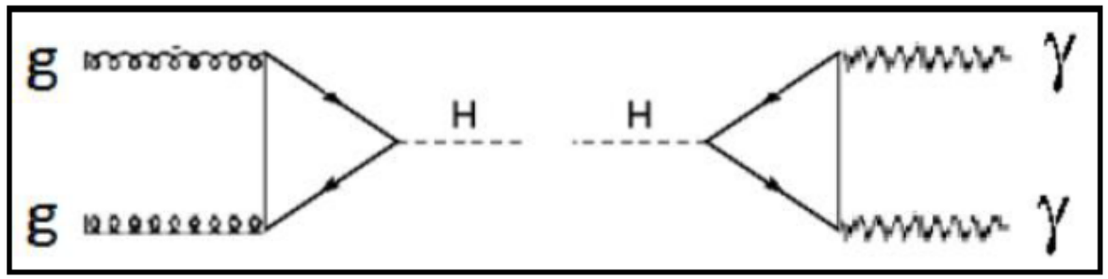
extra fermions

popular for many years:

- chiral fourth Fermion generation
- exact replication of three SM generations

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{pmatrix} t' \\ b' \end{pmatrix}_L$$

$$u_R, d_R, c_R, s_R, t_R, b_R, t'_R, b'_R$$

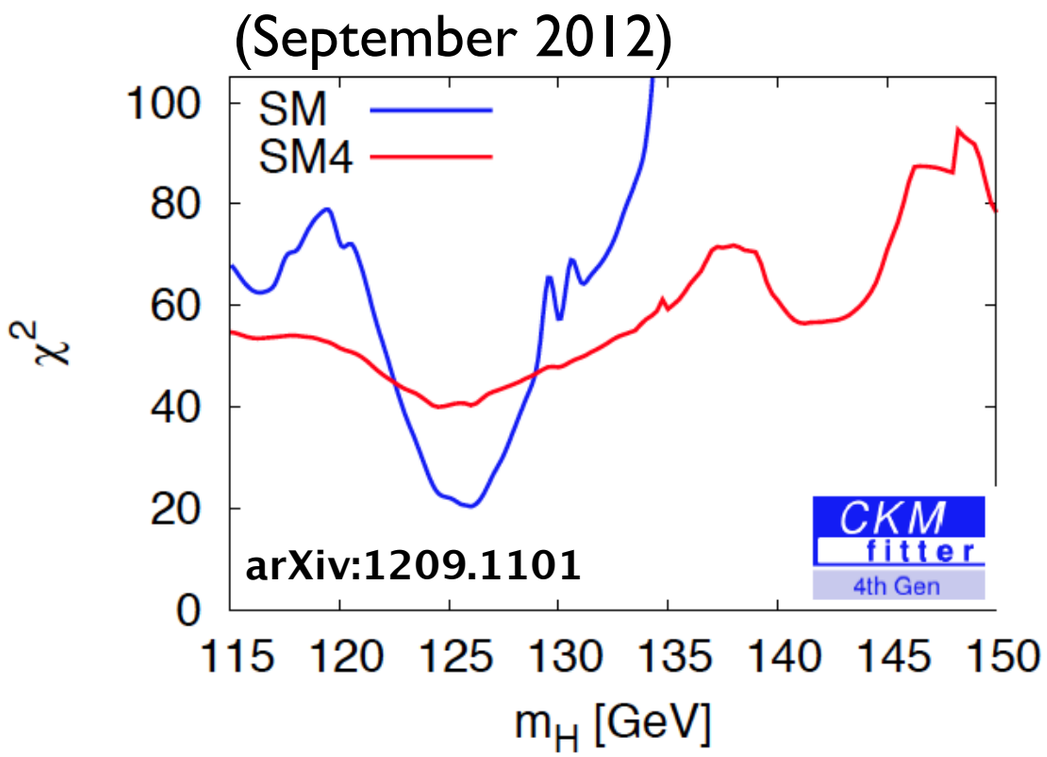


now ruled out!

- connection with Higgs through loops
- use CKMfitter for combined fit of SM parameters
- first thing after Higgs discovery...

➡ SM4 ruled out at 5.3σ

- small caveat: assumes minimal Higgs sector!



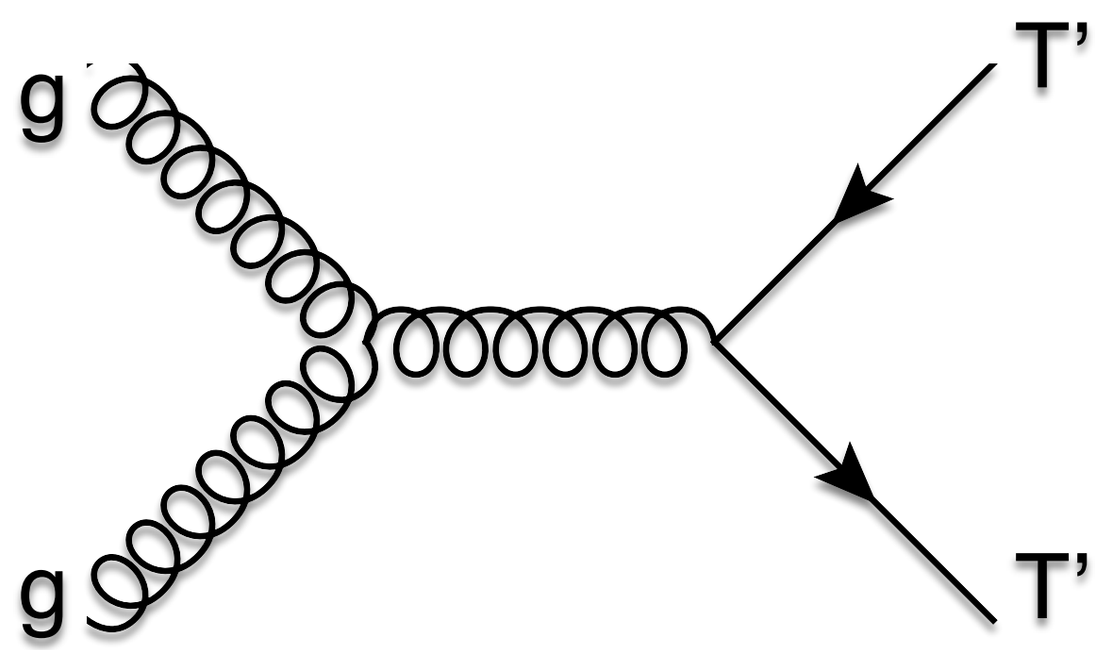
vector-like quarks

what are vector-like quarks:

- they are quarks: coloured, charged, spin 1/2 particles
- no difference between chiralities: they couple to left- and right- handed charged currents (in the same way)

➡ VL quarks can have mass terms without violating gauge invariance!

- not constrained through Higgs discovery
- new motivation through di-photon excess



vector-like quarks

[JHEP 08 (2015) 105]

Singlets

$$\mathbf{1}_{2/3} = T$$

$$\mathbf{1}_{-1/3} = B$$

Doublets

$$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$$

$$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$$

$$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$$

Triplets

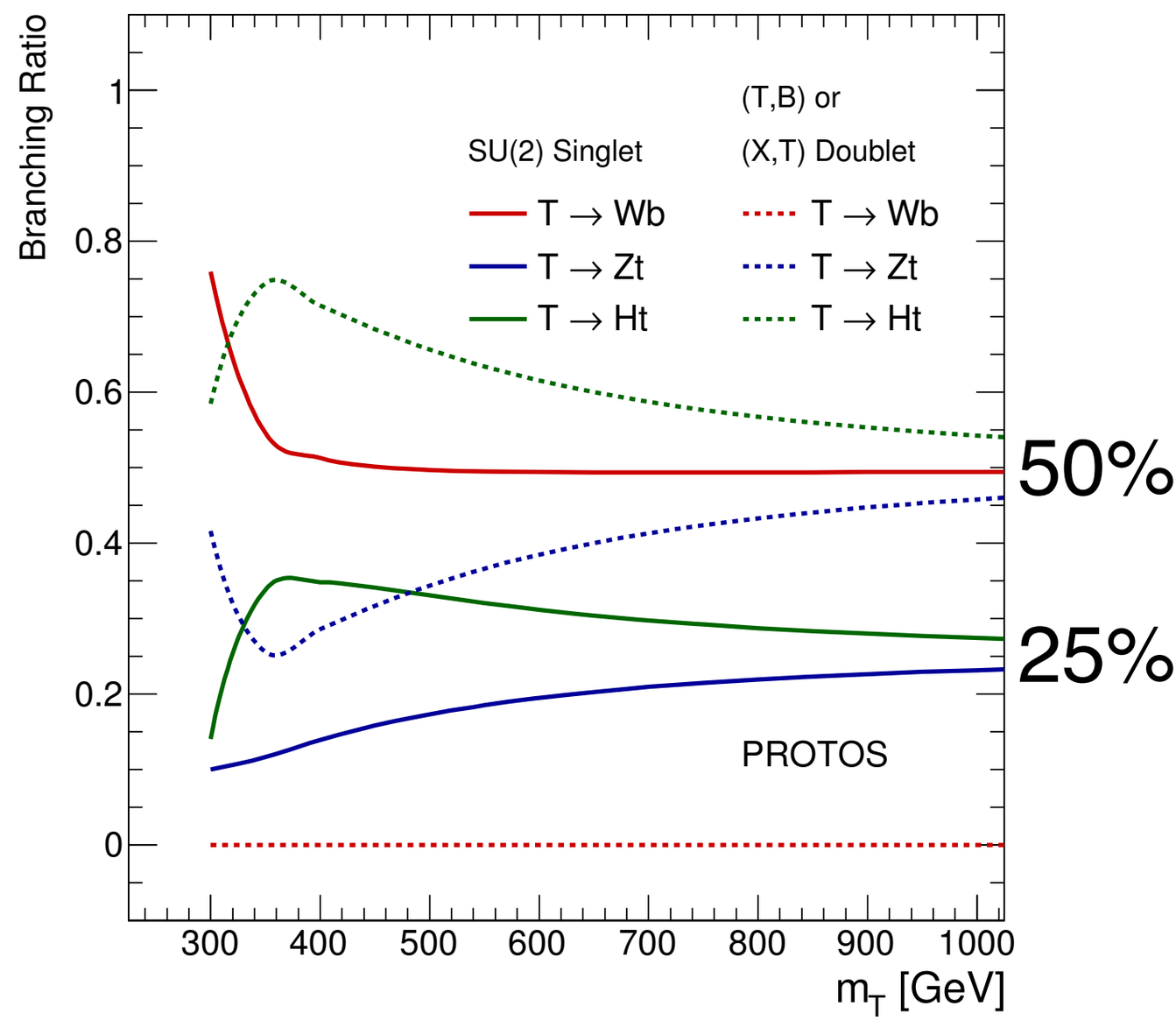
$$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$$

$$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$$

Notation:

$\text{Isospin}_{\text{Hypercharge}}$

$$\left.\begin{array}{l} T \to +2/3 \\ B \to -1/3 \\ X \to +5/3 \\ Y \to -4/3 \end{array}\right\} \text{Electric charge}$$

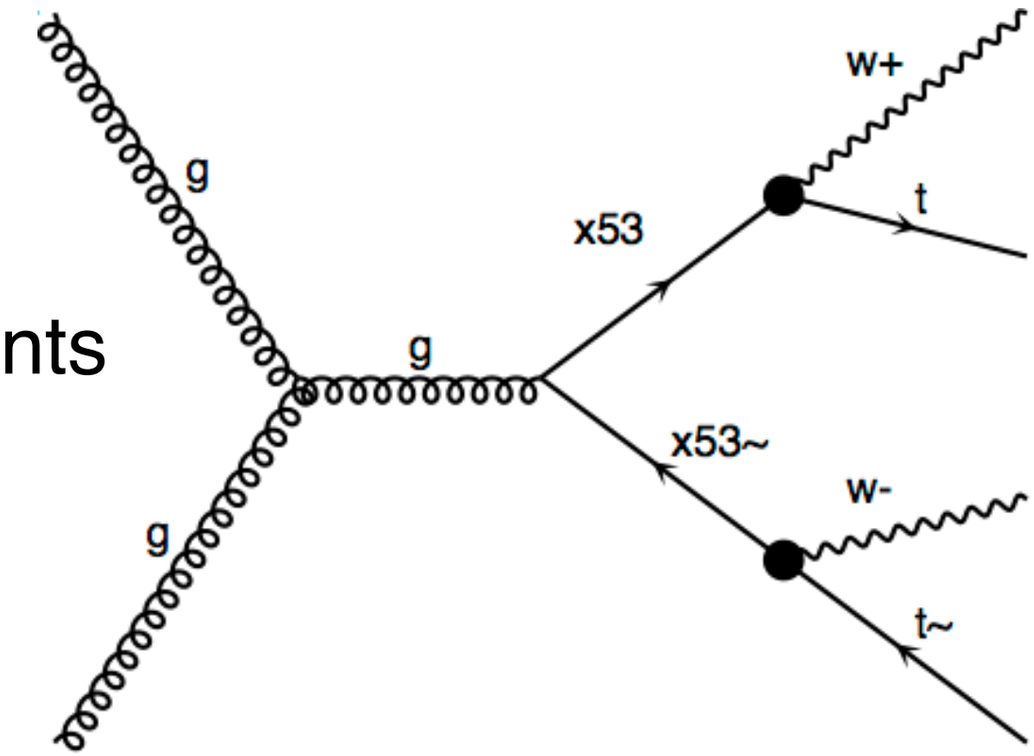


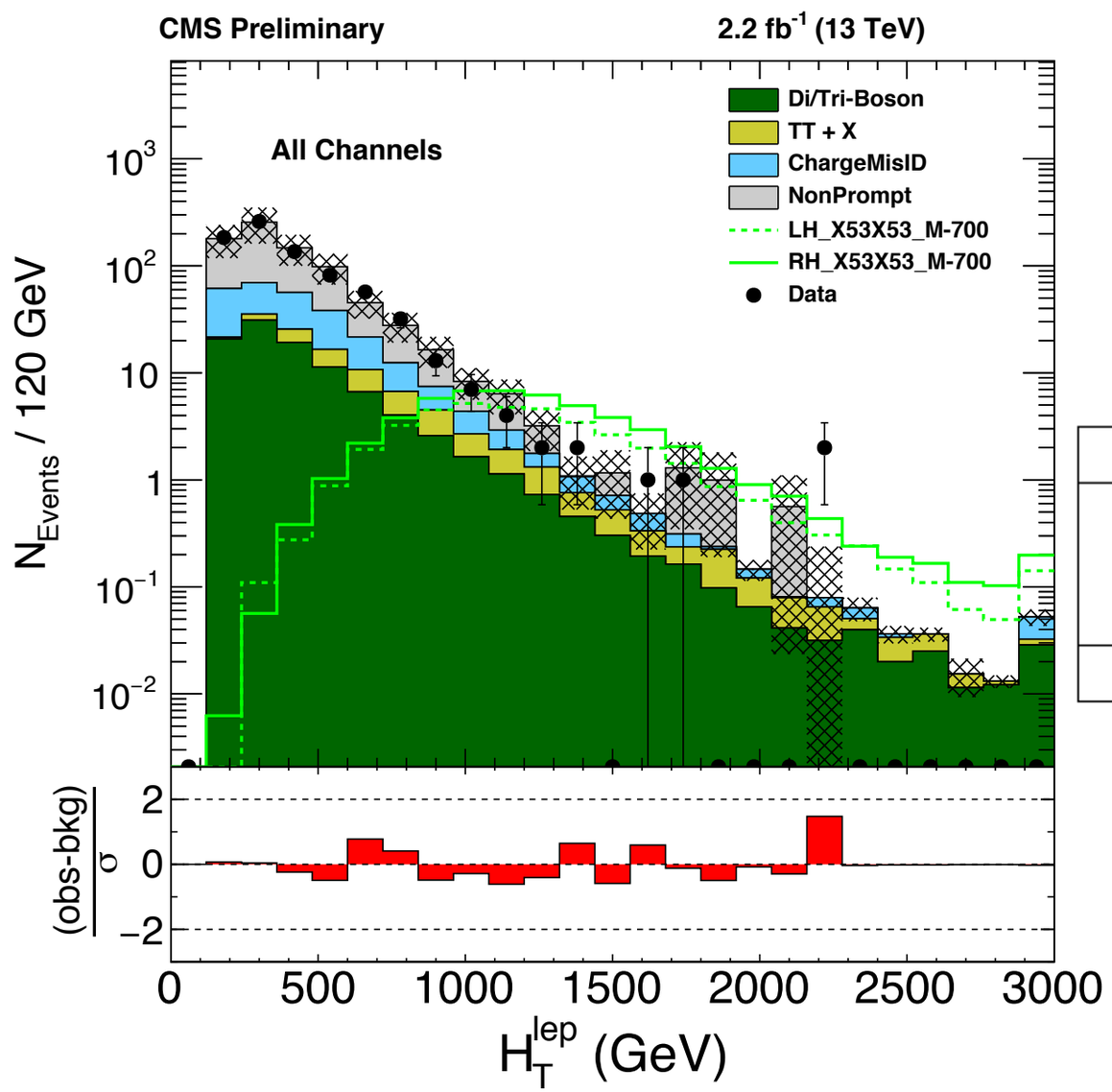
vector-like quarks: pair production

[CMS-PAS-B2G-15-006]

$X^{5/3}$ in same-sign di-lepton final state:

- first VLQ result at 13 TeV
- clean same-sign lepton selection
- backgrounds from opposite-sign events with charge mis-measurements





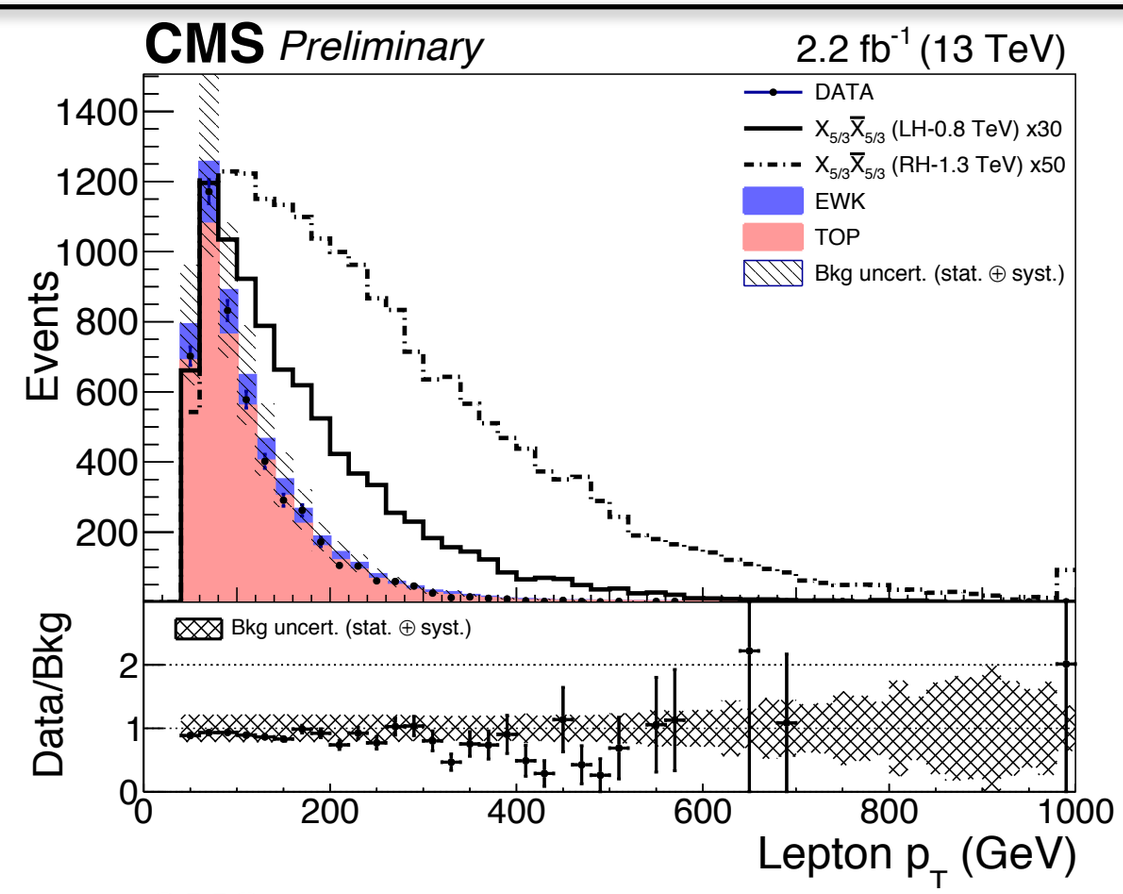
Channel	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	6.47 ± 2.02	4.38	7
Electron-Muon	8.72 ± 3.24	9.14	3
Di-muon	2.80 ± 1.70	3.55	1
All	17.98 ± 5.58	17.06	11

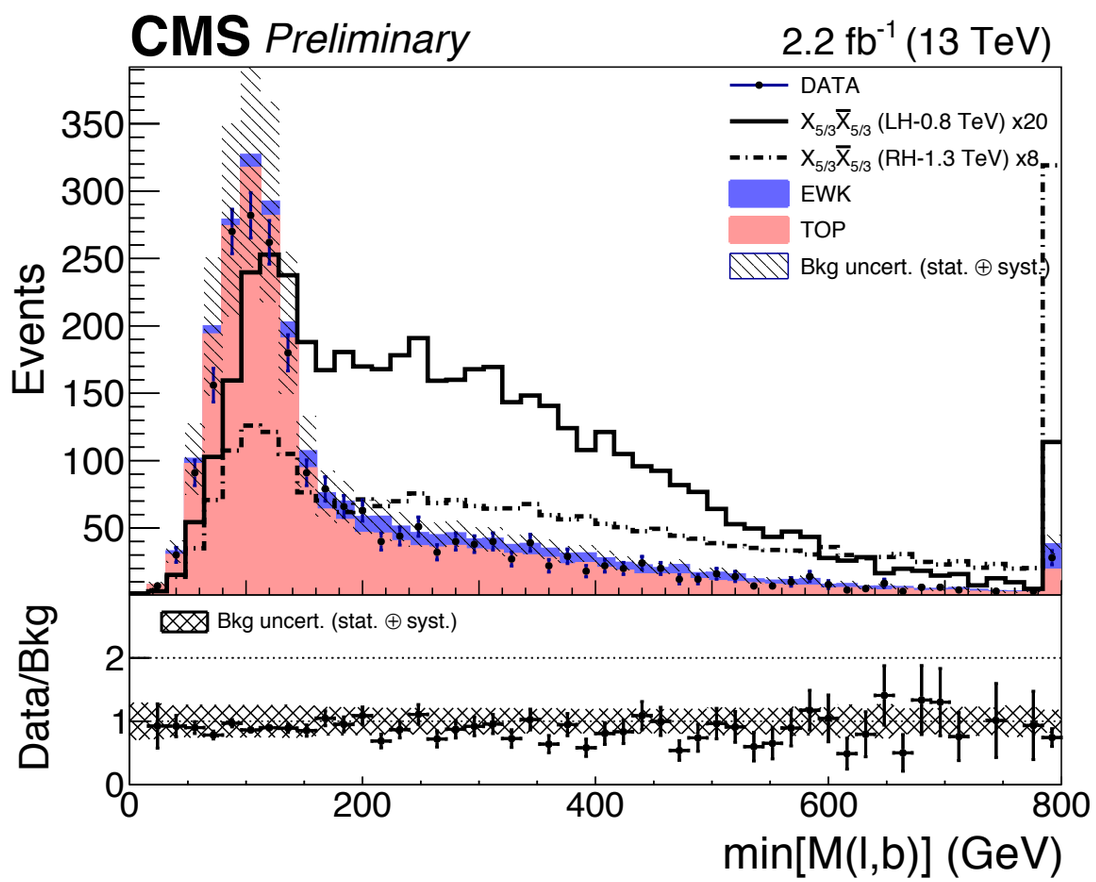
vector-like quarks: pair production

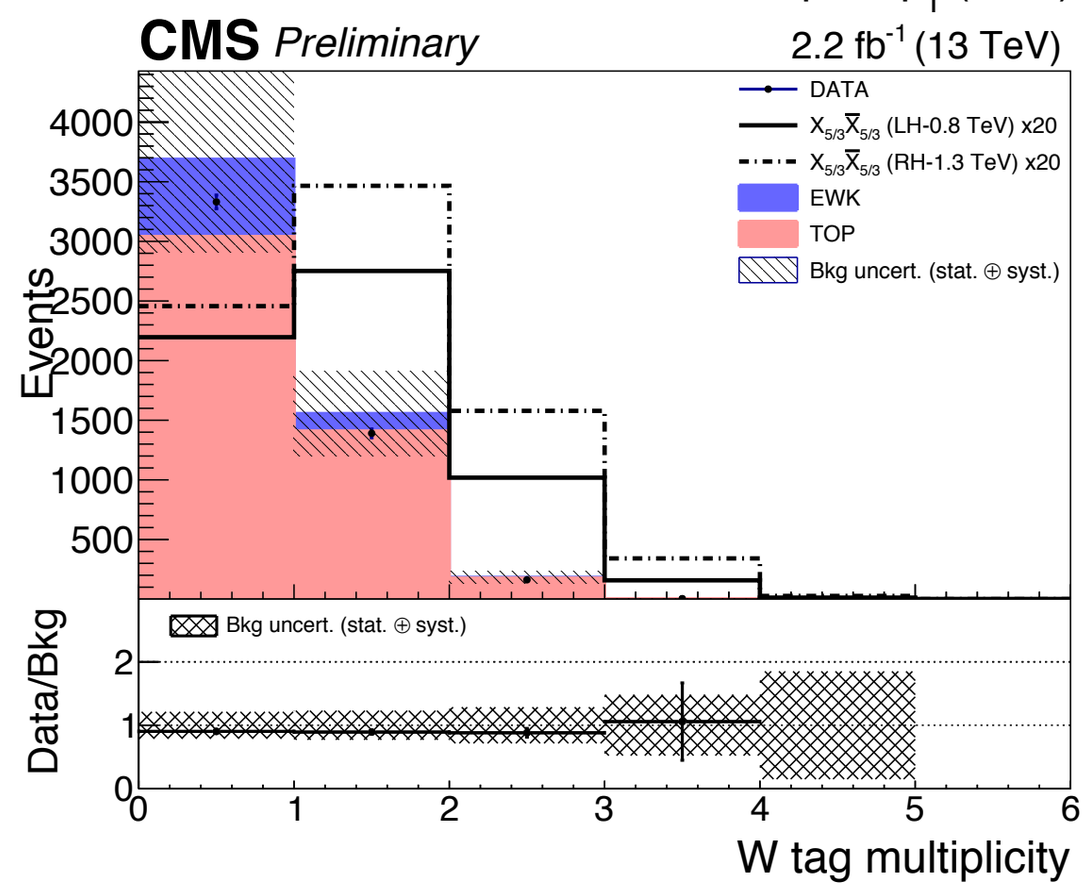
[CMS-PAS-B2G-15-006]

$X^{5/3}$ in lepton+jet final state:

- first VLQ result at 13 TeV
- high lepton/jet momentum
- many jets
- event categorisation based on W/b-tags



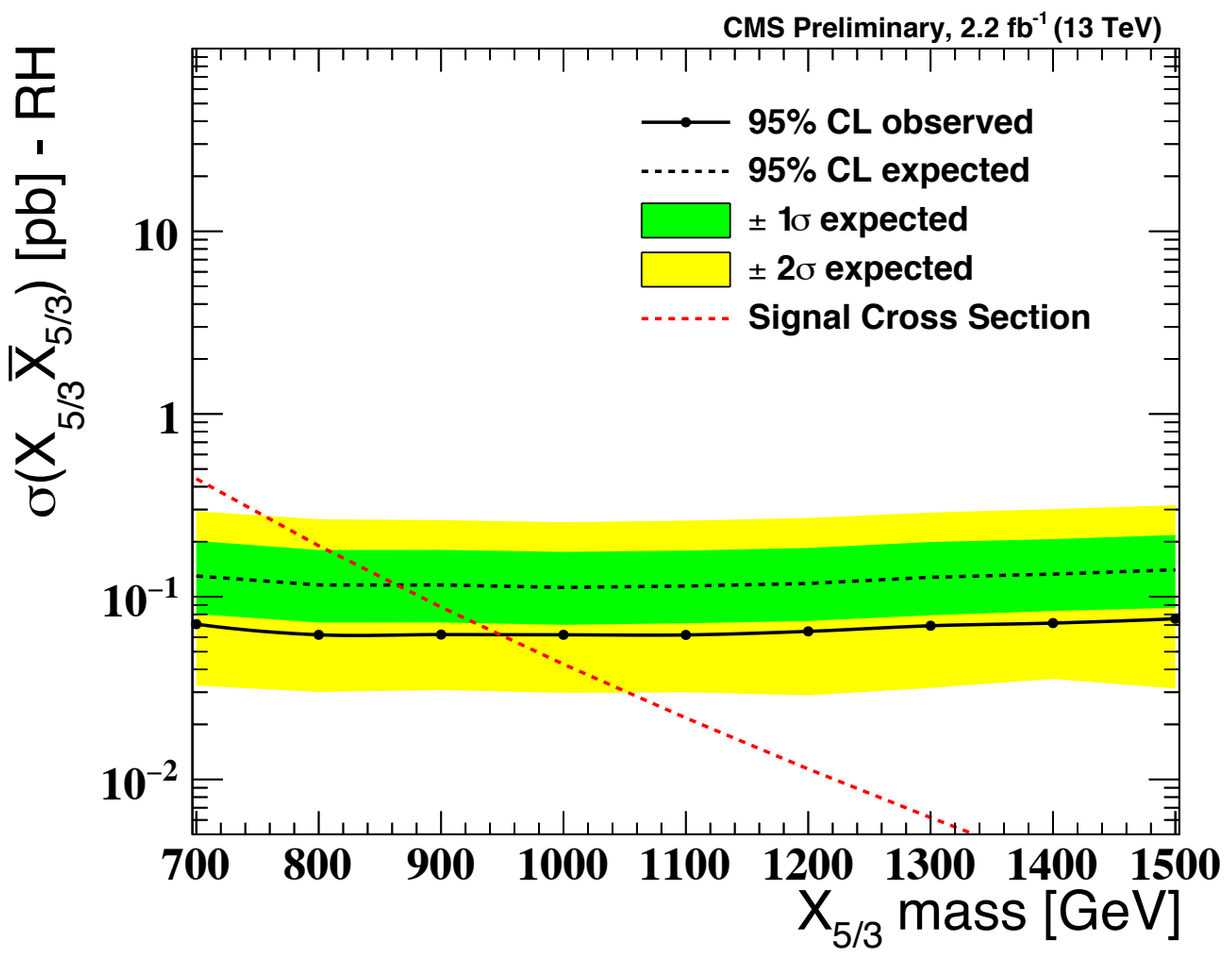


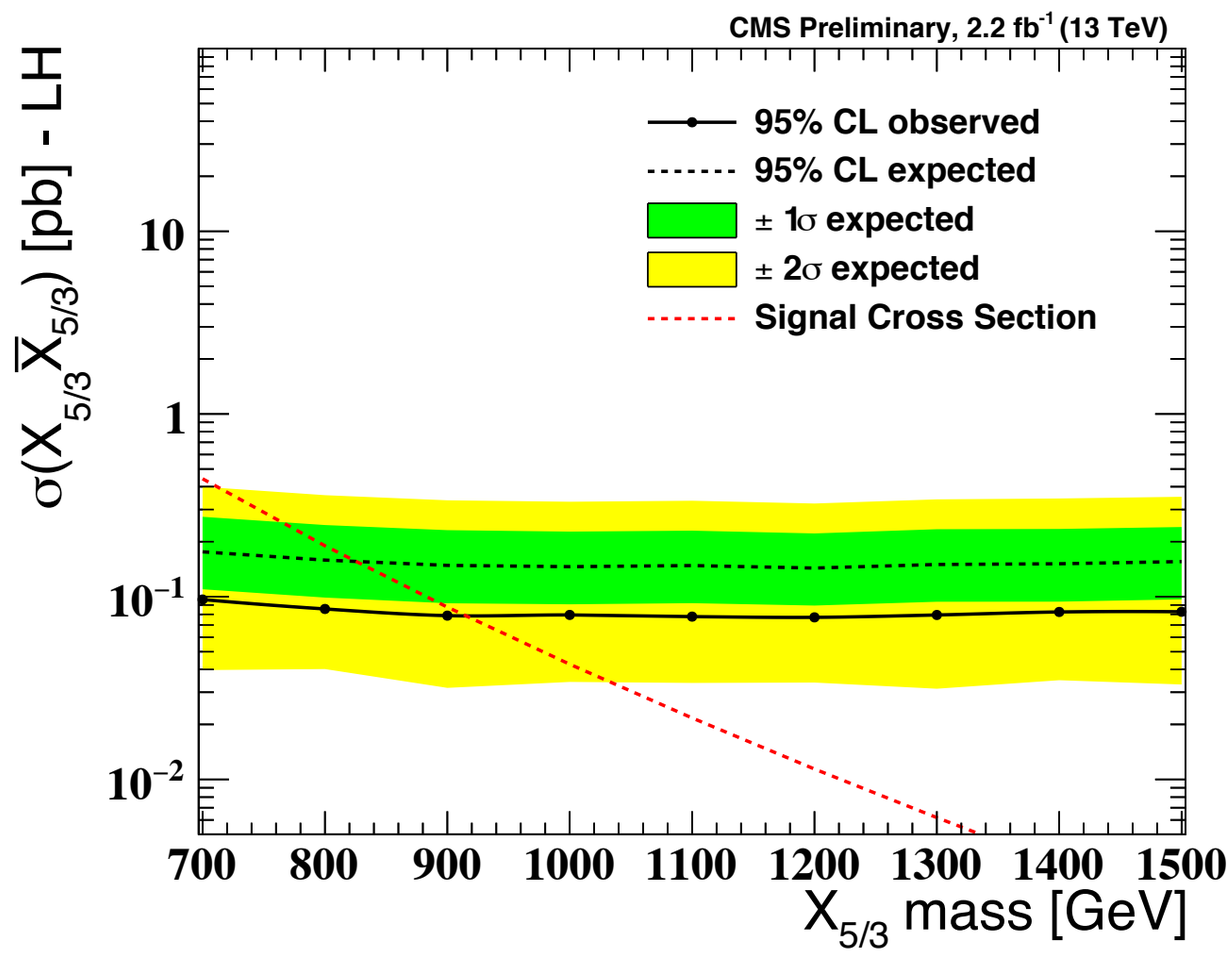


vector-like quarks: pair production

[CMS-PAS-B2G-15-006]

$X^{5/3}$ combined result:





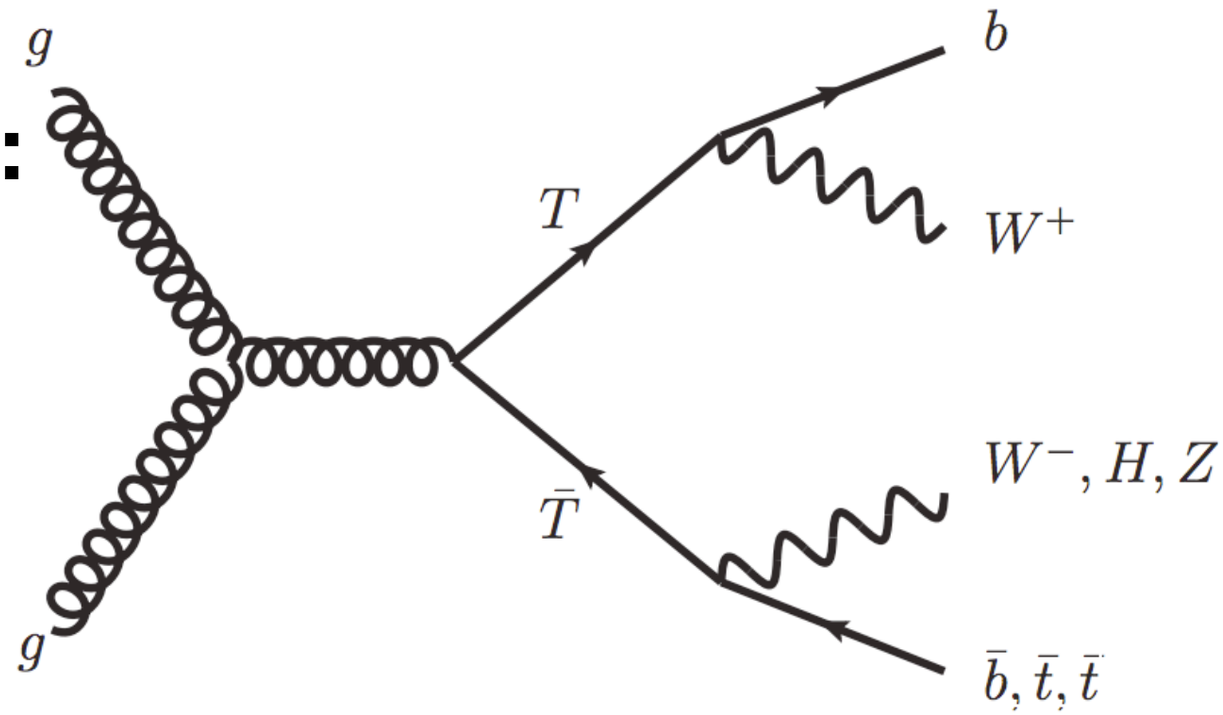
- exceeds Run I limits already now!

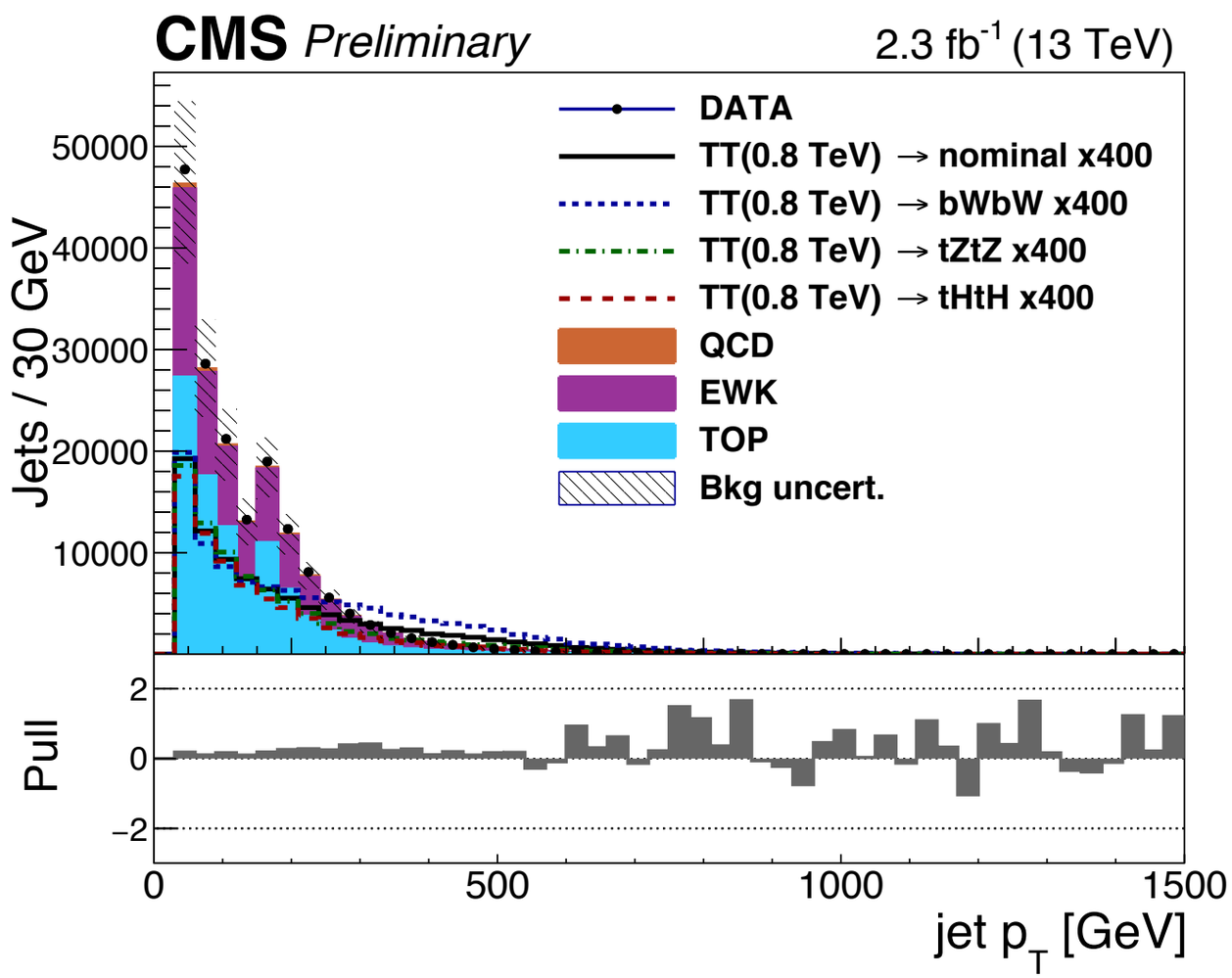
vector-like quarks: pair production

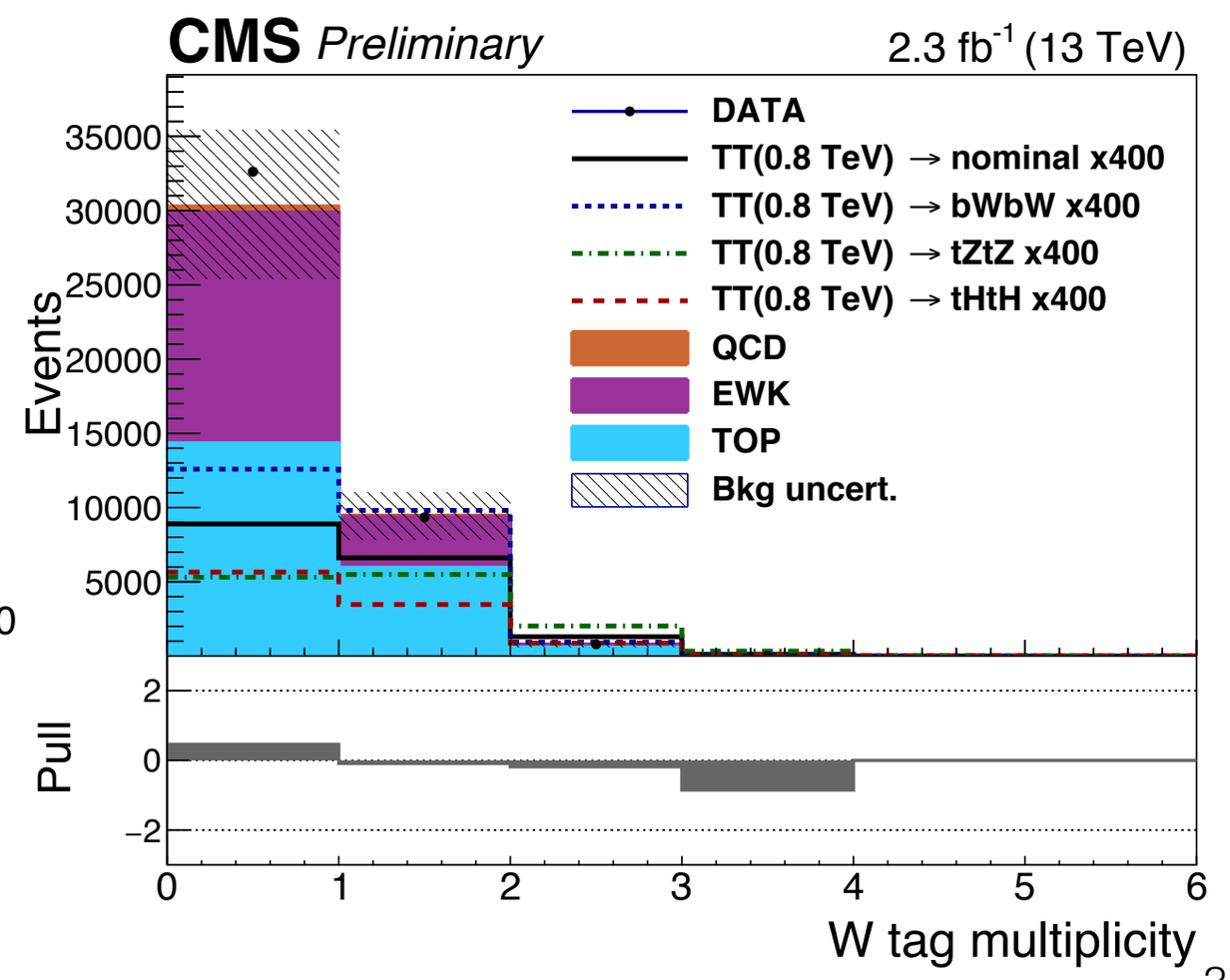
[CMS-PAS-B2G-16-002]

$T^{2/3}$ in lepton+jets final state:

- inclusive search for all possible decay modes (many!)







- this looks good now, but it was a headache (see next slide)

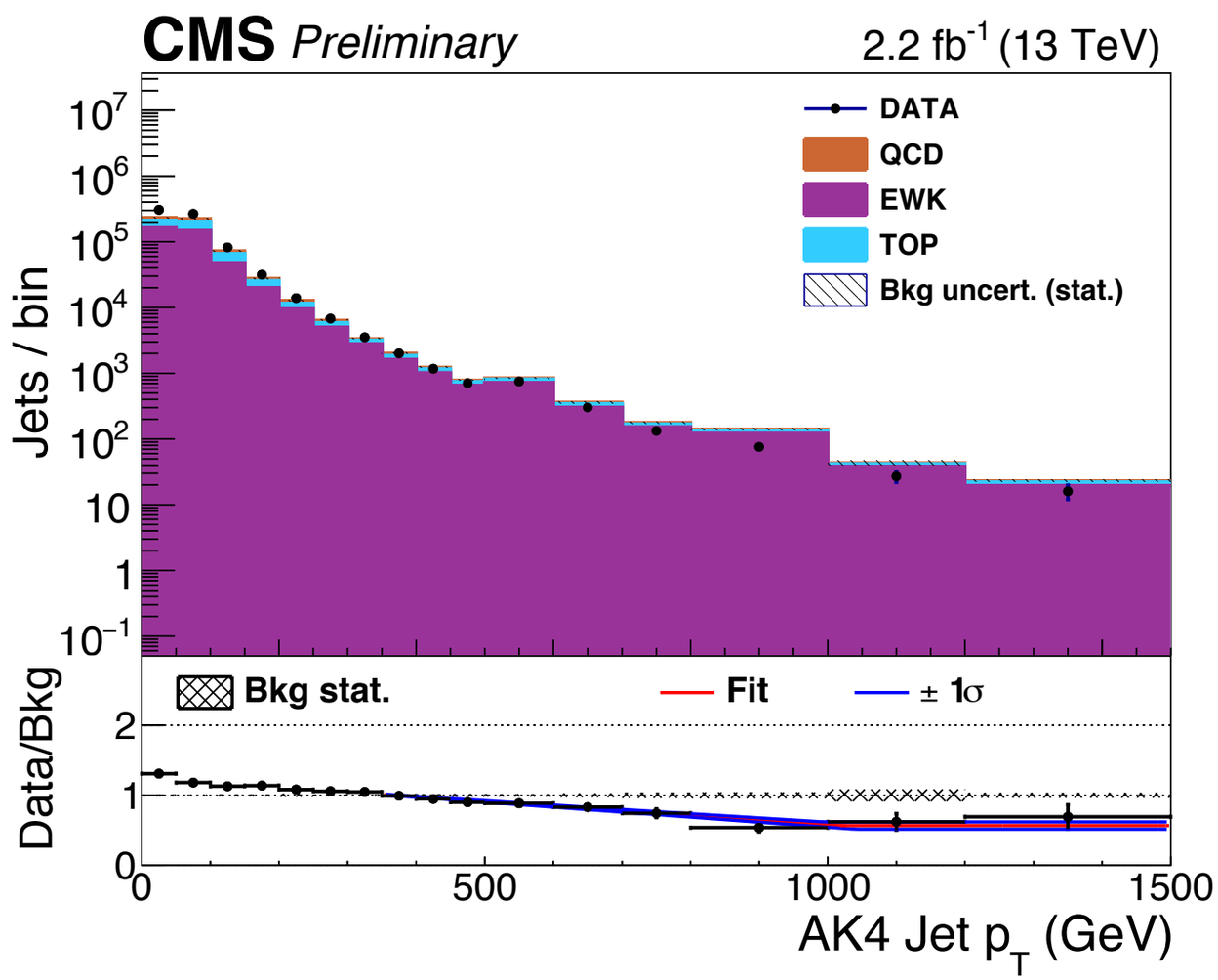
vector-like quarks: pair production

[CMS-PAS-B2G-16-002]

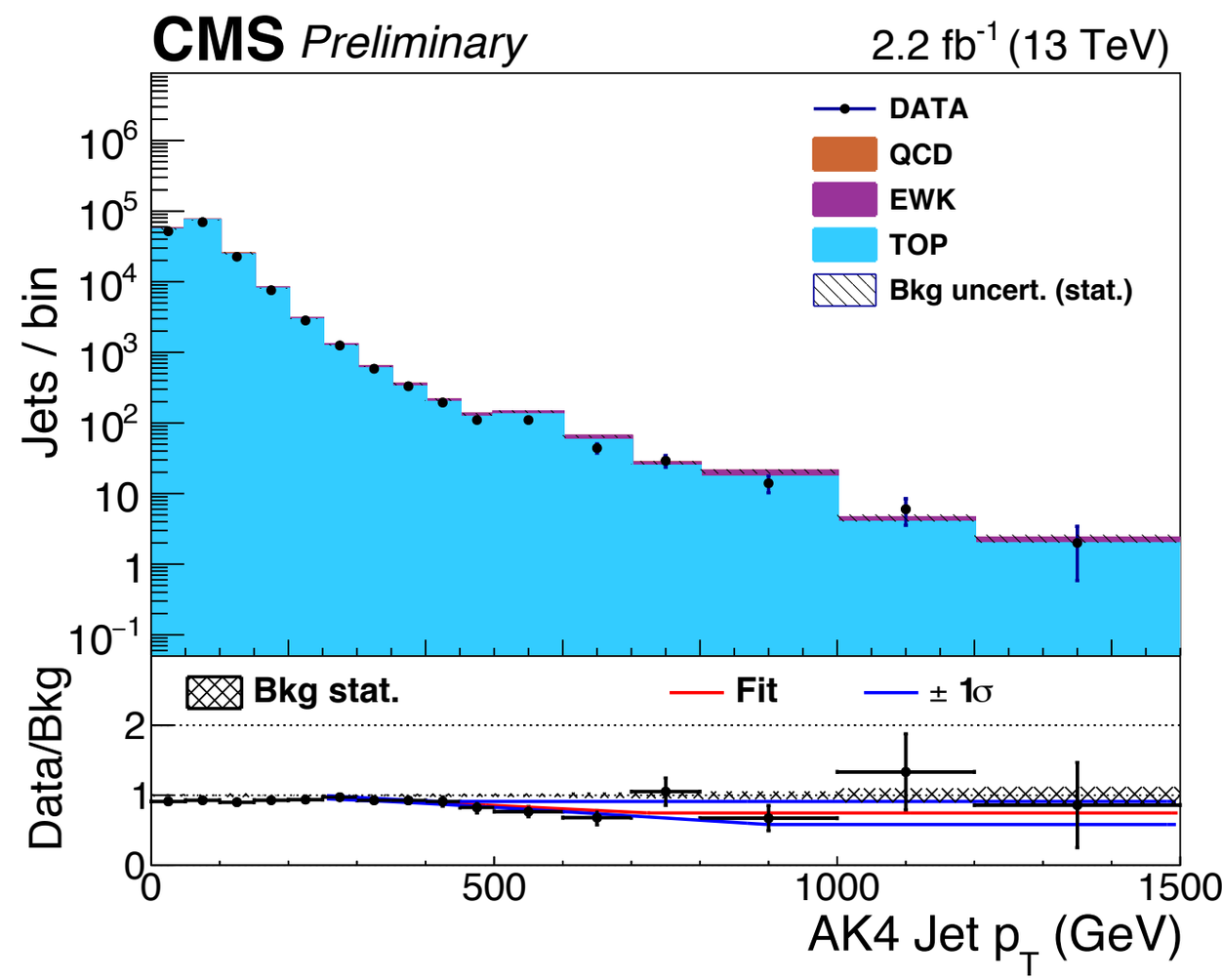
$T^{2/3}$ in lepton+jets final state:

- jet p_T reweighting

EWK control region:



ttbar control region:



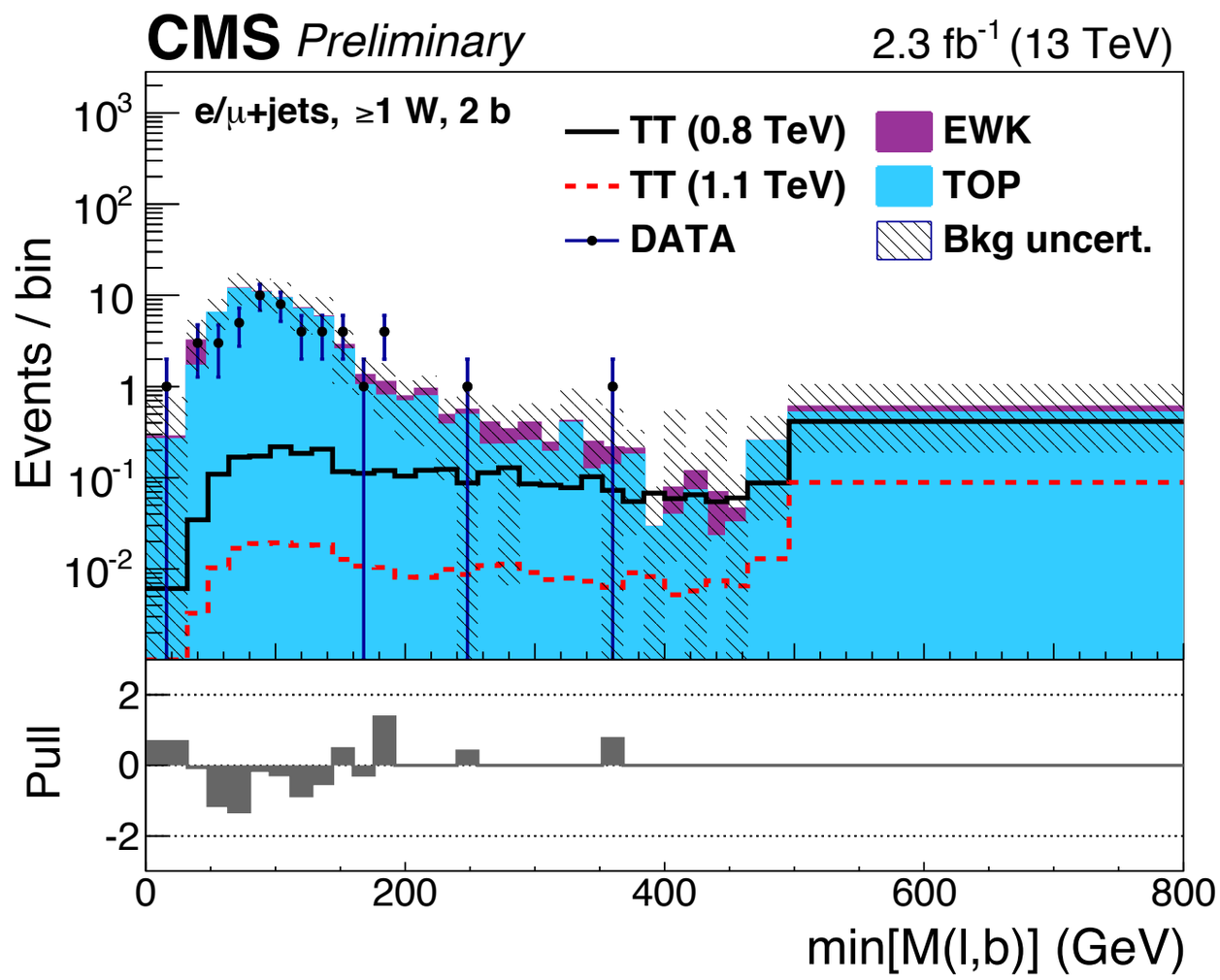
- used to derive jet p_T reweighting factors

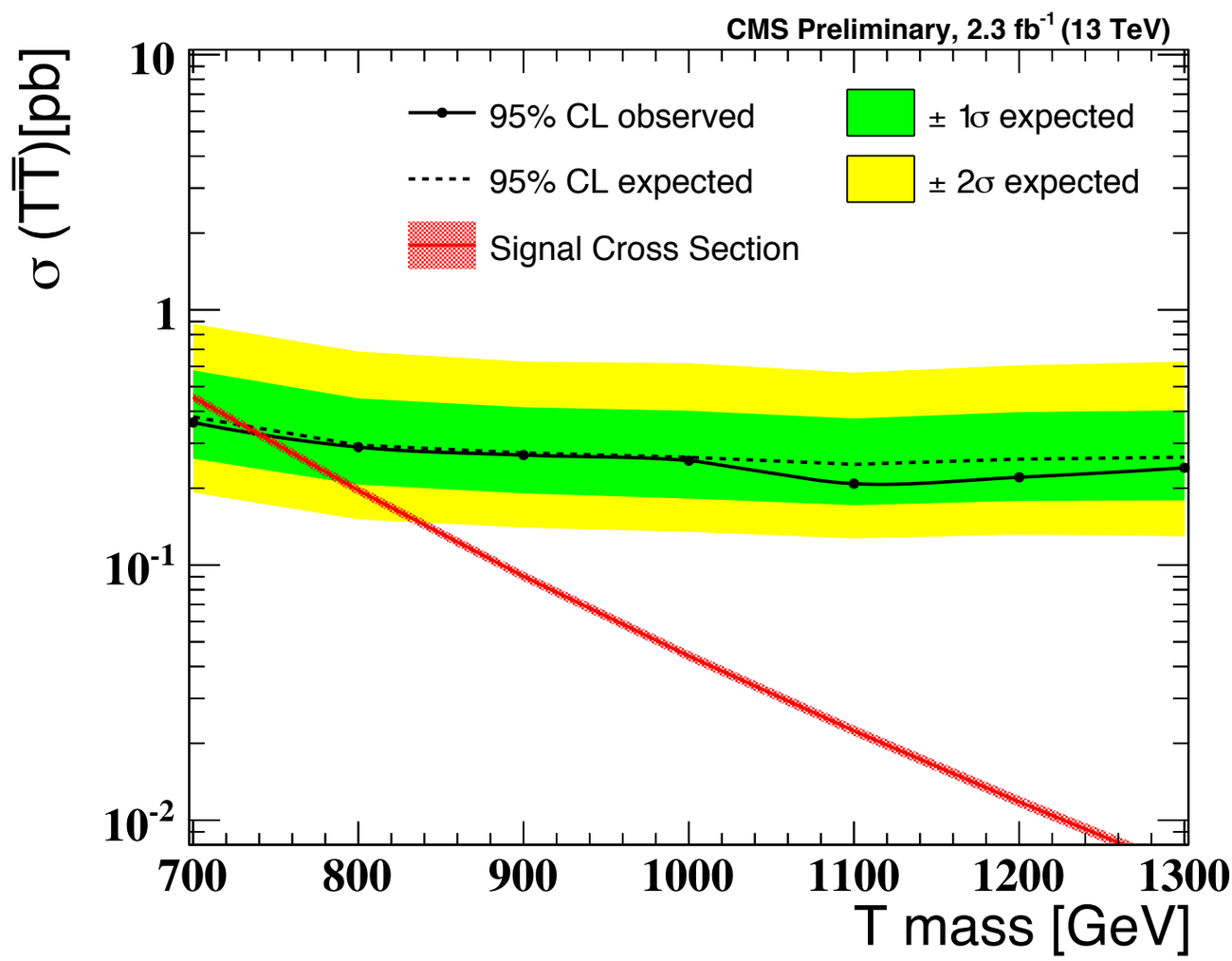
vector-like quarks: pair production

[CMS-PAS-B2G-16-002]

$T^{2/3}$ in lepton+jets final state:

- divide events in 16 categories (lepton, b-tag, W-tag)
- analyse min[M(l, j)] spectrum
- background model validated in control regions

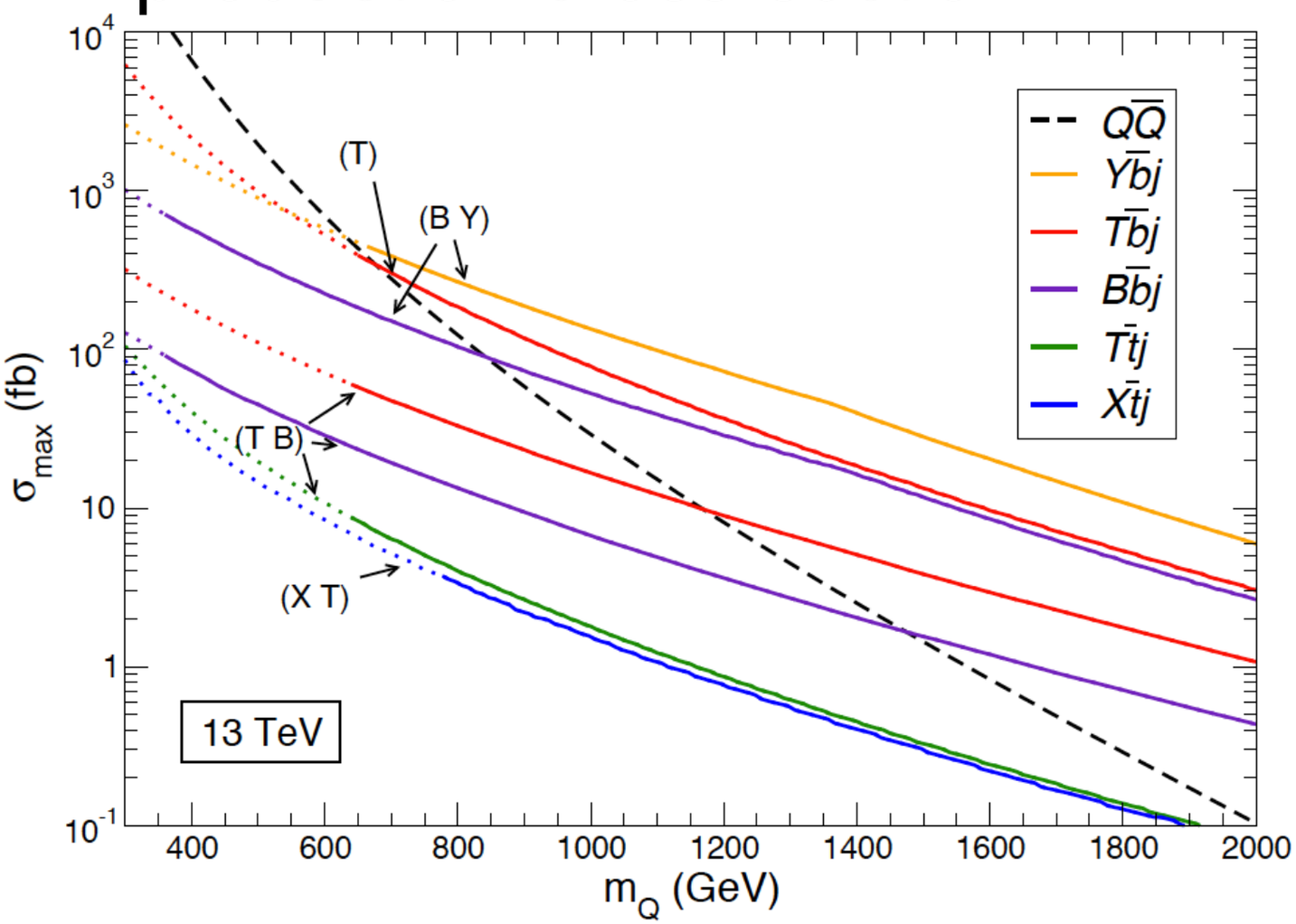


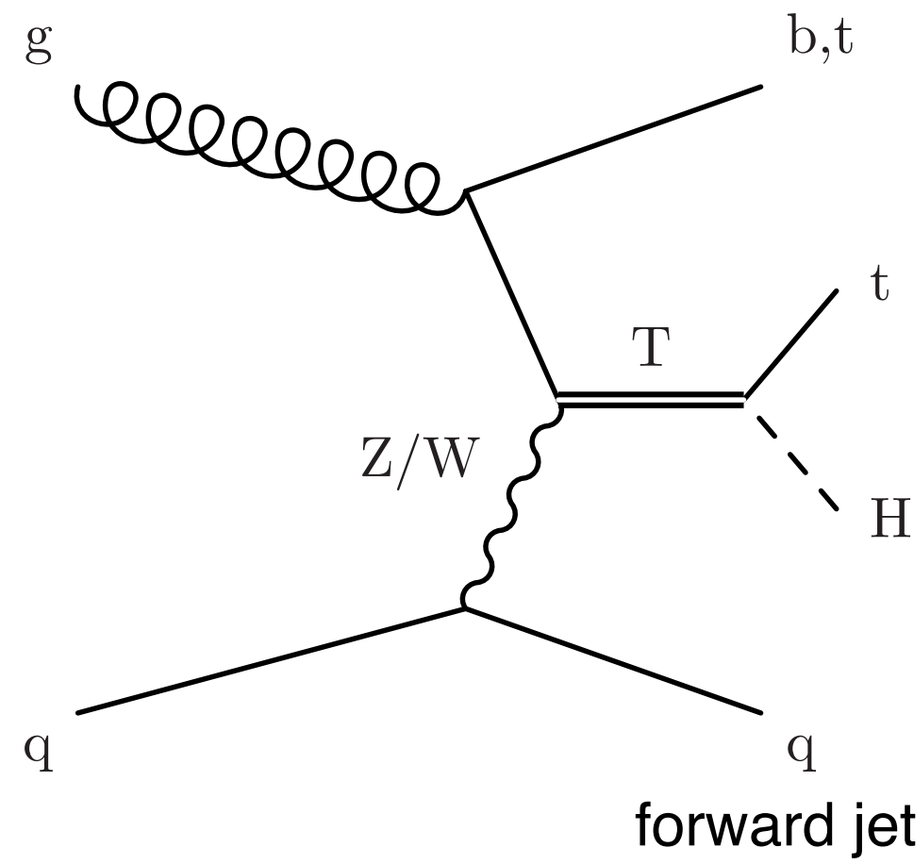


- limits competitive with 8 TeV

vector-like quarks: single production

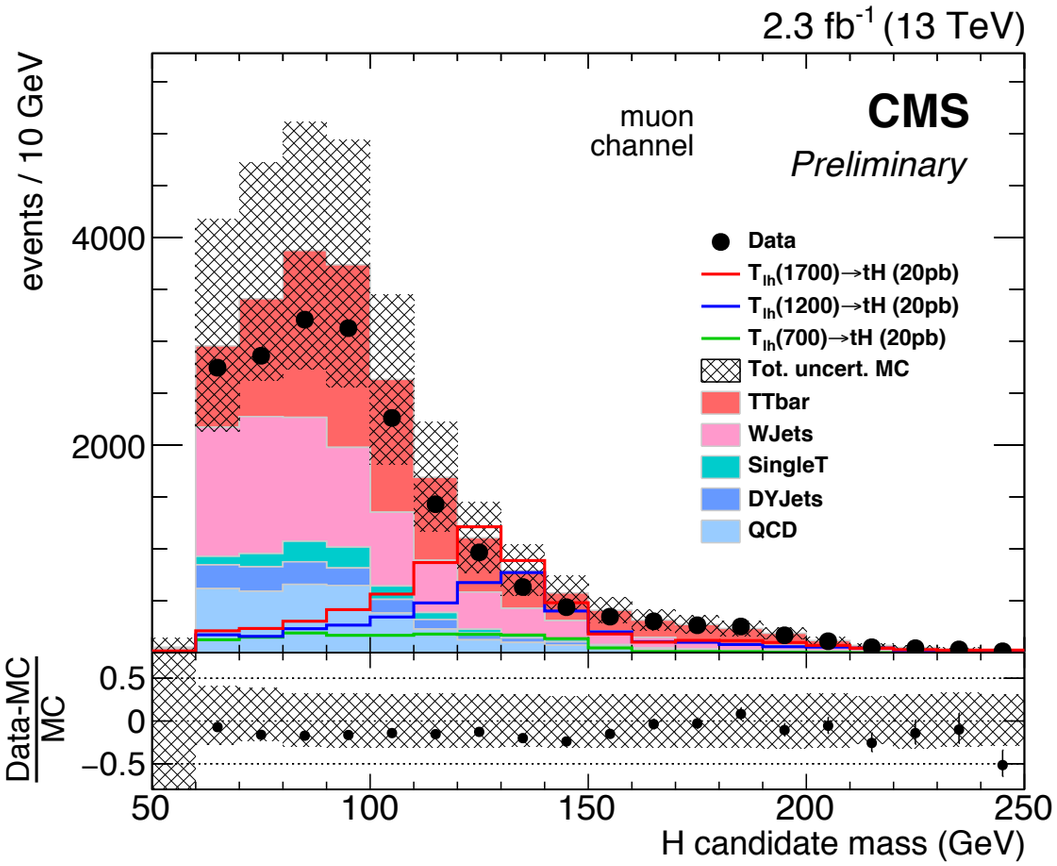
production cross-section:

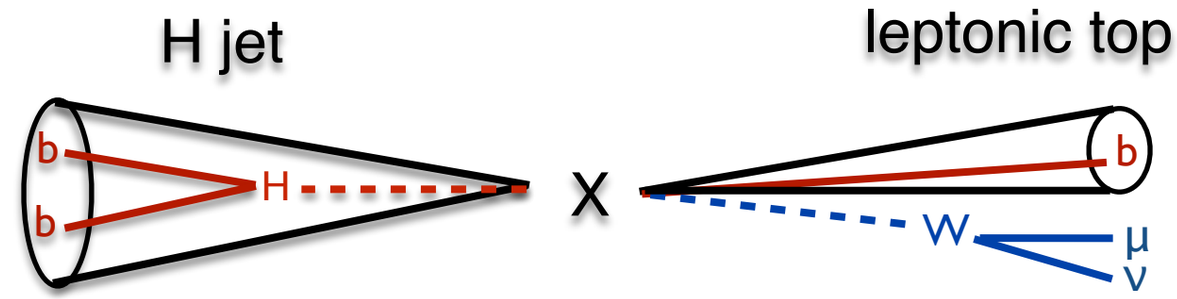


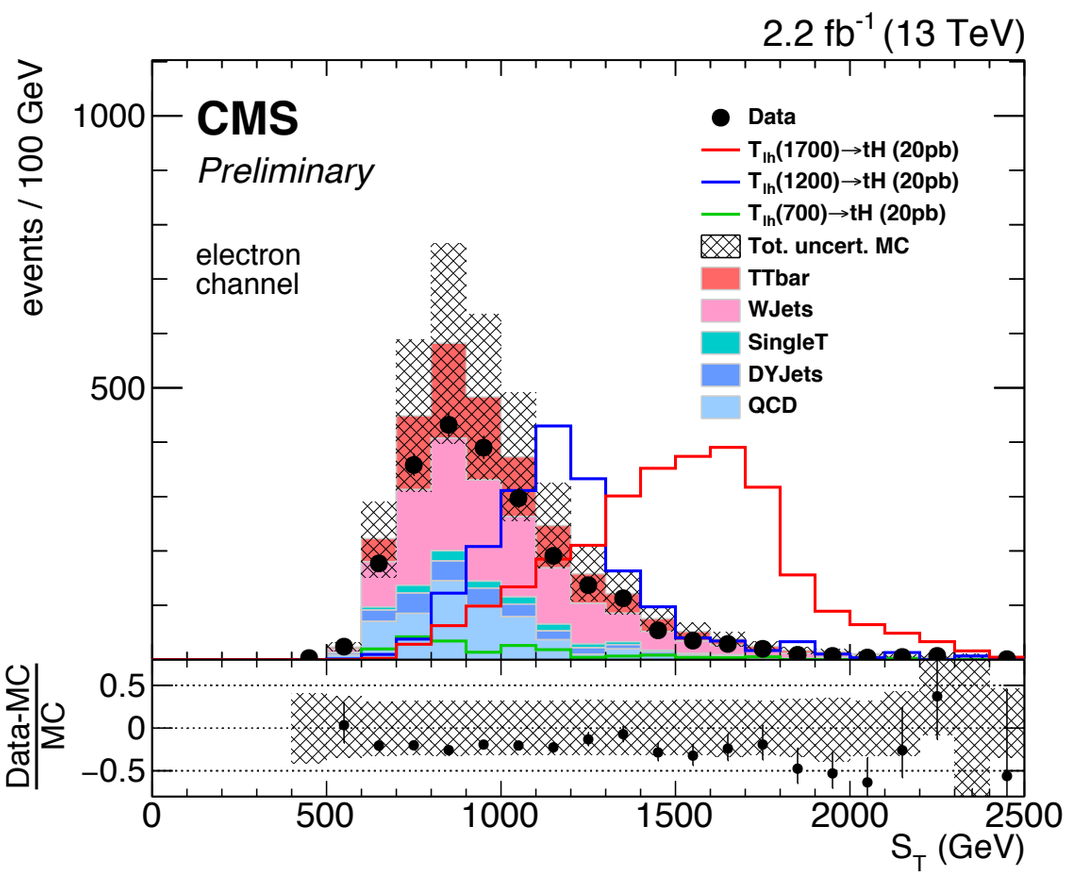


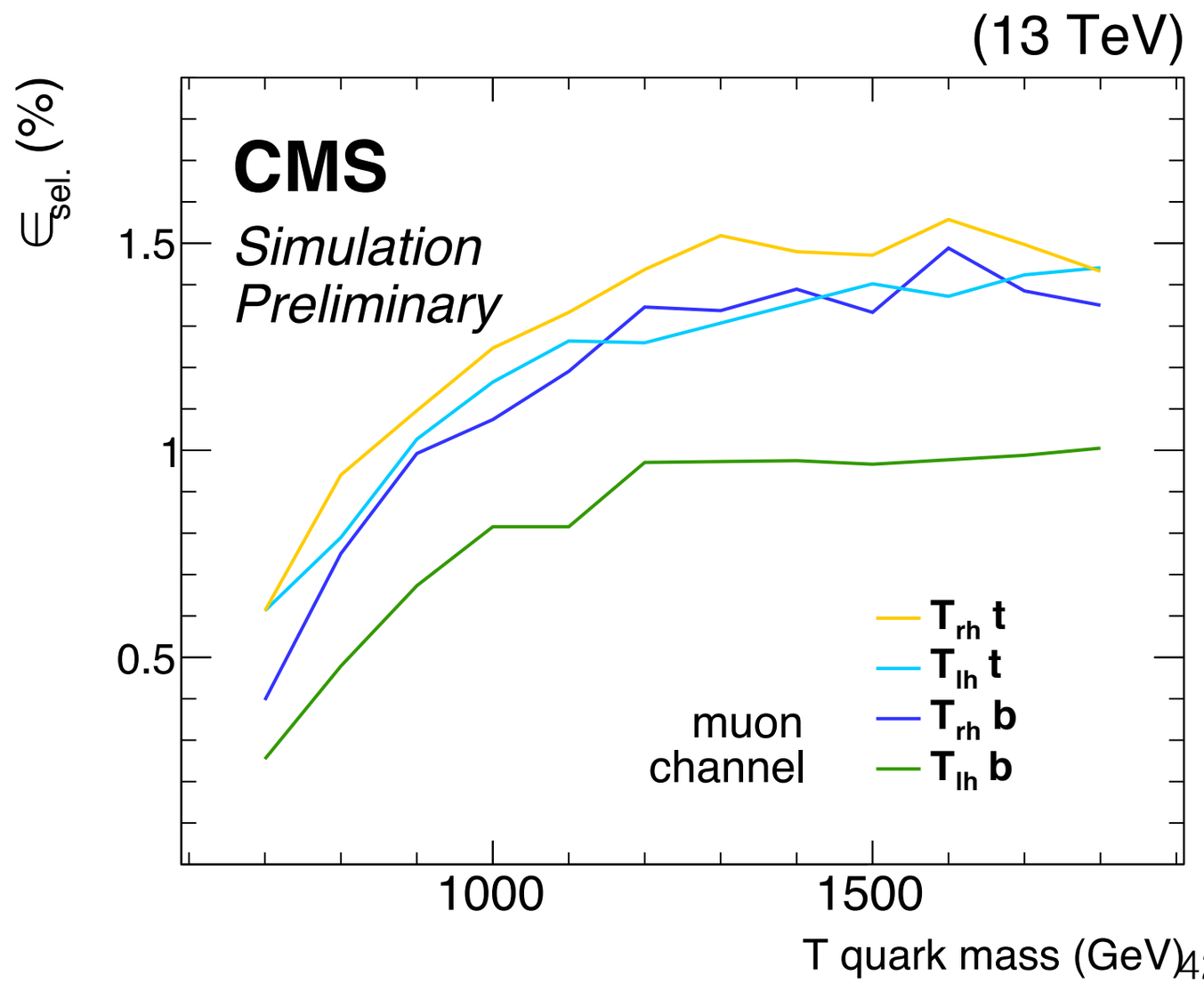
- higher cross sections at high masses
- allows to set limits on model parameters

vector-like quarks: single production T→tH [CMS-PAS-B2G-15-008]







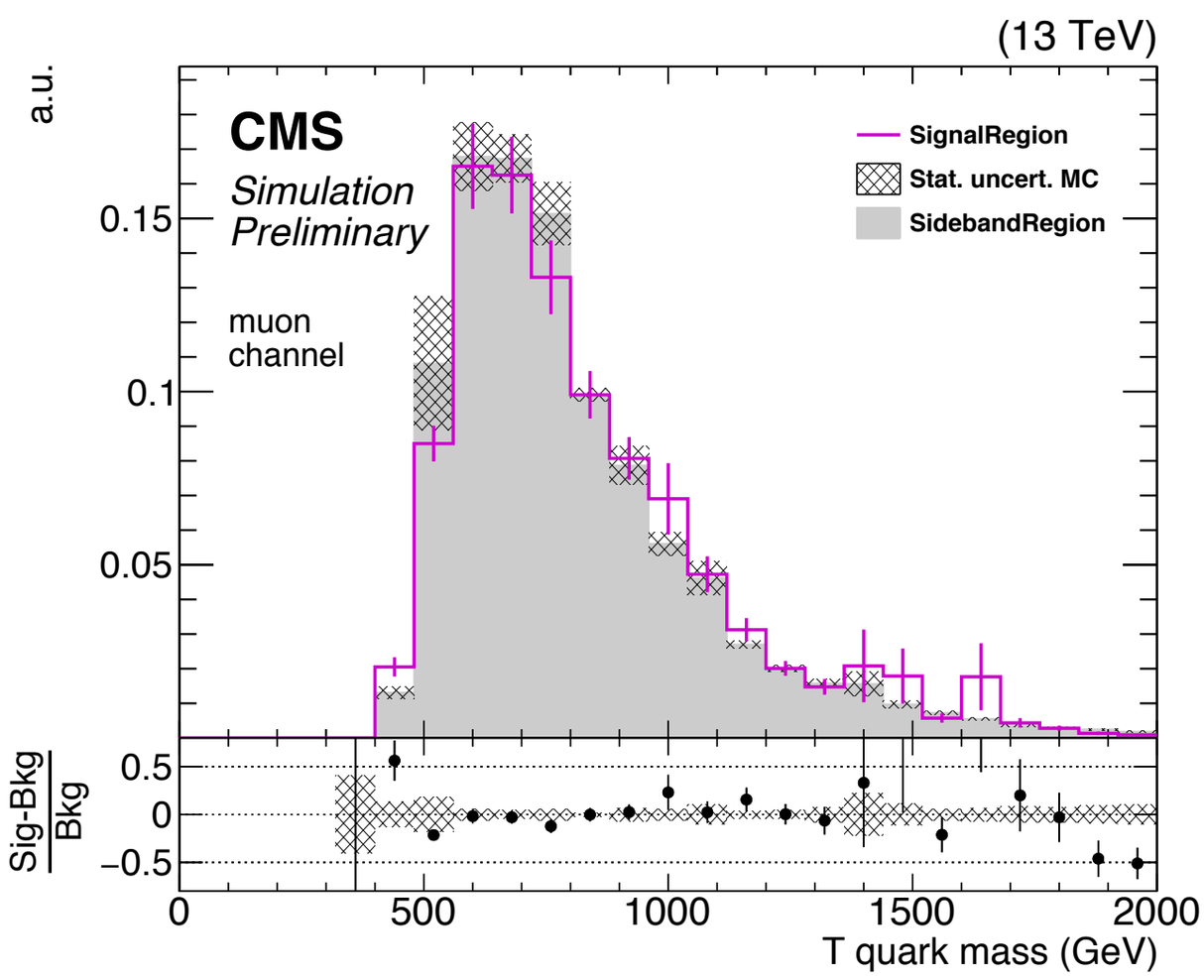


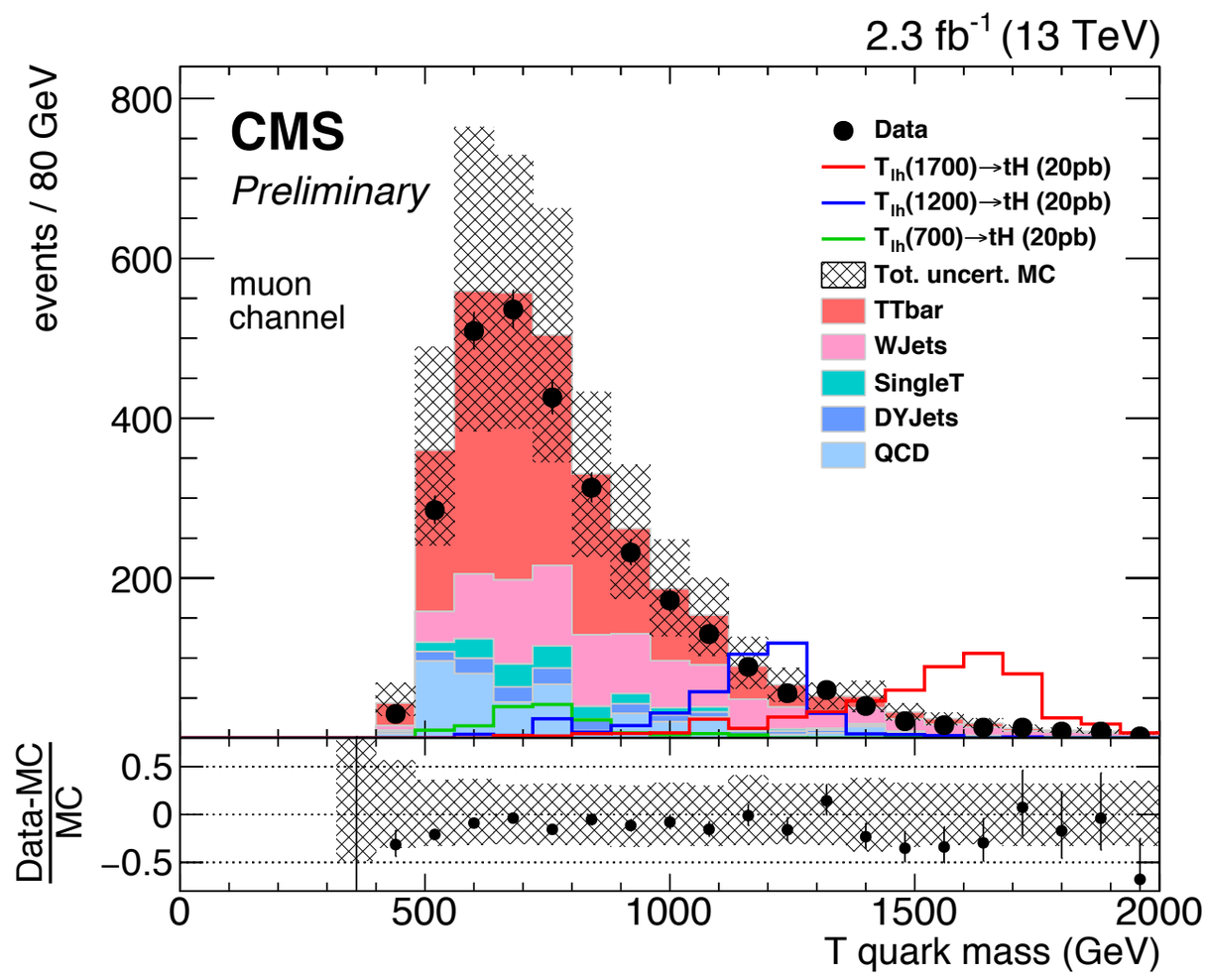
vector-like quarks: single production T→tH [CMS-PAS-B2G-15-008]

background estimation

- entirely data-driven (shapes and normalisation)
- background region: no forward jet, subjet b-tag veto

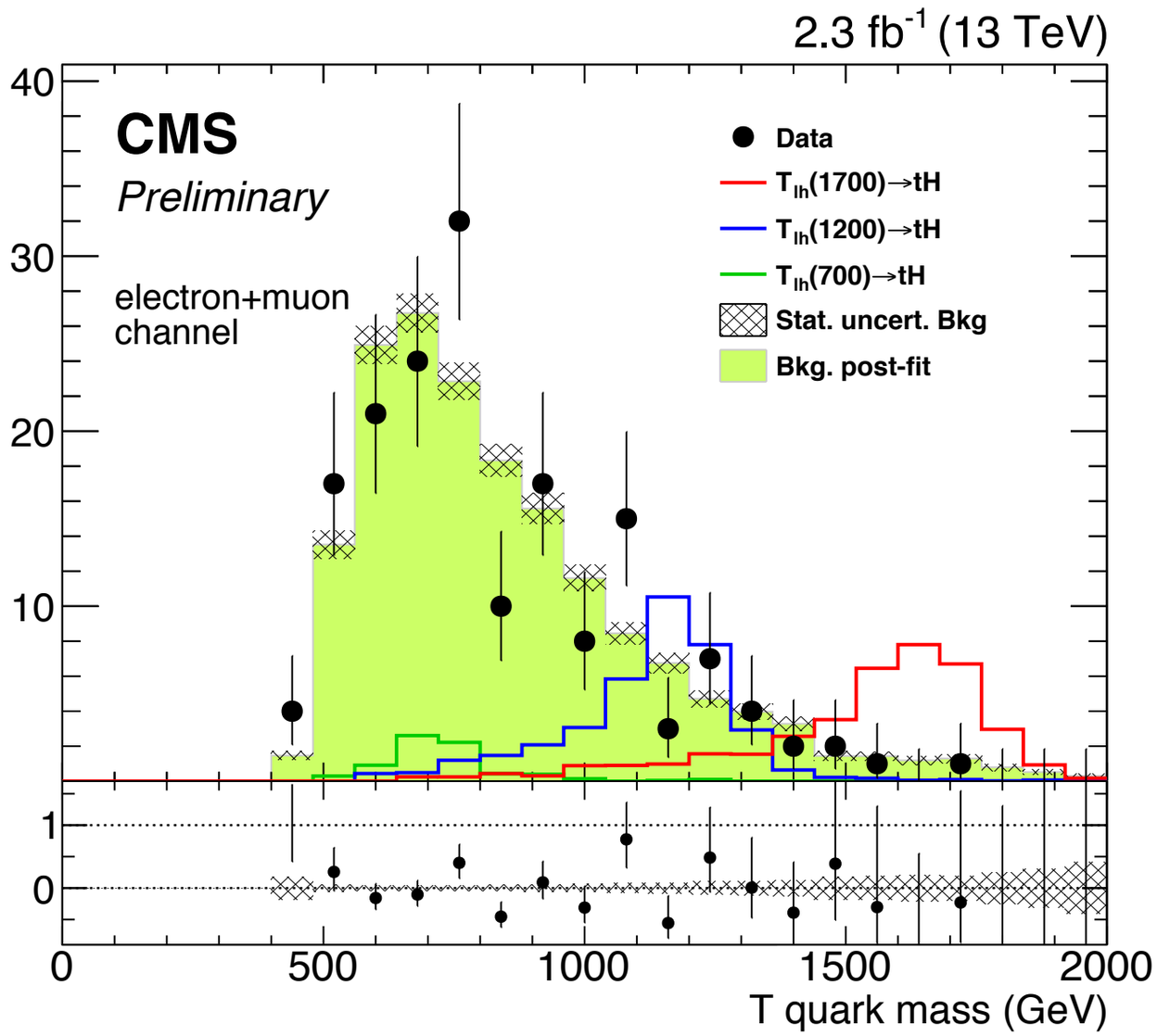
region	signal	sideband
number of subjet b-tags (H cand.)	exactly 2	exactly 1
number of forward jets	at least 1	exactly 0



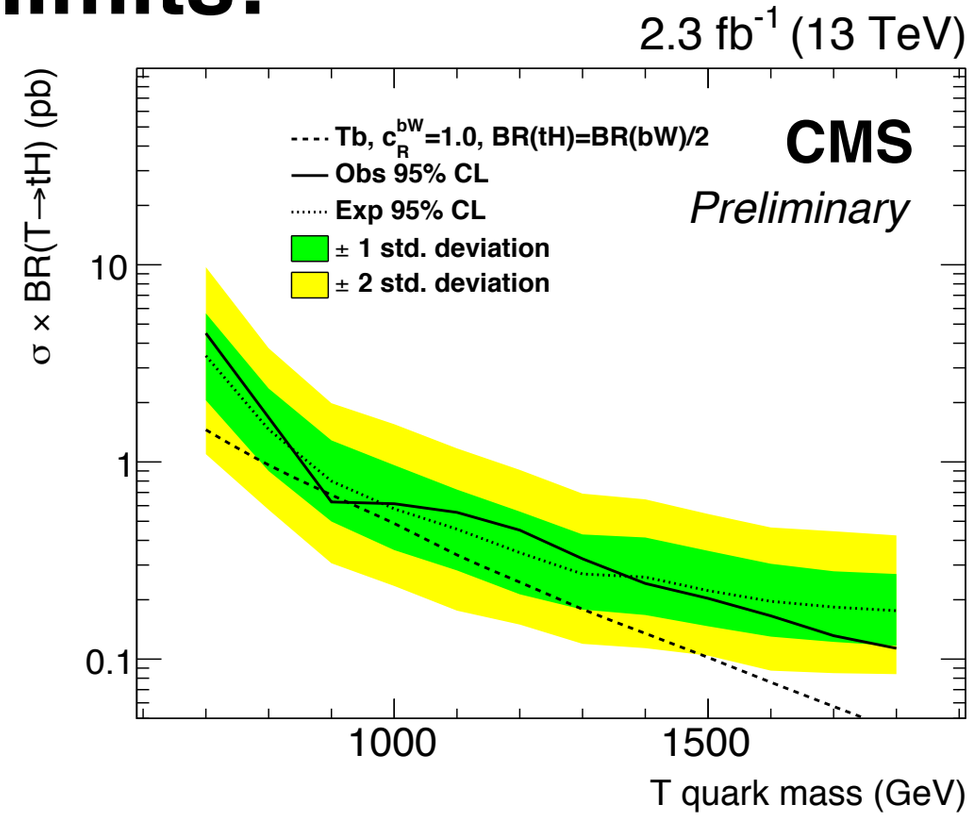


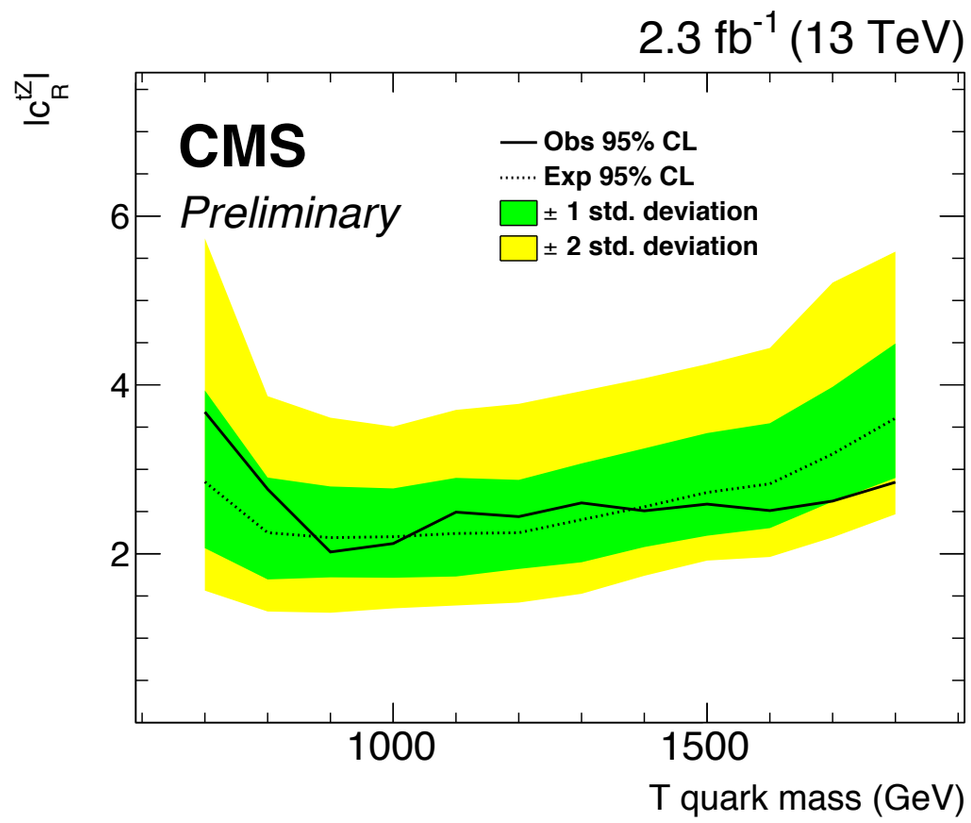
vector-like quarks: single production T→tH [CMS-PAS-B2G-15-008]

result:



limits:





conclusions

- run II is ongoing (until end of 2018)
- many great results already now
  - precision measurements
  - searches for new physics
- standard model still rules
- now probing unknown territory
- many new results expected for summer

backup

$X^{5/3}$ in same-sign di-lepton final state:

After requiring two tight, same-sign leptons with p_T greater than 30 GeV we impose the following requirements:

- Quarkonia Veto: $M_{ll} > 20\,\text{GeV}$
- Associated Z-boson Veto: veto any event where either of the leptons in the same-sign pair reconstructs to within 15 GeV of the mass of the Z-boson with any other lepton in the event not in the same-sign pair.
- Primary Z-boson Veto: invariant dilepton mass (M_{ll}) $>$ 106.1 or $<$ 76.1 GeV for dielectron channel only. If the muon charge is mismeasured, its momentum will also be mismeasured so a selected muon pair from a Zboson will not fall within this invariant mass range.
- Leading lepton $p_T > 40\,\text{GeV}$
- Number of Constituents $>= 5$
- $H_T^{lep} > 900\,\text{GeV}$

$X^{5/3}$ in lepton+jet final state:

We begin by defining event preselection criteria consistent with the signal topology. The following selection is applied: lepton $p_T > 50$ GeV, $E_T^{miss} > 100$ GeV, $N_{jets} \geq 3$ with jet $p_T > 30$ GeV and $|\eta| < 2.4$, p_T (leading jet) > 200 GeV, and p_T (sub leading jet) > 90 GeV. In addition at least one of the jets is required to be tagged as originating from a b quark [28]. In Fig. 4, we show the differences in signal and background as characterized by a few kinematic variables, the number of jets (N_{jets}), missing E_T (E_T^{miss}). Decay products of heavy particles such as $X_{5/3}$ can have large Lorentz boost, and their subsequent decay products can merge into a single jet. The "n-subjettiness" [29] algorithm measures the likelihood of a jet having n subjets (1, 2, 3, etc). Mass grooming techniques are used to remove soft jet constituents so that the mass of the hard constituents can be measured more clearly. The "pruning" [30] algorithm is currently used to identify boosted hadronic W boson decays. We require a W tagged jet to have $p_T > 200$ GeV, $|\eta| < 2.4$, pruned mass between 65 and 105 GeV, and the ratio of n-subjettiness variables $\tau_2/\tau_1 < 0.55$. Figure 4 shows the number of b tagged and W tagged jets (bottom row).

$T^{2/3}$ in lepton+jets final state:

We select events with one electron or muon, usually from the decay of a W boson in the bW channel or from the $t \to Wb$ decay in the tZ or tH channels. Electrons and muons must have $p_T > 40$ GeV and pass the tight identification and isolation requirements described previously. We discard events having extra loose electrons or muons with $p_T > 10$ GeV.

We select events with three or more jets, where the highest corrected jet p_T is greater than 150 GeV, and the second highest p_T is greater than 75 GeV. E_T^{miss} must be greater than 60 GeV to reduce multijet background events. The final selection criterion is a veto on boosted Higgs tagged jets, which creates a signal region orthogonal to that of an ongoing dedicated $T \to tH$ analysis. Figure 2 shows distributions of lepton p_T, jet p_T, E_T^{miss} along with the total number of jets, number of b tagged jets, and number of W tagged large-radius jets. These distributions include the jet p_T reweighting procedure described below.