# Searches: discovery techniques and/or limits in CMS


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# Statistical methods in CMS searches to date

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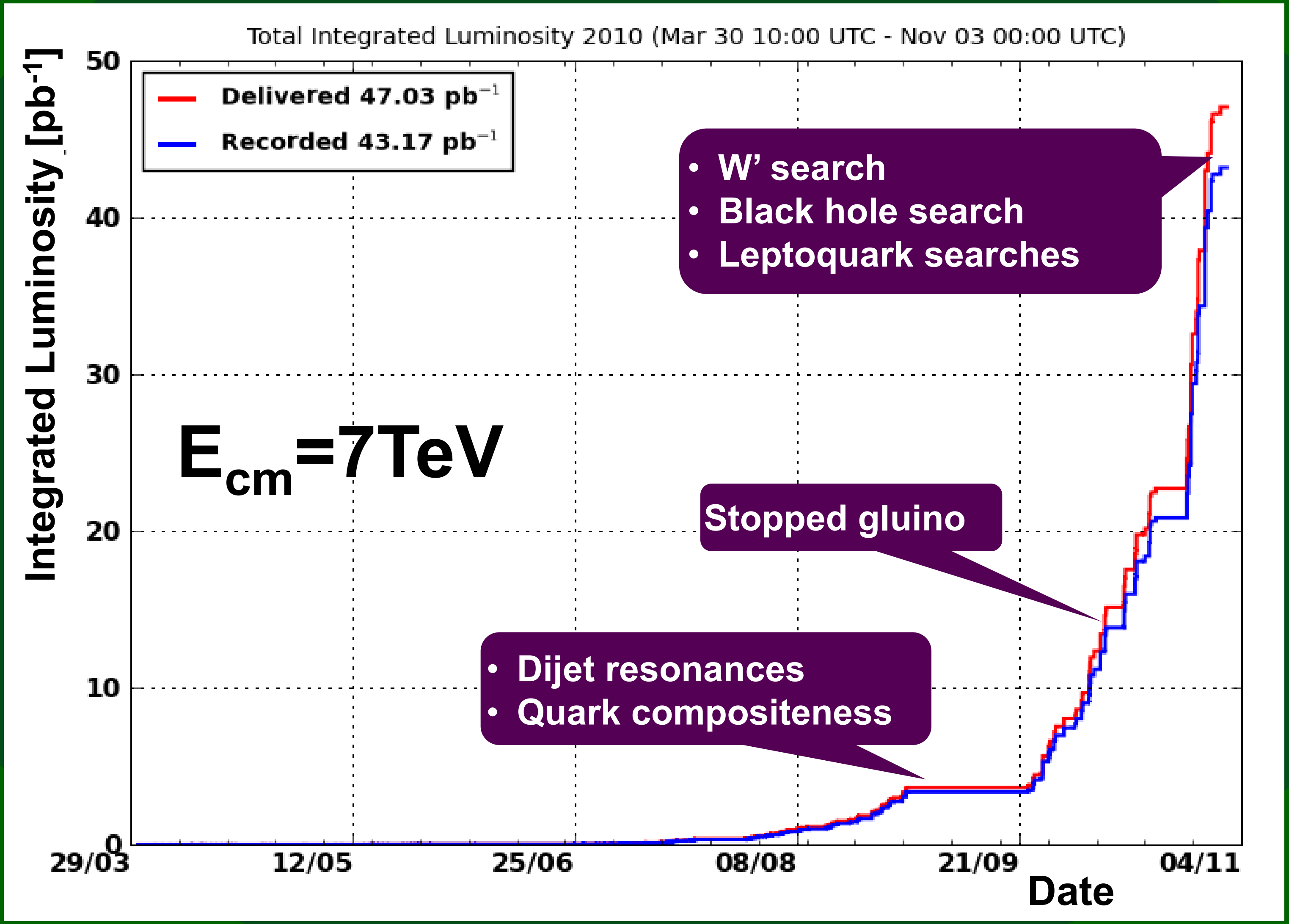
# Experimental Apparatus

# The Large Hadron Collider


***The collisions for today's talk***

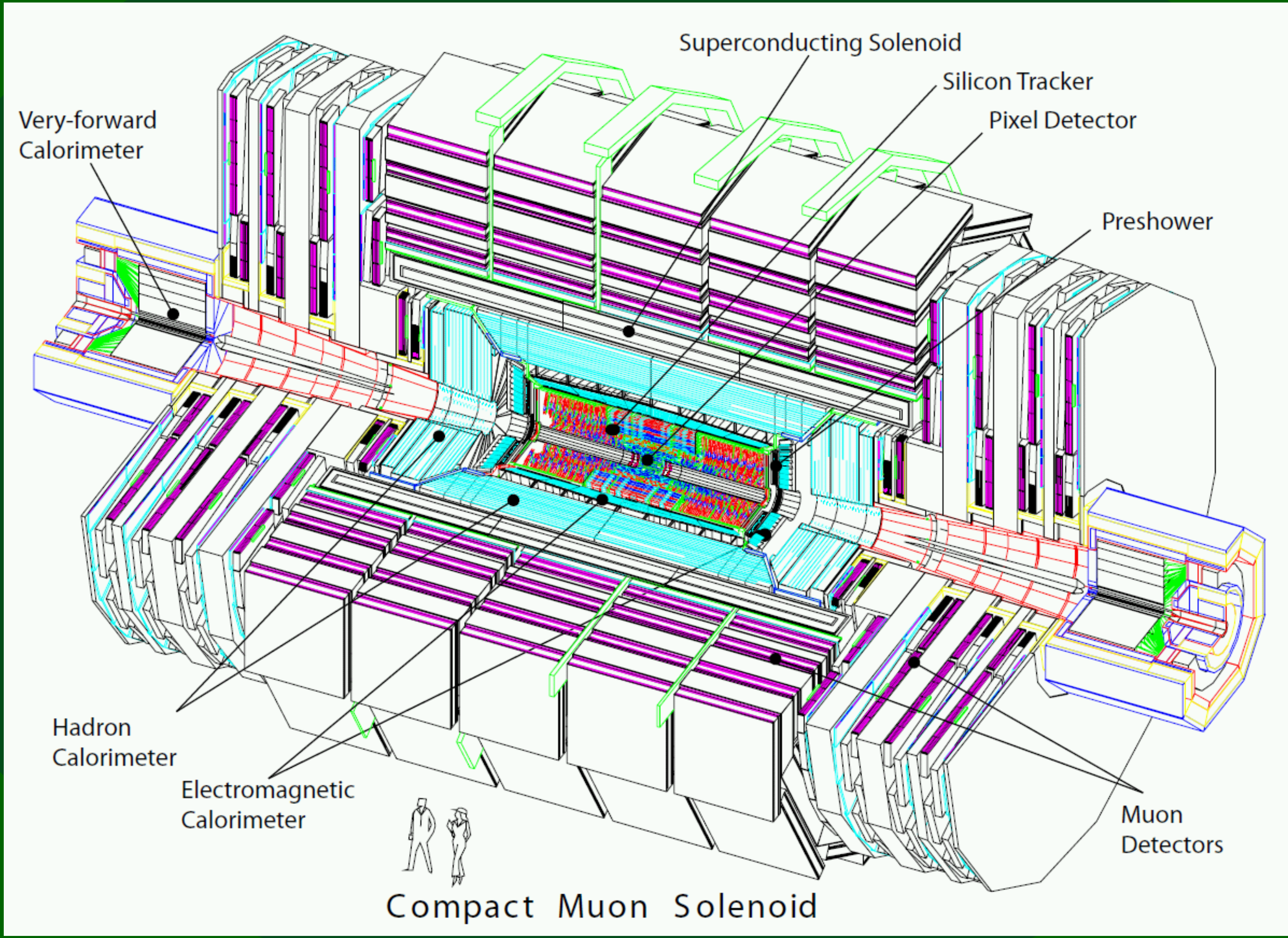
- $pp$
- $E_{c.m.}$ = 7TeV
  - Energies up to 2TeV previously explored at Tevatron
  - Design: 14TeV
  - 1st collisions: 30 of March, 2010

# LHC performance




Peak luminosity: $L = 205 \mu b^{-1} s^{-1}$

# The CMS Detector




Design emphasizes tracking and EM calorimetry

# The basic tools

| How do we construct intervals? | Nuisance parameters |
| --- | --- |
| Bayesian approach | Integrated (marginalization) |
| Neyman construction (frequentist, inversion of hypothesis test) | Multidimensional construction natural<br>But in practice, use a hybrid approach (Cousins Highland) and integrate |
| Likelihood ratios | Minimization (Profiling, "MINOS") |

We'll discuss power constraints and other approaches later on.

***The experimentalist perspective***

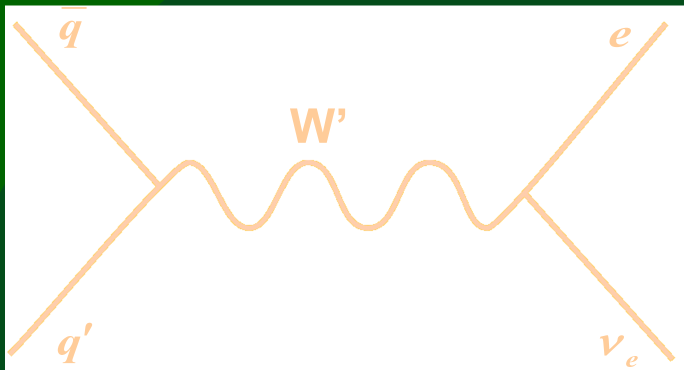
Claiming a discovery first is the best case scenario.
But claiming a discovery is also the worst case scenario if you got it wrong.

Which of these statistical tools helps us get it right?

→A "pragmatic" approach is typical.
No standard approach. Yet.

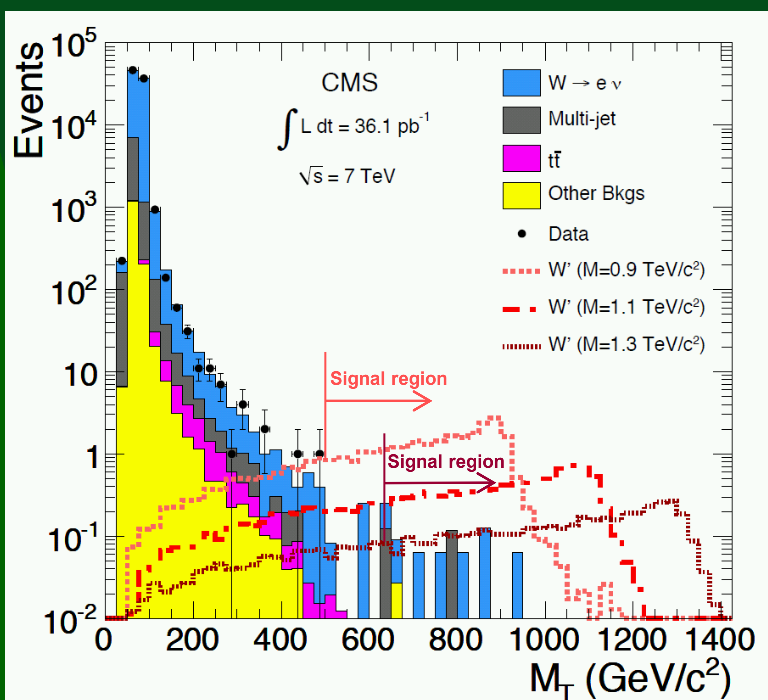
# Bayesian

# W' search




### *Experimental signature*

- Isolated electron
- $p_T$ imbalance (done with particle-flow energies, $E^{miss}_T$)




### *Reference model*

- W' has W-like fermionic couplings
- W' does not couple to other gauge bosons
- Tevatron limits: $m_{W'} > 1.1$TeV
- signal from Pythia, cross section scaled to NNLO

### *Observable*

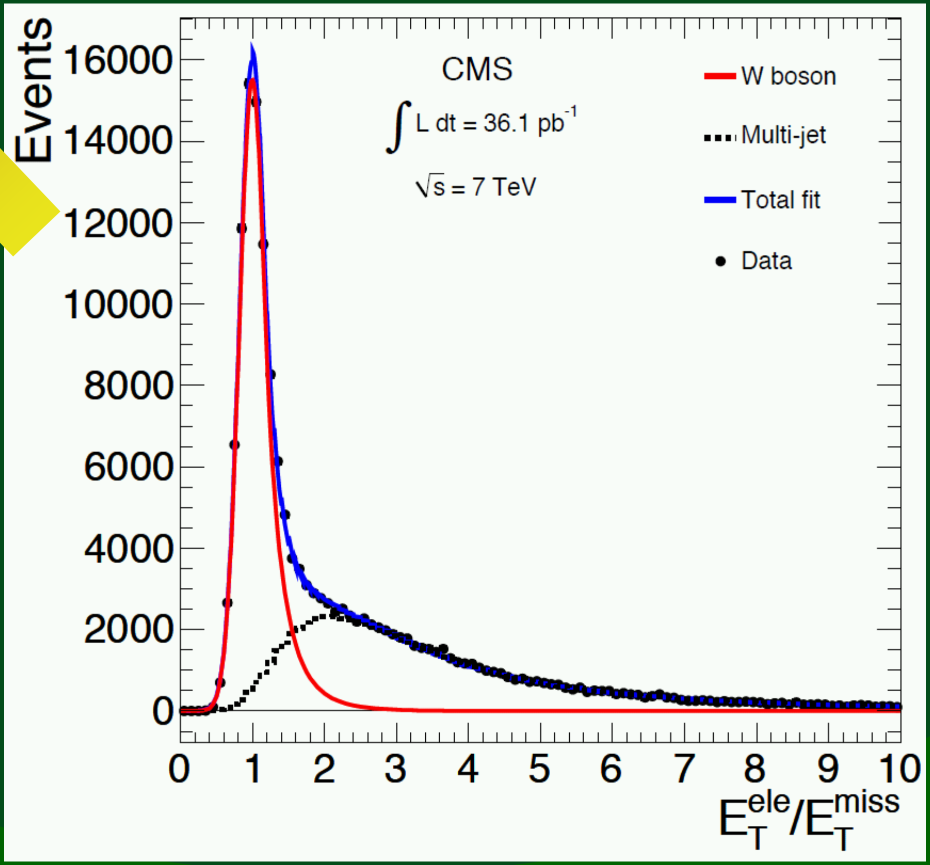
Number of events with $M_T$ > threshold

- $(M_T)^2 = 2E^e_T E^{miss}_T \left(1 - \cos \Phi_{eE^{miss}_T}\right)$
- Threshold chosen a-priori as a function of $m_{W'}$

# W' backgrounds

Estimating the main backgrounds:

- The two main backgrounds are W+jets and multijet production
- Data-driven techniques to estimate their shapes (unfortunately, beyond talk's scope)
- Normalizations from a fit to the (other-background subtracted) data



# W' limit setting

The simplest scenario, as far as limit setting goes:

- A counting experiment (Poisson probability in each $M_T$ bin)
- No interference between backgrounds and signal
- Systematic uncertainties factorize easily

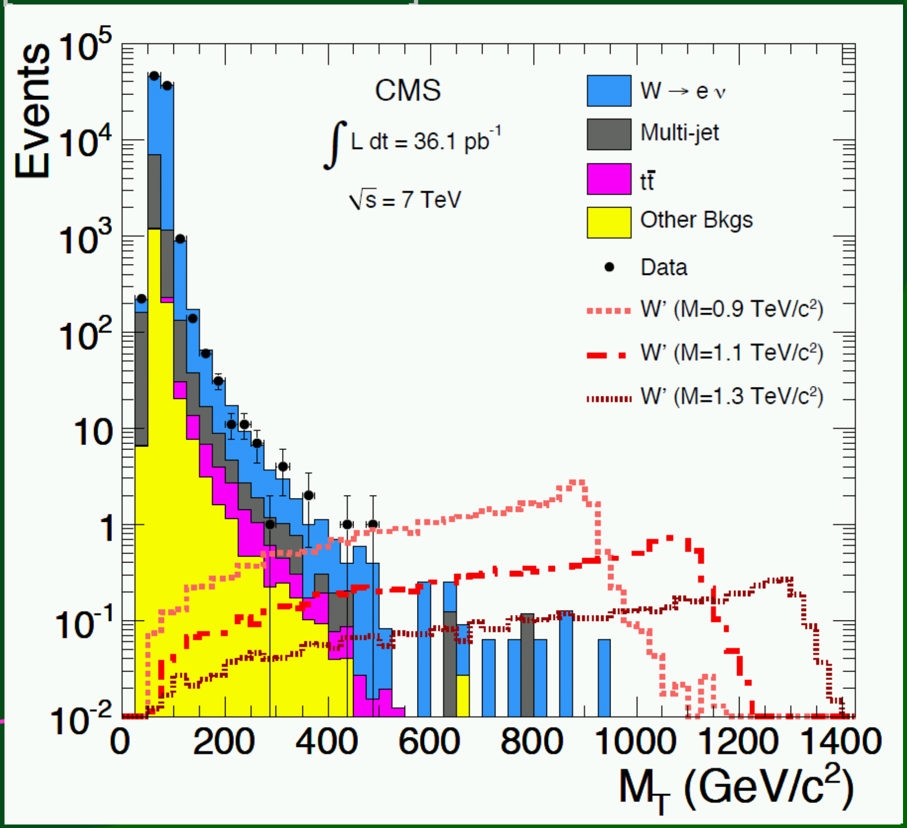
Integrated luminosity

$$N_{pred} = b + \mathcal{L}\varepsilon\sigma_{eff}$$

Selection efficiency (for that bin)

Use a simple Bayesian procedure [Fermilab-TM-2104]

- nuisance parameters are integrated out
- priors:
  - $p(\sigma_{eff}) = \begin{cases} \text{const} & \text{if } 0 < \sigma_{eff} < \sigma_{max} \\ 0 & \text{otherwise} \end{cases}$
  - log normal priors for the nuisance parameters $b, \mathcal{L}, \varepsilon$
    - background uncertainty (e.g. fit results) summarized in one number
    - typical approximation




Rule out a W' with mass below 1.36TeV at 95% CL

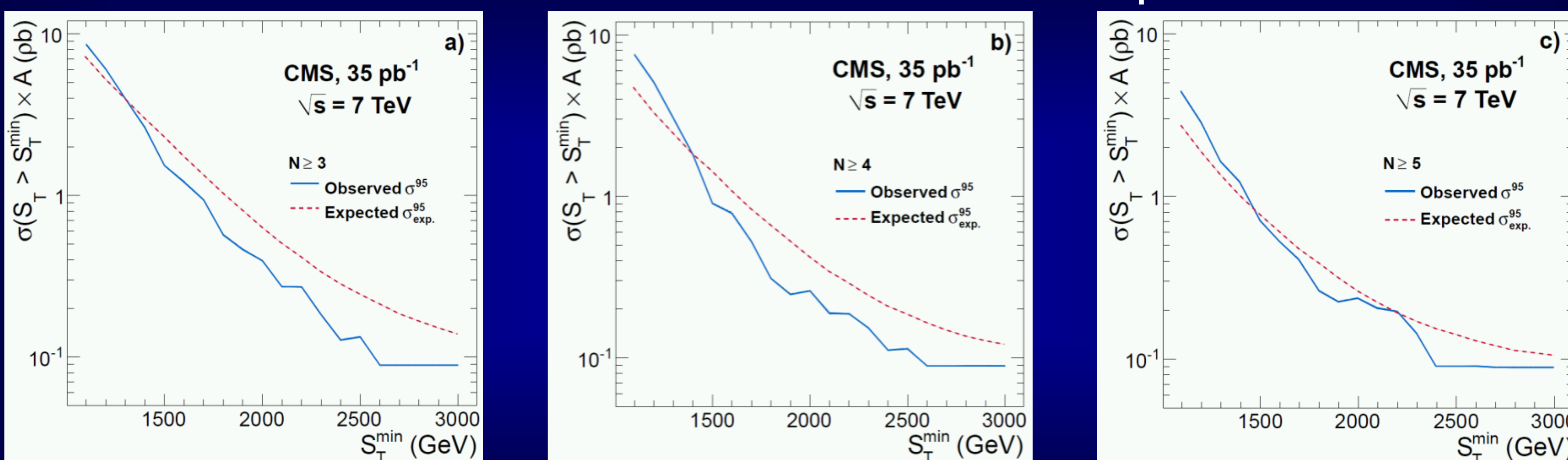
# Covering all Bayeses

CMS searched for:

- 1st generation leptoquarks in the two electron + two jet final state [redacted]
- 2nd generation leptoquarks in the two muon + two jet final state [redacted]
- Microscopic black holes [[redacted] see also [redacted]]

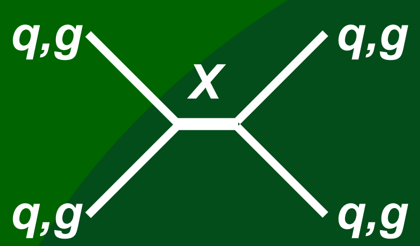
With statistical treatments identical to that in the W' search

The black hole search contains also model independent limits:




Only 10% worse, as one object multiplicity (N) dominates the signal models

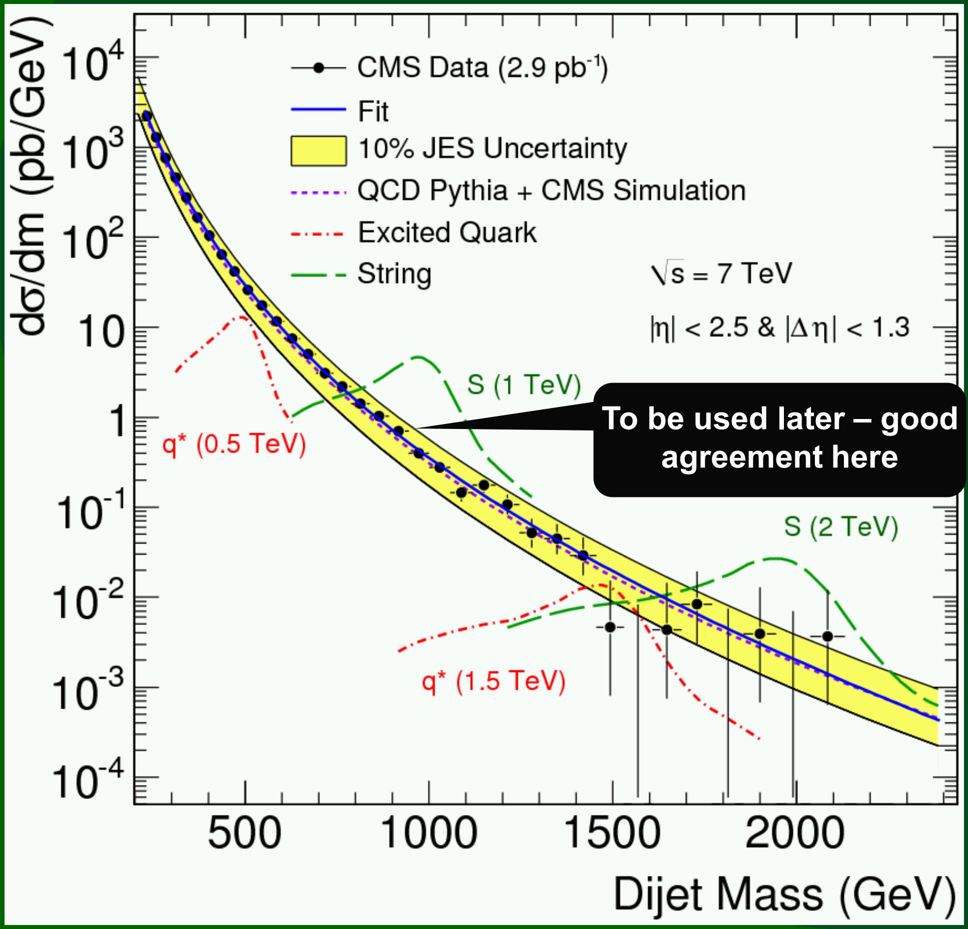
# Dijet resonance search




***Models***

- dijet resonances common in new physics models
- eight specific models studies in paper
- signal models for $qq$, $qg$ and $gg$ final states

→ also model-independent limits




***Experimental signature*** - the two jets…

- Single jet trigger required
- $|\eta_1, \eta_2|<2.5$ and $|\Delta\eta|<1.3$

***Observable***

Event counts as a function of dijet mass

- binning predefined. Width ≈ resolution.

***Background estimate***

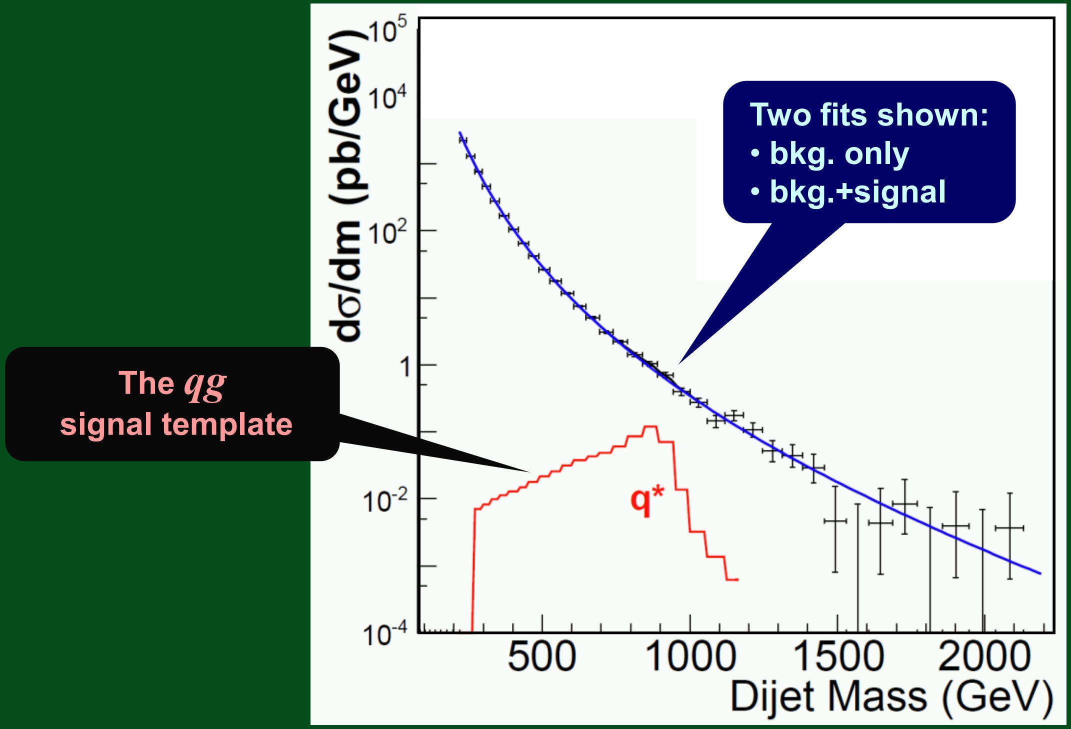
By fit. Best is with 4 parameter function:

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{p_2 + p_3 \ln\left(\frac{m}{\sqrt{s}}\right)}}$$

- “best” is out of 3 predefined functional forms
- $\chi^2$ / ndof = 32 / 31

# Resonance significance

The JES uncertainty band may visually overstate the data – fit agreement, due to bin-to-bin correlations →quantify the biggest discrepancy in 0.5 – 2.0 TeV




- Fluctuation at mass of 900 GeV has local significance of 1.7σ from LLR ($\Delta\chi^2$)
- Significance reduced to **0.2σ** accounting for "look elsewhere effect."
  - p-value calibrated using ensemble tests
- No resonance observed → proceeding to set limits

# Limit setting & systematics

Statistics-only Bayesian limit setting

- A counting experiment (Poisson probabilities)
- No interference between backgrounds and signal

For each $m_{res}$:

- For each $m_{jj}$ bin:

$$N_{pred} = b + \mathcal{L}\varepsilon\sigma_{eff}$$

Integrated luminosity → $\mathcal{L}$

$b$ from background + signal fits

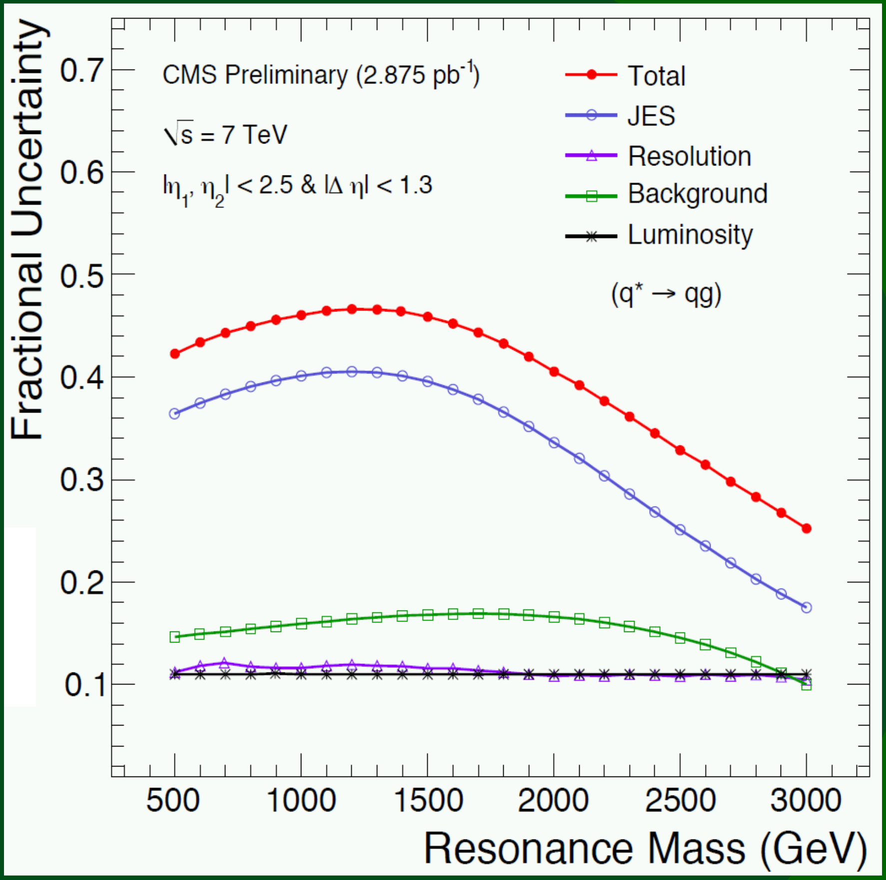
Signal template → $\varepsilon$

- Uniform prior for the cross section:

$$p(\sigma_{eff}) = \begin{cases} \text{const} & \text{if } 0 < \sigma_{eff} < \sigma_{max} \\ 0 & \text{otherwise} \end{cases}$$

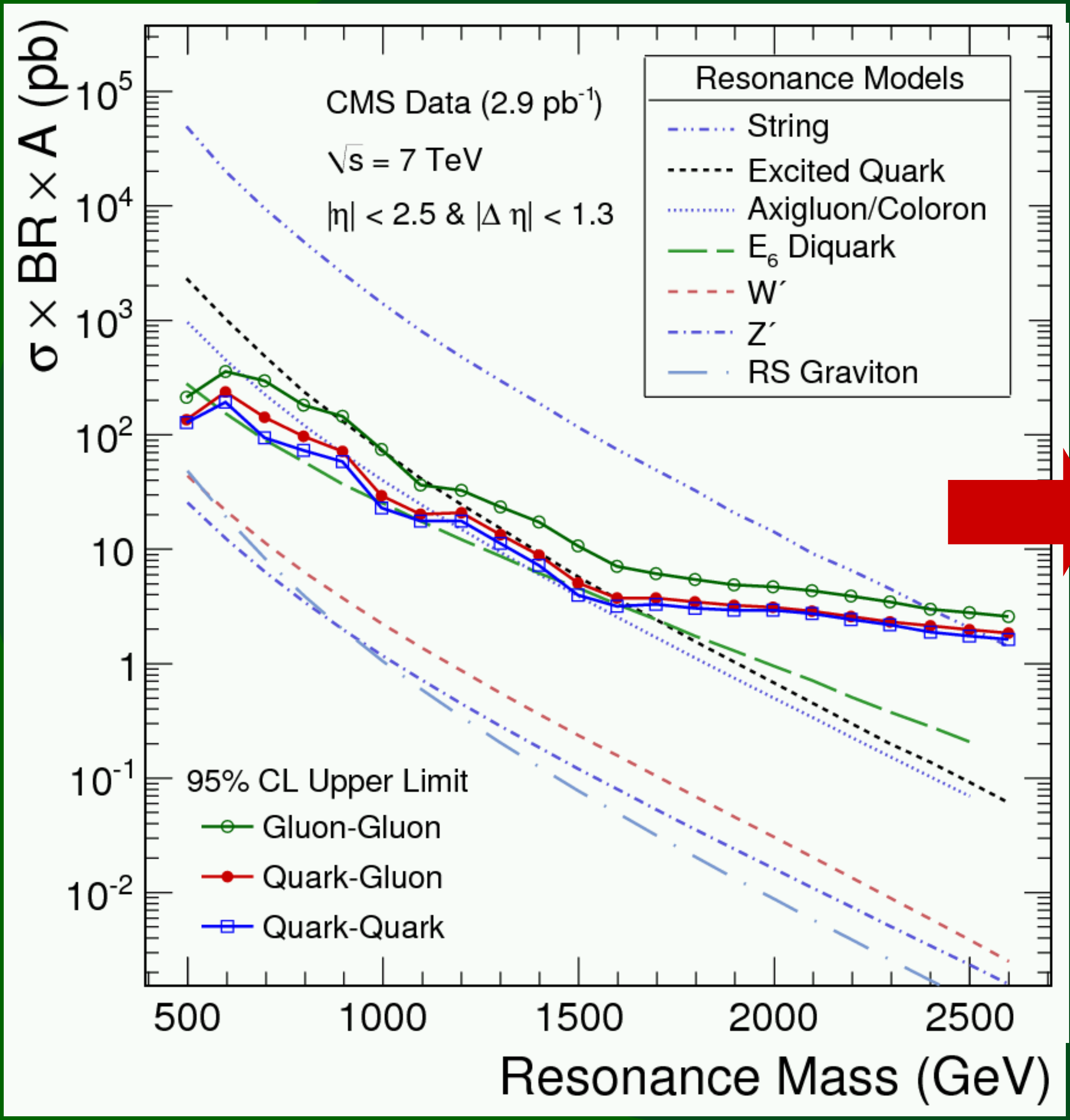
Incorporate systematic uncertainties at each mass by smearing the posterior $p(\sigma)$ with a Gaussian

- Approximate, but here, also conservative
- Verified frequentist coverage at 1TeV for $\sigma$=limit value
  - Without systematics, coverage ~95%
  - With JES systematic, coverage >98%




- Systematic uncertainties increase cross section limits by 15-50% depending on resonance mass and parton content
- Mass limits decrease by ~10% with inclusion of systematic uncertainties

# Results




| Model | Exclusion regions [TeV] |
|---|---|
| String resonance | 0.50 – 2.50 |
| Excited quark | 0.50 – 1.58 |
| Axigluon / Coloron | 0.50 – 1.17 & 1.47 – 1.52 |
| $E_6$ diquark | 0.50-0.58, 0.97-1.08, & 1.45-1.60 |

# $CL_s$

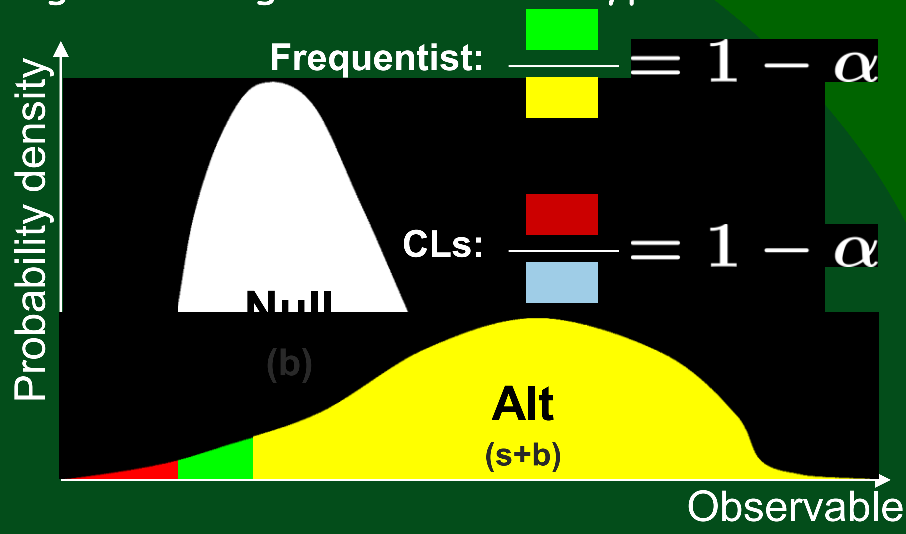
# The CLs method

The CLs method is to exclude regions of phase space where

where $\alpha$ is the desired confidence level

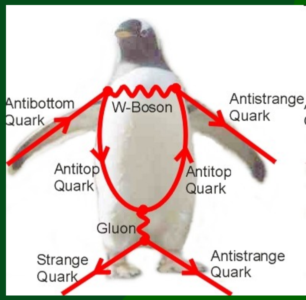
- an LLR observable is recommended
- sometimes a statistics-only LLR used

E.g. excluding an alternative hypothesis




***Criticism***

- "What a horrible name!" Still, it's just a name
- Fundamentally unsound – neither frequentist nor Bayesian




***But***

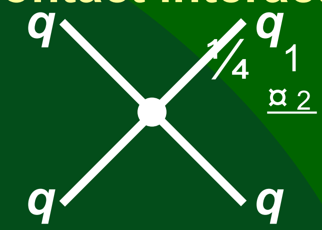
- Corresponds to frequentist limits when experiment is fully sensitive
- (Partially?) satisfies the real need for power constraints
  - graceful degradation
  - has been producing sensible results for over a decade

# Quark compositeness

***Model***

- Quark compositeness will first appear as a contact interaction
- Model independent turn-on, details can vary at high energies

**Contact interaction**

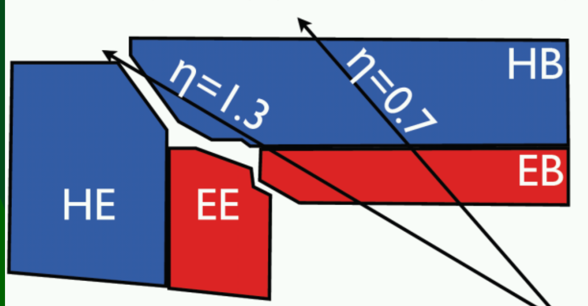



***Experimental signature***

Enhanced central dijet production

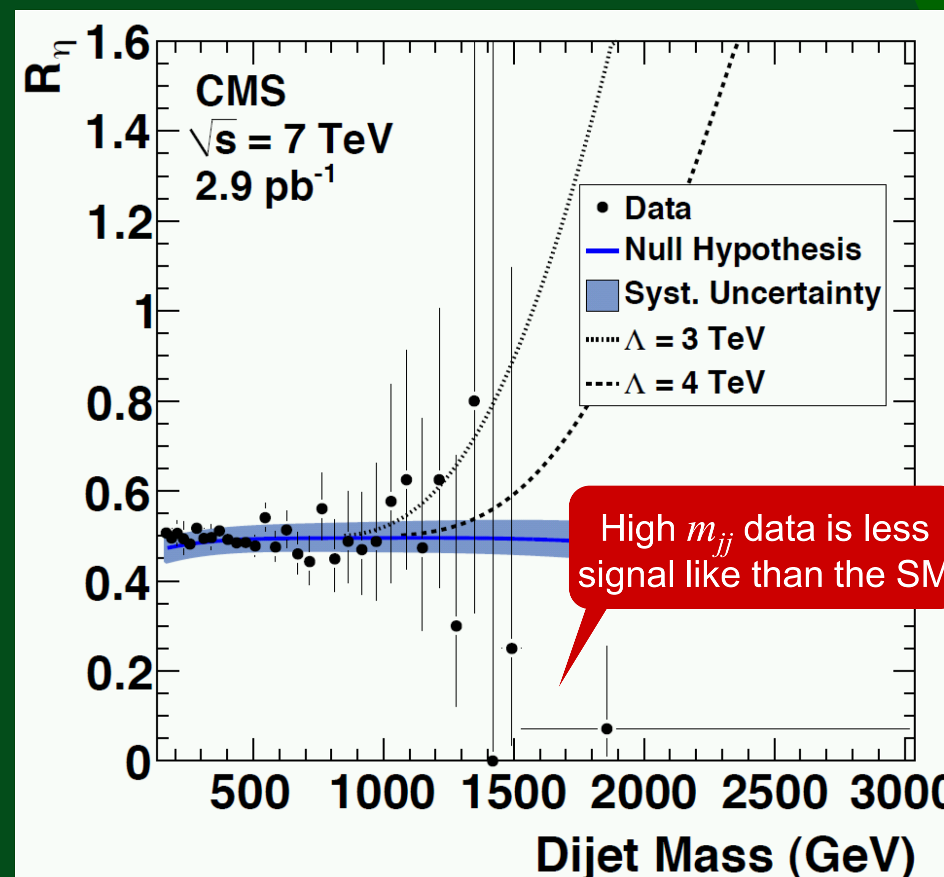
***Observable***

$$R_\eta = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)} = \frac{N(\text{inner})}{N(\text{outer})}^*$$




*Both jets inner or outer.

- "Ratio of Poisson means" problem
- $m_{jj}$ binning as dijet resonance search




***Background estimate***

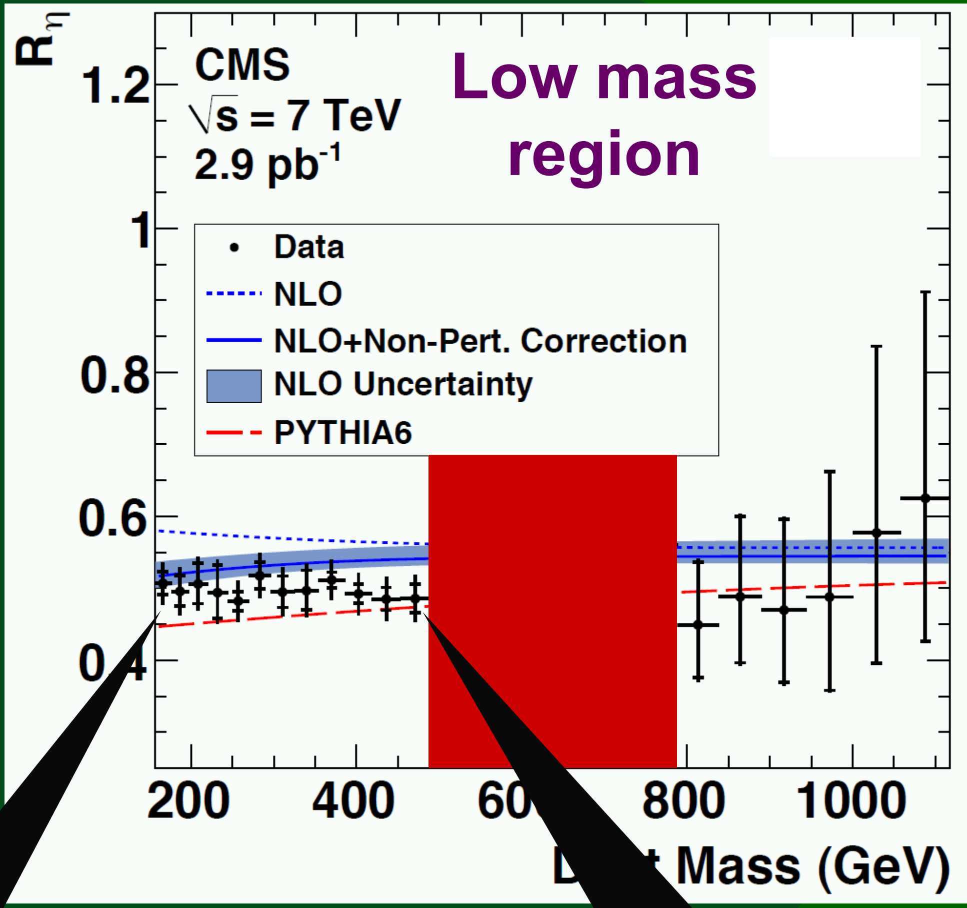
NLO calculations + NP corrections +
a shift from a fit to data in a low $m_{jj}$ region

# $R_\eta$ and SM

Shift from the normalization is:

Fit to data gave an offset of:

- Two sided p-value (from ensemble testing with full systematic variations) is 0.29




## Overall, data consistent with SM

Offset for entire range:

$$-0.037 \pm 0.007(\text{stat.}) \pm 0.039(\text{syst.})$$

- Two sided p-value is 0.34

→ Proceeding to set limits on $\Lambda$

**Vertical line: total uncertainty**

**Horizontal tick: statistical uncertainty**

Note: Hard to estimate consistency with this visualization

# Implementing $CL_s$

All probabilities conditioned on the observed total (inner + outer) number of events for that $m_{jj}$ bin

- Standard and extremely useful treatment of "Ratio of Poisson means" problem

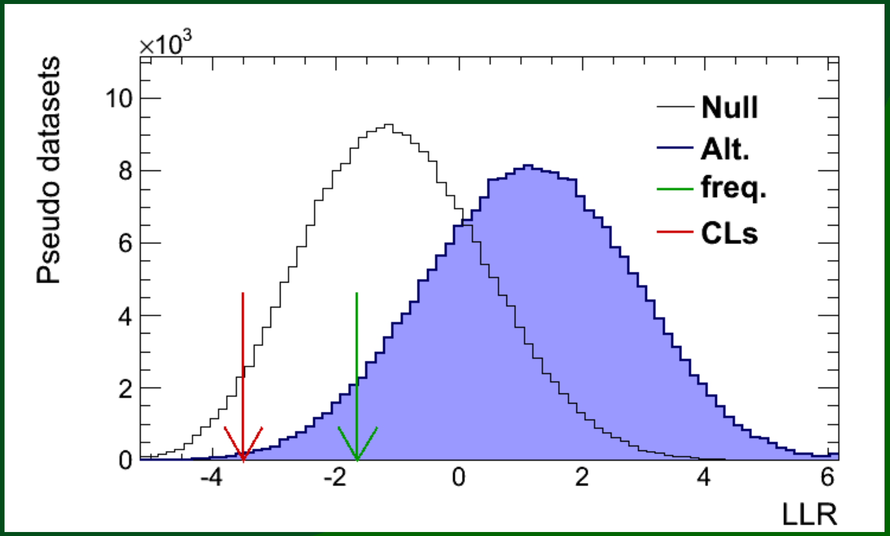
  [Przyborowski and Wilenski, "Homogeneity of results in testing samples from Poisson series with an application to testing clover seeds for dodder", Biometrika 31 (1940)]


Test statistics is the log likelihood ratio for SM and SM+CI hypotheses

$$\mathcal{R}_{LL} = \ln\left(\frac{\mathcal{L}_{\mathrm{SM\ +\ signal}}}{\mathcal{L}_{\mathrm{SM}}}\right)$$

- Each $\Lambda$ value evaluated separately
- Brute force integration of nuisance parameters (i.e., ensemble tests)
- Low $R_\eta$ at high masses → Low $CL_b$
  → need to examine extreme tails of $CL_{s+b}$

A painful combination!

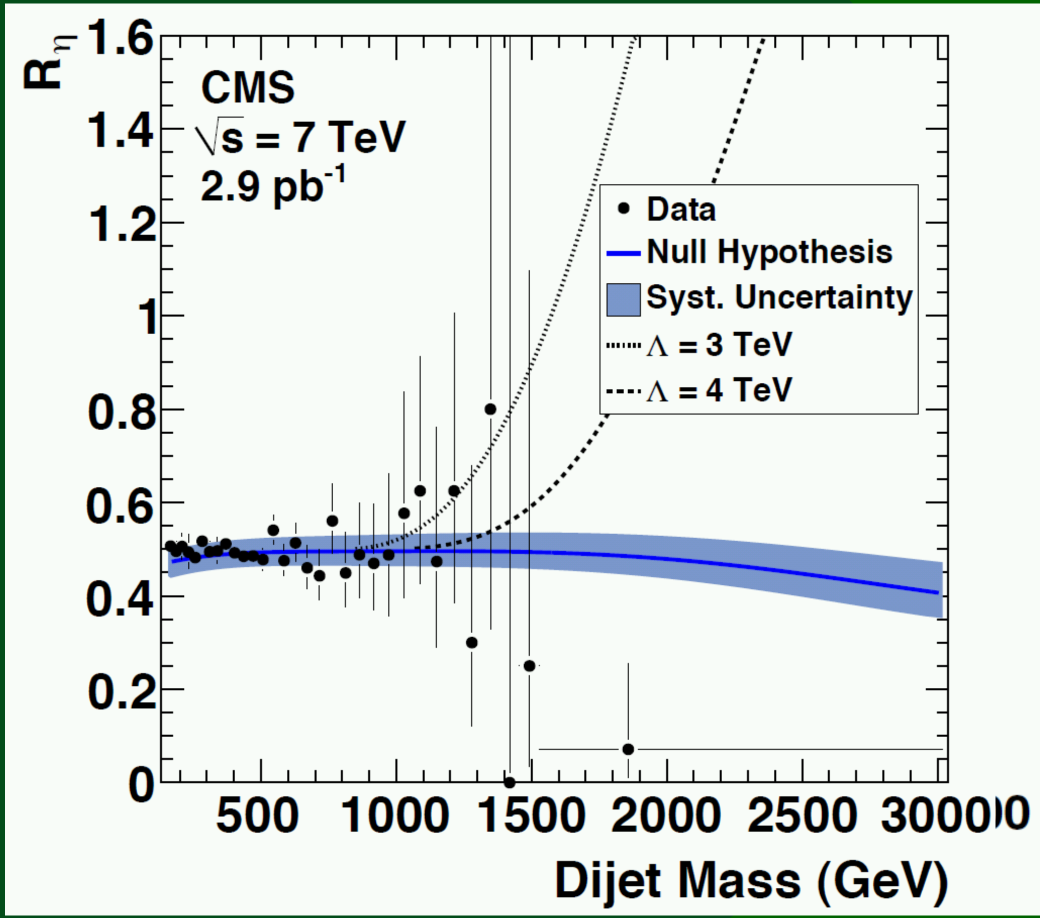



Stopping conditions:

- $\Lambda$ value included/excluded at 2σ level
- CLs value known at 0.5% accuracy

# Limits

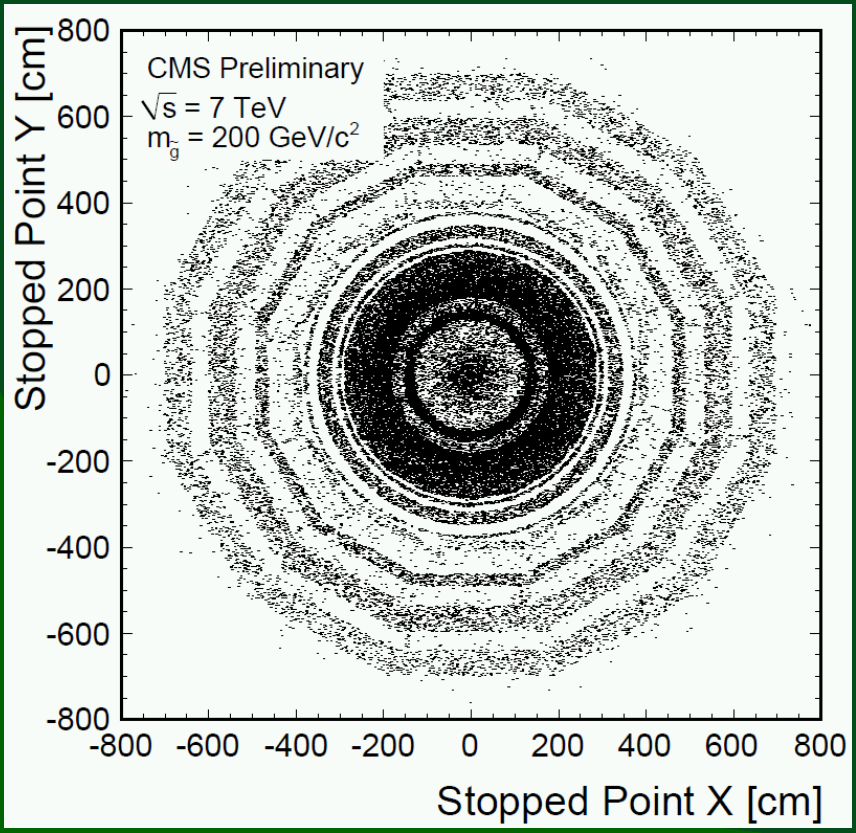
- Expected 95% CL exclusion is $\Lambda < 2.9\,\mathrm{TeV}$
- Exclude all models with $\Lambda < 4\,\mathrm{TeV}$ at 95% CL
  - Relevant tail probability $(CL_{s+b})$ is smaller than 1-$\alpha$ by a factor of >100



# Stopped gluinos

### Model

- New, heavy,quasi-stable particles
  - In particular, split SUSY
- Searching for charged R-hadrons
  - Lifetime: 75ns – $10^6$s, $m_{\text{gluino}}$: 150-500 GeV
  - Up to $10^6$s, since still expect to see an event




### Experimental signature

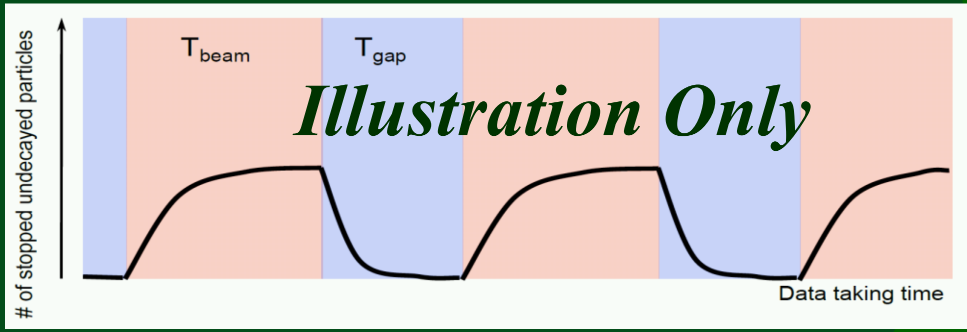
Out of time energy deposits in calorimeters

+ vetoes on cosmic rays, beam halo, detector noise

### Observable

Number of events with a lifetime window

- from 50ns to 1.256•$\tau_{\text{gluino}}$
- after each bunch crossing / fill




### SM-background rate

For each of the two strongest cuts:

$$R^{\text{after}}_{\text{search}} = R^{\text{before}}_{\text{search}} \frac{R^{\text{after}}_{\text{control}}}{R^{\text{before}}_{\text{control}}}$$

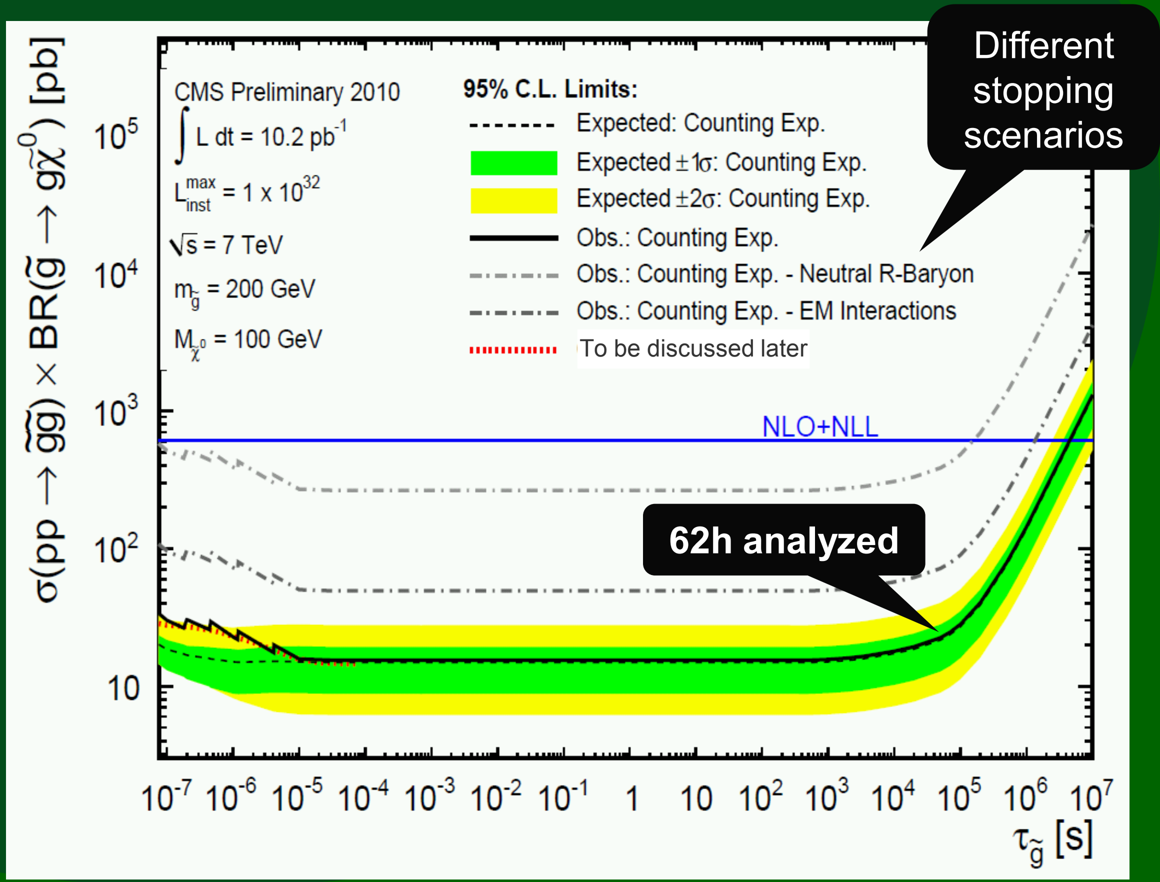
- strongest → $R^{\text{after}} \ll R^{\text{before}}$
- Uncertainties from stability in time, timing simulation, integrated luminosity

# CLs limits

| Lifetime [s] | Expected background (± stat. ± syst. ) | Observed |
|---|---|---|
| $10^{-7}$ | 0.8 ± 0.2 ± 0.2 | 2 |
| $10^{-6}$ | 1.9 ± 0.4 ± 0.5 | 3 |
| $\geq 10^{-5}$ | 4.9 ± 1.0 ± 1.3 | 5 |

No indication of signal
→proceed to set limits

- CLs method
- Nuisance parameters integrated out
  - Background rate 23%
  - Integrated luminosity 11%
  - JES 7%



# Back to Bayes

# Stopped gluinos – time profile

***2nd Observable***

The time of the selected events

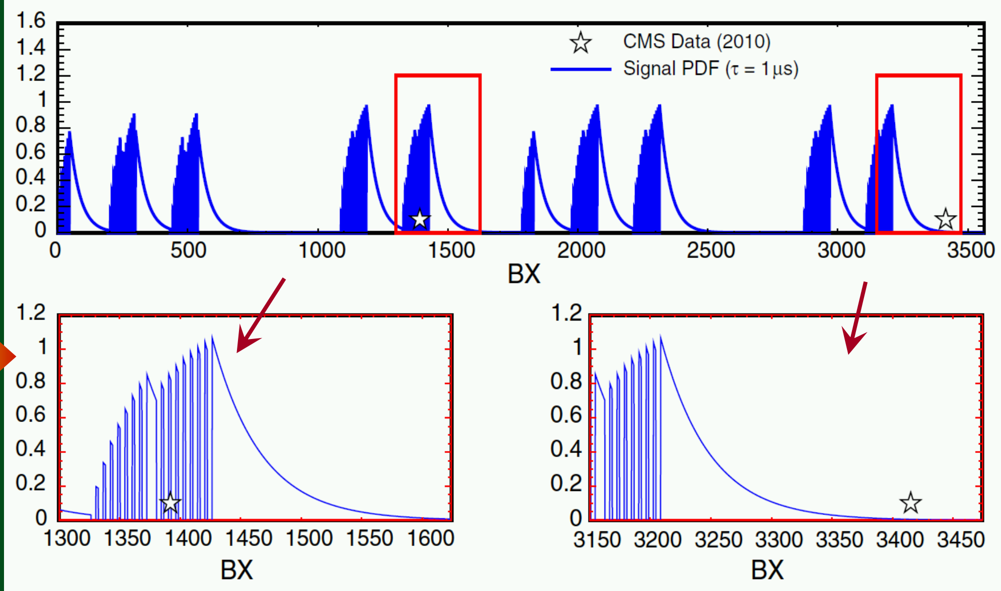
- same time windows

Signal shape

- depends on lifetime – 75ns to $10^{-4}$s

Background shape flat

- instrumental noise dominates




No indication of signal → proceed to set limits

- Calculate likelihood as a function of
  - background amount (per LHC filling scheme)
  - effective signal cross-section
- Calculate posterior probability using uniform priors in both
  - Limit from 95th quantile
- Nuisance parameters integrated out
  - Integrated luminosity 11%
  - JES 7%

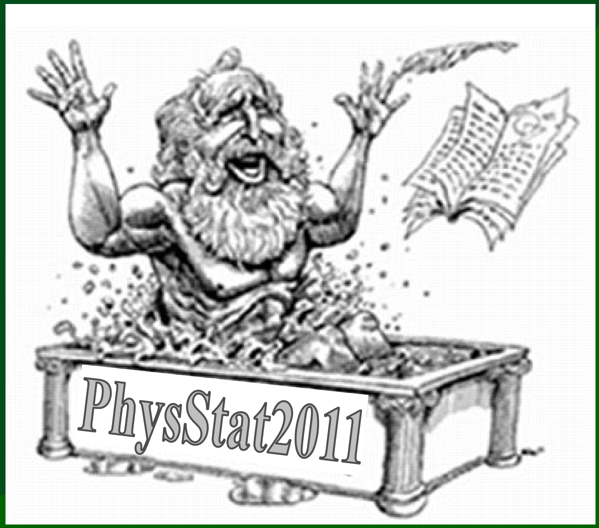
# Summary

CMS searches published using:

- Bayesian limits
  - prior constant as a function of searched for cross-section
- The CLs method
  - constraining the limits according to the power of the measurement is a must
  - Points to a need

Many ideas, methods, and checks based on Tevatron experience

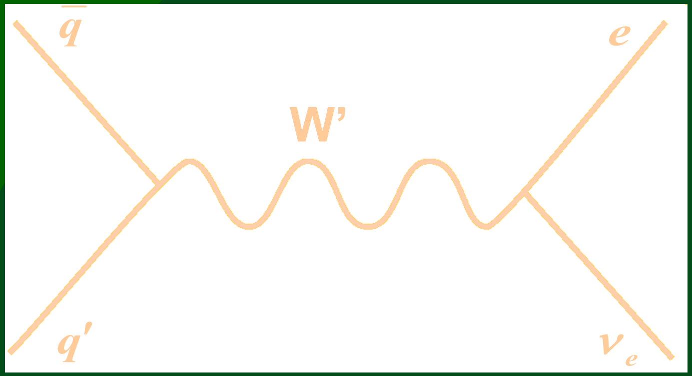
Will we have an LHC standard method?

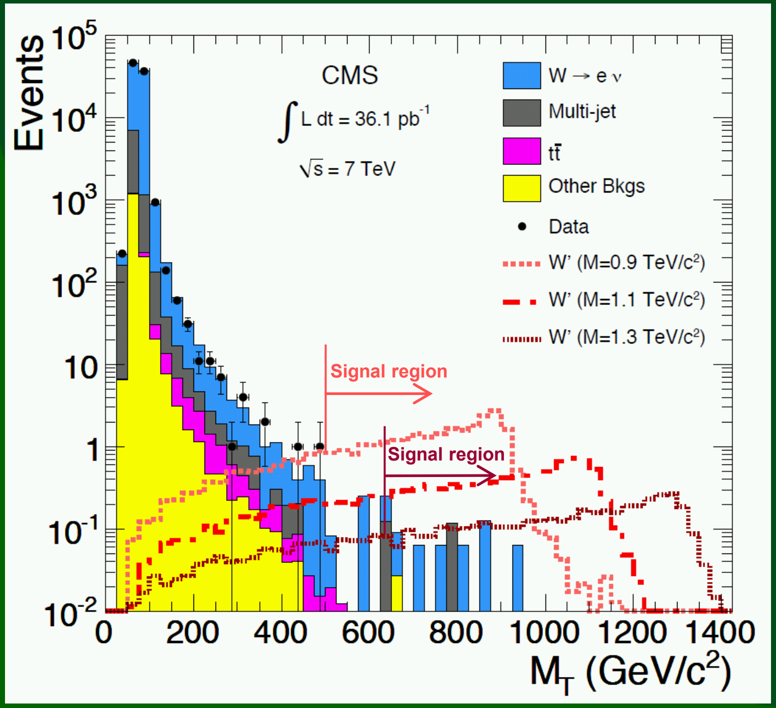


# Back up slides

arXiv:1012.4945 (hep-ex)

# W' search




### *Experimental signature*

- Isolated electron
  - $p_T$>30GeV, |η|<2.5
  - Triggers the data acquisition
- $p_T$ imbalance (done with energies though, $E^{miss}_T$)
  - from the full-event reconstruction "particle flow"
  - $\Delta\Phi_{eE_T^{miss}} > 2.6$
  - $0.4 < \frac{E_T^e}{E_T^{miss}} < 1.5$

### *Reference model*

- W' has W-like fermionic couplings,
- W' does not couple to other gauge bosons
- Tevatron limits: $m_{W'}$ > 1.1TeV
- signal from Pythia, cross section scaled to NNLO

### *Observable*

Number of events with $M_T$ > threshold

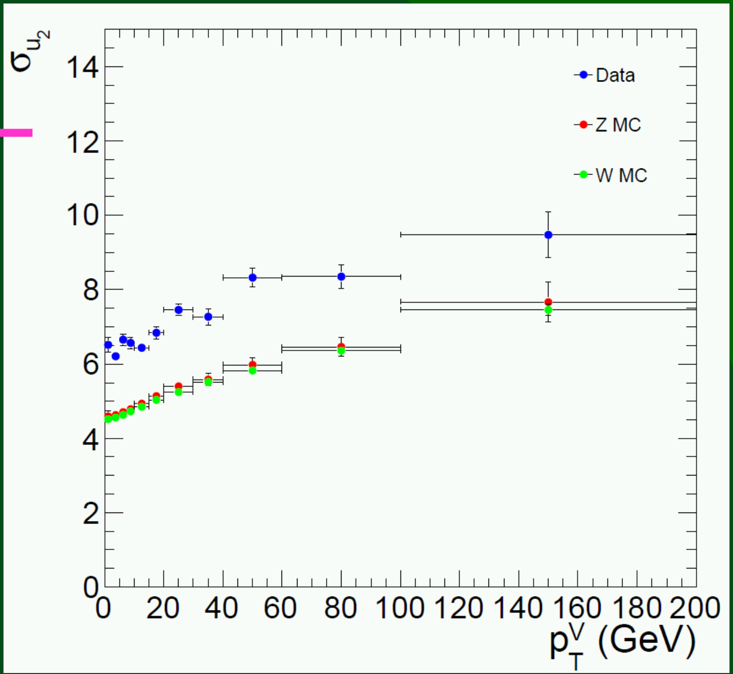
$$(M_T)^2 = 2E_T^e E_T^{miss}\left(1 - \cos\Delta\Phi_{eE_T^{miss}}\right)$$

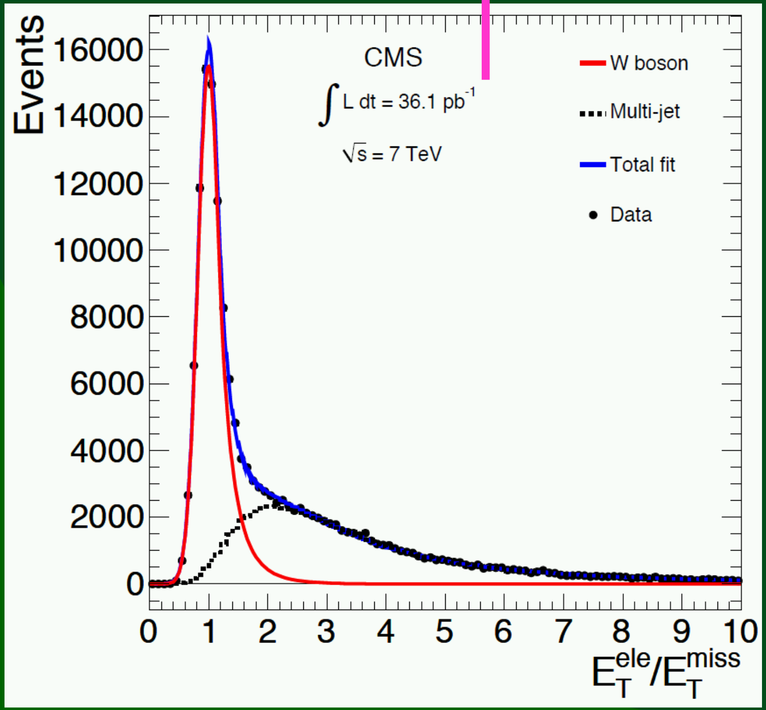
Threshold chosen a-priori as a function of $m_{W'}$

# W’ backgrounds

Estimating the main backgrounds:

- Hadronic recoil of W taken from Z data
    - not a big effect
- Multijet spectra taken from sample with non-isolated e candidates
- Their normalizations from a fit to the other-background subtracted data



# Black hole search

### *Model*

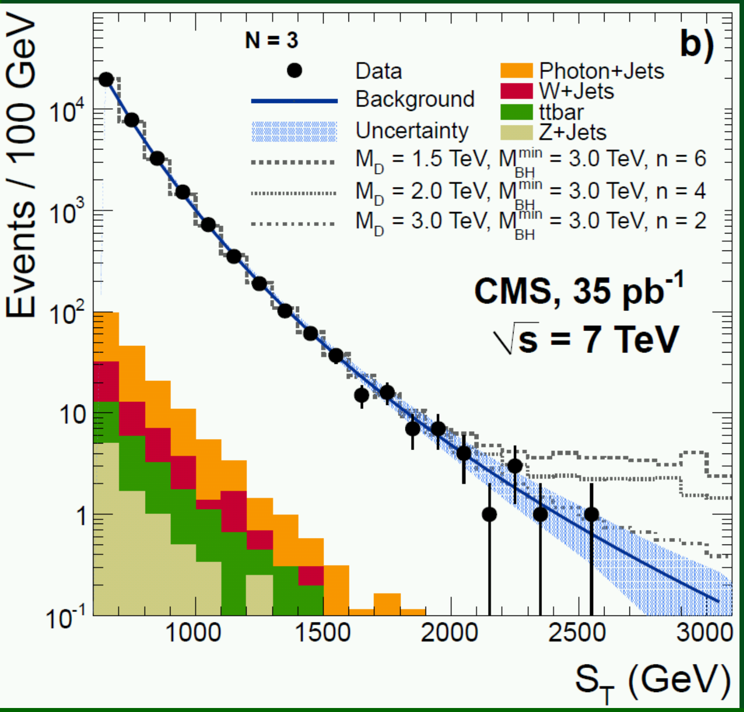
- ADD: $n$ large flat extra dimensions
  [Arkani-Hamed et al., PLB **429** (1998) 263]
  →lower Planck scale $M_D$
- Microscopic black holes in thermal equilibrium → decay via Hawking radiation
- Neglect energy untrapped by the black hole - too model dependent

### *Experimental signature*

Hawking radiation – democratic production

- All objects selected with $p_T$>20GeV
- Mostly quarks & gluons → jets
- Also electrons, photons and muons
- Objects separated by ΔR>0.3 (in Φ,η plane)
- Little graviton radiation expected
  [Emparan et al., PRL **85** (2000) 499]

Lots (at least >2) of them with large total $p_T$!




### *Observables*

N = Number of objects

$S_T$ = scalar sum of $p_T$s of objects with $p_T$>50GeV d

- low sensitivity to pile up & for QCD's ISR & FSR

Threshold chosen a-priori for each model

### *Signal*

- BlackMax / CHARYBDIS2 generator
- $$\sigma \approx \pi r_s^2 \propto \frac{1}{M_D^2}\left(\frac{M_{BH}}{M_D}\right)^{\frac{2}{2+n}}$$

# Black hole limit setting