Search for BSM Decaying to Top Quarks

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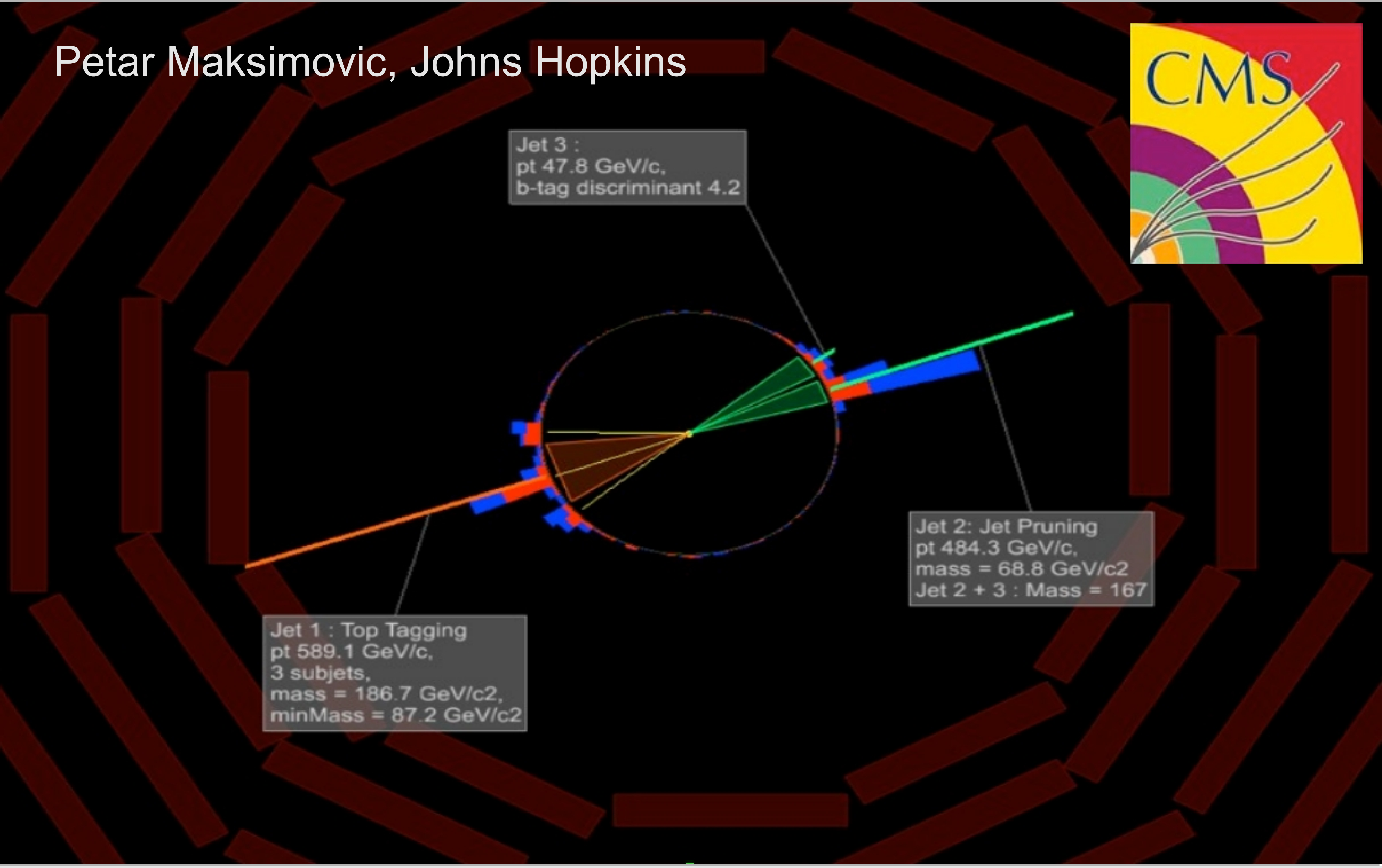
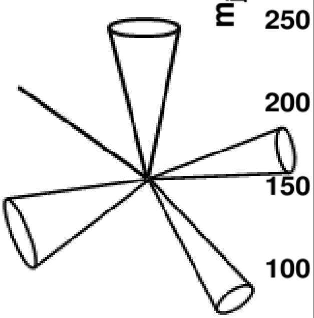


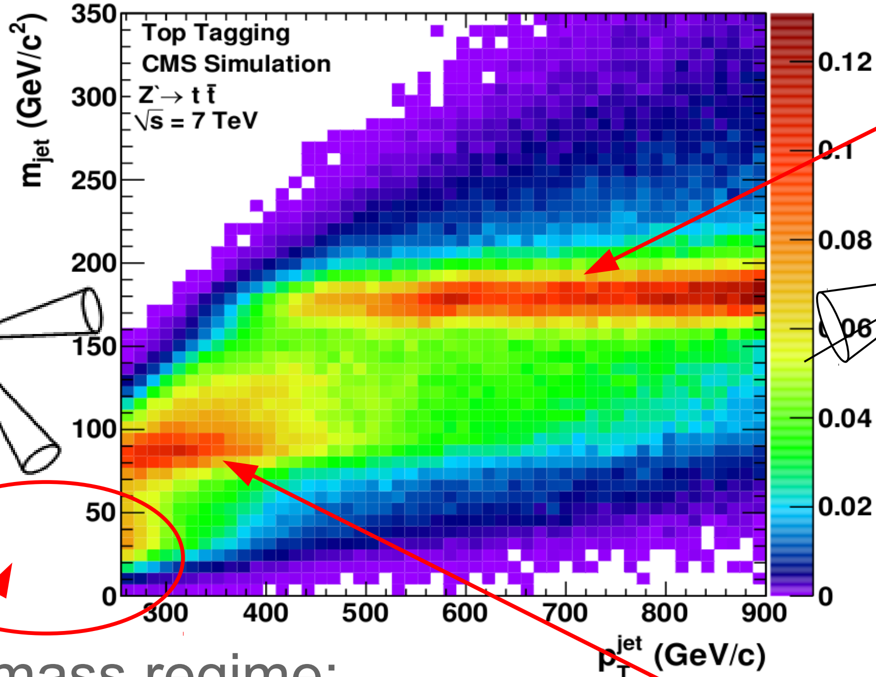
Why $t\bar{t}$?

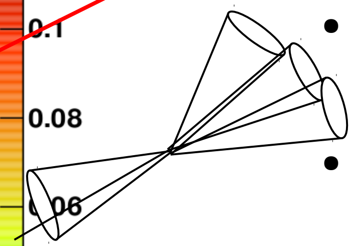
- In many BSM models, third generation is special (esp. top)
- Easiest to study the spectrum of $t\bar{t}$ invariant masses, $m_{t\bar{t}}$
  1) Narrow resonance (Γ << resolution)
  2) Not-so-narrow resonance (use Γ ~ 10% of mass)
  3) Enhancement of the spectrum (no bump)

→ model-independent search for BSM by studying $m_{t\bar{t}}$ distribution!

Three kinematic regimes







High mass regime:

- relativistic ("boosted") top quarks
- hadronic top decay products (jets) merge
- need to break them into sub-jets ...
- … using dedicated jet clustering tools
- no b-tagging

Low mass regime:

- isotropic event topology
- `standard' top selection
- combinatorial event reco. (kinematic fit)
- b-tagging

"Intermediate mass" regime:

- partially merged hadronic top decays
- neither high nor low mass work well
- b-tagging works

"Low mass" lepton+jets

TOP-11-009

- Event selection identical to $t\bar{t}$ cross-section measurement
  - isolated leptons (both μ and e), and $E_{\mathrm{T}}^{\mathrm{miss}} > 20\ \mathrm{GeV}/c$
- Top quarks not very energetic → no jet merging
  - Events reconstructed using a full kinematic fit
- Backgrounds:
  - QCD from data
    - normalization from template fit to $E_{\mathrm{T}}^{\mathrm{miss}}$
  - All other backgrounds ($t\bar{t}$, W+heavy flavor, W+light flavor) from MC
    - however, MC templates can morph according to systematics
      → to a large degree, data driven as well

"Low mass": systematics

Uncertainty	Variation	Type
Luminosity	4.5%	rate
Electron efficiency (trigger + ID + isolation)	3%	rate
Muon efficiency (trigger + ID + isolation)	3%	rate
$t\bar{t}$ cross section	15%	rate
Single top cross section	30%	rate
W/Z+jets yield	50%	rate
Drell-Yan yield	30%	rate
W/Z+c+X	100%	rate
W/Z+b+X	100%	rate
Muon multijet yield	50–75%	rate
Electron multijet yield	45–70%	rate
Jet energy scale	p_T,η dependent	shape
Jet energy resolution	6–20% per jet	shape
b tagging efficiency (b jets $p_T < 670$ GeV)	1.6–8% per jet	shape
b tagging efficiency (c jets $p_T < 670$ GeV)	Twice that for b jets	shape
b tagging efficiency ($p_T > 670$ GeV)	Twice that at 670 GeV	shape
Mistagging rate	11%	shape
Factorisation scale for W events	$\pm 1\sigma$ generator parameters	shape
$t\bar{t}$ modelling	$\pm 1\sigma$ generator differences	shape
Factorisation scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Matching scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Multiple collisions	8% inelastic cross section	shape

MC templates can morph in the Likelihood governed by these parameters!

"Low mass" e+jets: data and backgrounds

(μ+jets similar, in backup)

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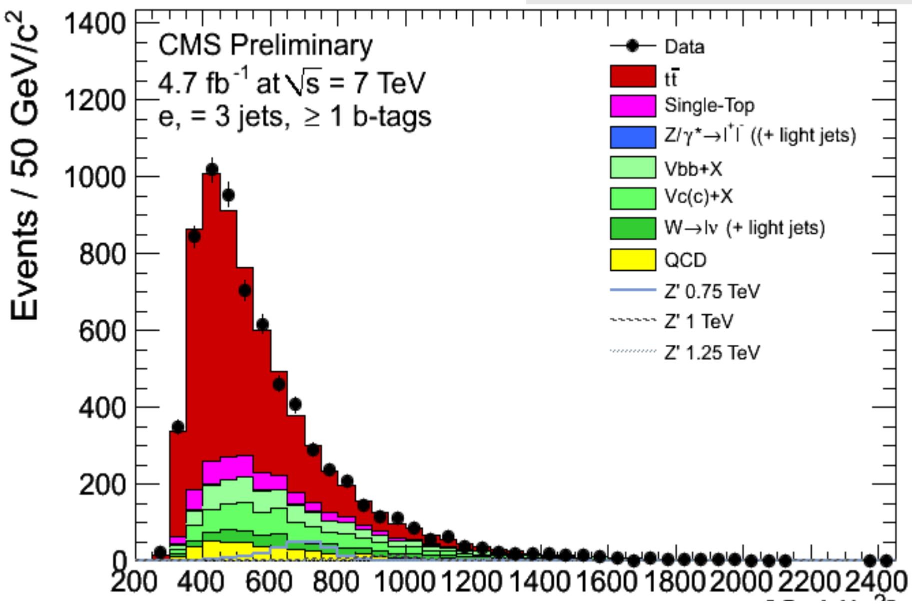

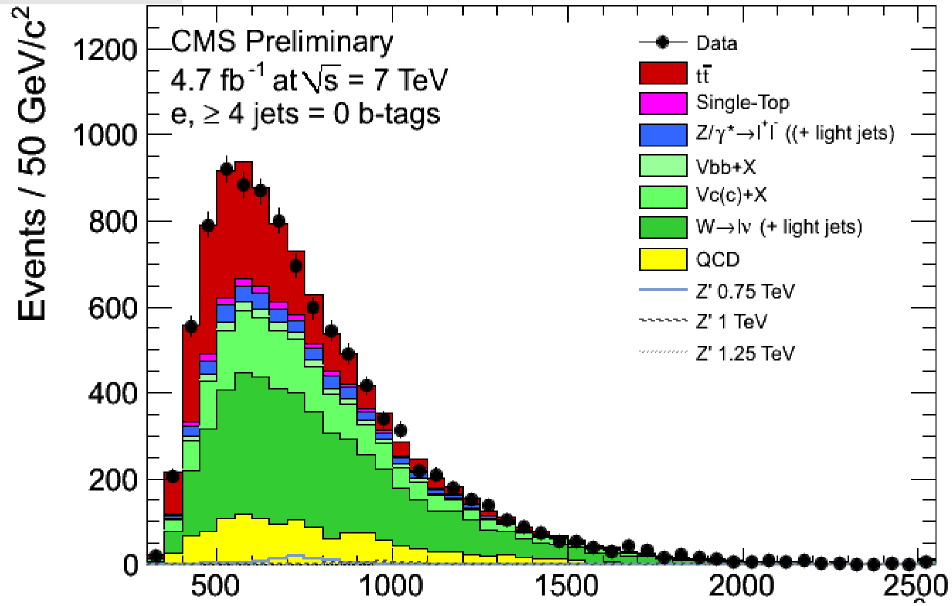

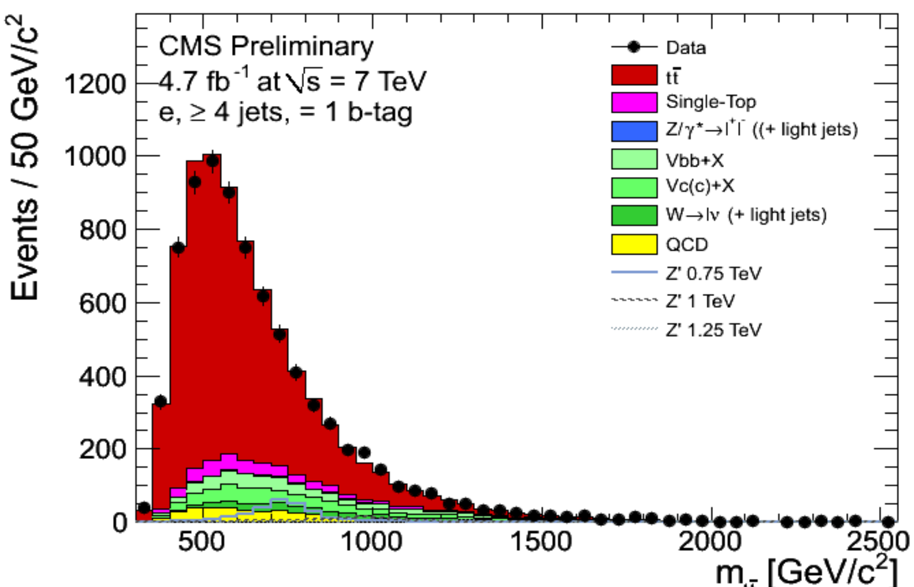

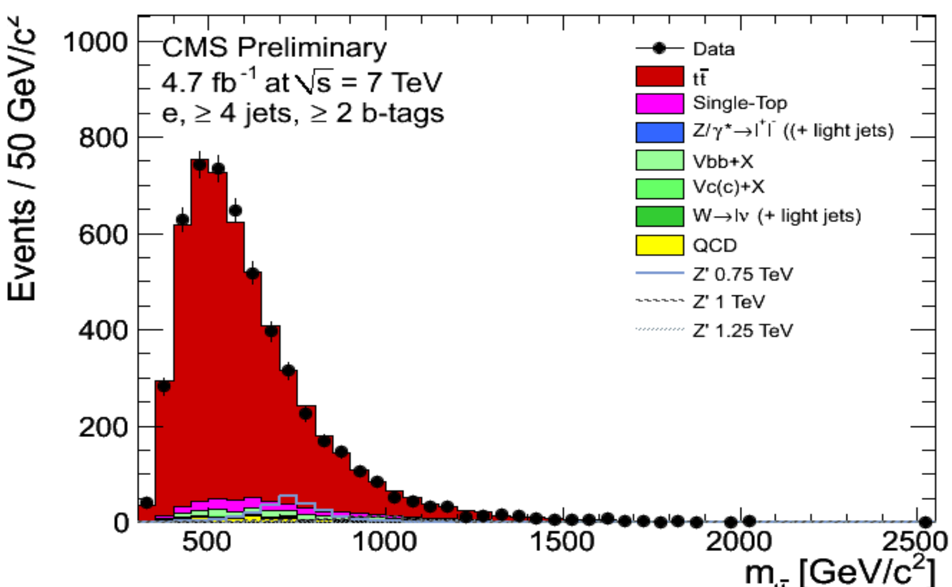

“Low mass” lepton+jets: limits

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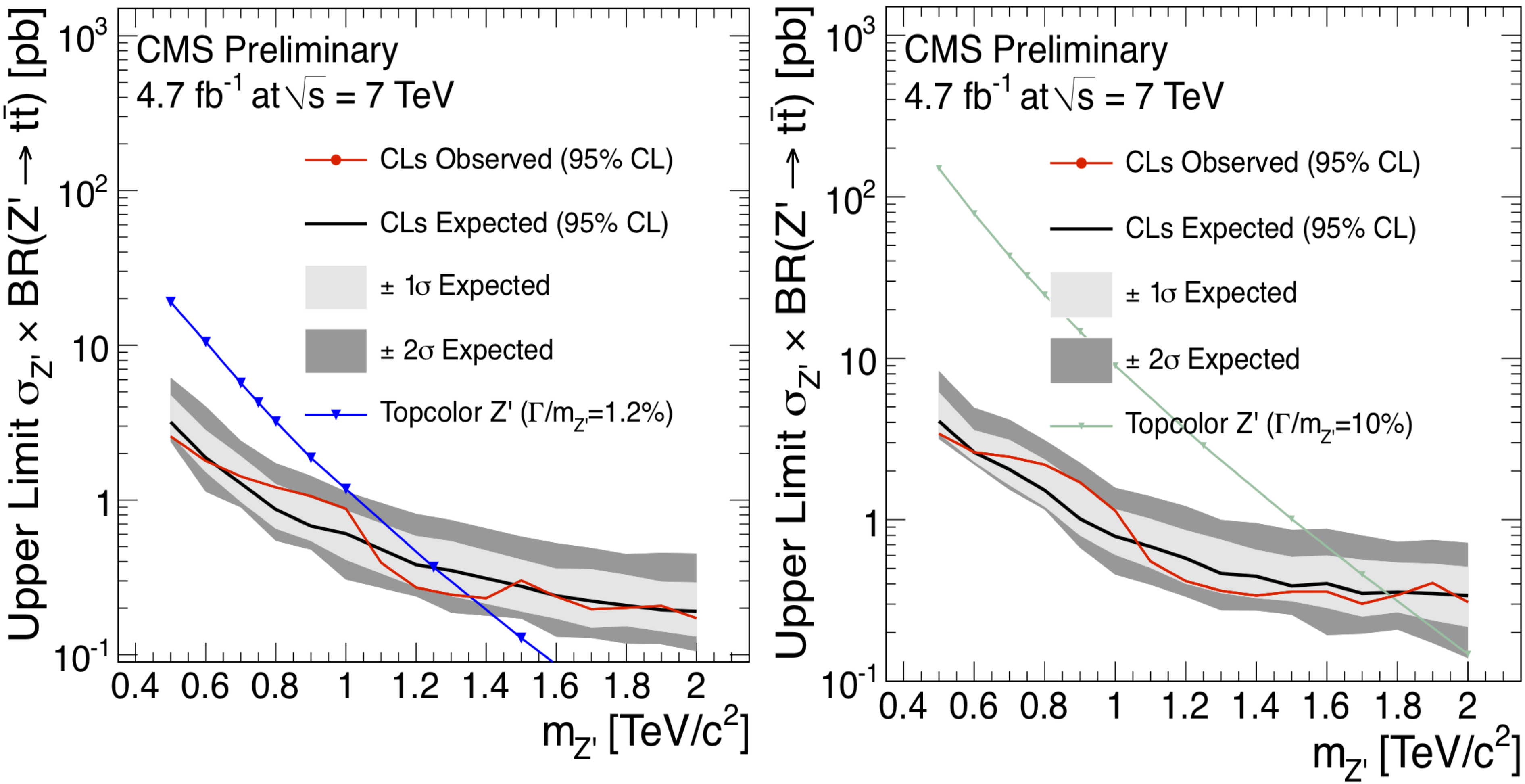

"Low mass" KK gluon limit

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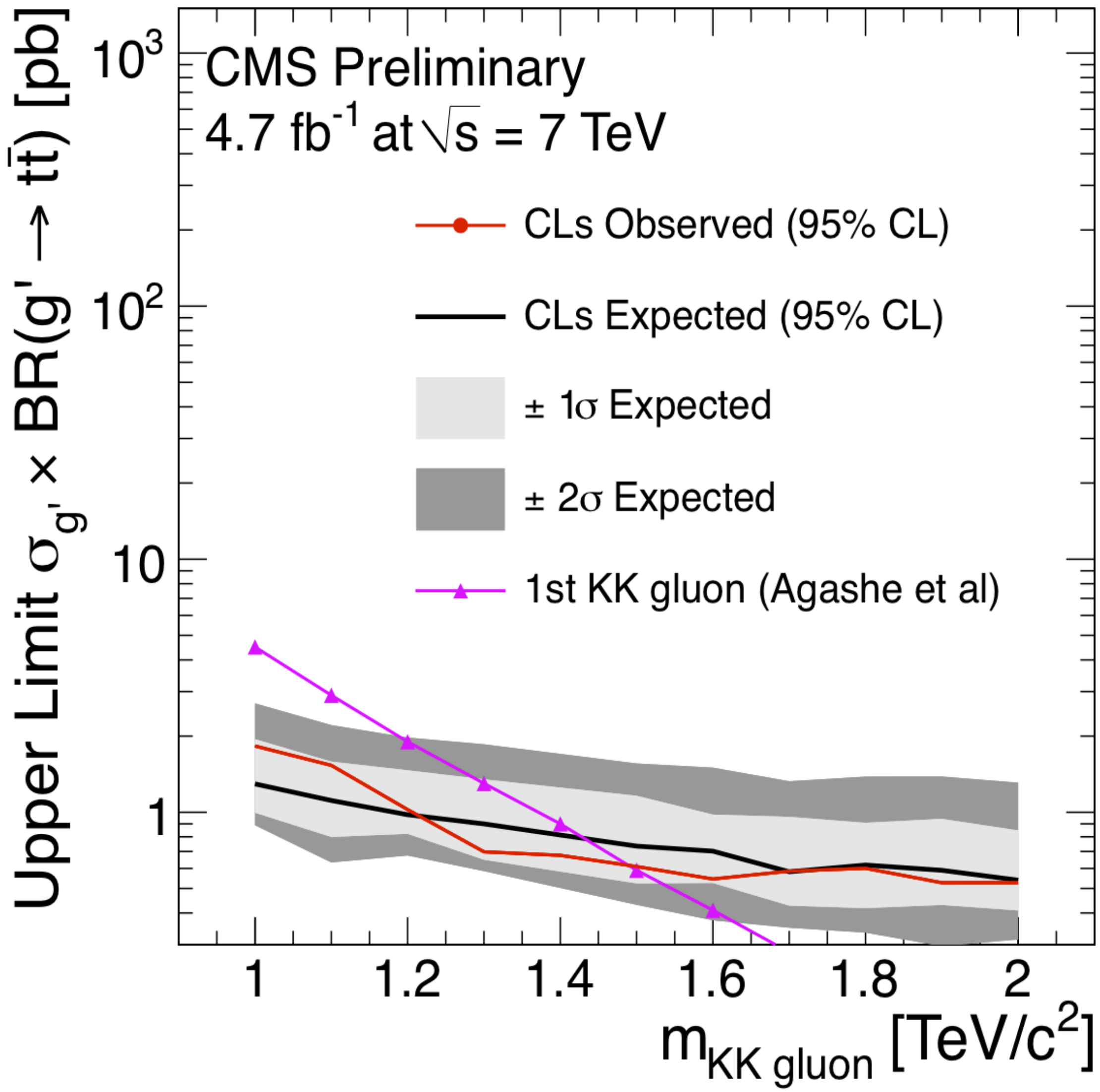

"High mass" lepton+jets

EXO-11-055

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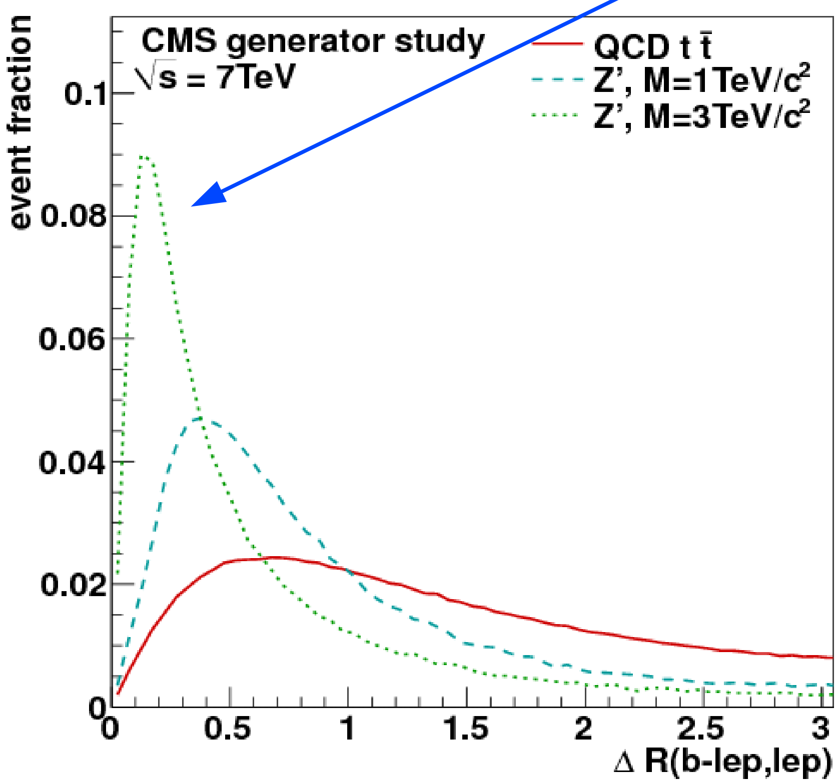
- More boosted, two well-separated hemispheres
- One side: lepton + b-jet, other side: likely merged top
- Trigger:
  - High quality electron, $p_T^e > 70\ \mathrm{GeV}/c$ and $|\eta| < 2.5$
  - High quality muon, $p_T^\mu > 35\ \mathrm{GeV}/c$ and $|\eta| < 2.1$
- Basic selection:
  - At least two jets within $|\eta| < 2.4$ with
    $$p_T > 150\ \mathrm{GeV}/c \text{ and } p_T > 50\ \mathrm{GeV}/c$$
  - Veto if there is second lepton (e or μ)
  - "2D cut" (isolation for boosted tops)
  - $H_T^{\mathrm{lep}} \equiv E_T^{\mathrm{miss}} + p_T^\ell > 150\ \mathrm{GeV}$ ($\approx p_T$ of W)

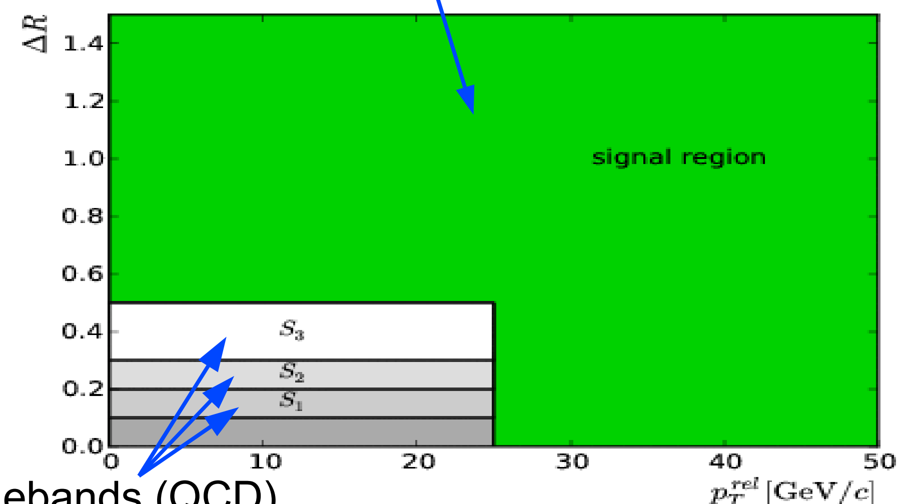
Lepton isolation for boosted tops?

- In "low mass" regime, lepton isolation is key to suppress QCD
  - isolation = cut on energy in a fixed cone around the lepton...
- Problem: as $p_T(t)$ increases, b-jet is closer to lepton → inefficient



- Solution: "2D cut":

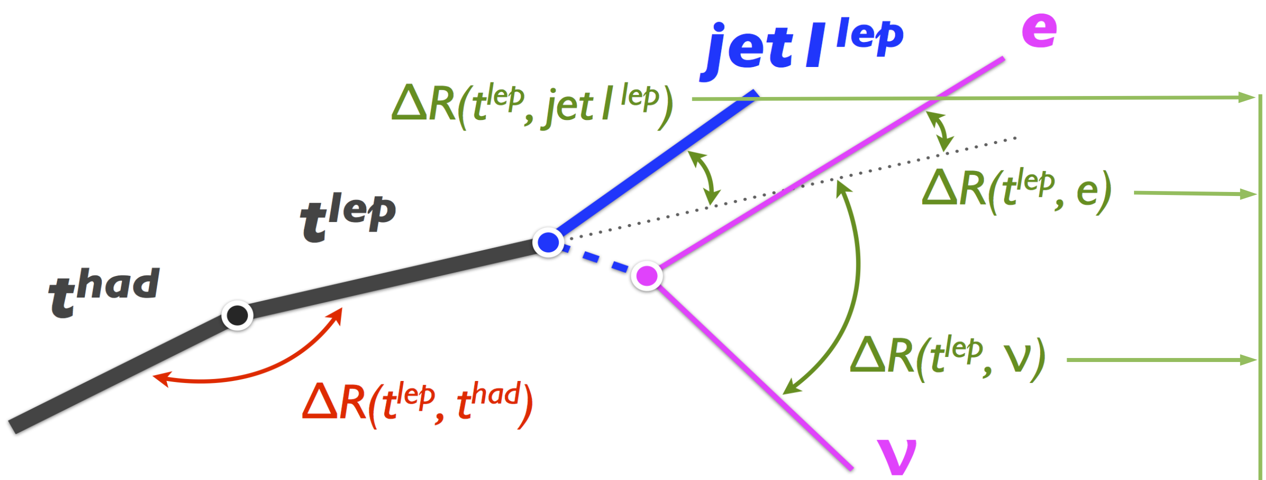
$$\Delta R(\ell, \text{closest jet}) > 0.5$$
$$\text{OR} \;\; p_T^{\text{rel}}(\ell, \text{closest jet}) > 25 \text{ GeV}/c$$



Reconstruction of $m_{t\bar{t}}$

- Reconstruct n's four-vector:
  - set $p_{\mathbf{T,\nu}}$ = MET
  - solve quadratic eqn.

$$p_{z,\nu}^{\pm} = \frac{\mu p_{z,\ell}}{p_{\mathrm{T},\ell}^2} \pm \sqrt{\frac{\mu^2 p_{z,\ell}^2}{p_{\mathrm{T},\ell}^4} - \frac{E_\ell^2 p_{\mathrm{T},\nu}^2 - \mu^2}{p_{\mathrm{T},\ell}^2}}$$



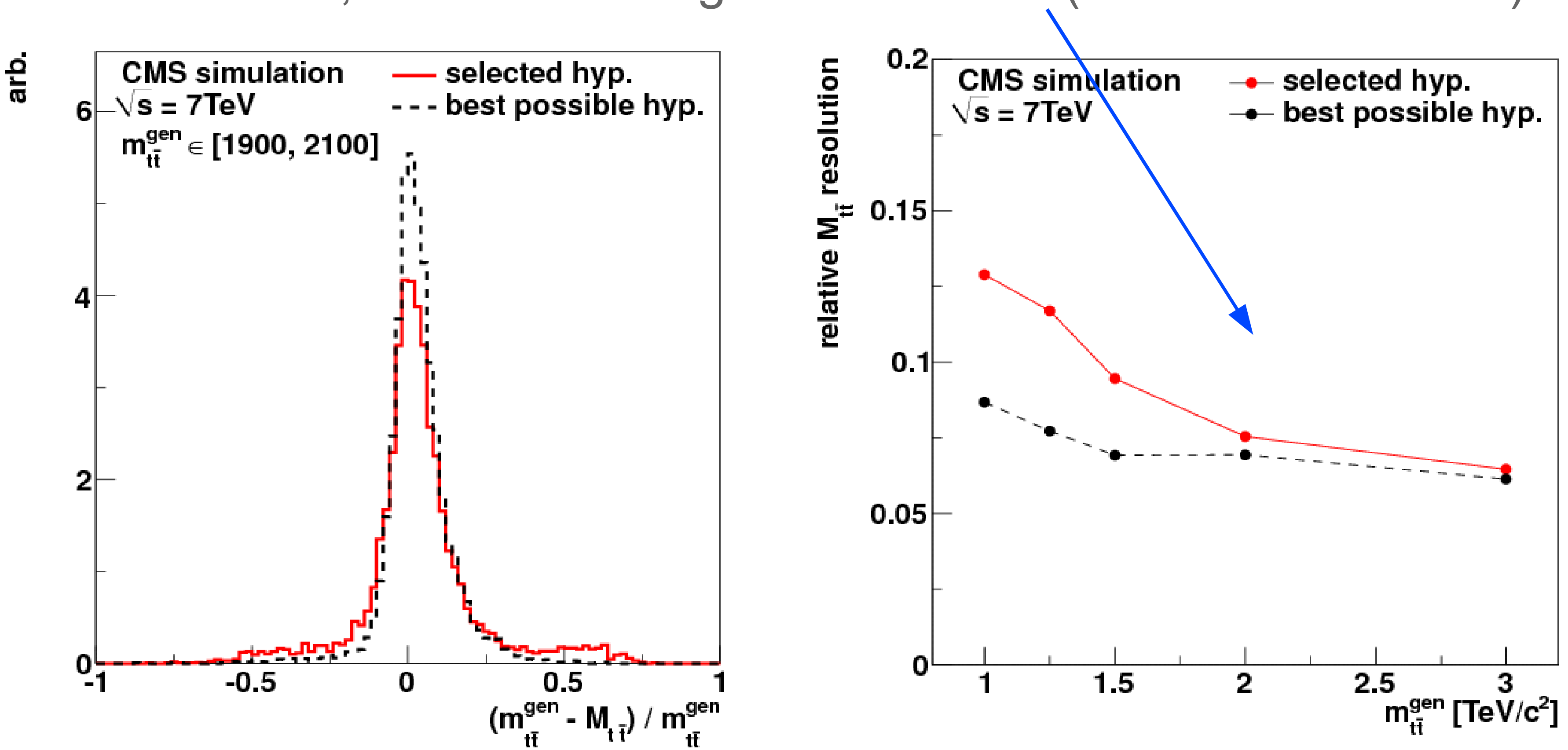
- Select which jet goes with W (lepton + "ν"): minimize

$$\Delta R_{\text{sum}} = \Delta R(b_l, t_l) + \Delta R(\nu, t_l) + \Delta R(\mathrm{l}, t_l)$$

Event reconstruction in “high mass” analysis

EXO-11-055

- Top decay products are well separated
- Simple jet-to-parton association is performed
- Works well, but better at higher Z' masses (more back-to-back)



Background determination

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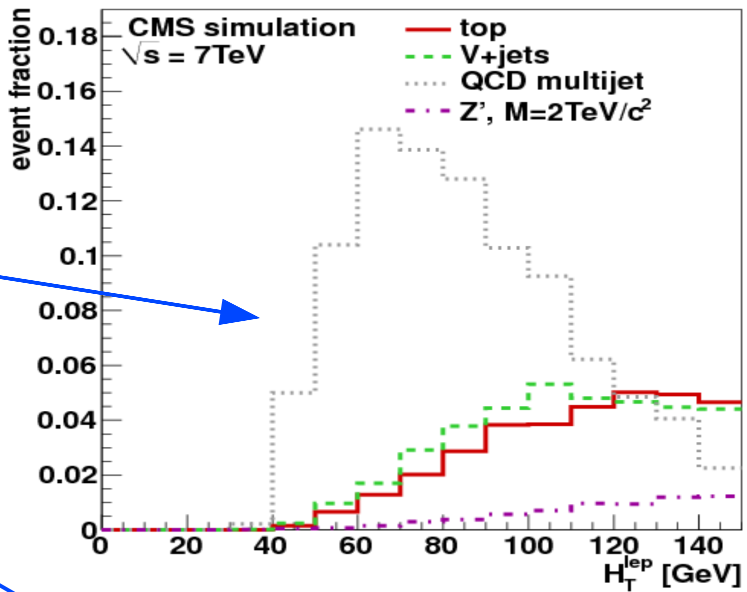
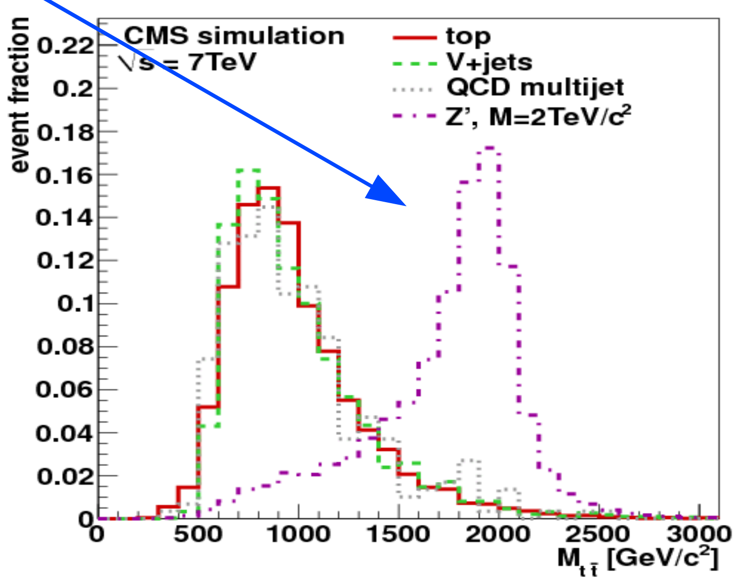
- Sample with low H_T^{lep} is signal depleted
    - Template fit of H_T^{lep} determines background normalizations
    - Used to define likelihood in the signal region (high H_T^{lep})
- We fit both simultaneously!
    - Likelihood = product of two likelihoods for 1D distributions of H_T^{lep} and $m_{t\bar{t}}$
    - Template morphing for shape-changing systematics





Result of background "fit"

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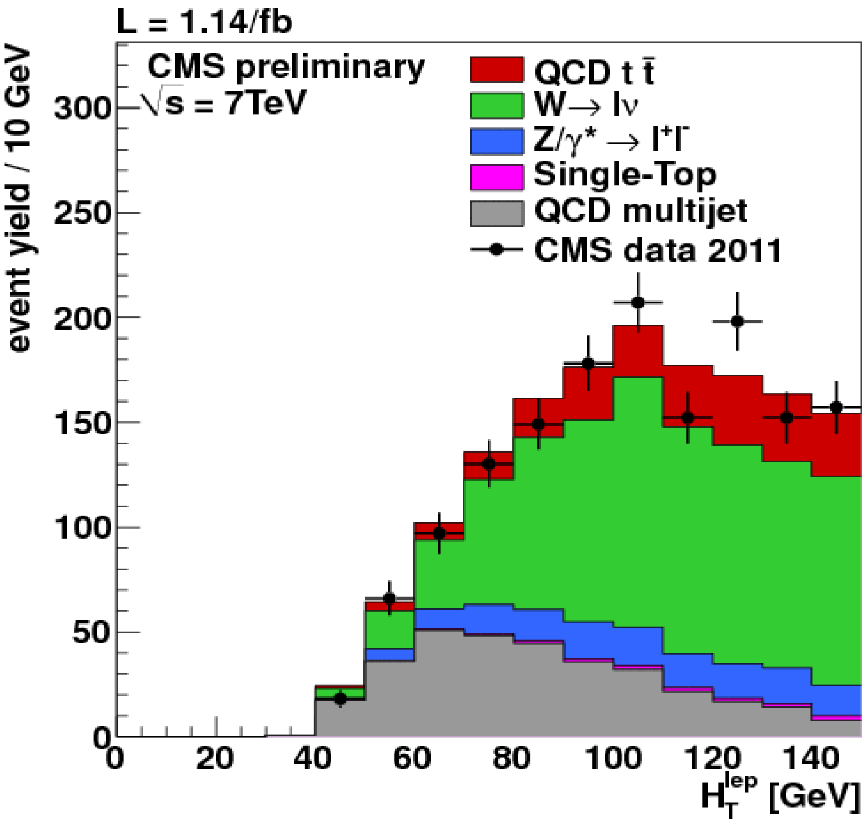
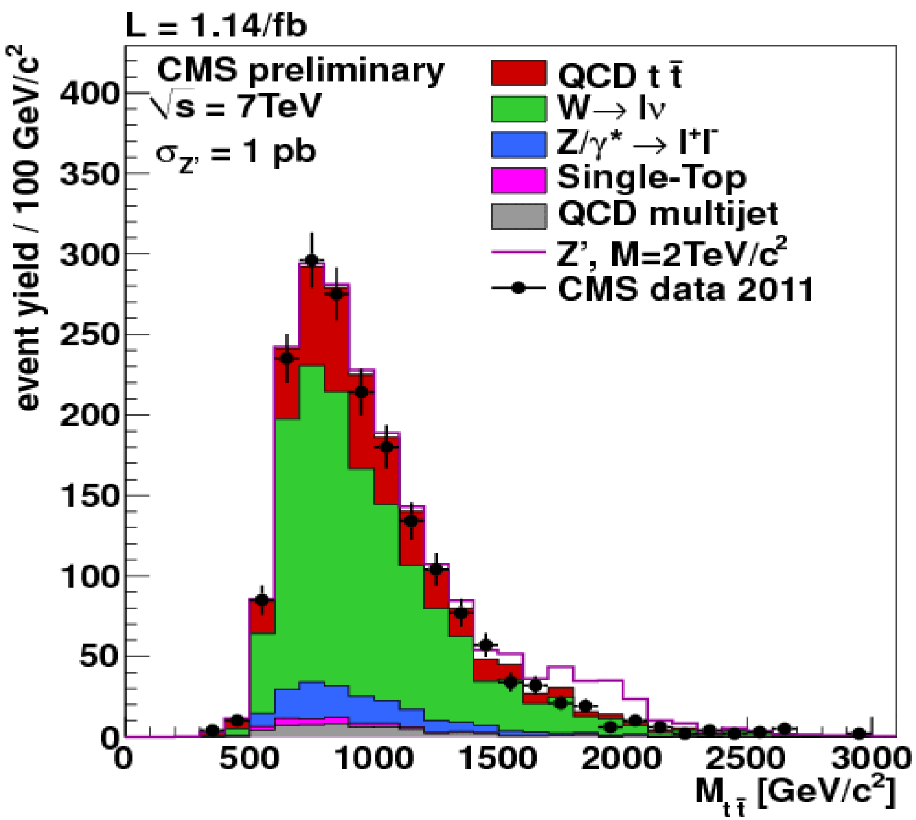
- In fact, not a fit, but Bayesian marginalization
  - Maxima of posteriors <==> "fit results"
- Dominated by W+jets (no b-tagging or top tagging)

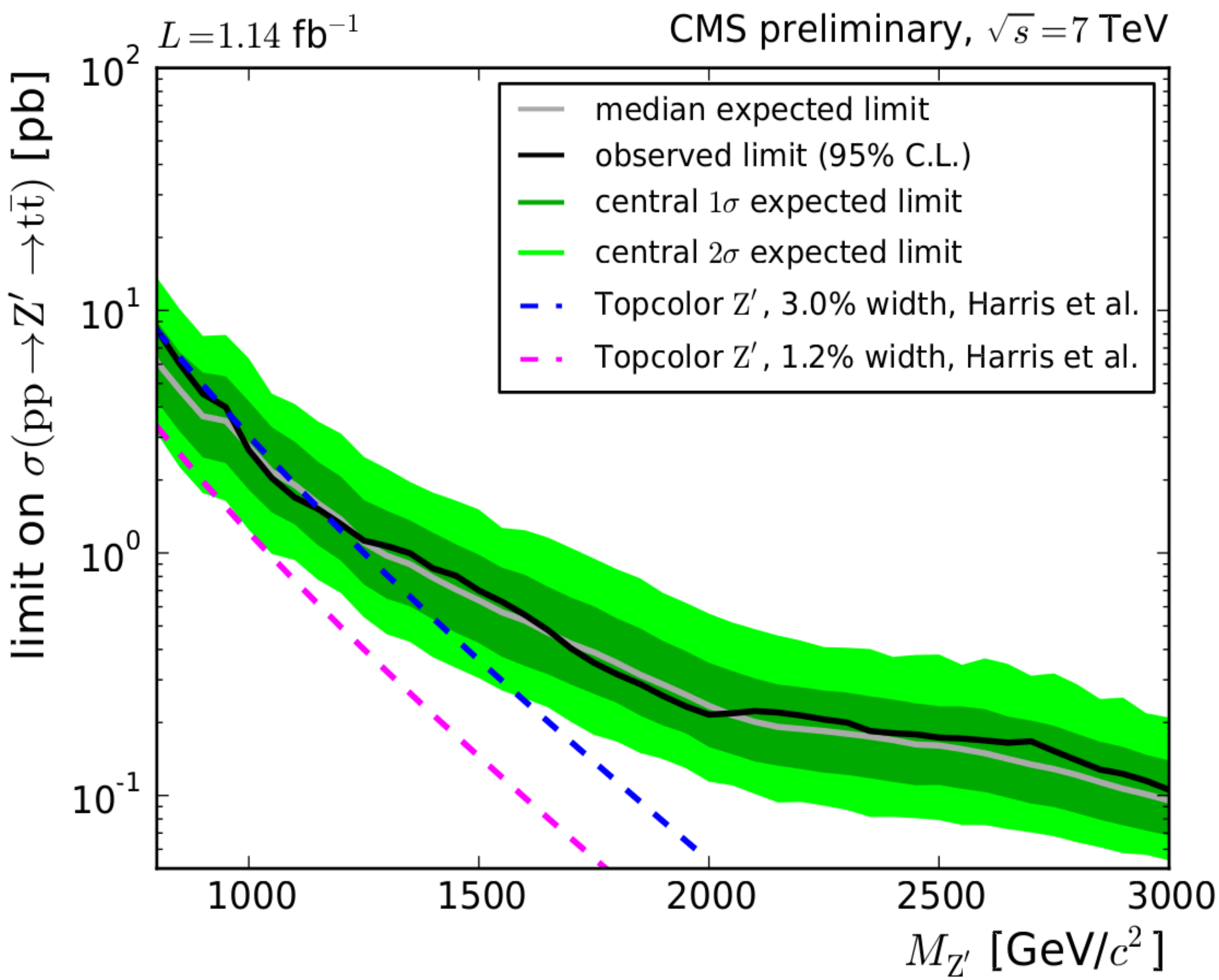




Limit in μ+jets

EXO-11-055

- Only 1.14 fb-1 used!
  - a powerful analysis
- Being updated now, ready by summer
- Bayesian limit
  - CLs for summer

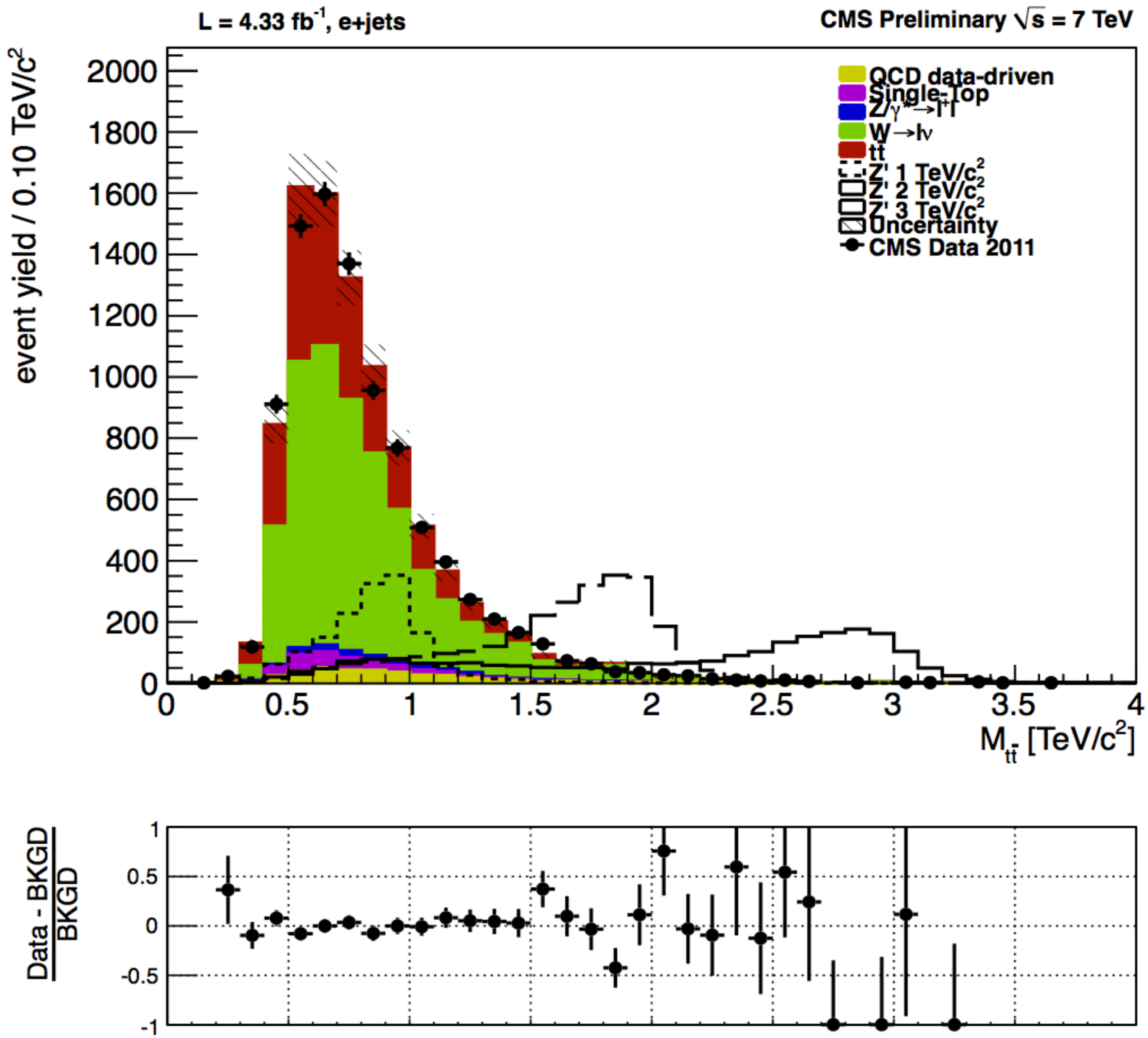


e+jets: data and backgrounds

EXO-11-092

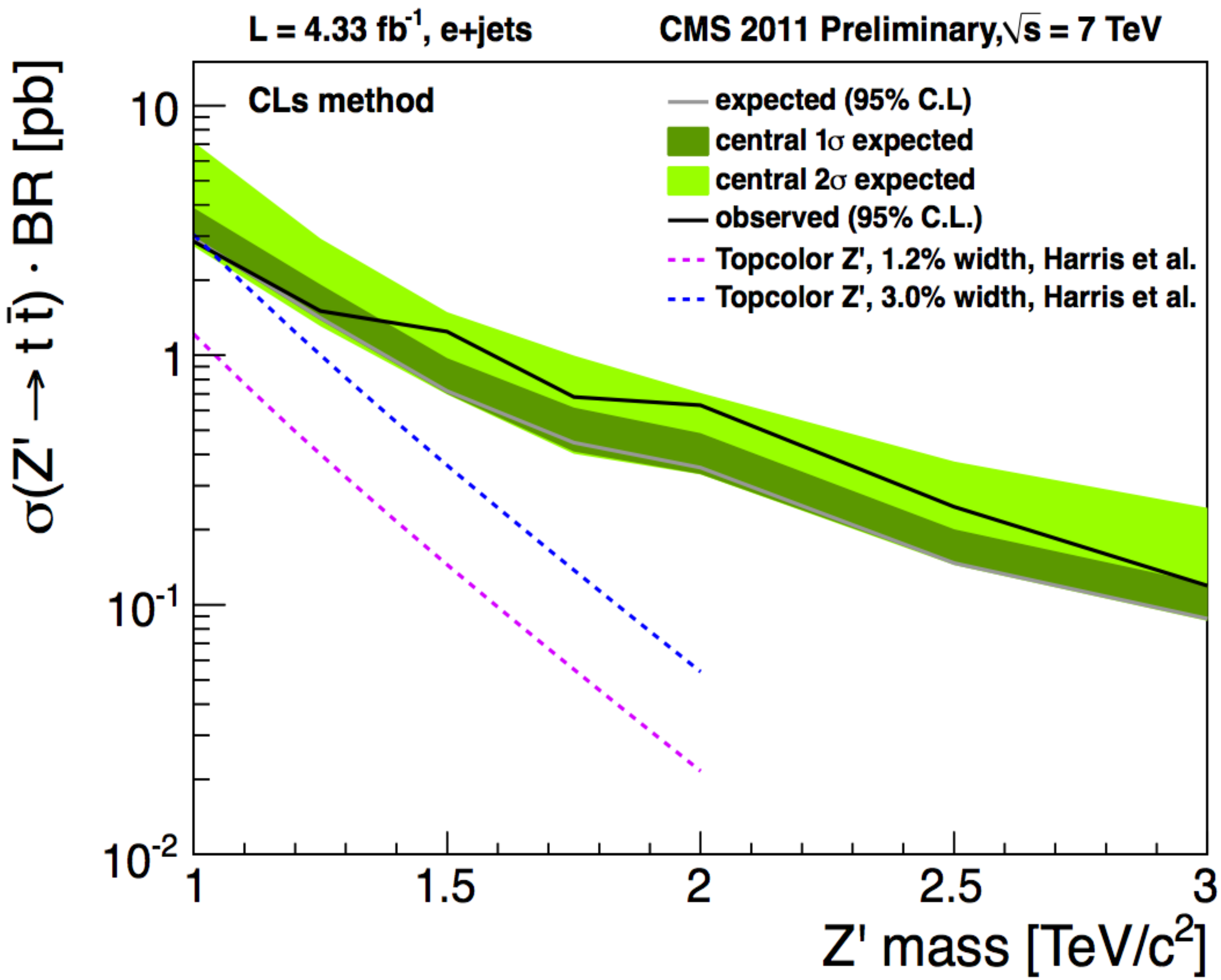
- Backgrounds normalized from MC
  - W+jets
  - Z+jets
- Constrain norm. within large syst. errors (30%)
- 1D template fit

  (with template morphing)

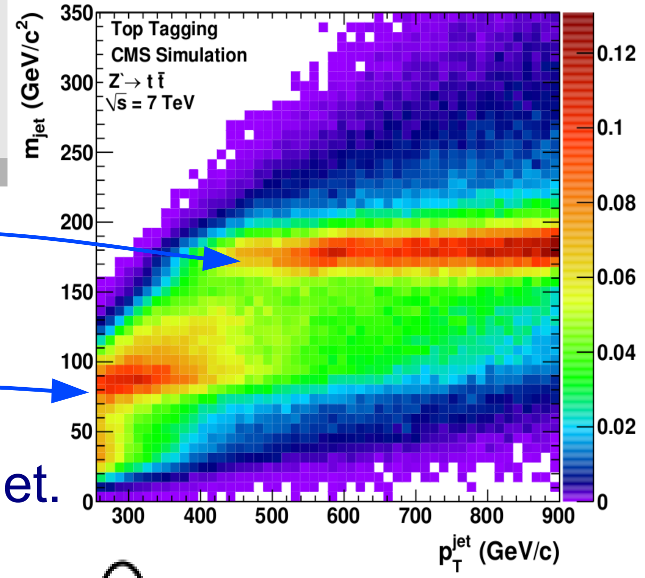


Limit in e+jets

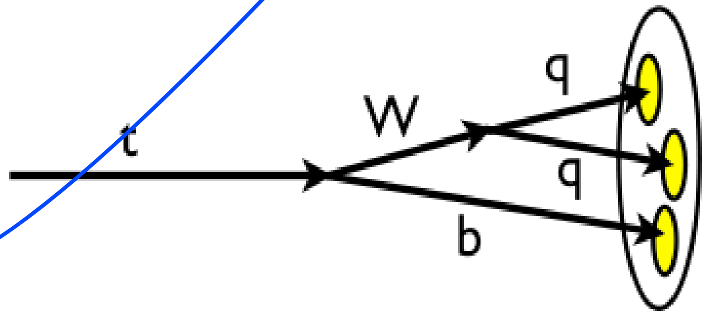
EXO-11-092



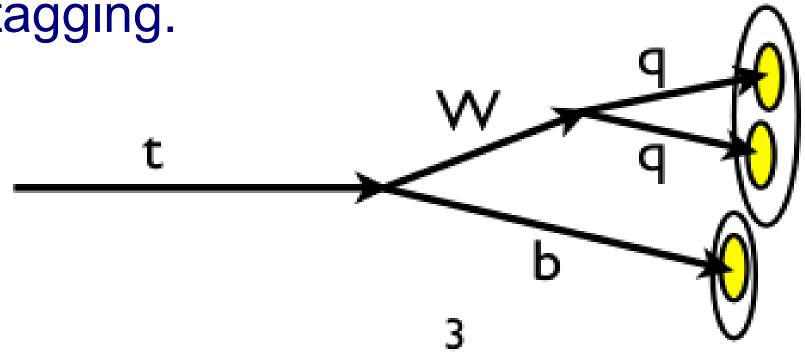
Boosted hadronic top



- Energetic top → jets merge
- Type 1 (single jet):
  - all three jets from top merged into a single jet.
  - JHU TopTagger.



- Type 2 (two jets):
  - two jets from W are contained in a single jet + b-jet separately
  - W tagging plus b tagging.

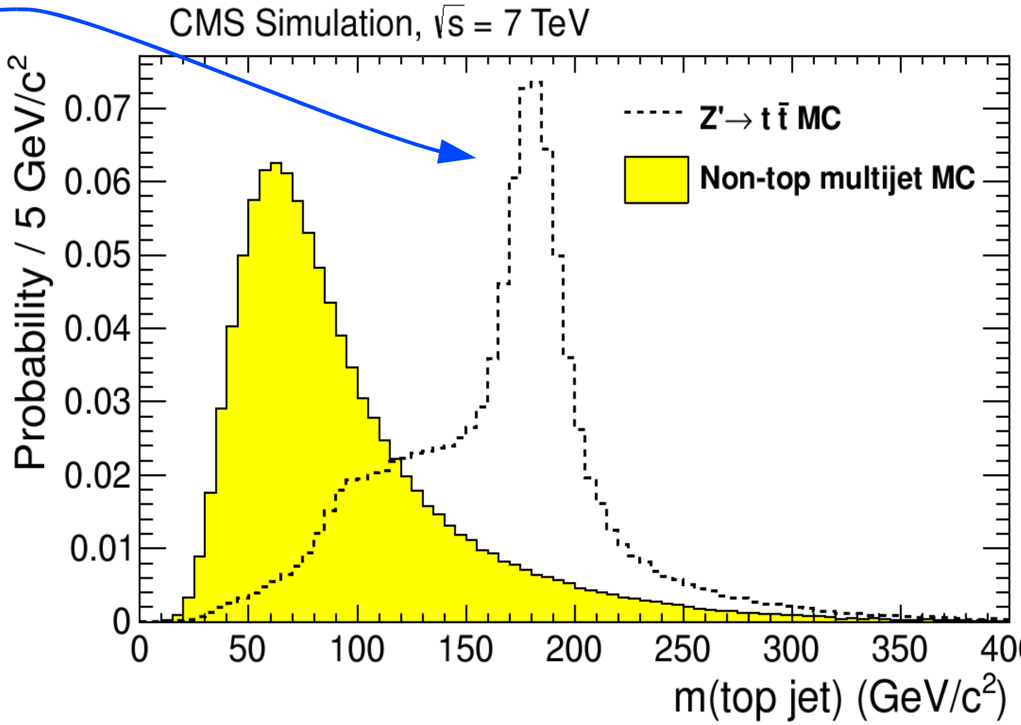


Top Tagging

JME-10-009

- "JHU Top Tagger" (Kaplan, Rehermann, Schwartz, and Tweedie, arXiv:0806.0848), tweaked by CMS
- Cluster jets with Cambridge-Aachen with R=0.8; retrace two steps of clustering sequence back to find subjets
- Three variables
  - jet mass (~ m_t)
  - number of subjets
  - min pairwise mass (~ m_W)

$$
\begin{aligned}
140 < m_{\text{jet}} &< 250 GeV/c^2 \\
N_{\text{subjets}} &\geq 3 \\
m_{\text{min}} &> 50 GeV/c^2
\end{aligned}
$$



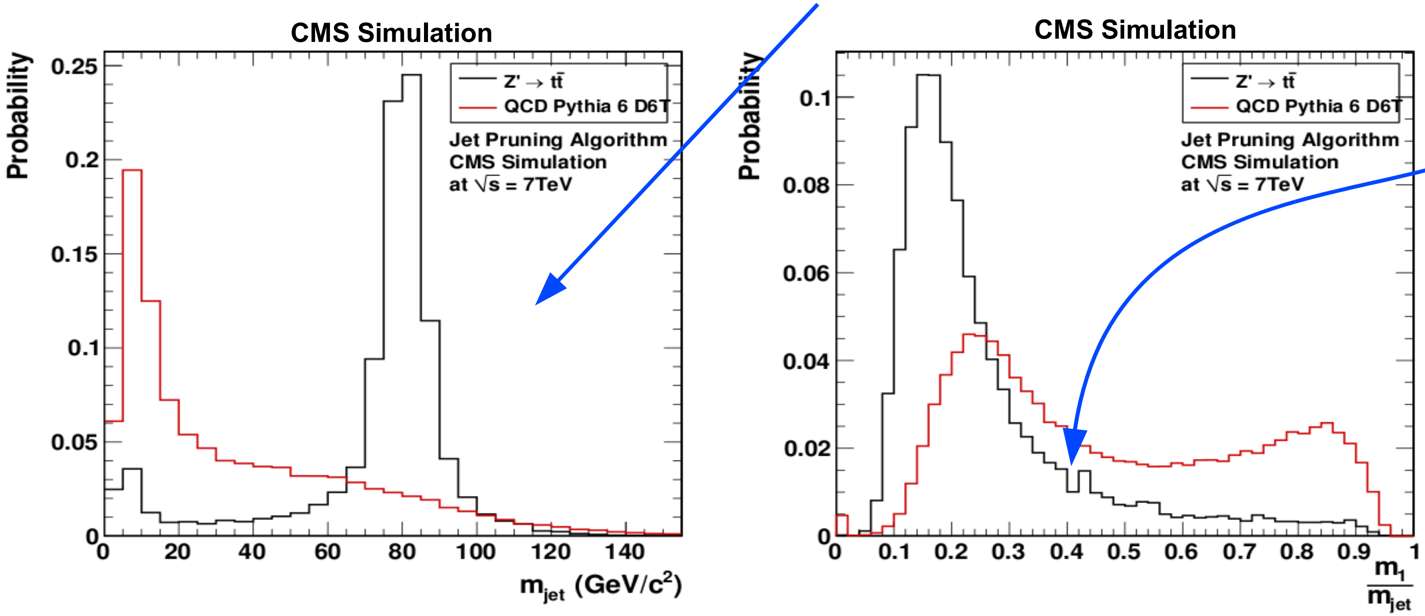
W tagging

JME-10-009

- Jet pruning
  - Ellis, Vermillion, Walsh (arXiv:0903.5081)
  - Improves mass resolution by removing soft, large angle particles
- Undo last step of jet clustering (also CA 0.8) to find two subjets. Identify W's with:
  - "Mass drop",
  - Pruned jet mass

$$\mu \equiv \frac{m_{\text{leading subjet}}}{m_{\text{jet}}} < 0.4$$

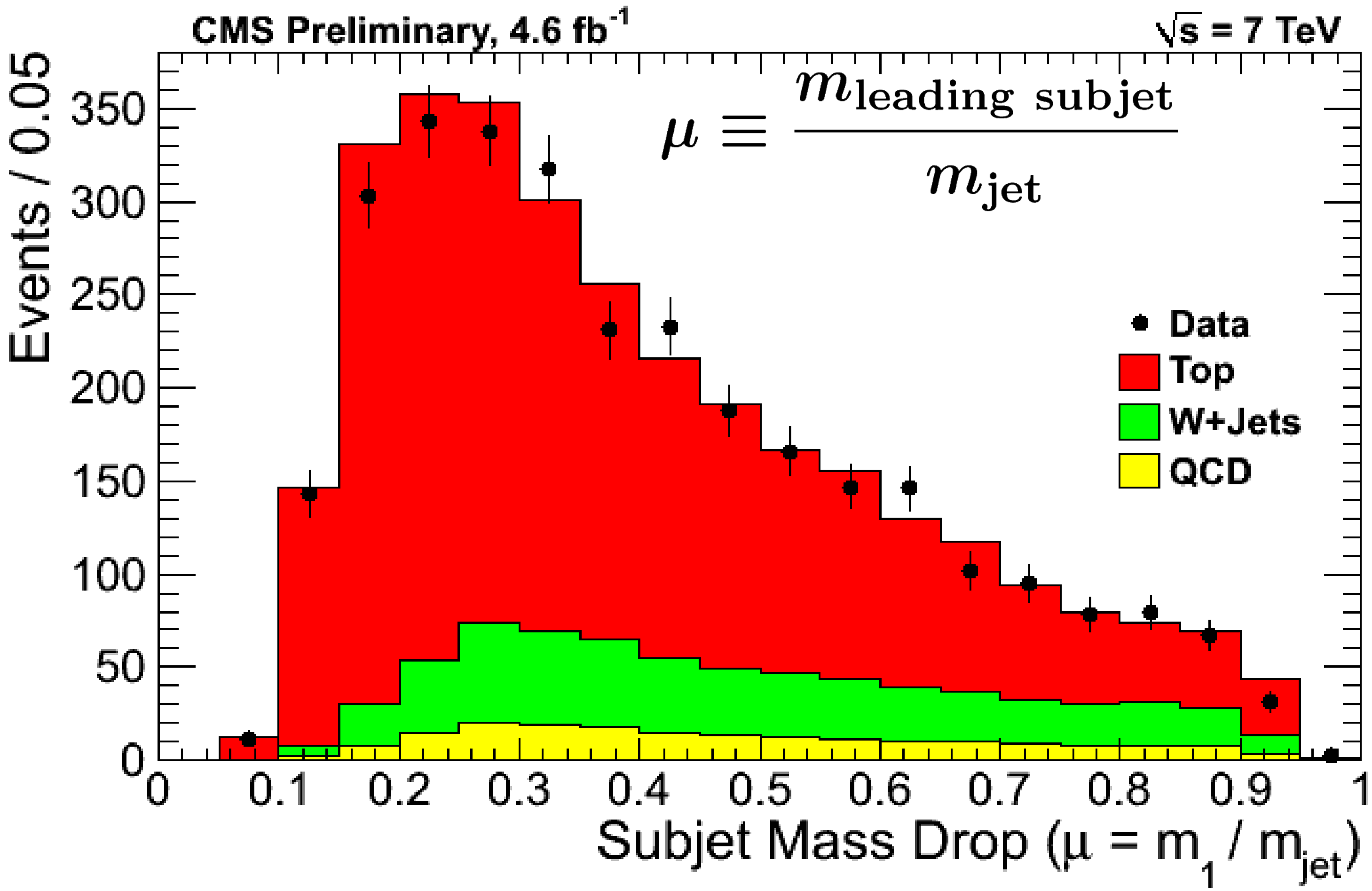
$$60 < m_{\text{jet}} < 130 GeV/c^2$$



Validating jet substructure in data

EXO-11-006

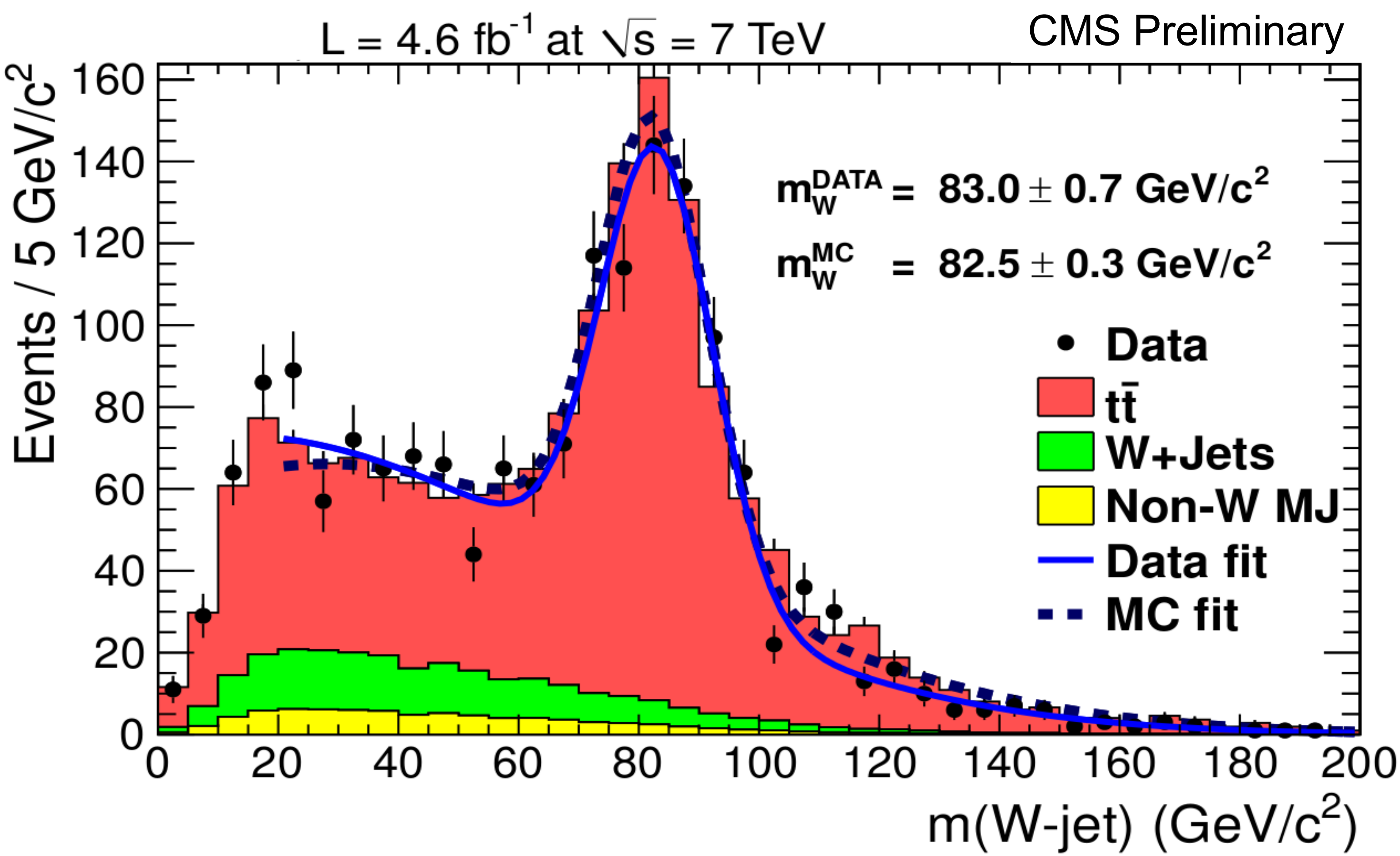
- In “low mass” lepton+jets sample, look for merged W's
- Test MC (Madgraph + Pythia Z2) → work surpringly well !



Validating jet substructure in data (2)

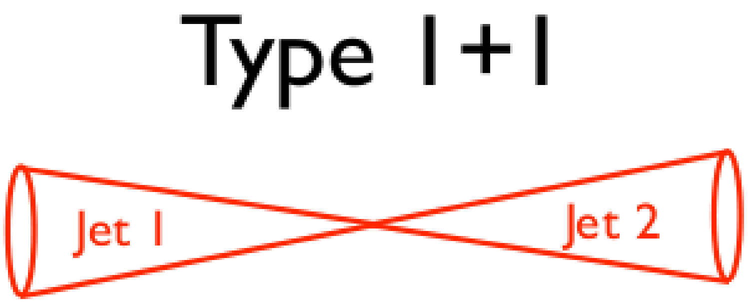
EXO-11-006

- Use W peak from W-tagged jets for "substructure energy scale" = 1.01 ± 0.01
- Also measure efficiency correction for MC = 0.97 ± 0.03

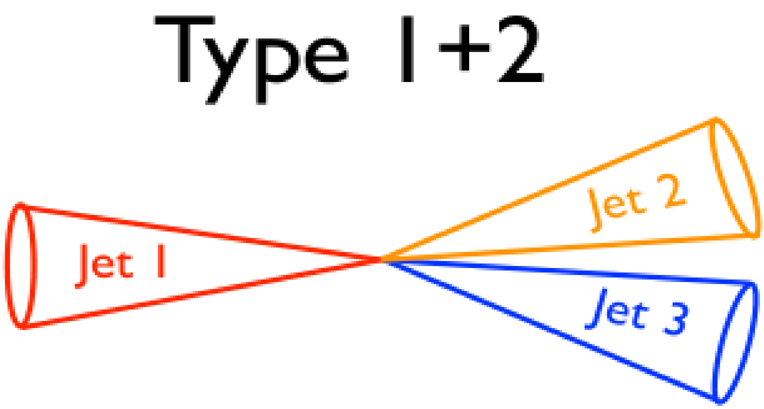


$Z' \rightarrow t\bar{t}$ in all-hadronic: two event topologies

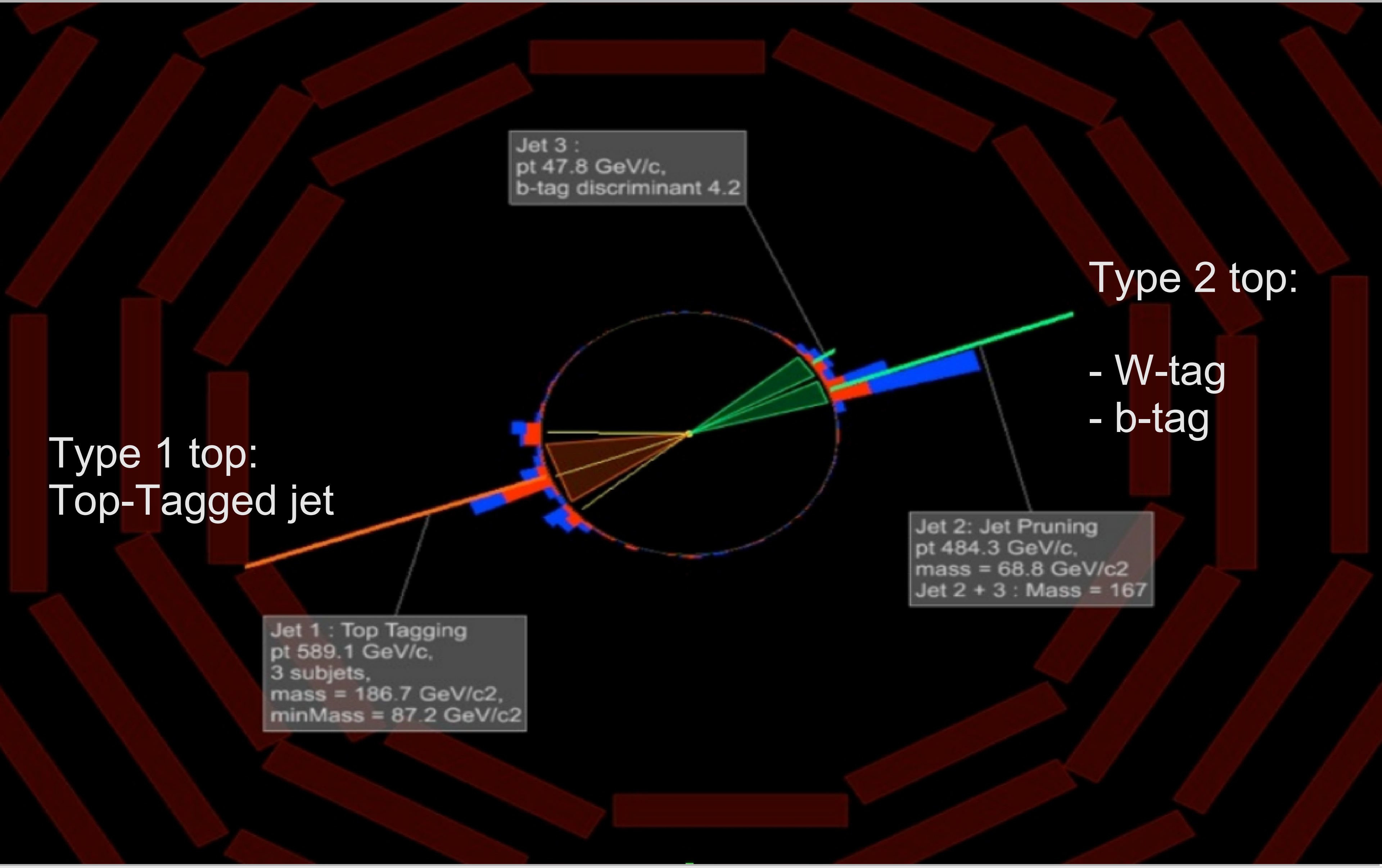
- Aimed at higher Z' masses
- Type 1+1
  - Jet p_T>350 GeV/c
  - Events with two top tags



- Type 1+2
  - Jet p_T>350, 200, 30 GeV/c
  - 140 < m_{jet} < 250 GeV/c^2
  - Top tag in one hemisphere
  - W tag + b-tag on the other

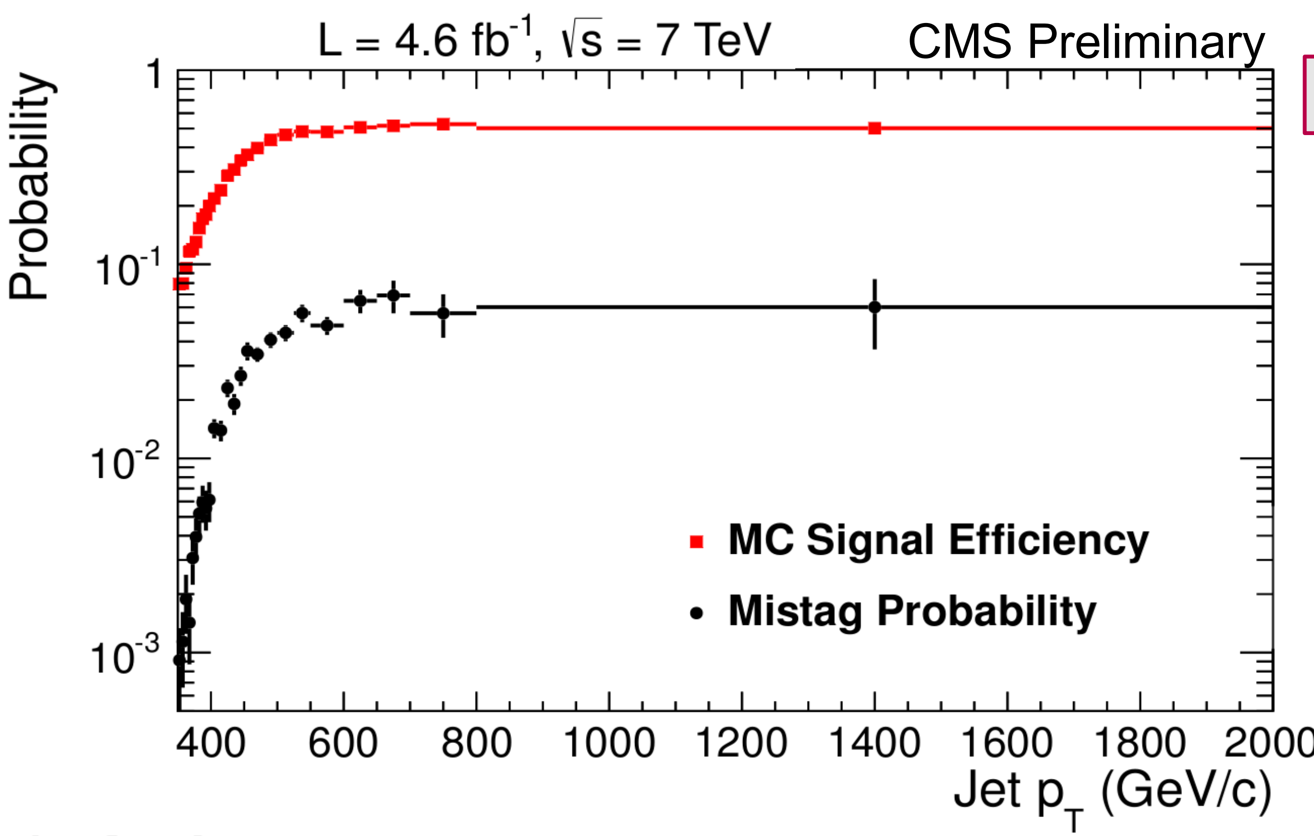


Example of a “Type 1+2” candidate



Mistag probability for Top Tagging

- Probability to mis-identify a non-top QCD jet as a top tag
- Obtained from “substructure sideband” in Type 1+2 events

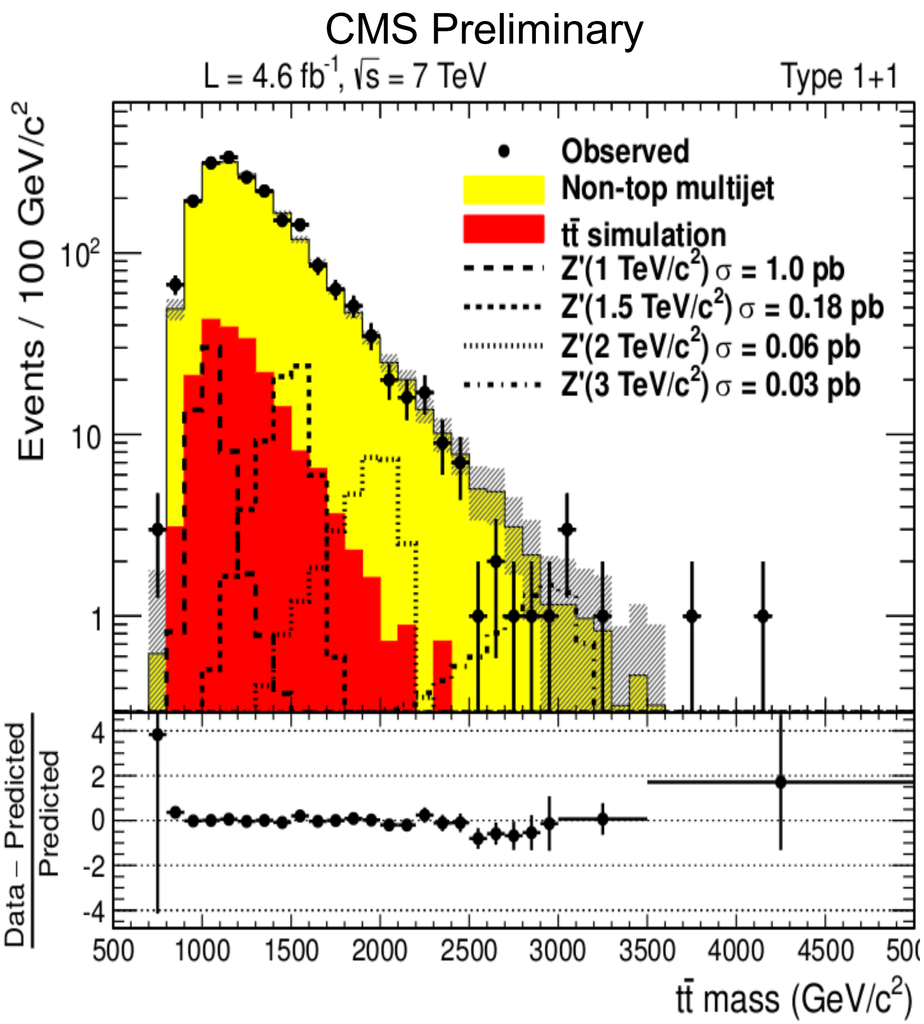


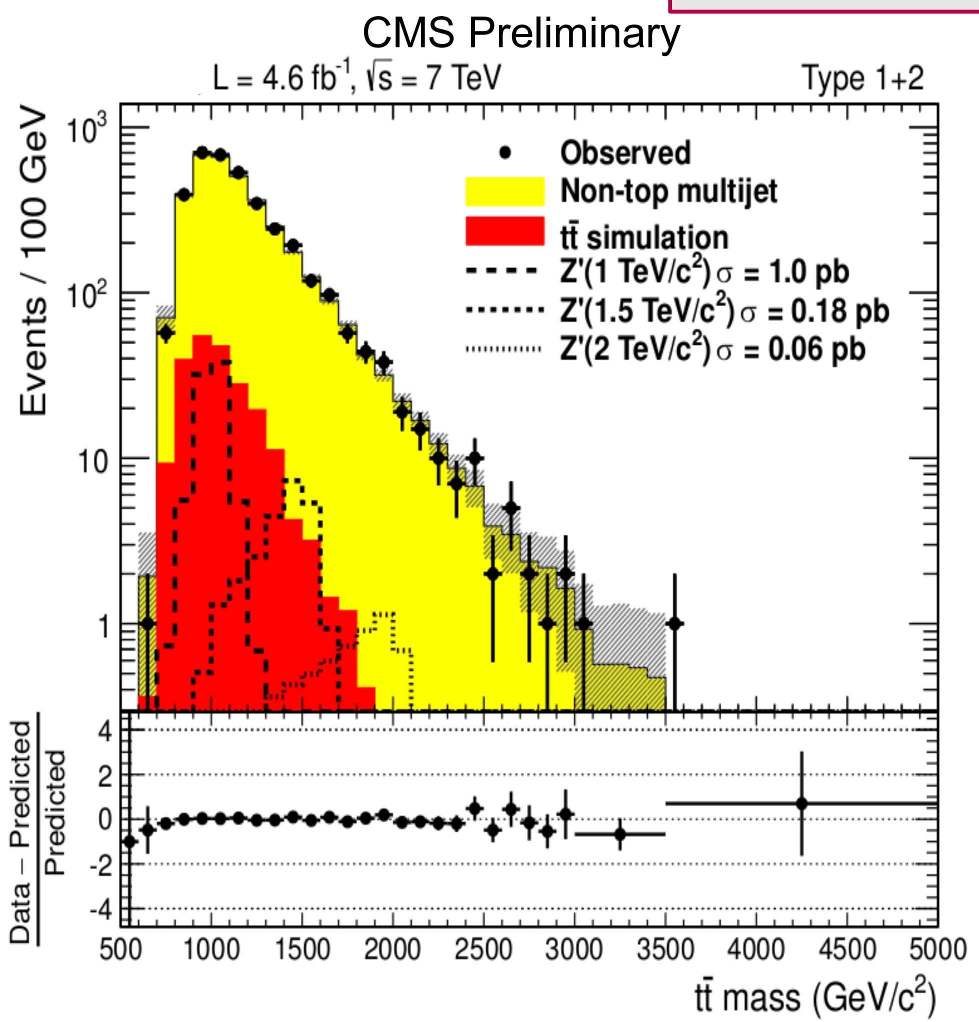
EXO-11-006

- Apply to pre-top-tag $m_{t\bar{t}}$ distribution to get non-top background

All-hadronic: data + background prediction

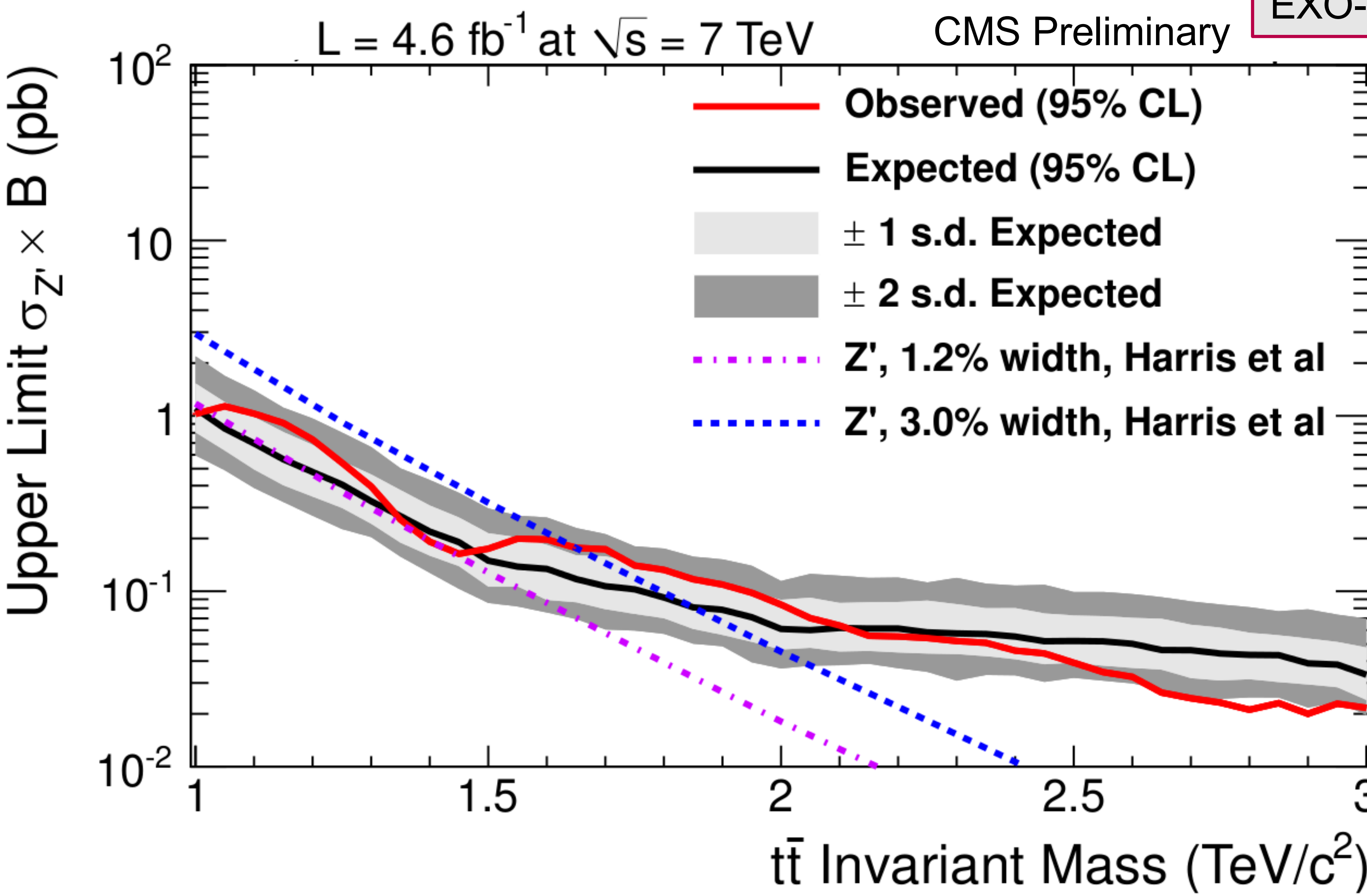
EXO-11-006





All-hadronic: limit for narrow width

EXO-11-006



All-hadronic: limit for 10% width

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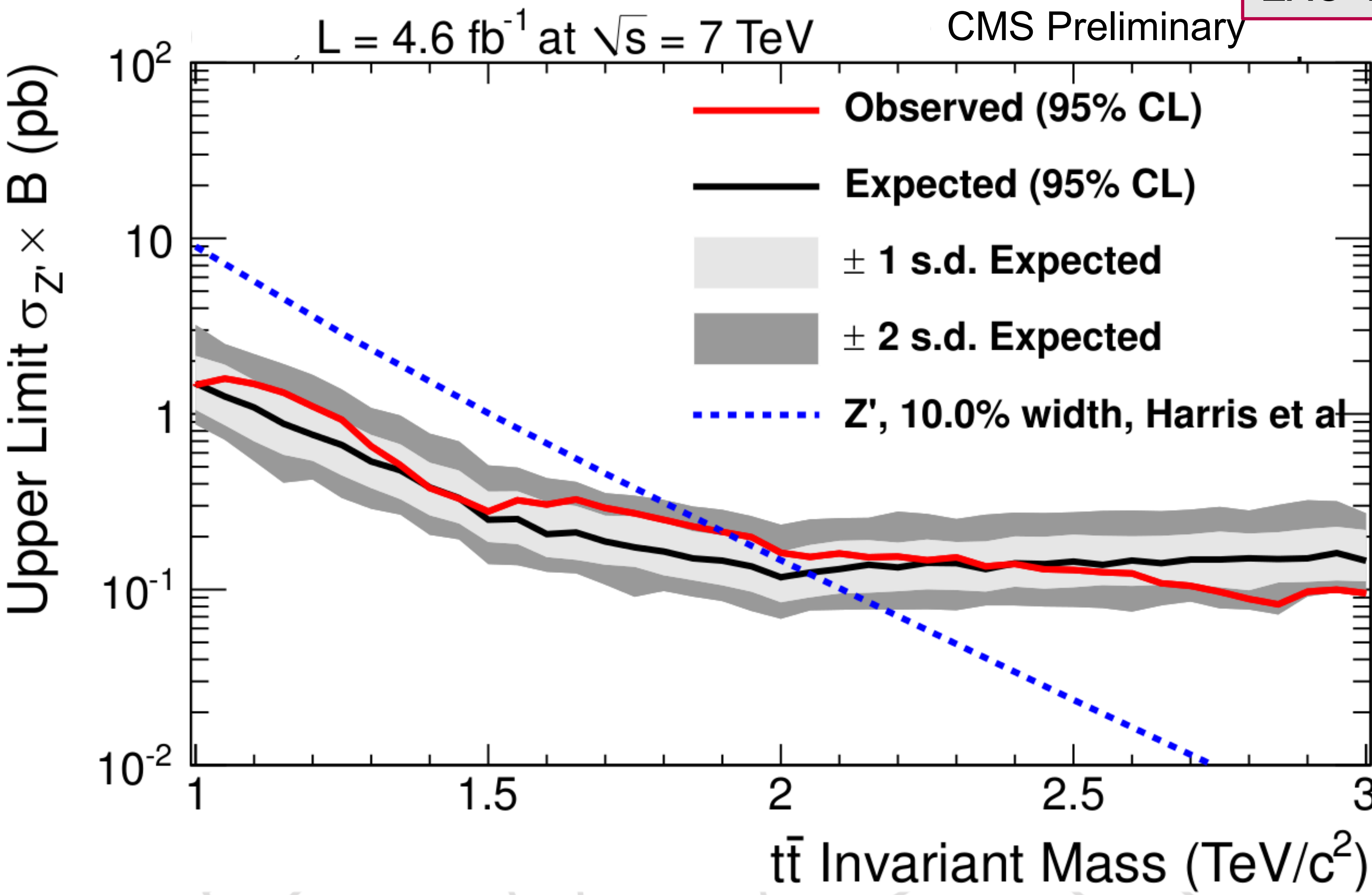
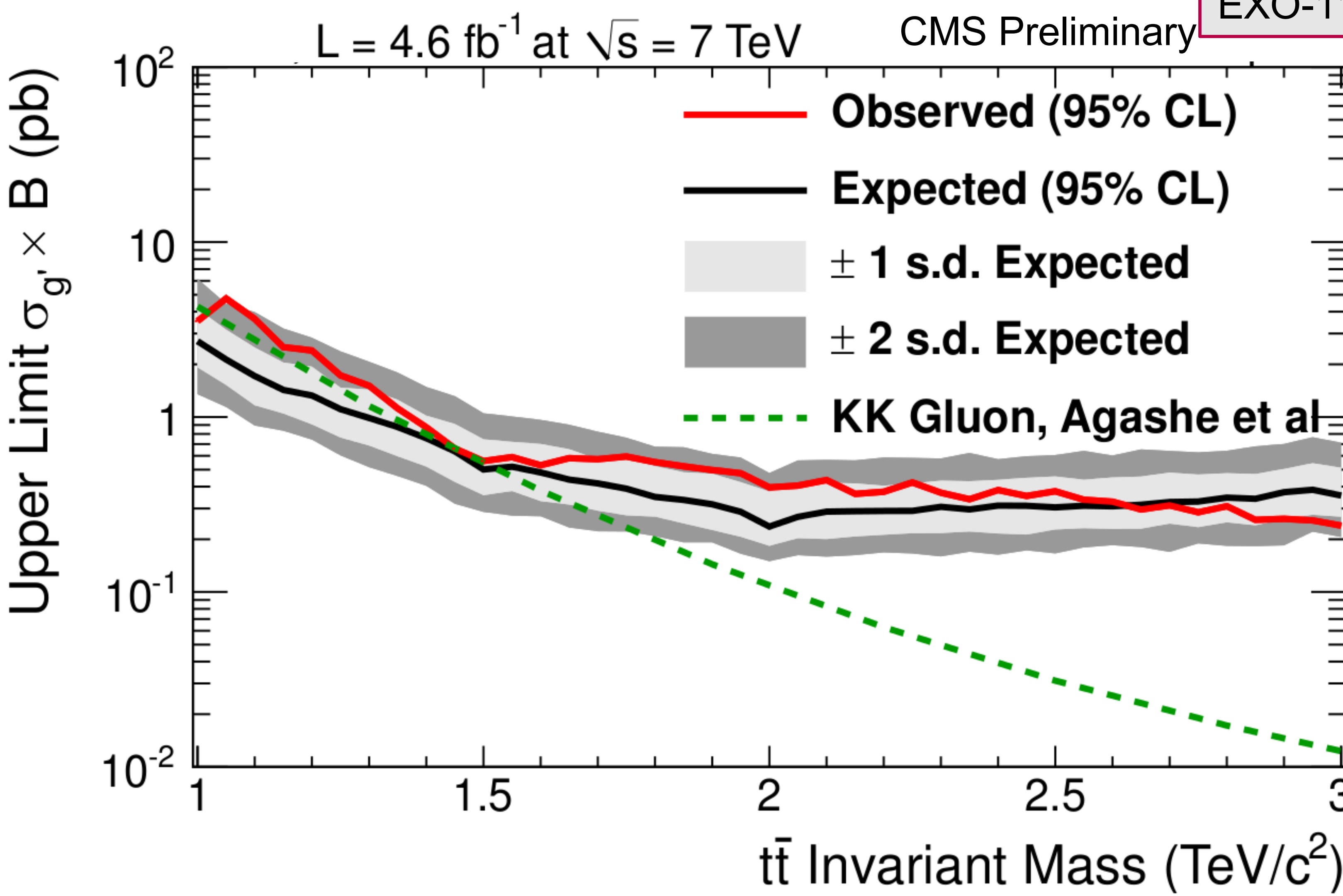


All-hadronic: limit for KK Gluon

EXO-11-006



All-hadronic: general enhancement

- What if there is no peak, just change in $m_{t\bar{t}}$ spectrum?
- Set limit on

$$\mathcal{S} = \frac{\int_{1\mathrm{TeV}}^{+\infty} \left(\frac{\mathrm{d}\sigma_{SM+NP}}{\mathrm{d}m_{t\bar{t}}}\right) \mathrm{d}m_{t\bar{t}}}{\int_{1\mathrm{TeV}}^{+\infty} \left(\frac{\mathrm{d}\sigma_{SM}}{\mathrm{d}m_{t\bar{t}}}\right) \mathrm{d}m_{t\bar{t}}}$$

  - Assume same efficiency as SM $t\bar{t}$ production

- Integrate $m_{t\bar{t}} > 1TeV/c^2$ correct for smearing in $m_{t\bar{t}}$

	1+1	1+2
Expected SM $t\bar{t}$ events	194 ± 106	129 ± 80
Expected non-top multijet events	1546 ± 45	2271 ± 130
Total expected events	1740 ± 115	2400 ± 153
Observed events	1738	2423
$t\bar{t}$ efficiency	$(2.5 \pm 1.3) \times 10^{-4}$	$(1.6 \pm 1.0) \times 10^{-4}$

EXO-11-006

- Counting experiment gives CLs limit: $\mathcal{S} < 2.6$ @ 95% C.L.

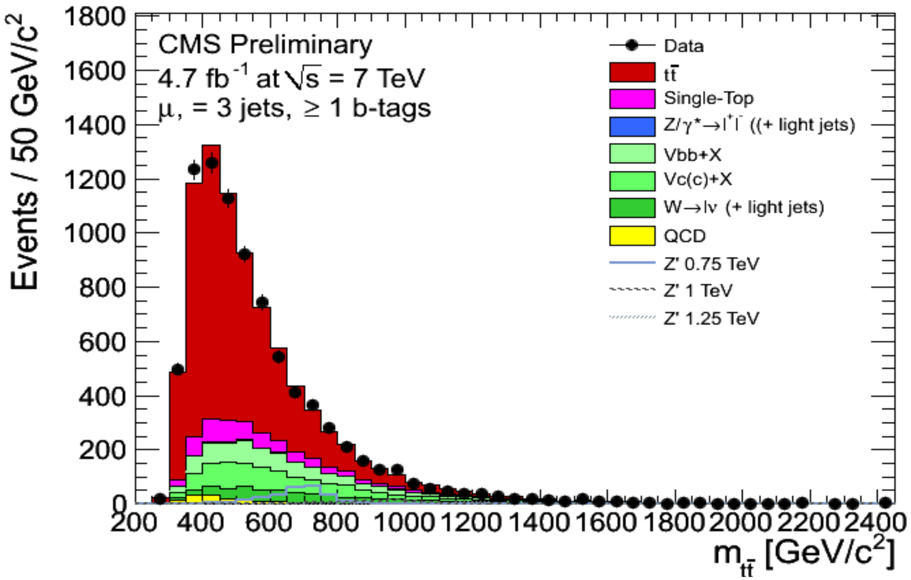
Summary

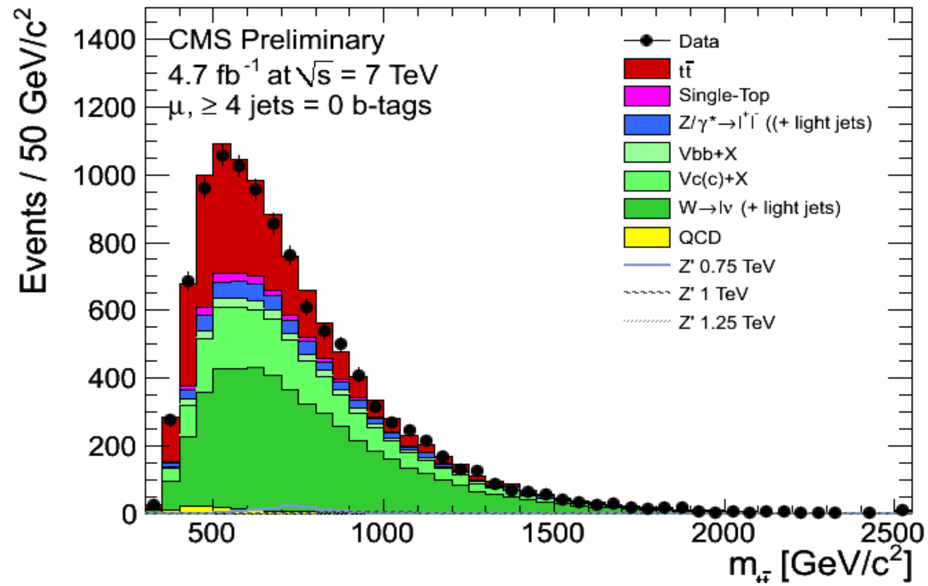
- CMS searches for $t\bar{t}$ resonances are in full swing
- Already reached sub-picobarn limits (depending on the model)
  - individual searches rule out Z'/KKg below 1.2-2 TeV
- For summer – easy:
  - update μ+jets to 4.6 fb-1
  - combine high mass measurements (ready to do so)
- For summer – may or may not be easy:
  - add top tagging to lepton+jets analyses
  - add b-tagging to both lepton+jets and all-hadronic
- In any case, 2012 will be fun!

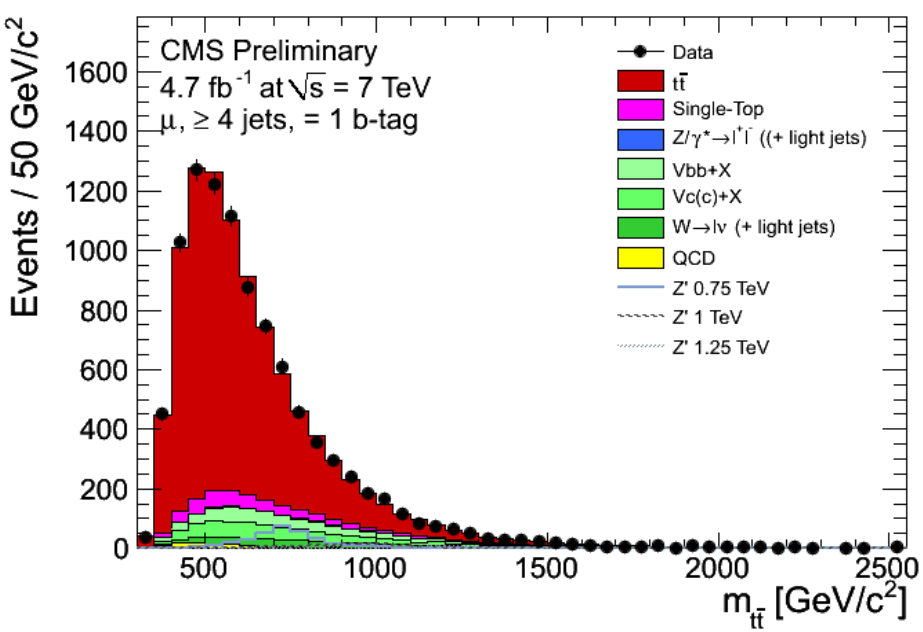
B A C K U P

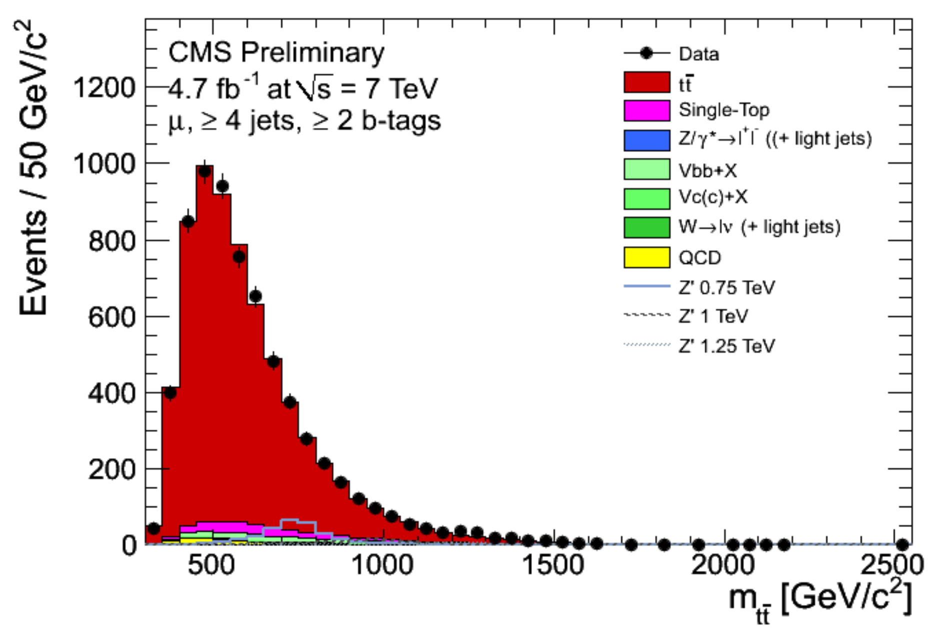
"Low mass" μ+jets

TOP-11-009







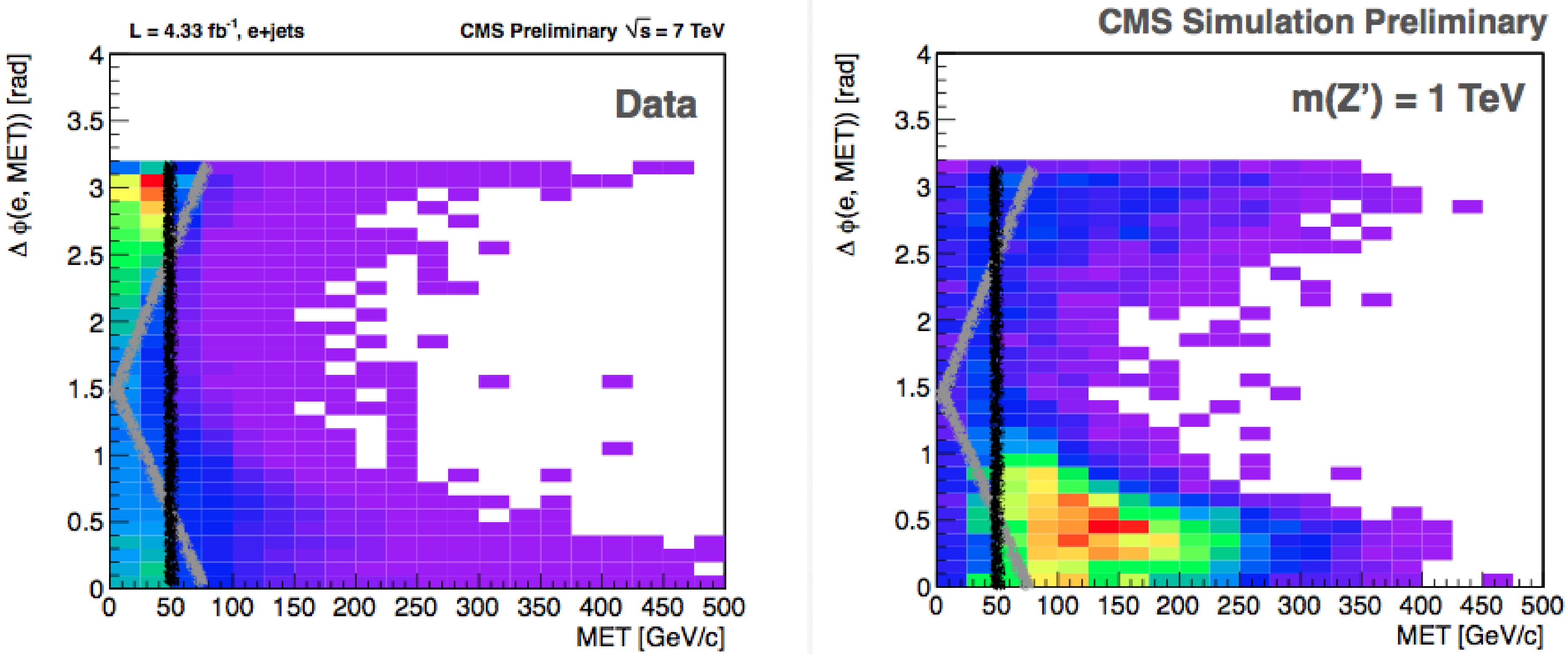


e+jets: further cuts to suppress QCD

EXO-11-092

- $E_T^{miss} > 50$ GeV and the “triangular cuts”:
- $\Delta\phi(e, E_T^{miss}) < \frac{1.5}{75} E_T^{miss} + 1.5, \quad \Delta\phi(e, E_T^{miss}) > -\frac{1.5}{75} E_T^{miss} + 1.5,$

$$\Delta\phi(j_1, E_T^{miss}) < \frac{1.5}{75} E_T^{miss} + 1.5, \quad \Delta\phi(j_1, E_T^{miss}) > -\frac{1.5}{75} E_T^{miss} + 1.5$$

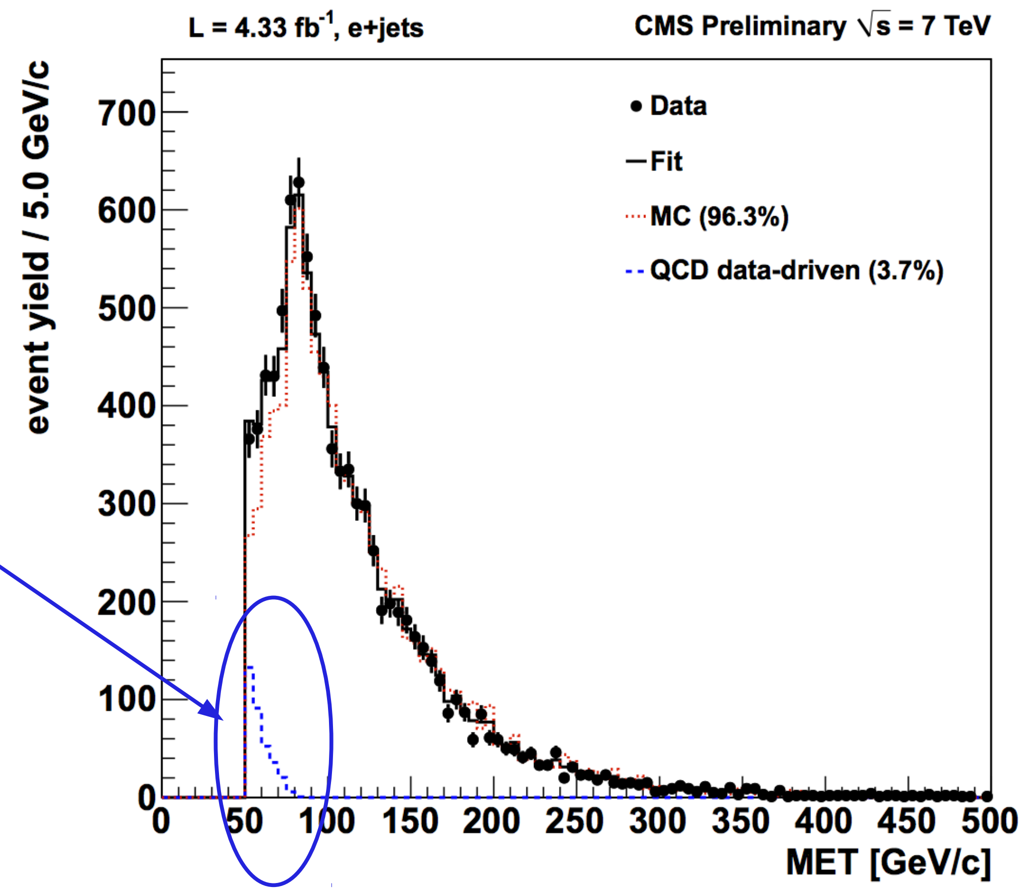


e+jets: QCD suppressed!

EXO-11-092

- QCD estimated from a 1D template fit of MET
- QCD template = invert electron ID and triangular cuts

==> After all the cuts, QCD is small



“High mass” systematics (e+jets)

Source of systematic uncertainty	Uncertainty	Type
$t\bar{t}$ cross section	15%	Rate
Single top cross section	15%	Rate
W+jets cross section	30%	Rate
Z+jets cross section	30%	Rate
QCD multijet	50%	Rate
Luminosity	4.5%	Rate
Trigger	4%	Rate
Jet Energy Scale	$\pm 1\sigma(p_T, \eta)$	Rate & Shape
Scale ($Q^2 = M(t)^2 + \sum p_T(\text{jet})^2$)	$2Q^2$ and $0.5Q^2$	Rate & Shape
Matching	2 and 0.5 $\times$ default	Rate & Shape
Pileup	$\pm 1\sigma$	Rate & Shape