SUSY and BEYOND

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on behalf of the

CMS collaboration

Hadron Collider Physics 2011, Paris

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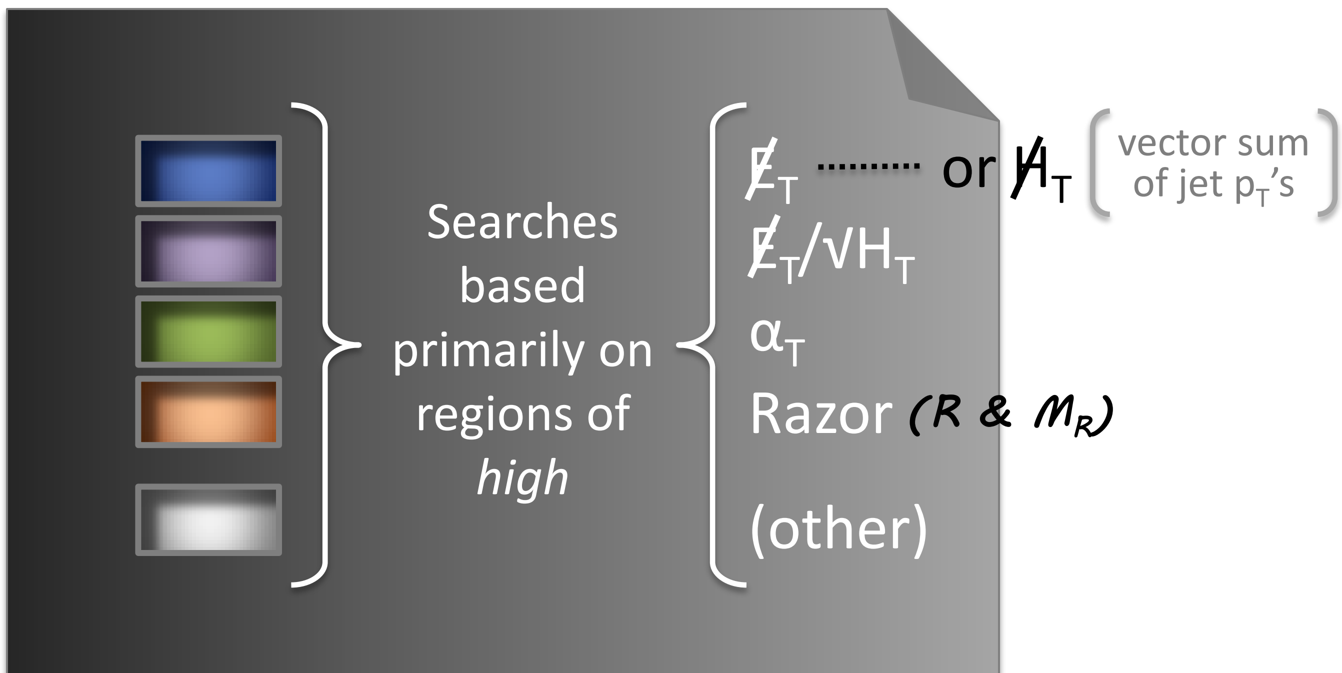
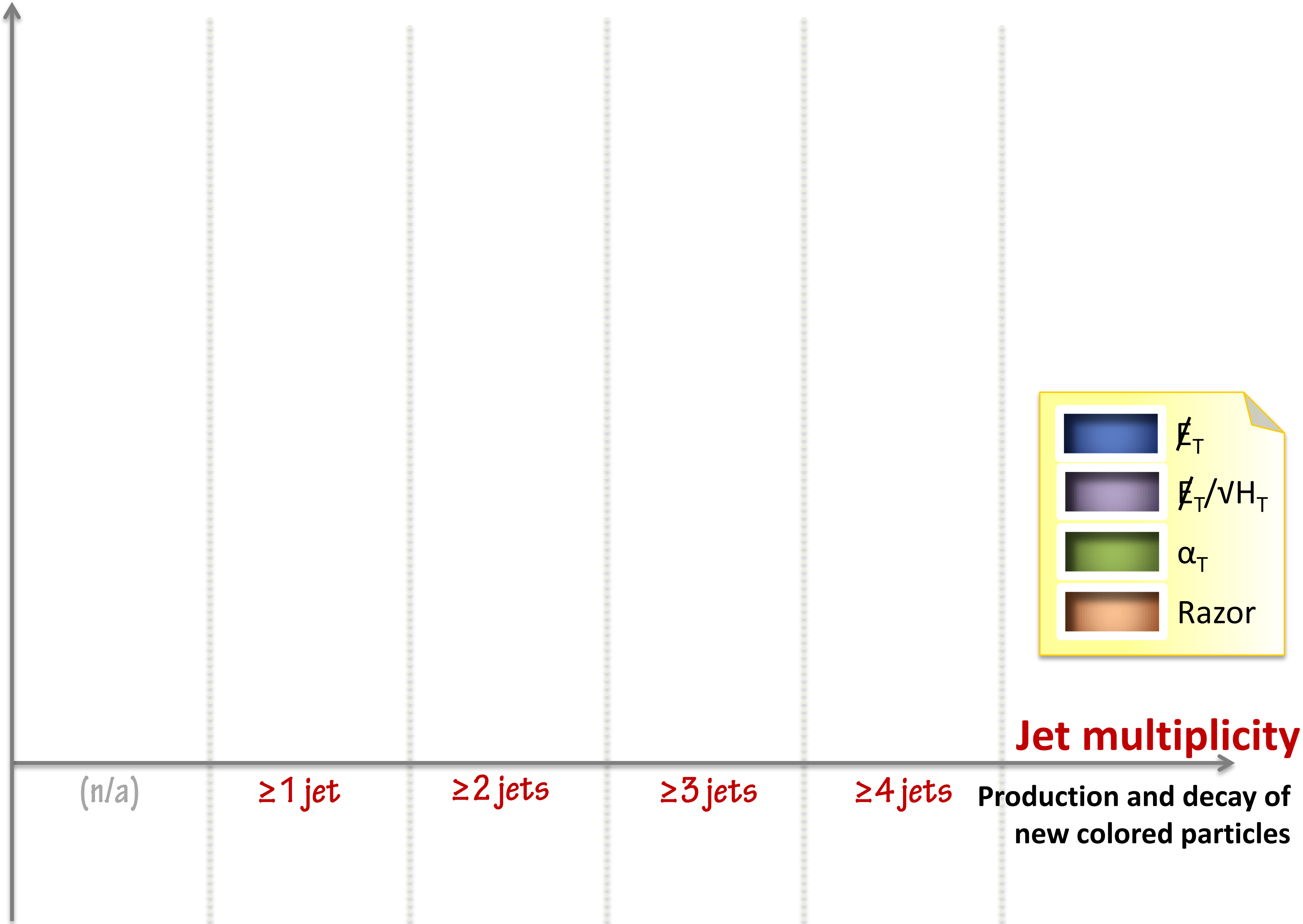
Signatures sought by SUSY searches

- High-p_T final states from decay of produced TeV-scale new particles.
- Missing transverse momentum ($\not{E}_T$) from decay into (meta-)stable dark matter candidates.



Signatures sought by SUSY searches



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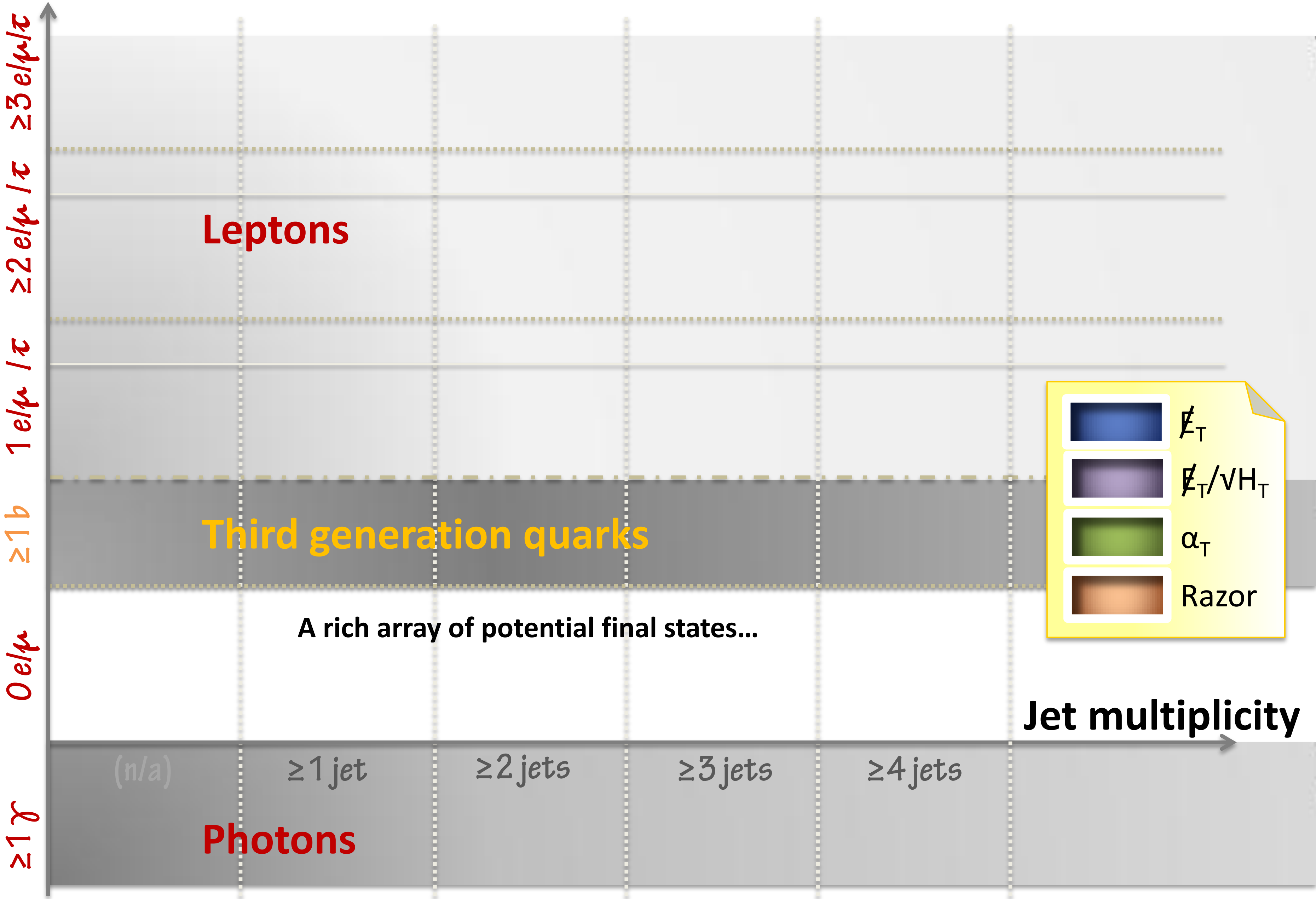

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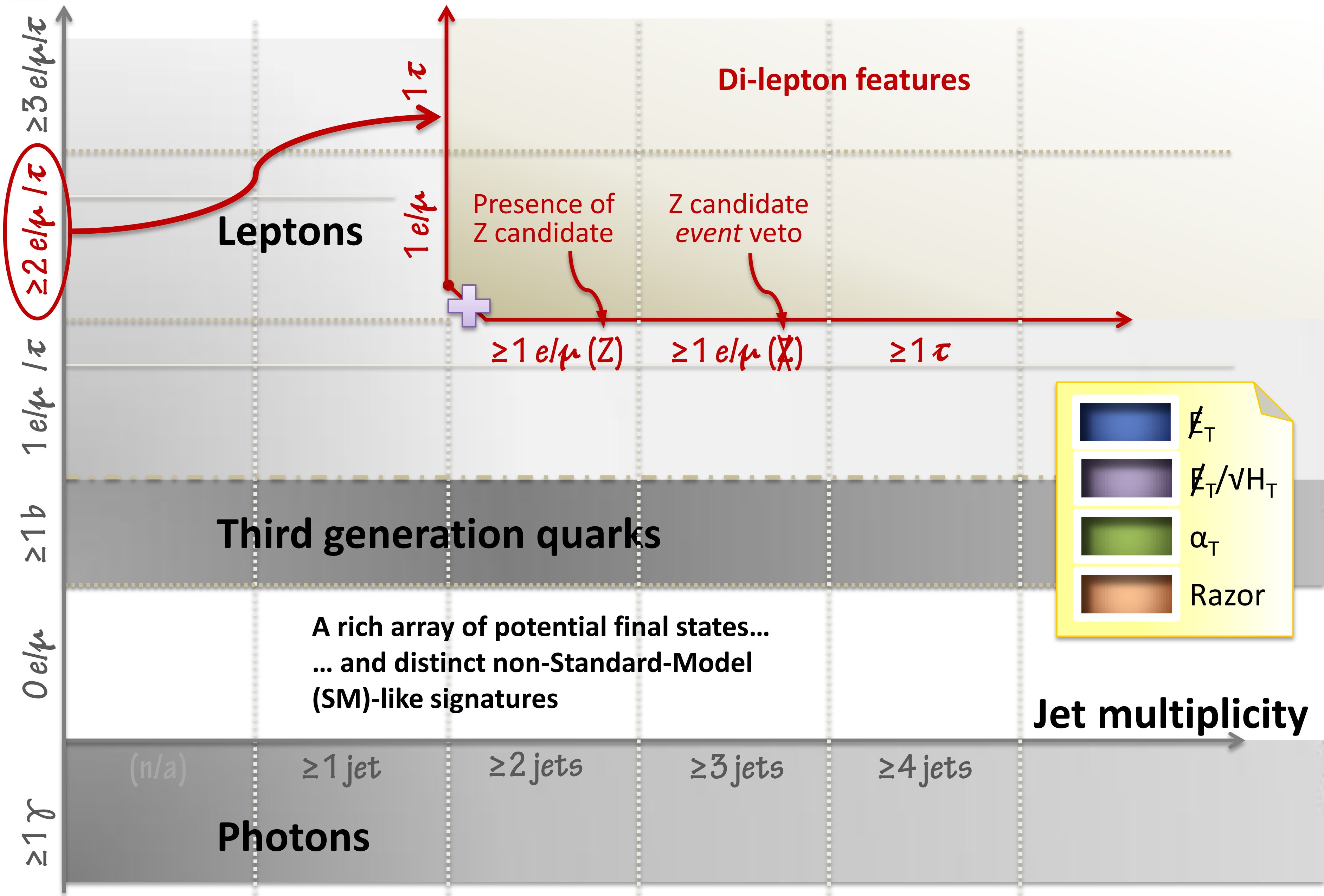
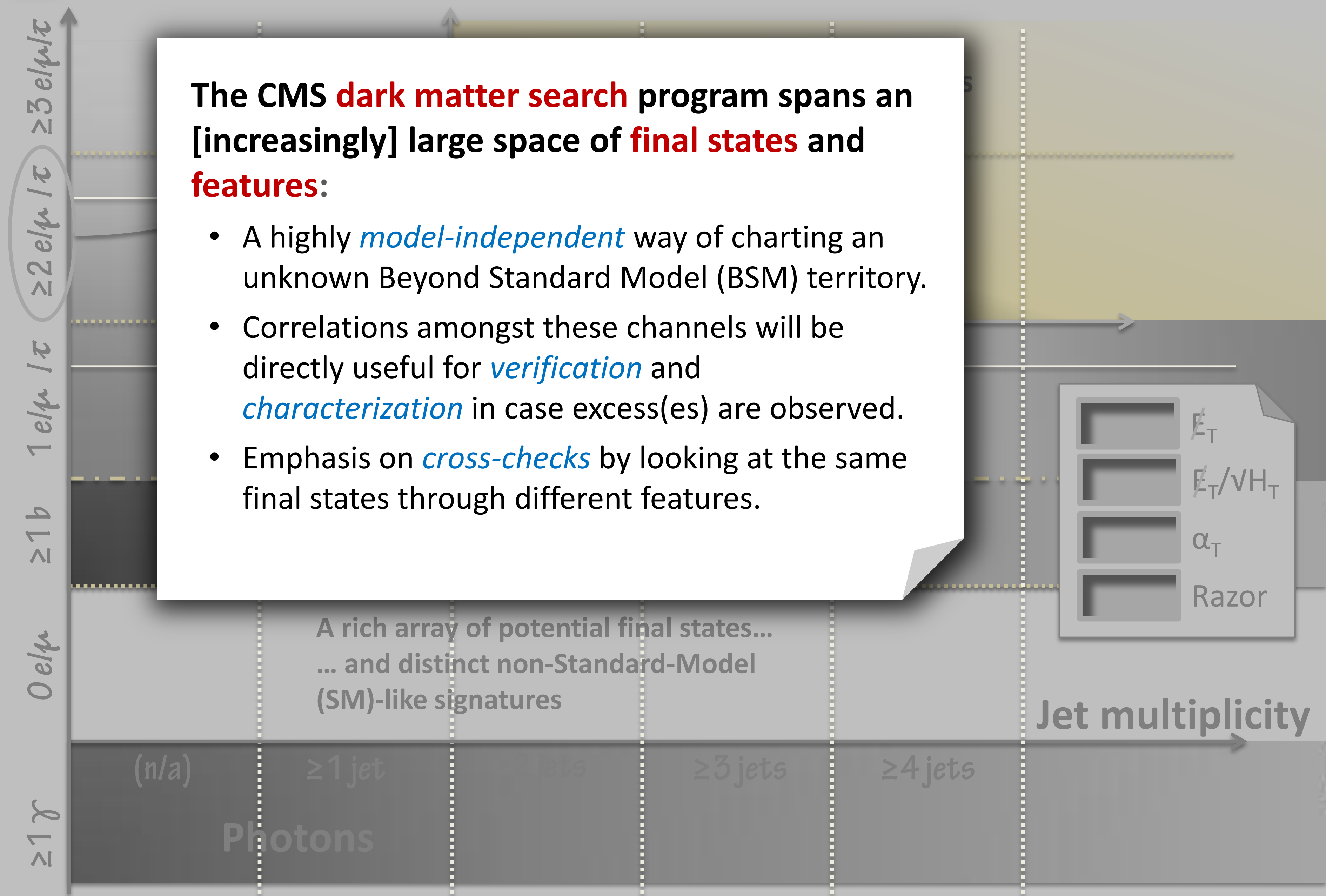


Signatures sought by SUSY searches

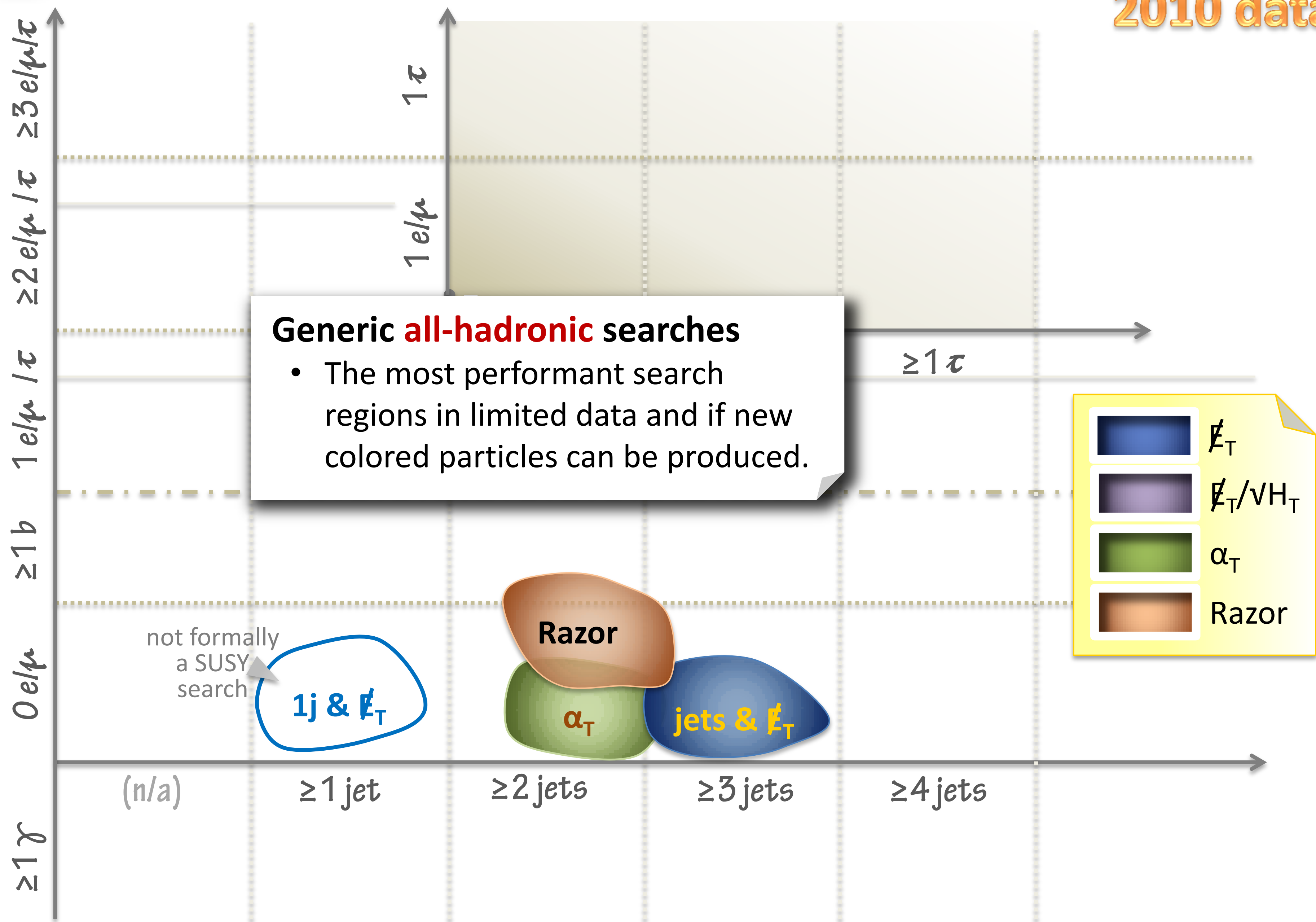
The CMS **dark matter search** **program spans an [increasingly] large space of** **final states** **and** **features**:

- A highly *model-independent* way of charting an unknown Beyond Standard Model (BSM) territory.
- Correlations amongst these channels will be directly useful for *verification* and *characterization* in case excess(es) are observed.
- Emphasis on *cross-checks* by looking at the same final states through different features.



Signatures sought by SUSY searches

~36pb^{-1} 2010 data

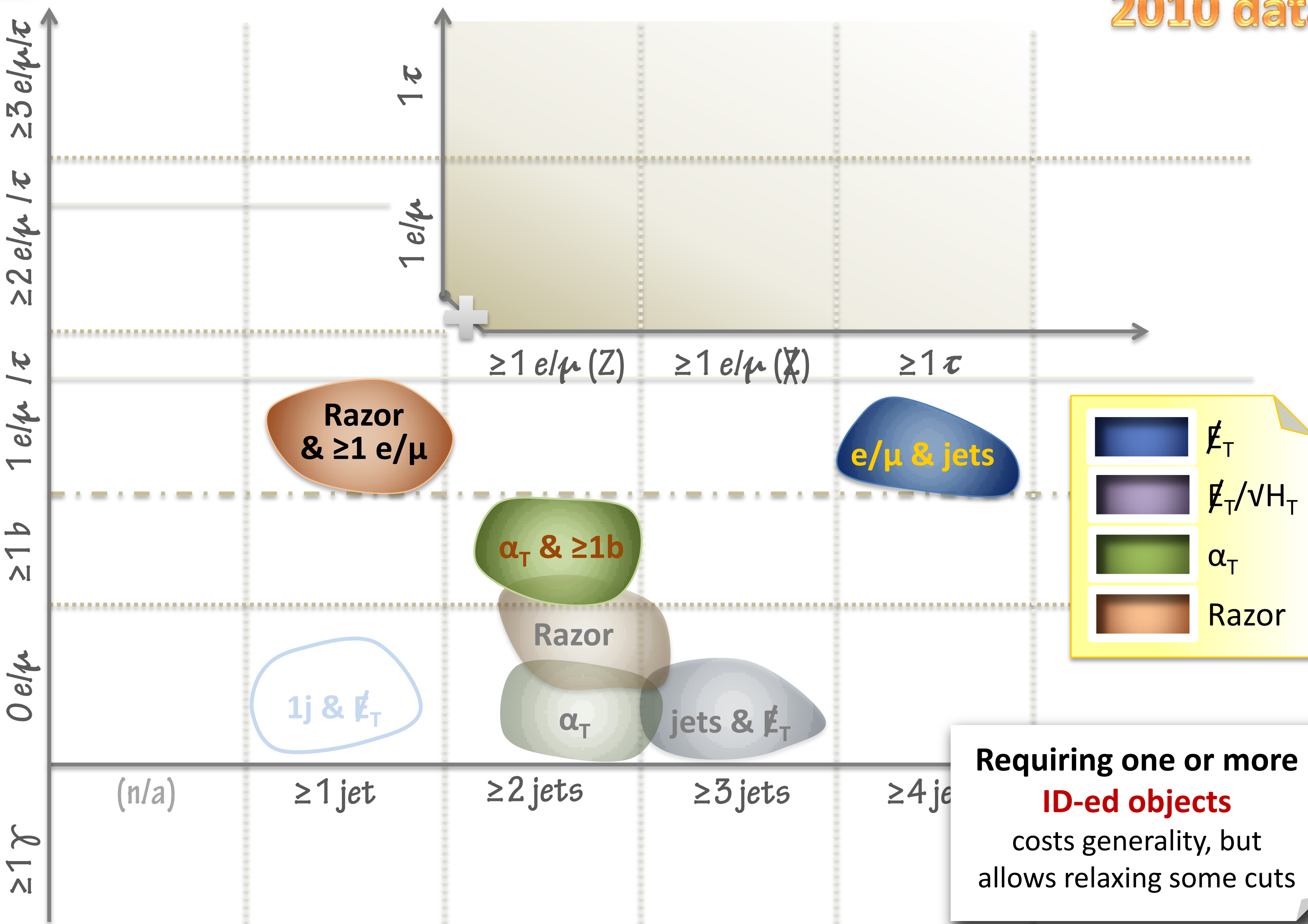


Generic all-hadronic searches

- The most performant search regions in limited data and if new colored particles can be produced.

Signatures sought by SUSY searches

~36pb^{-1} 2010 data



Requiring one or more ID-ed objects costs generality, but allows relaxing some cuts

Signatures sought by SUSY searches

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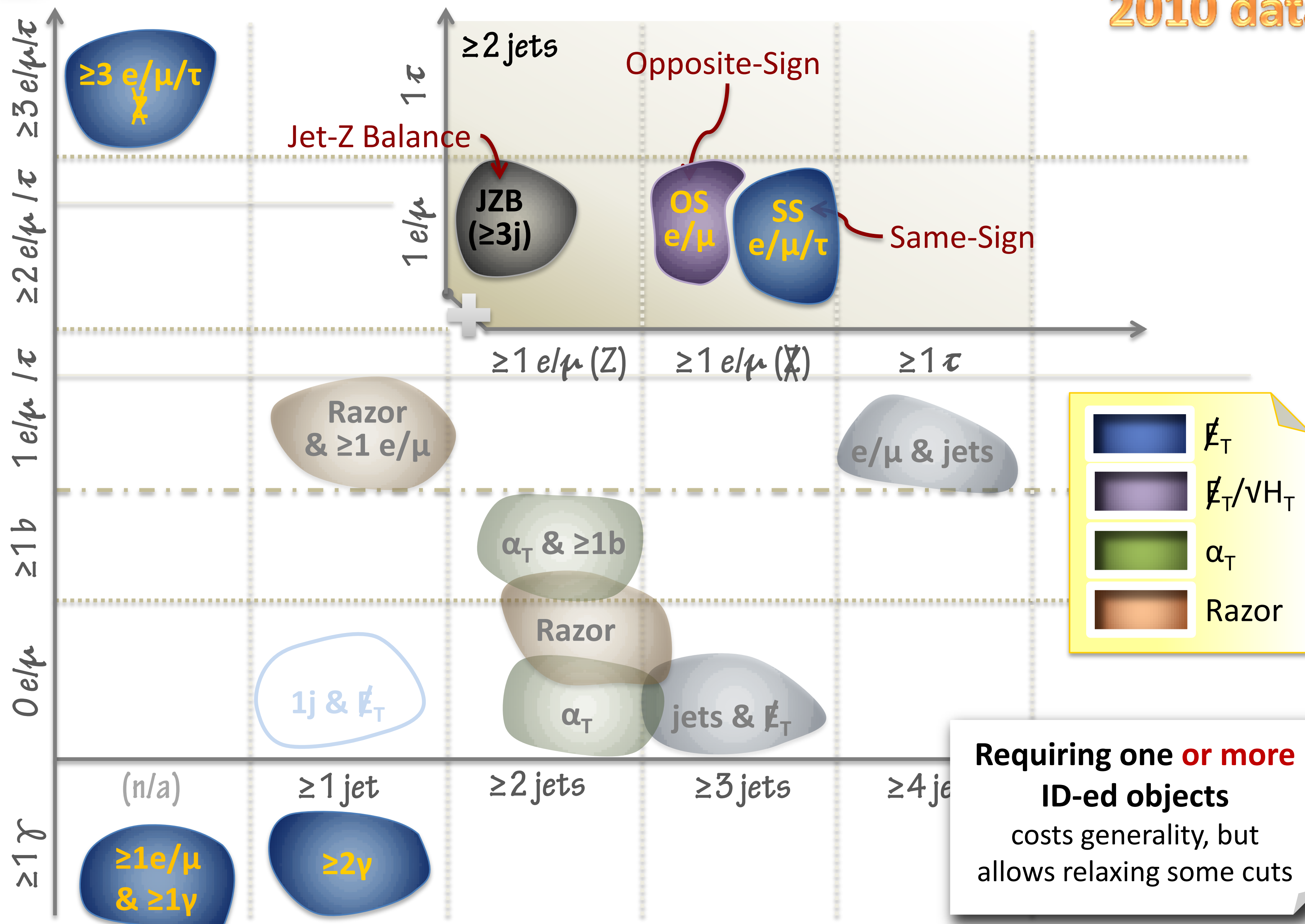


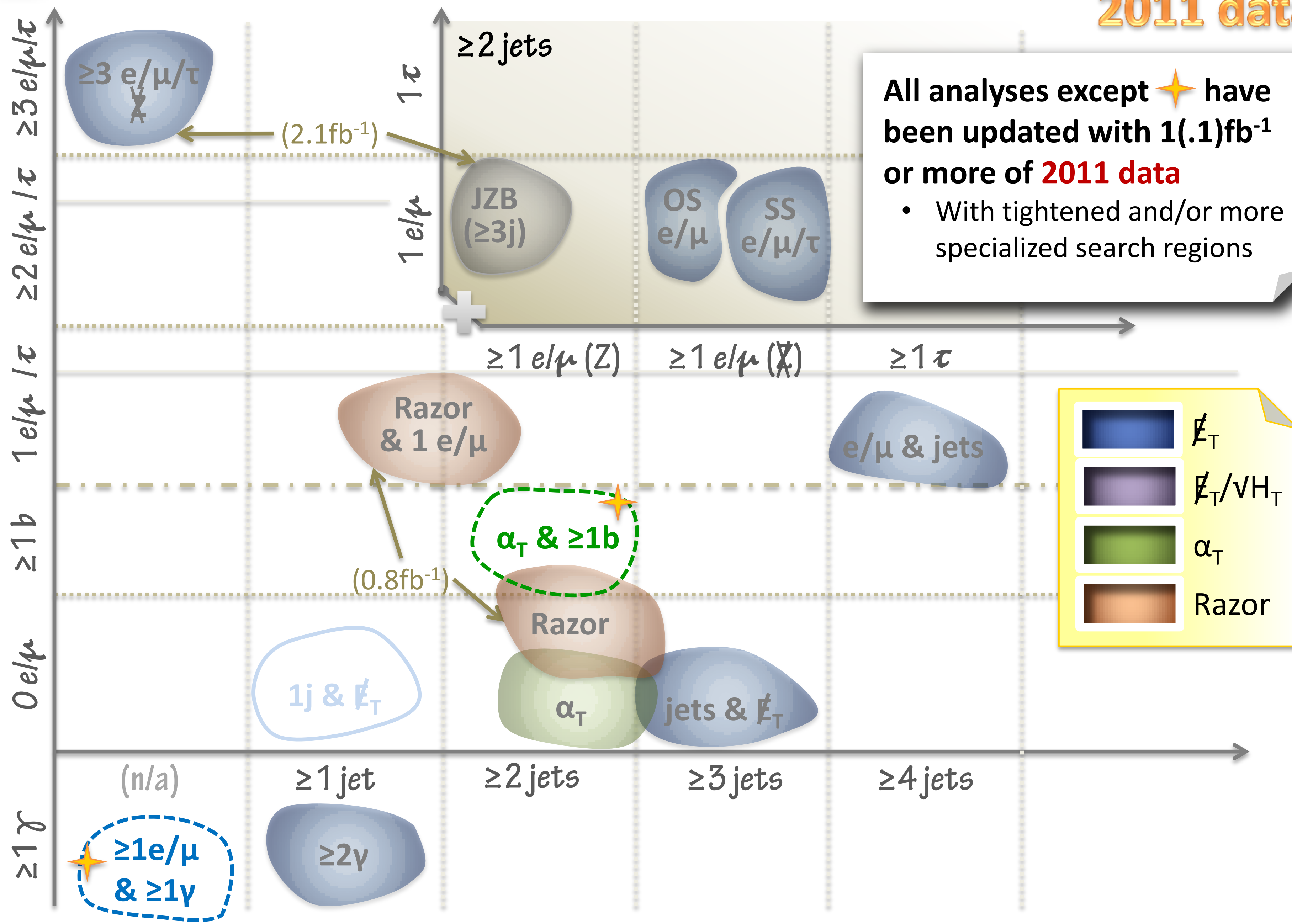
Requiring one or more ID-ed objects
costs generality, but allows relaxing some cuts

Signatures sought by SUSY searches

≳ 1fb^{-1} 2011 data

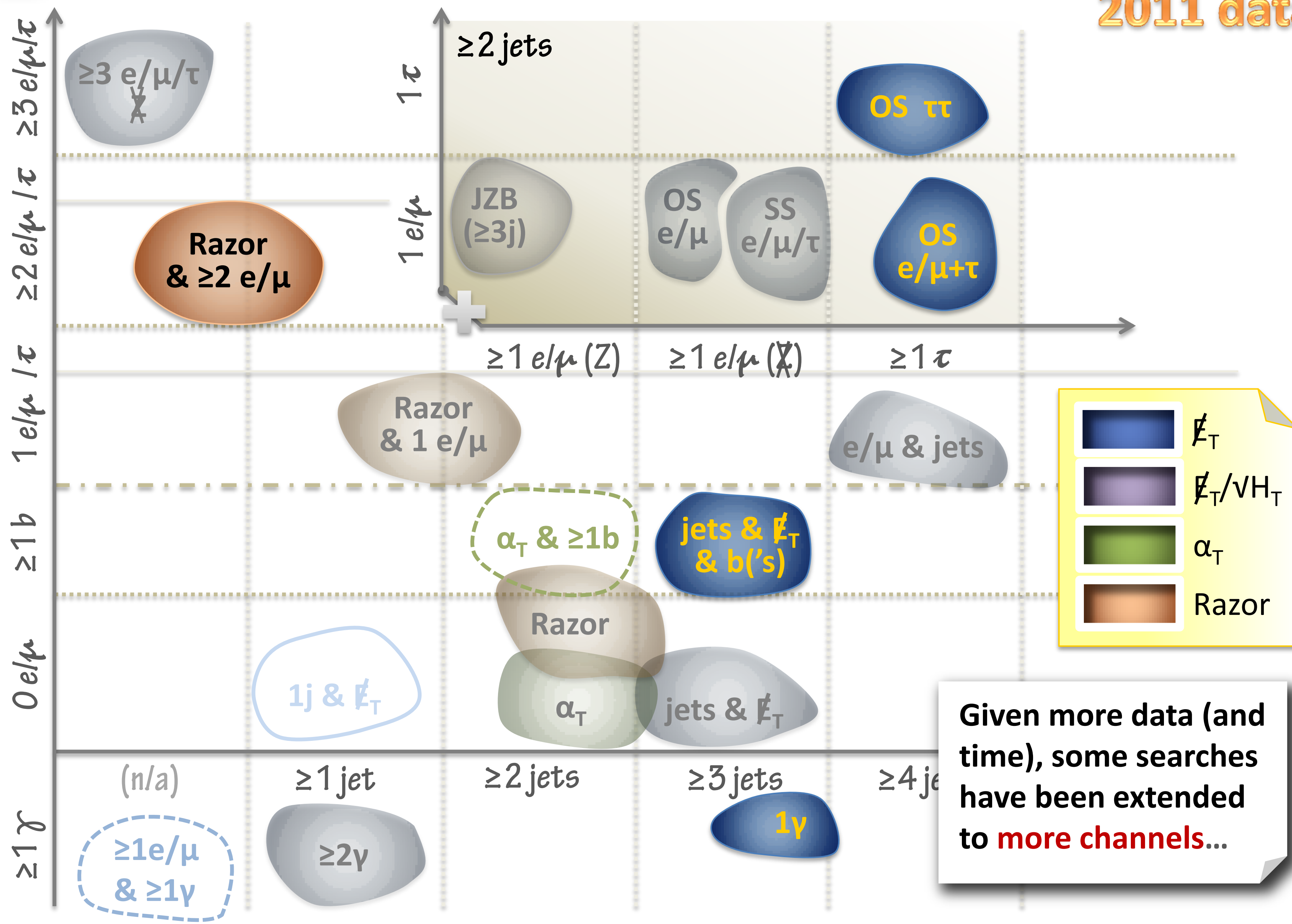
All analyses except ✦ have been updated with 1(.1)fb^{-1} or more of **2011 data**

- With tightened and/or more specialized search regions



Signatures sought by SUSY searches

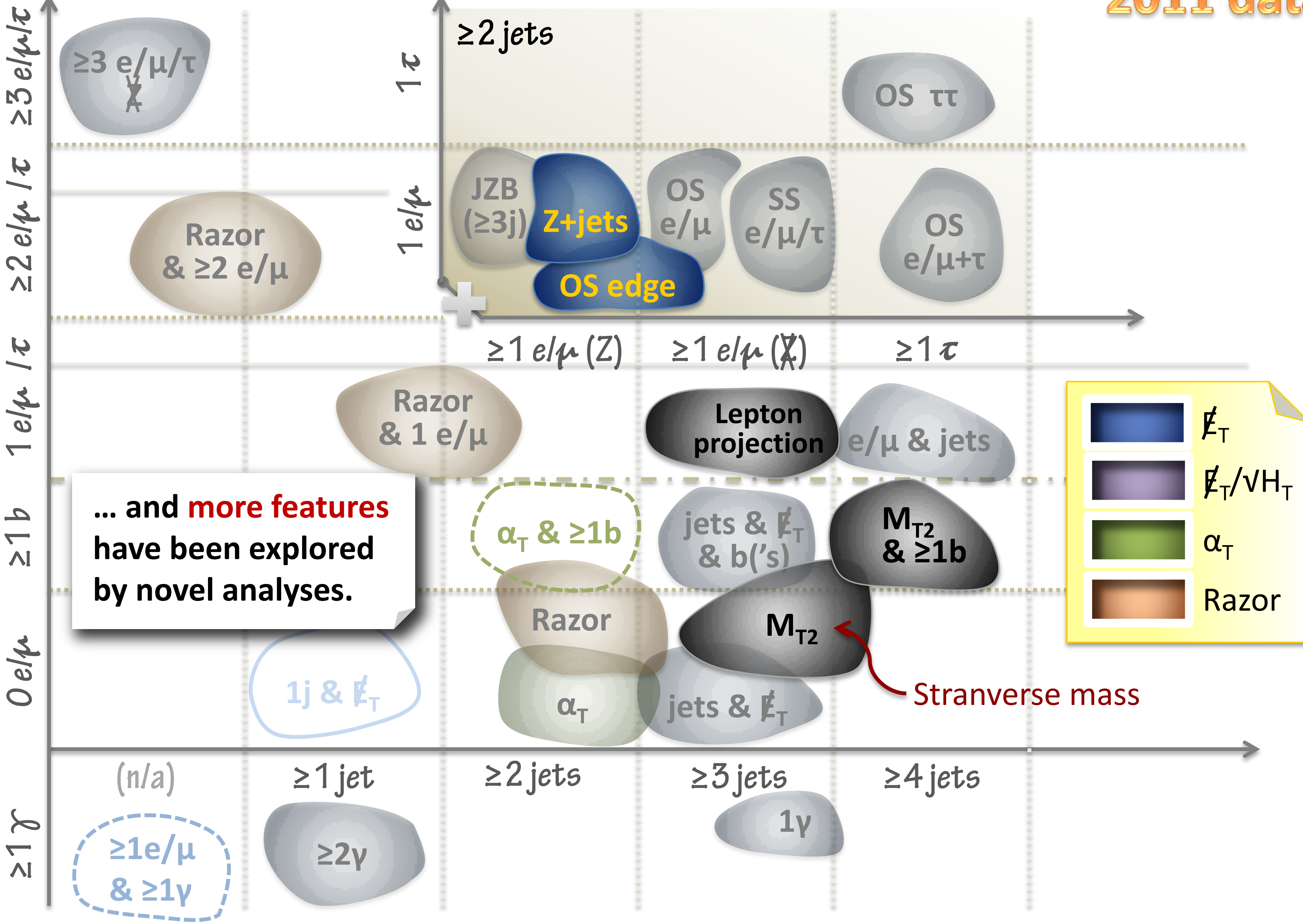
$\gtrsim 1 fb^{-1}$ 2011 data



Given more data (and time), some searches have been extended to more channels…

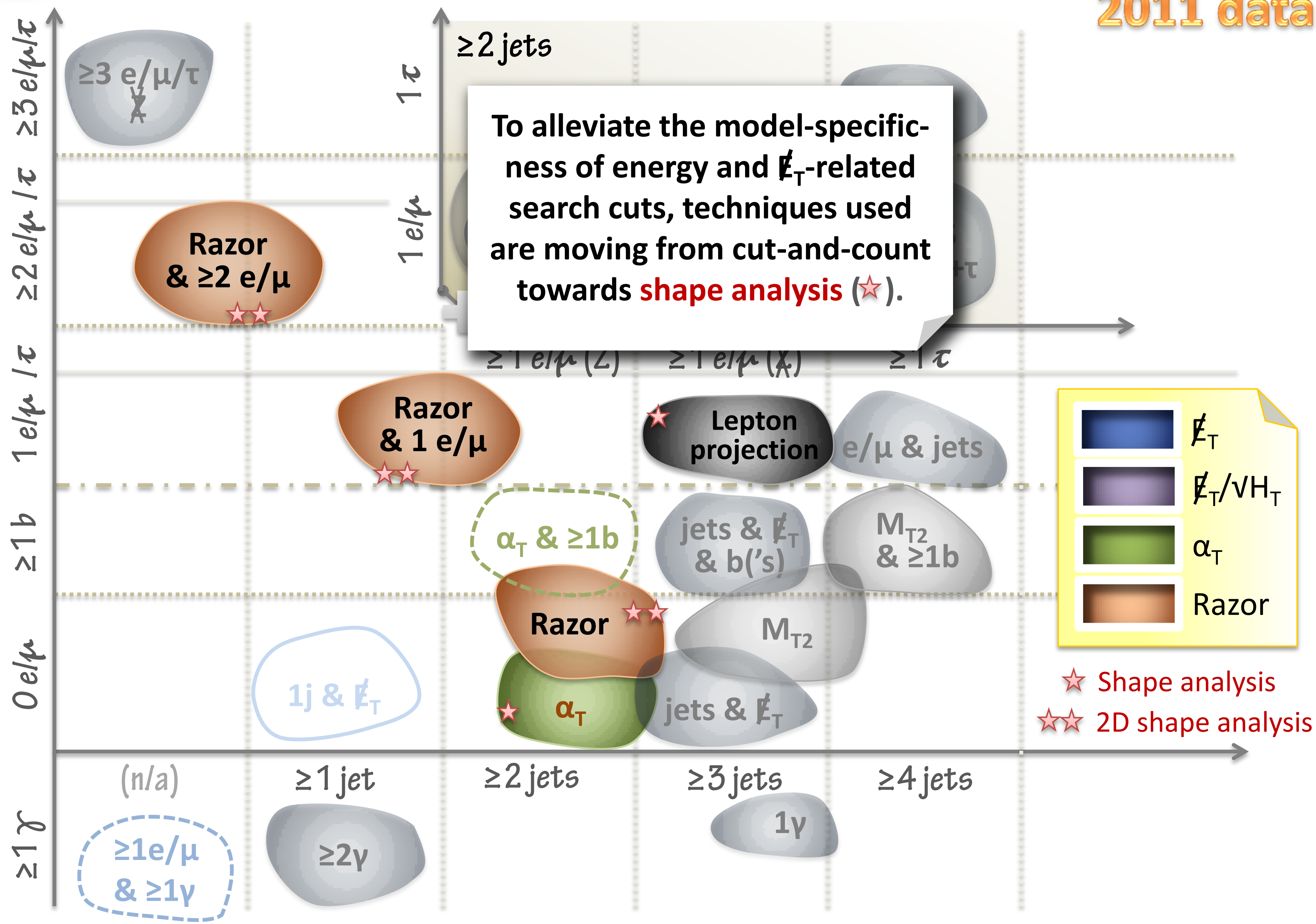
Signatures sought by SUSY searches

≳ $1 fb^{-1}$ 2011 data



Signatures sought by SUSY searches

$\gtrsim 1fb^{-1}$ 2011 data



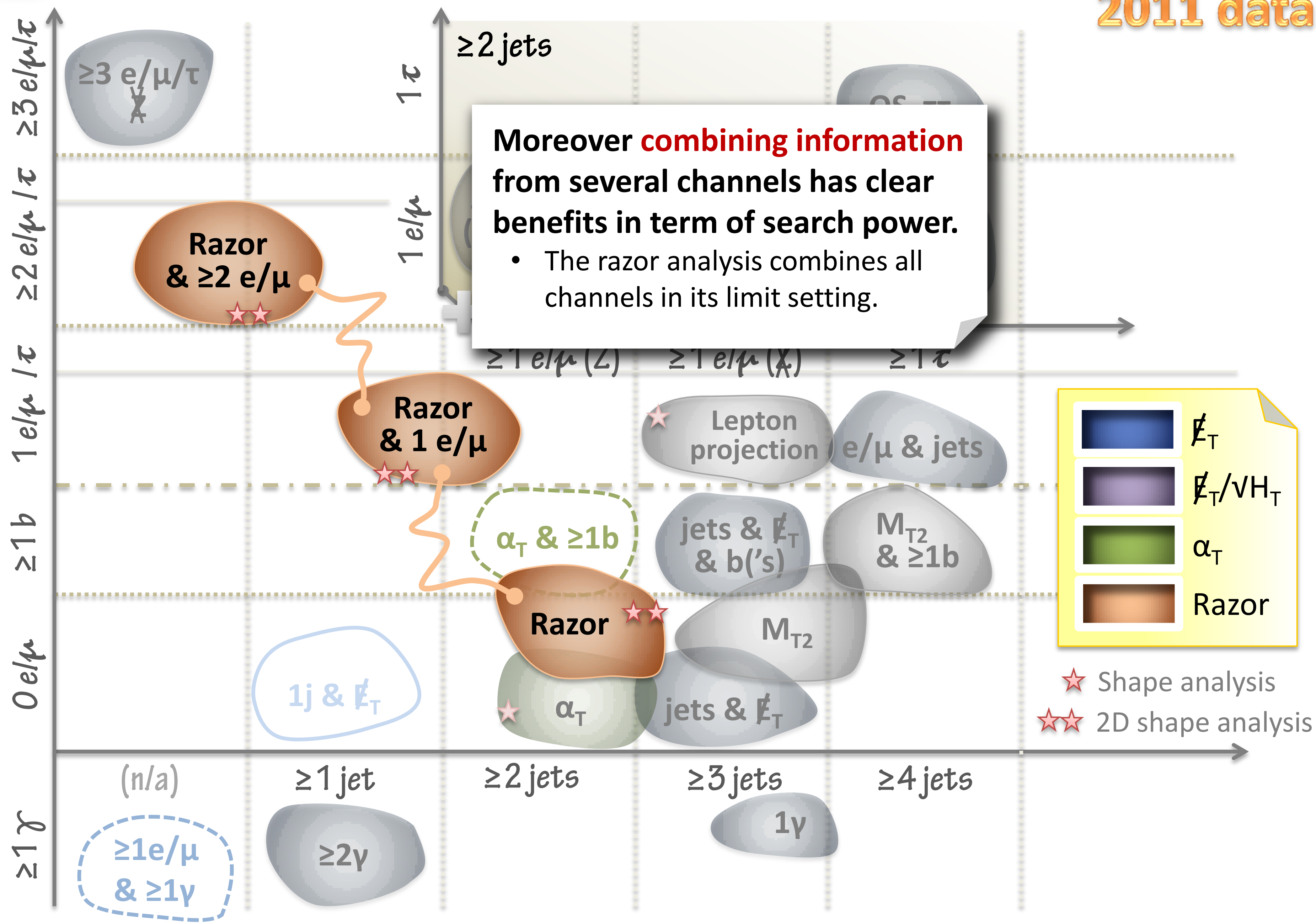
To alleviate the model-specific-ness of energy and $\not{E}_T$-related search cuts, techniques used are moving from cut-and-count towards **shape analysis** (☆).

Signatures sought by SUSY searches

≳ 1fb[-1] 2011 data

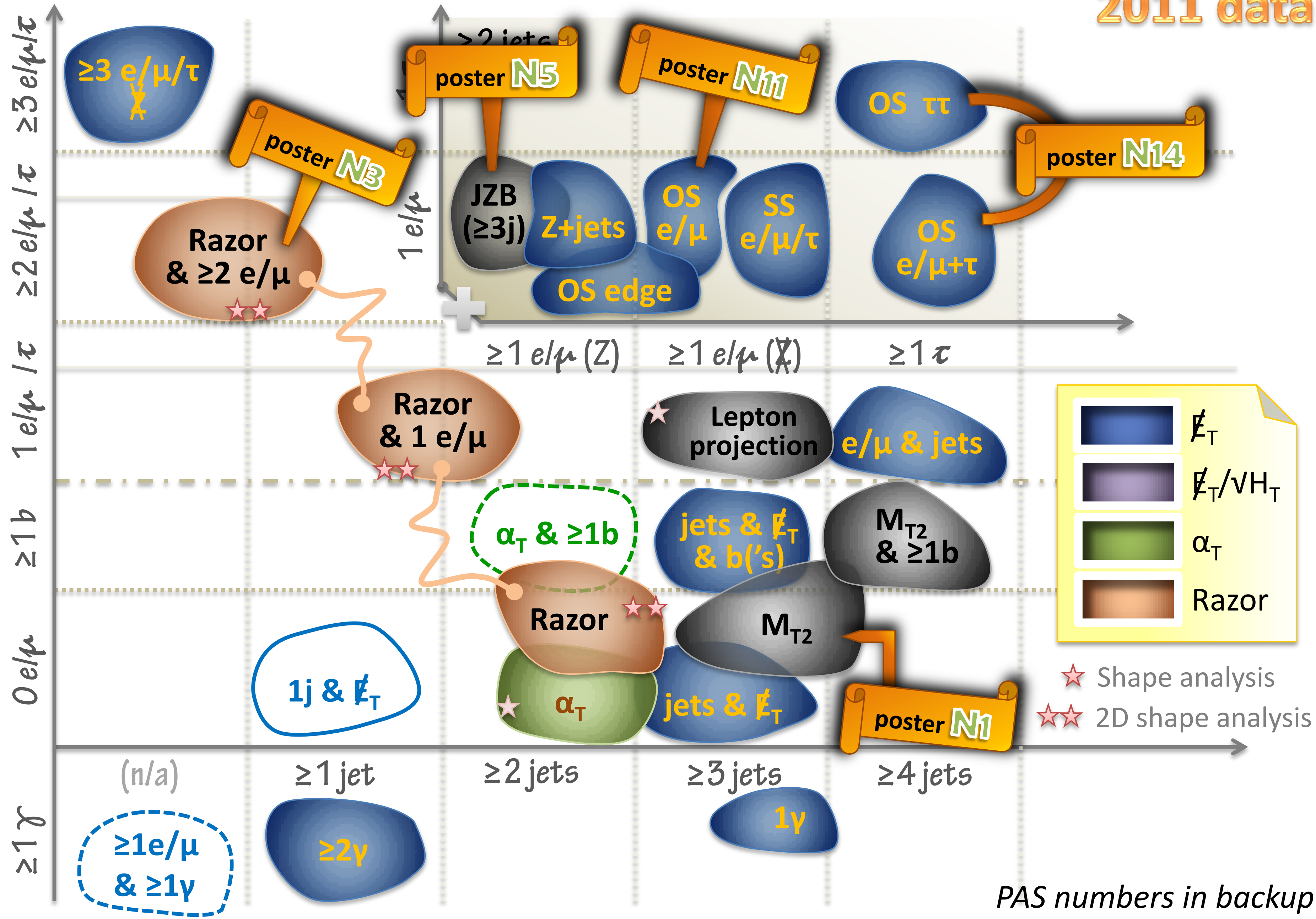
Moreover combining information from several channels has clear benefits in term of search power.

- The razor analysis combines all channels in its limit setting.



SUSY searches of CMS : Clickable links

$\gtrsim 1\,fb^{-1}$
2011 data



PAS numbers in backup

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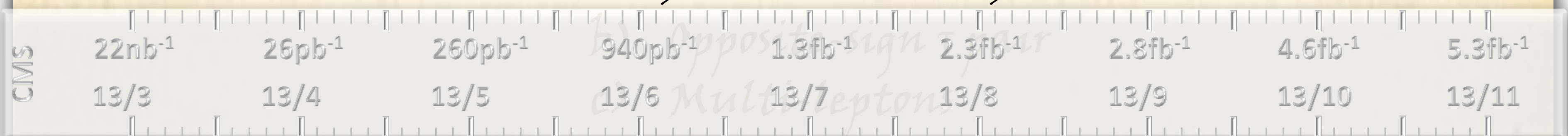
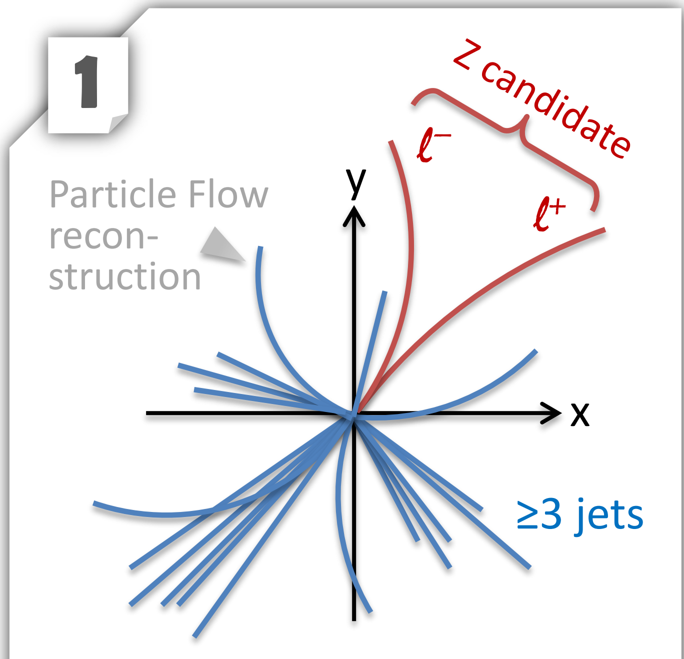
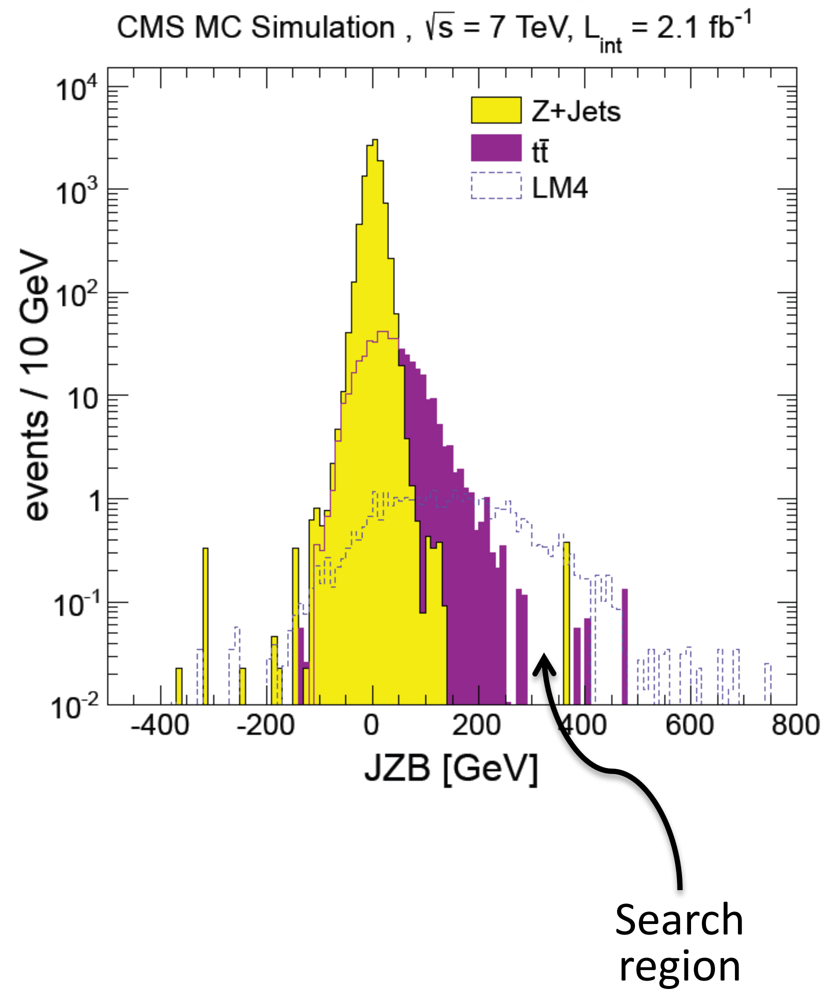


The Jet-Z Balance (JZB) method

poster N5



$$\mathrm{JZB} \equiv \Big|\sum_{\mathrm{recoil}} \vec{p}_T\Big| - |\vec{p}_T(\ell\ell)|$$



The Jet-Z Balance (JZB) method

poster N5

2 Only two significant SM backgrounds in JZB tails:

a) **Dileptonic tt** (and other flavor-symmetric processes)

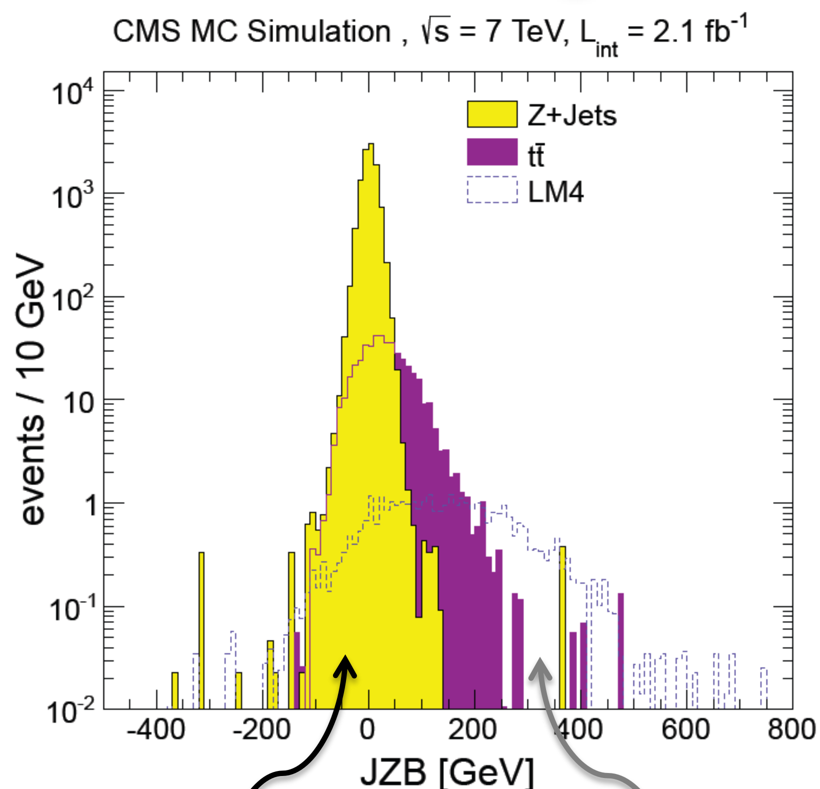
» Predict as average of yields in:

ℓℓ flavors	m(ℓℓ)
Opposite	Z window
Opposite	Side-band
Same	Side-band

Constructed to provide equal yield as in Z mass window (according to MC, verified in low |JZB| data)

b) **Z+jets** with mismeasured jets

» Estimate JZB > X yield as equal to that in JZB < -X region, after subtraction of (a).



~ symmetric about 0 for SM Z+jets

Search region

The Jet-Z Balance (JZB) method

poster N5

2

Only two significant SM backgrounds in JZB tails:

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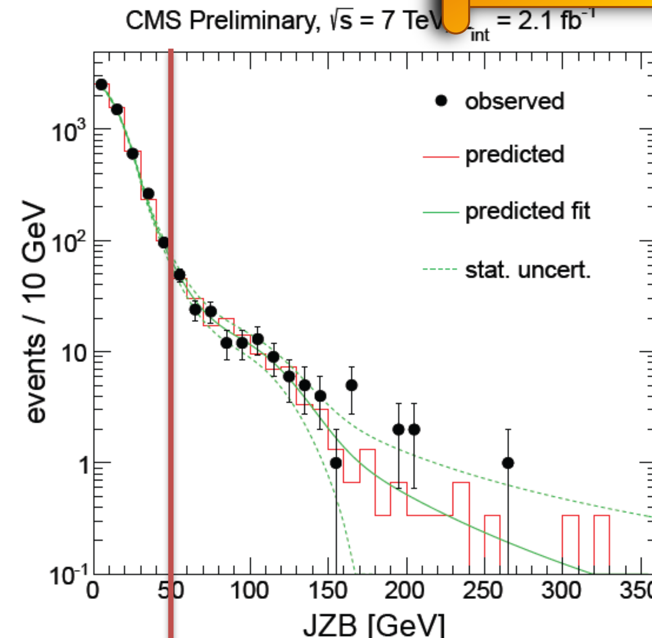

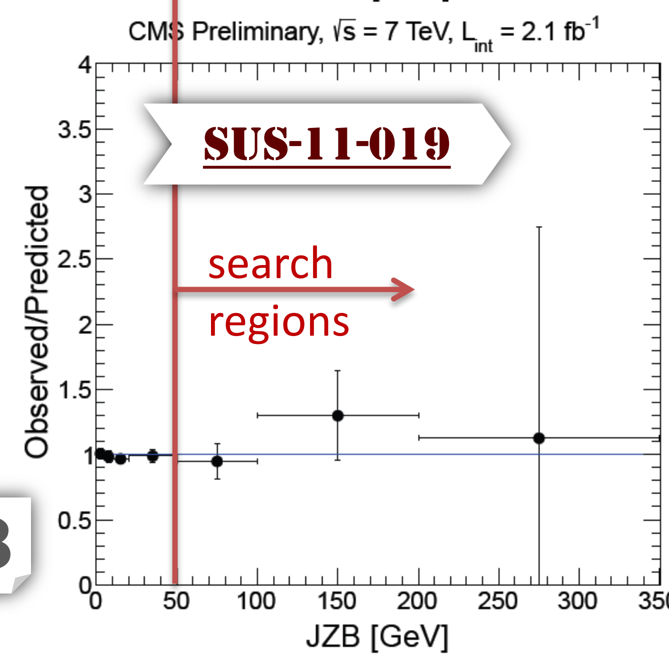

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CMS

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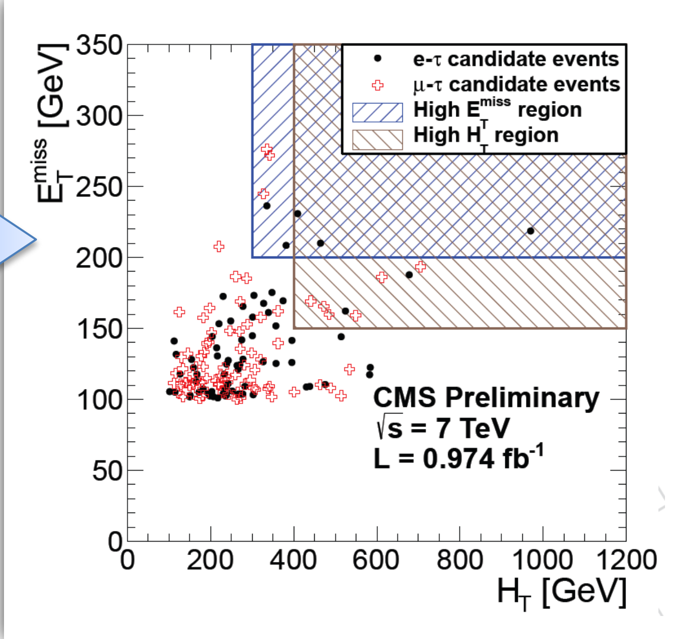
13/3	13/4	13/5	13/6	13/7	13/8	13/9	13/10	13/11

The Opposite-sign (OS) tau pairs search

poster N14

- Taus are a challenging reconstruction task:
  - Decays are simple and well-known, but huge background from jets.
  - About 1/3rd decay into (soft) e's and μ's.
  - The rest (τ_h) decay into hadrons and neutrinos.
    - » After isolation τ_h selection efficiency is ~30-40% for this search.

Channel	$p_T(l)$ threshold	Search region	
$e/\mu + \tau_h$	20 GeV	≥2 jets (p_T > 30)	$\not{E}_T > 150$, $H_T > 400$
			$\not{E}_T > 200$, $H_T > 300$
$\tau_h + \tau_h$	15 GeV	≥2 jets (p_T > 100), $\not{H}_T > 200$	



OS tau pairs : Background Estimations

poster N14

- $t\bar{t} \rightarrow \tau^+\tau^-X$:
  - Model $\not{E}_T$ with visible leptons in dilepton (e & μ) events:

$$\not{E}_T \sim p_T(\nu\nu) \sim p_T(\ell\ell) \times \frac{\varepsilon(\tau)}{\varepsilon(e/\mu)}$$

Correction factors: W polarization; $\not{E}_T$ resolution

- Jets misidentified as τ_h:

Loose-isolated τ_h sideband $\xrightarrow{\frac{P(\text{tight})}{P(\text{loose})}}$ Events w/ tight-isolated τ_h

$e/\mu + \tau_h$

SUS-11-007

Predicted	10.1 ± 1.7 (stat) ± 2.7 (sys) 7.5 ± 1.6 (stat) ± 1.9 (sys)
Observed	11 8

OS tau pairs : Background Estimations

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- Jets misidentified as τ_h:

Loose-isolated τ_h sideband $\xrightarrow{\frac{P(\text{tight})}{P(\text{loose})}}$ Events w/ tight-isolated τ_h

- Extrapolate from enriched control regions using relative selection efficiencies:

Back-ground	Control region
tt	≥2 b-tagged jets
QCD	$\lvert\Delta\phi(j_2, \not\!\!H_T)\rvert < 0.15$
$Z\rightarrow\nu\nu$	$Z\rightarrow\mu^+\mu^-$
W	$\lvert\Delta\phi(j_2, \not\!\!H_T)\rvert > 0.5$, no b-tagged jets

SUS-11-007

$e/\mu + \tau_h$

Predicted	10.1 ± 1.7 (stat) ± 2.7 (sys) 7.5 ± 1.6 (stat) ± 1.9 (sys)
Observed	11 8

$\tau_h + \tau_h$

Predicted	4.56 ± 1.08 (stat) ± 0.91 (sys)
Observed	3

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The Multi-lepton (≥3 e/μ/τ) search

$$\begin{pmatrix} 3\ell \\ \geq 4\ell \end{pmatrix} \times \begin{pmatrix} \text{relative} \\ \text{sign} \end{pmatrix} \times \begin{pmatrix} \text{flavor} \end{pmatrix} \times \begin{pmatrix} H_T > 200 \\ H_T < 200 \end{pmatrix} \times \begin{pmatrix} \not{E}_T > 50 \\ \not{E}_T < 50 \end{pmatrix}$$

= *52 channels*

- Very clean search regions:
  - A detailed catalog of 3 and ≥4 lepton channels, covering possibly many BSM theory footprints.
  - A wide range of kinematic regimes probed.
  - $\not{E}_T$ cut not required to regulate SM background:
    - » A golden channel for some signatures of R-parity-violating SUSY

See CMS-exotica talk by B. Dahmes tomorrow

The Multi-lepton (≥3 e/μ/τ) search

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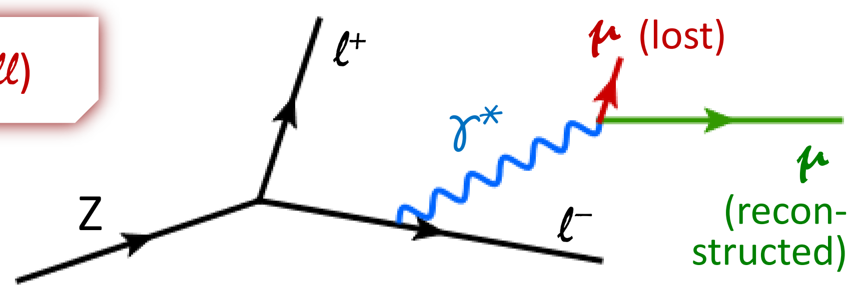
= *52 channels*

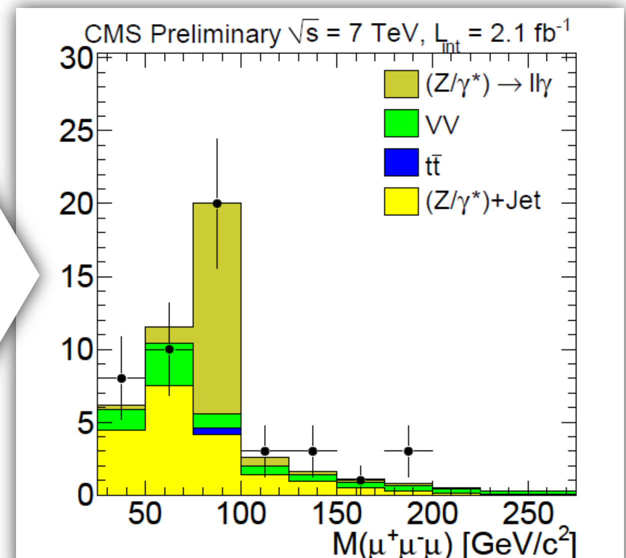
- Very clean search regions.
- Nevertheless, careful work has been done to understand backgrounds, especially the non-prompt:
  - e.g. $\ell\ell$+(γ→$\ell\ell$) from Z-peak in trilepton invariant mass.

See CMS-exotica talk by B. Dahmes tomorrow

$\ell\ell$+(γ→$\ell\ell$)



Asymmetric conversions



The Multi-lepton ($\geq$3 e/μ/τ) search

$$\begin{pmatrix} 3\ell \\ \geq 4\ell \end{pmatrix} \times \begin{Bmatrix} \text{relative} \\ \text{sign} \end{Bmatrix} \times \begin{Bmatrix} \text{flavor} \end{Bmatrix} \times \begin{Bmatrix} H_T > 200 \\ H_T < 200 \end{Bmatrix} \times \begin{Bmatrix} \not{E}_T > 50 \\ \not{E}_T < 50 \end{Bmatrix}$$

= *52 channels*

(All in good agreement with prediction)

SUS-11-008

- Very clean search regions.
- Nevertheless, careful work has been done to understand backgrounds, especially the non-prompt:

See CMS-exotica talk by B. Dahmes tomorrow

$\ell\ell$+(jet→ℓ) — Apply P(isolated track → e/μ); Extrapolate τ_h isolation sideband

$\ell\ell$+(γ→$\ell\ell$) — Conversion rate $N(\ell^+\ell^-\ell^\pm)/N(\ell^+\ell^-\gamma)$ measured on Z peak

Data driven

$t\bar{t}$

Diboson

Validated MC

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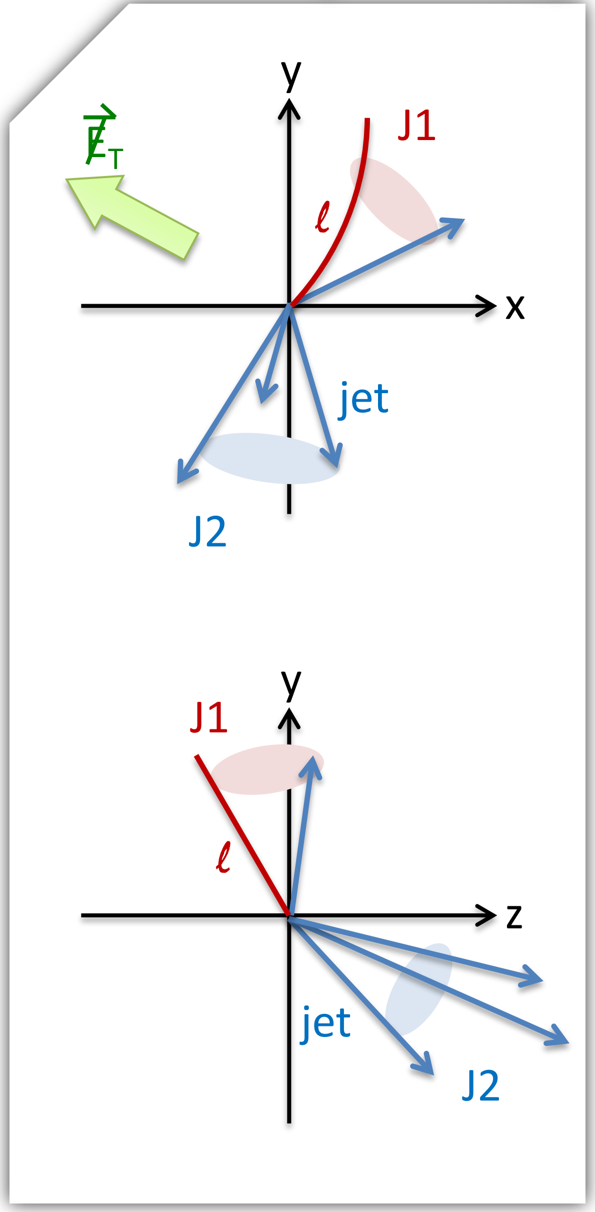
The Razor variables

poster N3

1. Cluster objects into two "megajets" a.k.a. hemispheres (J1, J2).



The Razor variables

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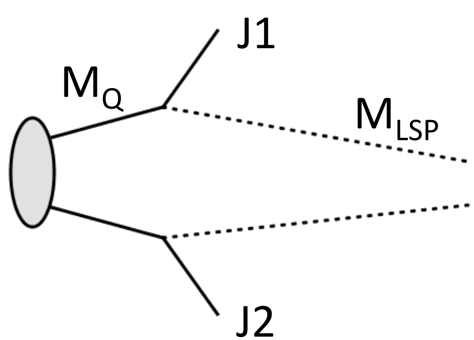
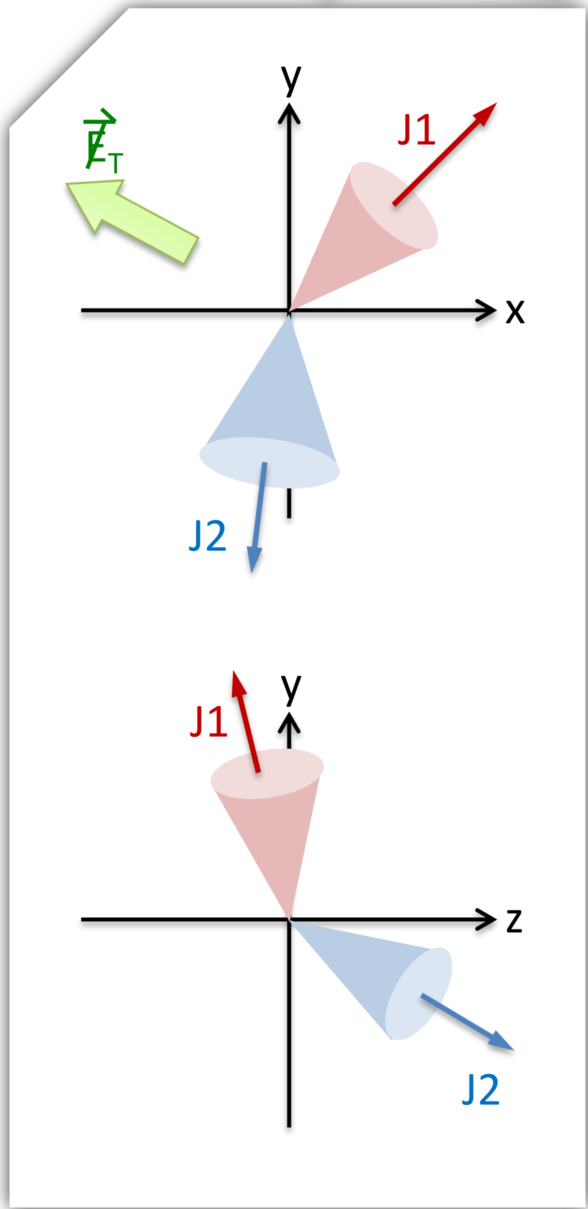
1 Cluster objects into two “megajets” a.k.a. hemispheres (J1, J2).

- **Analogy:** decay product J1 of a particle produced at rest has monochromatic energy ($2M_\Delta$):



$$M_\Delta = (M_Q^2 – M_{LSP}^2) / M_Q^2$$

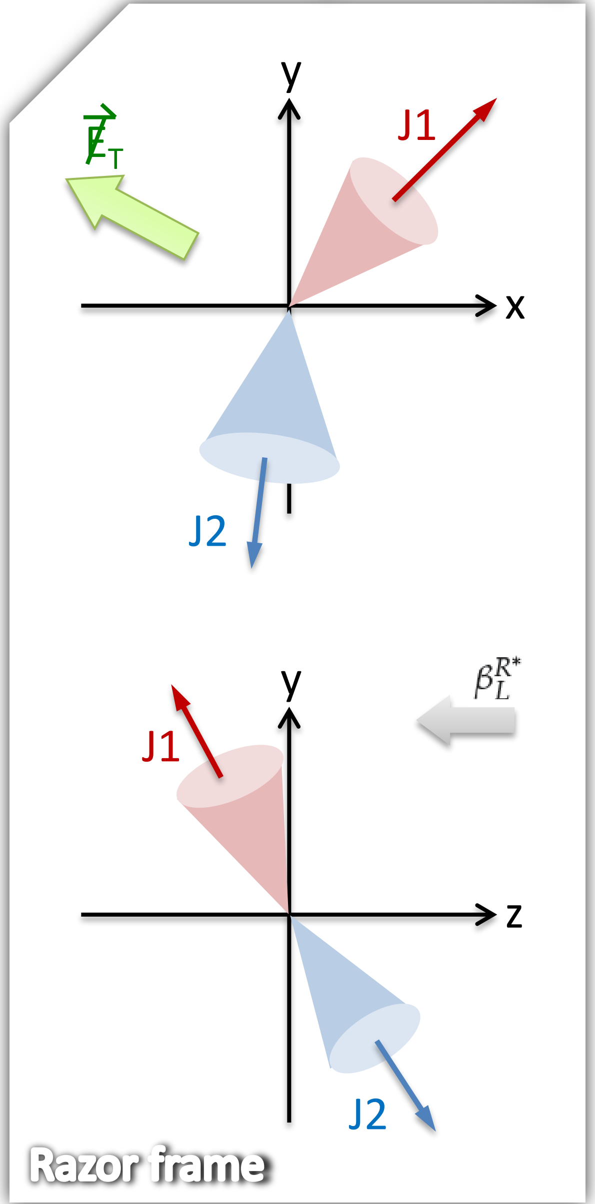
“ How can we estimate M_Δ? ”



The Razor variables

1 Cluster objects into two “megajets” a.k.a. hemispheres (J1, J2).

- **Analogy:** decay product J1 of a particle produced at rest has monochromatic energy ($2M_\Delta$):
- Reduce smearing from unknown incoming p_z by boosting to a frame where J1 and J2 z-momenta are equal and opposite:



Total energy (J1 + J2) in a Razor frame

2
$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

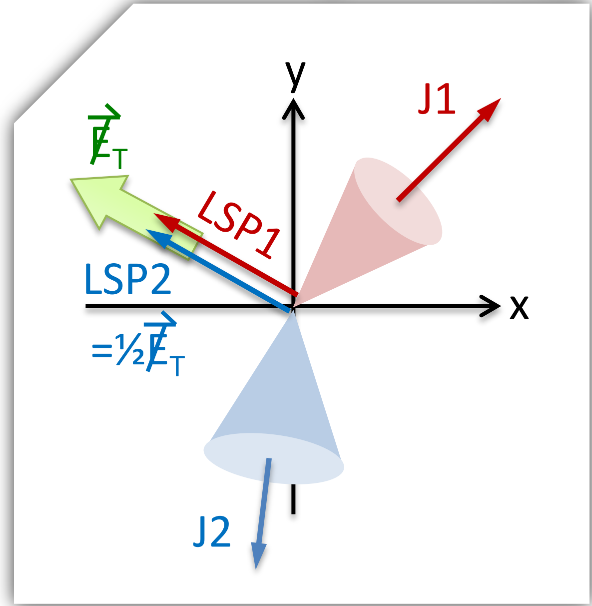
peaks around M_Δ

The Razor variables

poster N3

1 Cluster objects into two “megajets” a.k.a. hemispheres (J1, J2).

- **Analogy:** decay product J1 of a particle produced at rest has monochromatic energy ($2M_\Delta$):
- Reduce smearing from unknown incoming p_z by boosting to a frame where J1 and J2 z-momenta are equal and opposite:
- Divide $\vec{E\!\!\!/}_T$ equally into two “LSP momenta”, compute transverse mass for each decay chain:



$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2})}{2}}$$

Average transverse mass
end-point at M_Δ

Total energy (J1 + J2) in a Razor frame

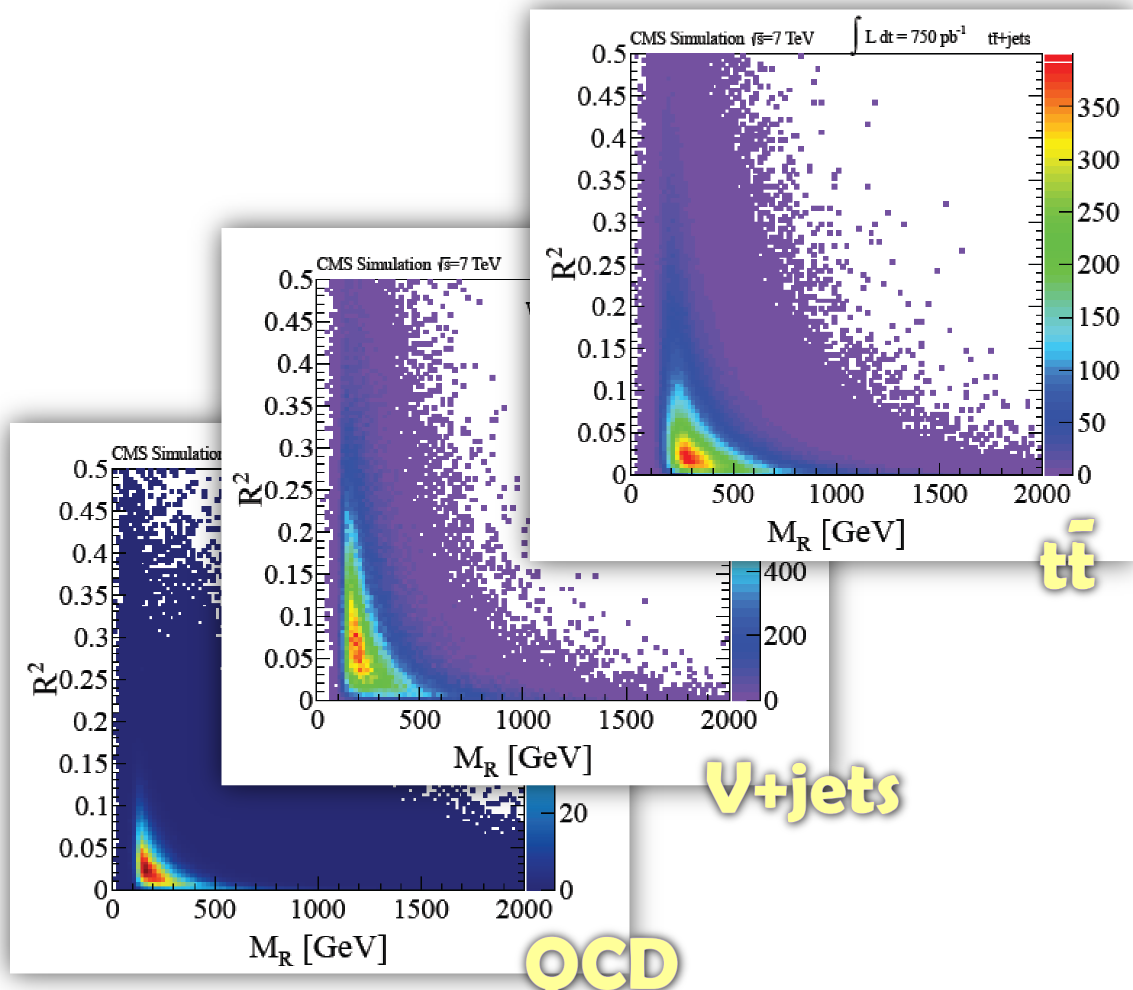
2
$$M_R \equiv \sqrt{(E_{j_1}+E_{j_2})^2 - (p_z^{j_1}+p_z^{j_2})^2}$$

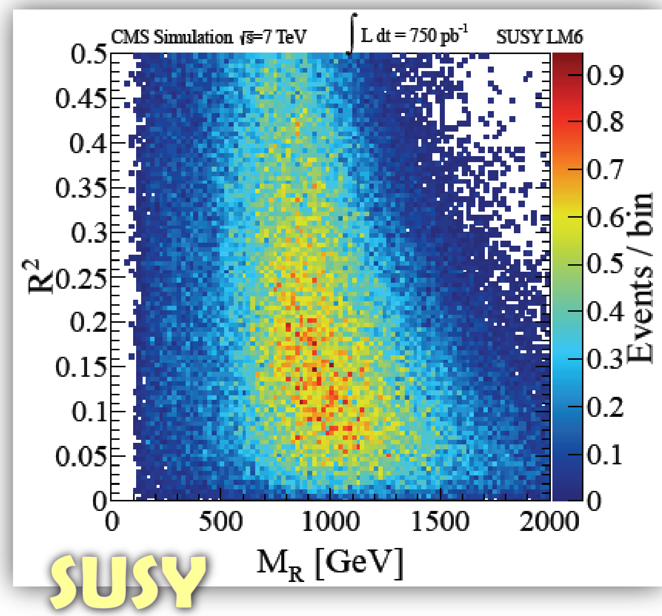
peaks around M_Δ

3
$$R \equiv \frac{M_T^R}{M_R}$$

A Razor advantage

poster N3





2

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

peaks around M_Δ

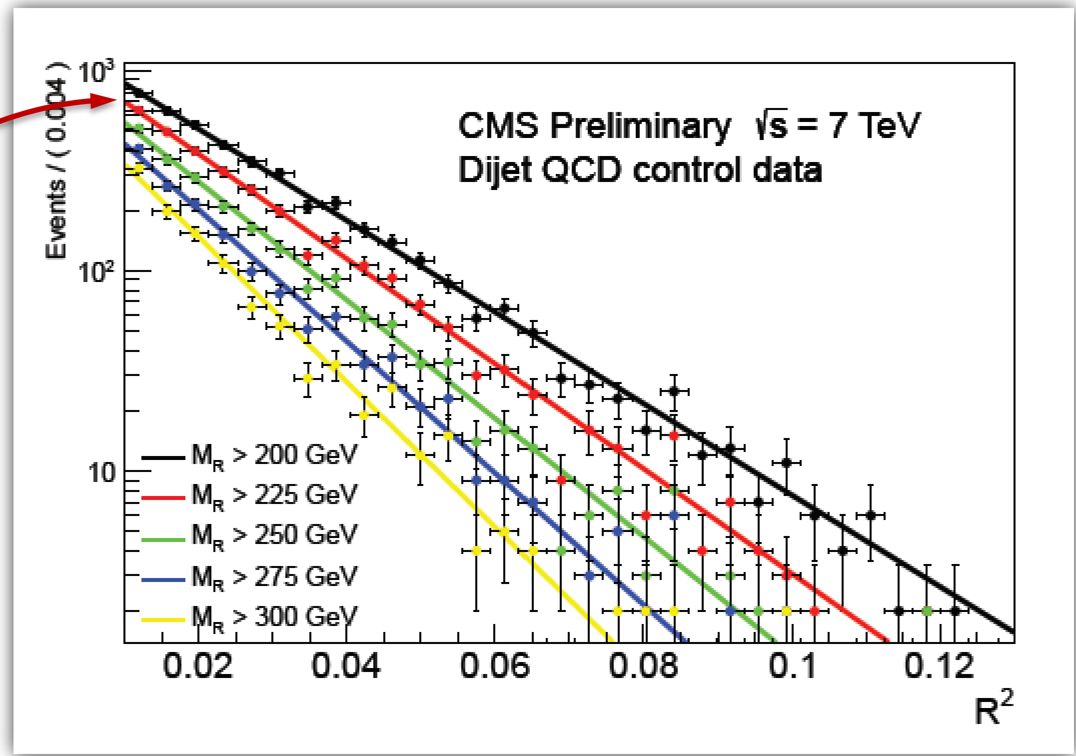
3

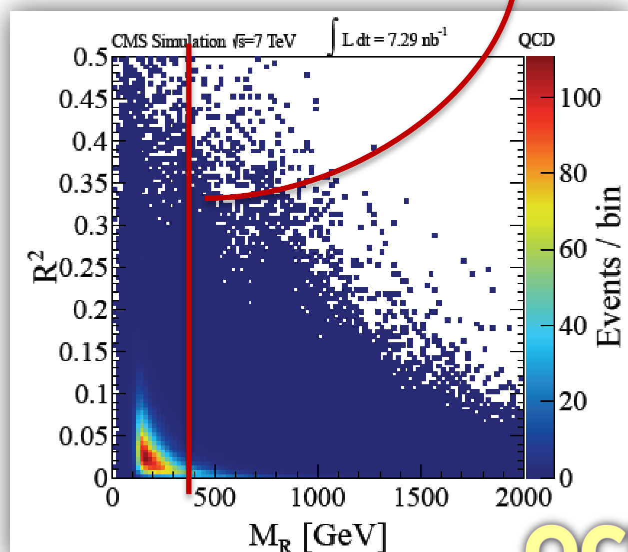
$$R \equiv \frac{M_T^R}{M_R}$$

Another Razor advantage

poster N3

For cuts on M_R (R), the distribution of R (M_R) has (2-)exponential shape for SM backgrounds:





QCD

2

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

peaks around M_Δ

3

$$R \equiv \frac{M_T^R}{M_R}$$

The Razor analysis

poster N3

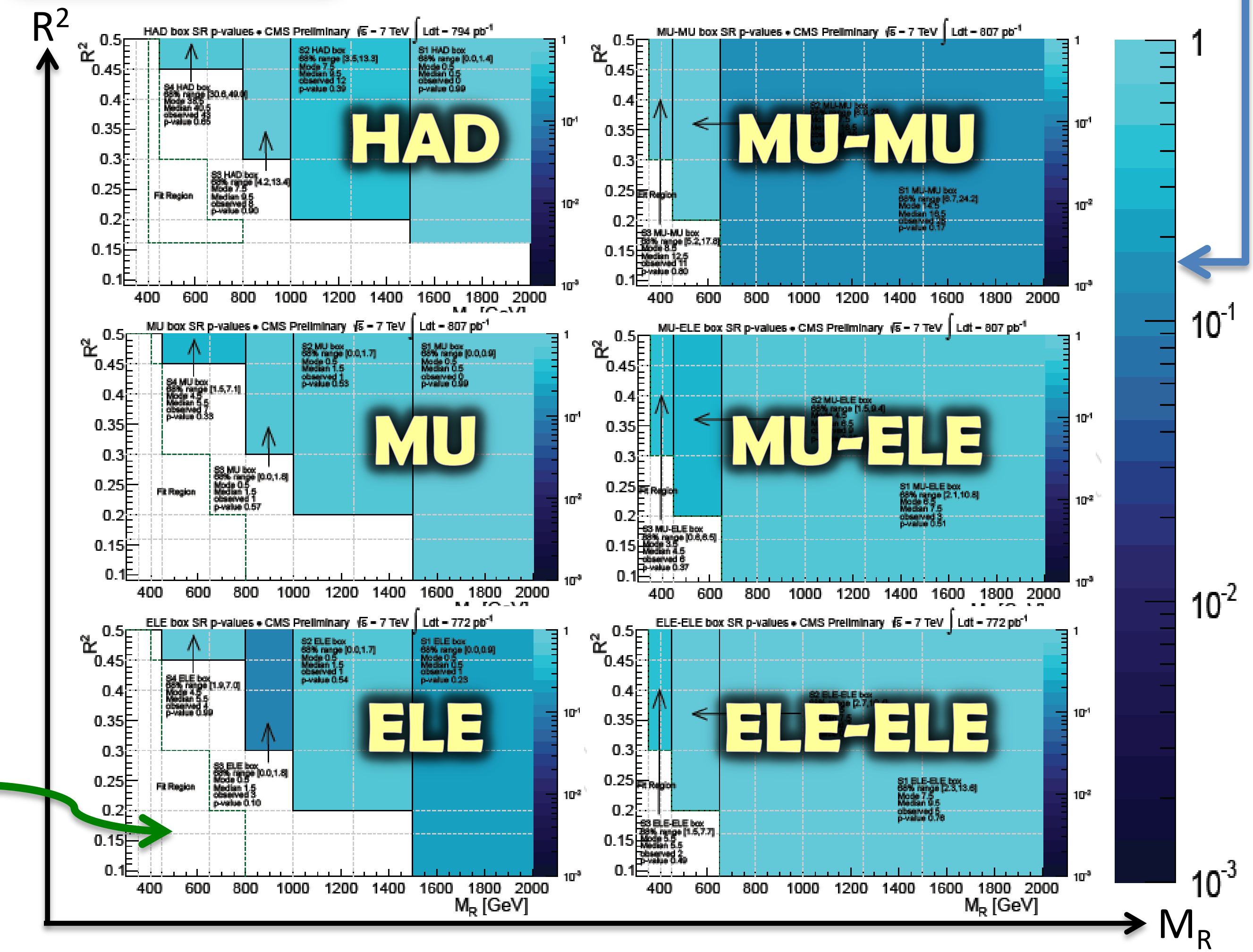
a Yield of each background modeled by a 2D functional form.

- Initial parameters & constraints extracted from enriched control regions in data.

b Combined SM fit performed in a sideband of each channel box.

c p-values for SM compatibility of data computed for various search regions.

SUS-11-008



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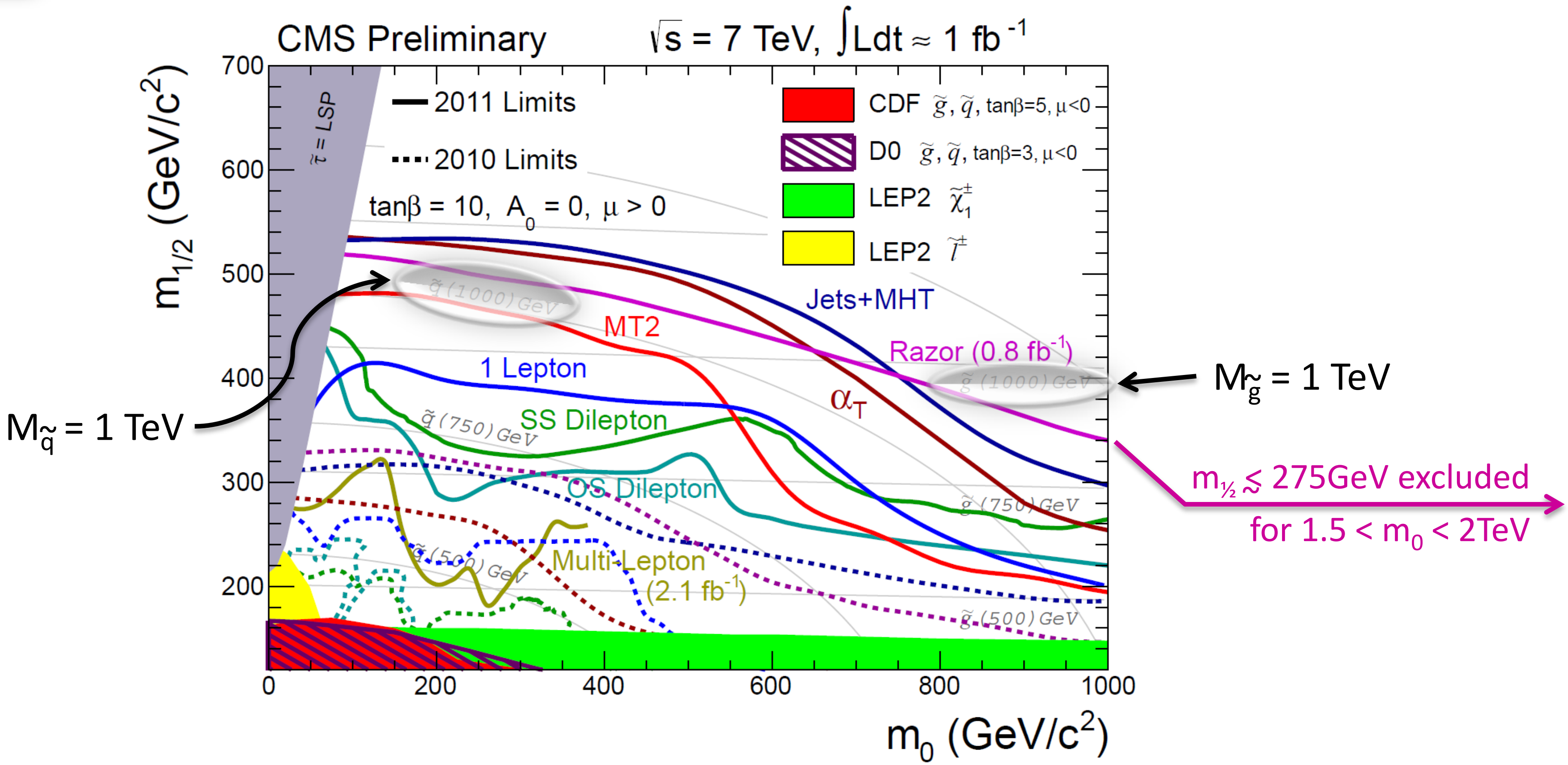
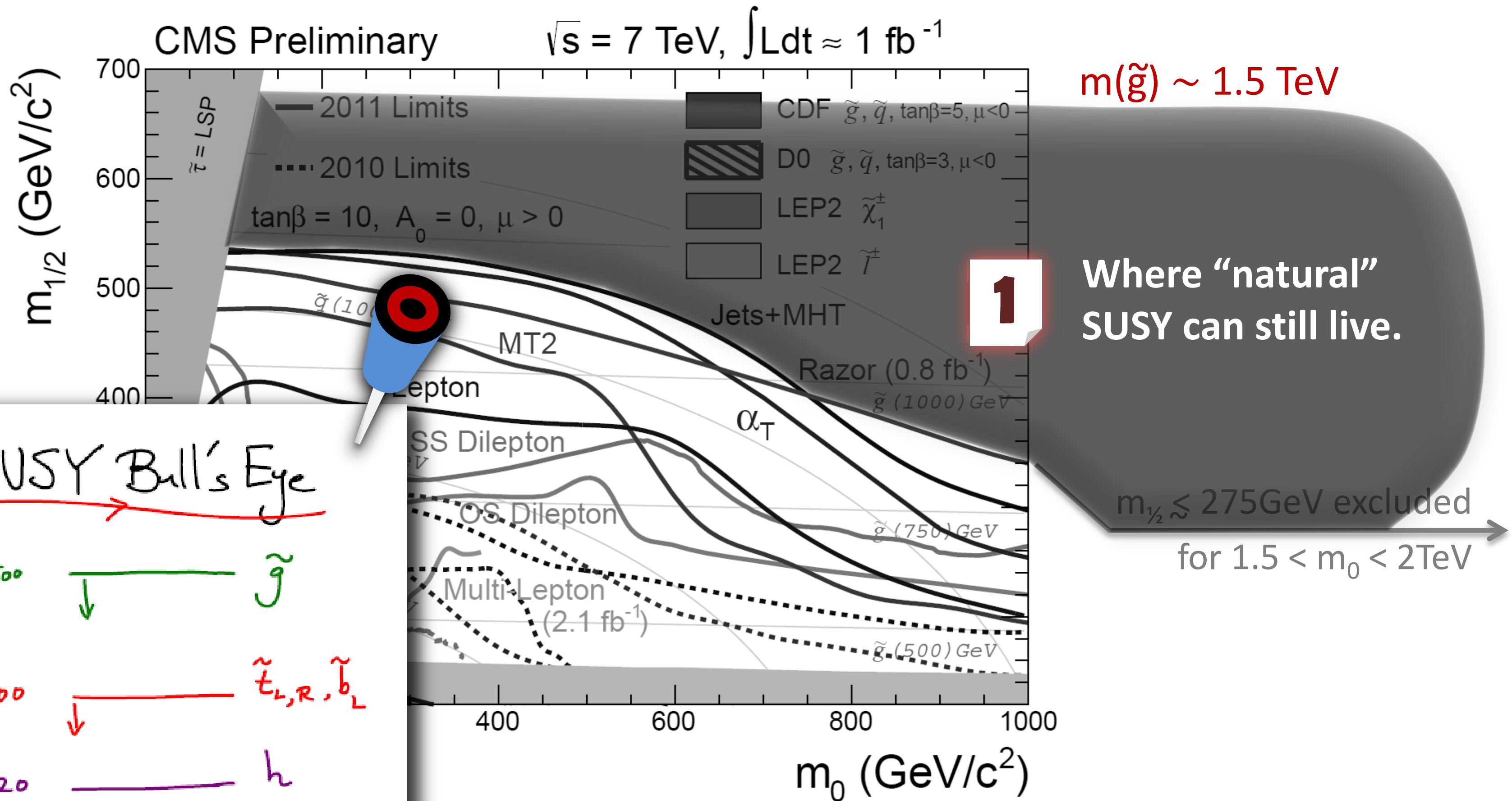
CMSSM Exclusion



We have **not** excluded...



SUSY Bull's Eye

1500 $\tilde{g}$

400 $\tilde{t}_{L,R}, \tilde{b}_L$

120 h

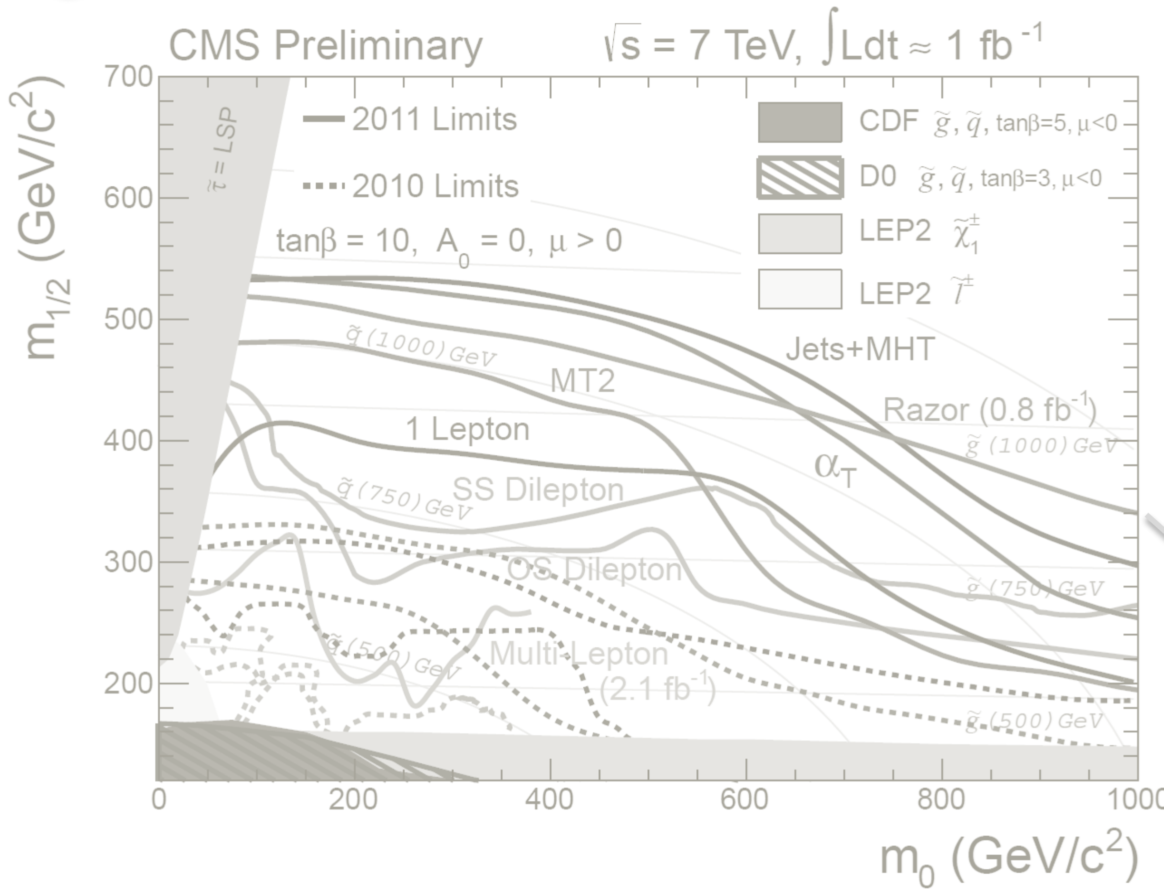
No wiggle room.

Limits: sharply quantify tuning.

N. Hamed

Implications of LHC results for TeV-scale physics: WG2 meeting

Beyond CMSSM exclusions…

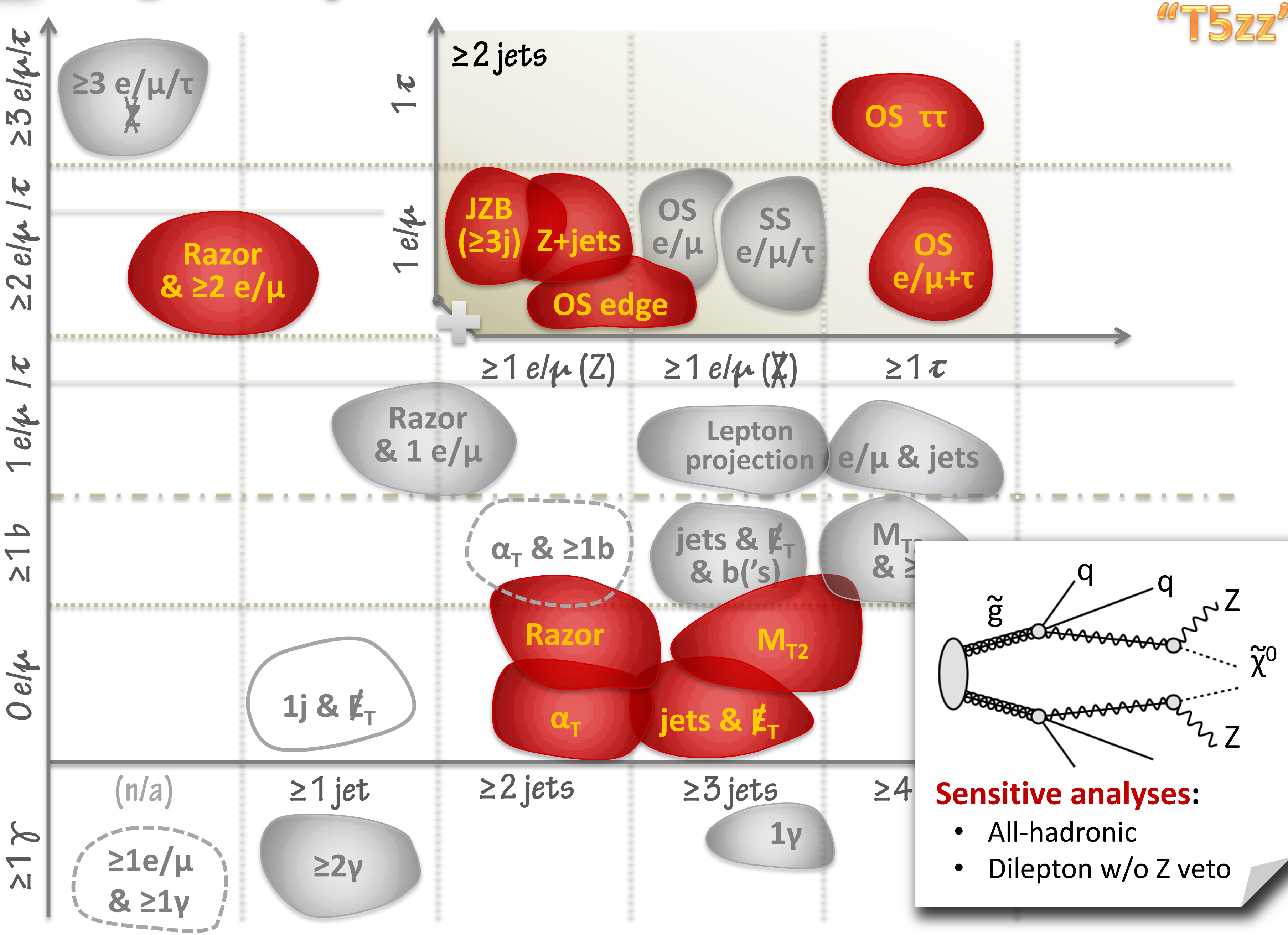


$m_{1/2} \lesssim 275$GeV excluded
for $1.5 < m_0 < 2$TeV

- We complement these benchmarks with Simplified Model Spectra (SMS):
  - Each SMS consists of a small list of new particles and their decays (~ 1 topology).
  - Can be thought of as building blocks/effective theories.
    - » How much do our results say about these reactions in isolation (assume 100% B.R.)?
    - » Signal contamination accounted for as applicable, but only from the SMS under study.

e.g. Footprint of a SMS Model

$\tilde{g}\tilde{g}$, $\tilde{g} \to qqZ\tilde{\chi}^0$
"T5zz"



Sensitive analyses:

- All-hadronic
- Dilepton w/o Z veto

e.g. Exclusion by various searches

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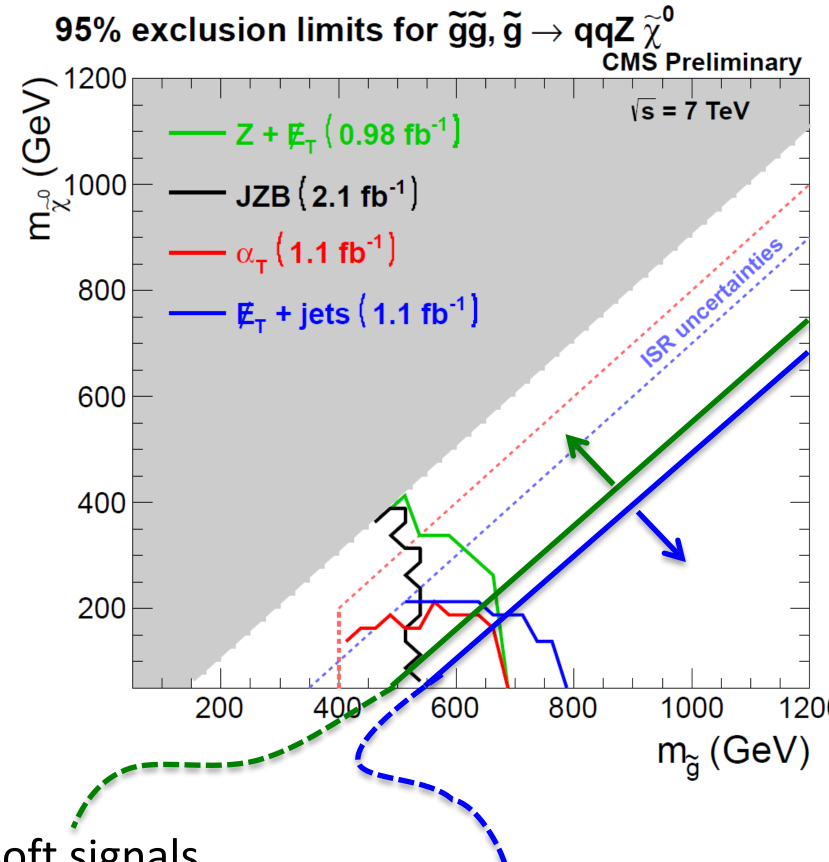
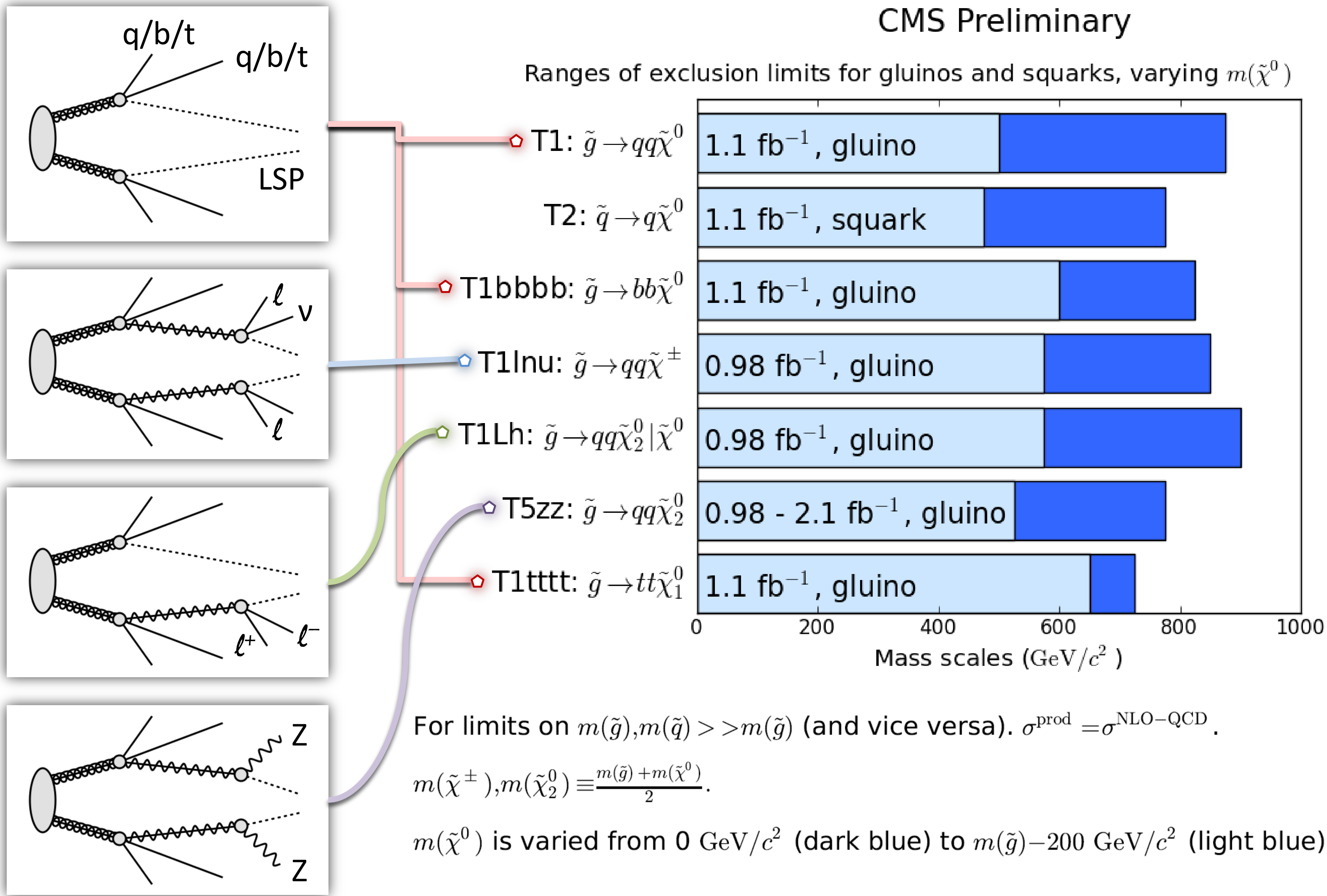


Soft signals, leptonic searches recover efficiency

Energetic signals, hadronic searches gain from larger branching ratio (B.R.)

SMS view of SUSY searches



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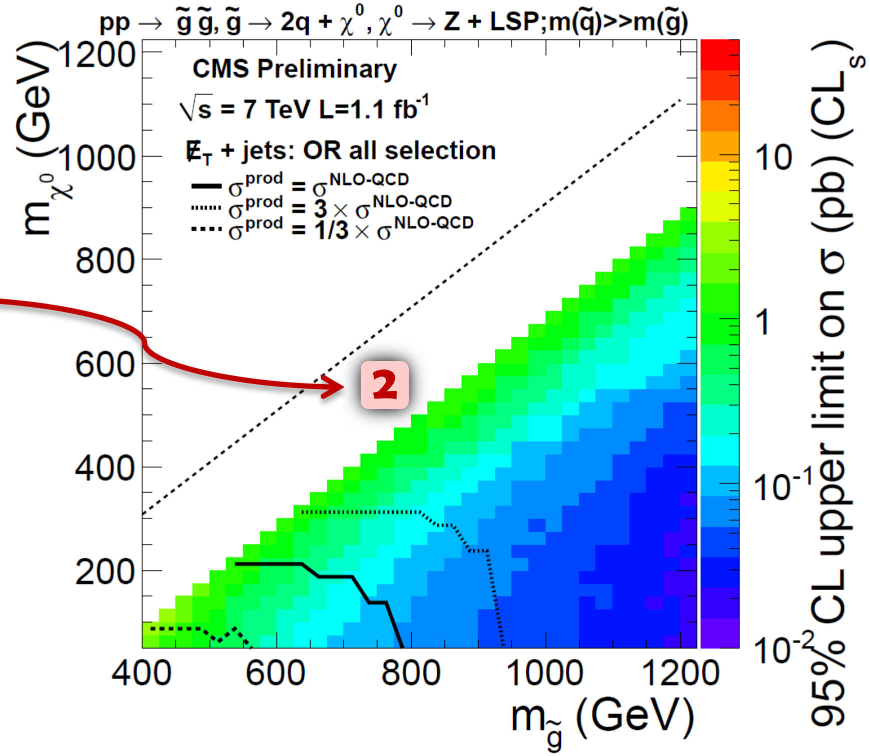

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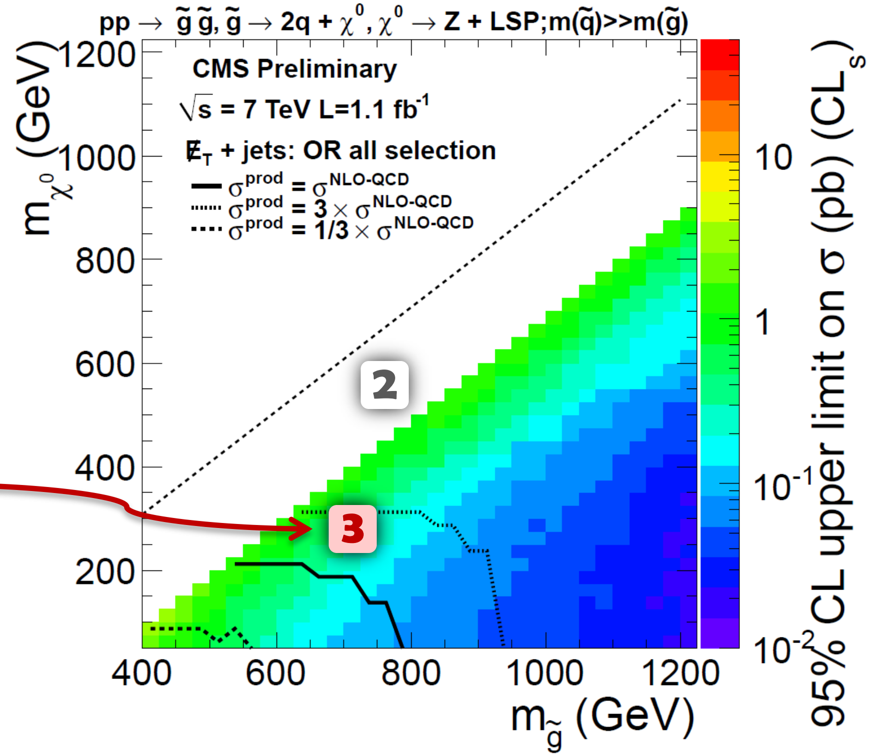

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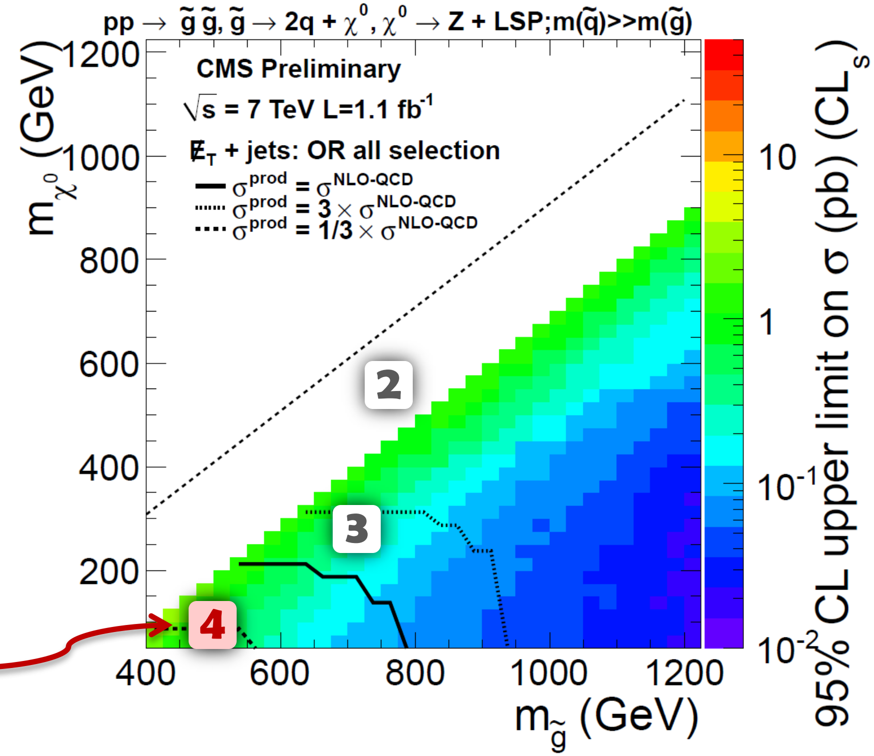

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"T1tttt"

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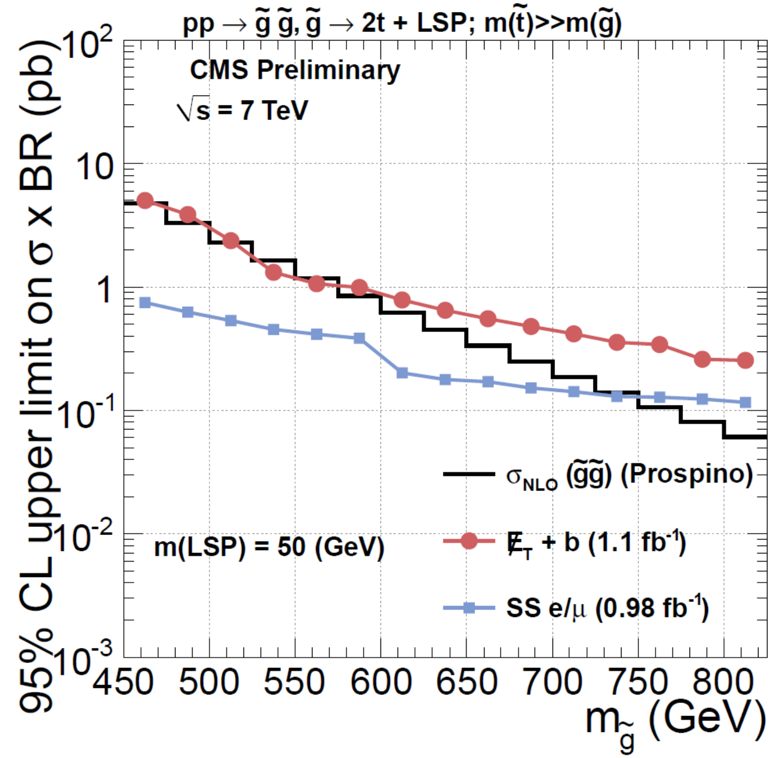
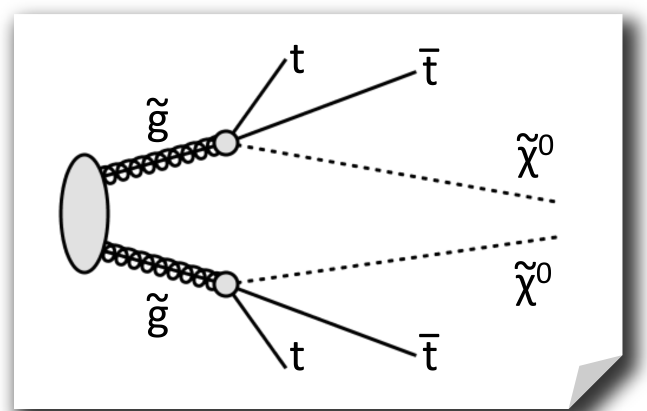
5 Direct production of stops/sbottoms…

- … however production via gluino decays have been ruled out to some degree.





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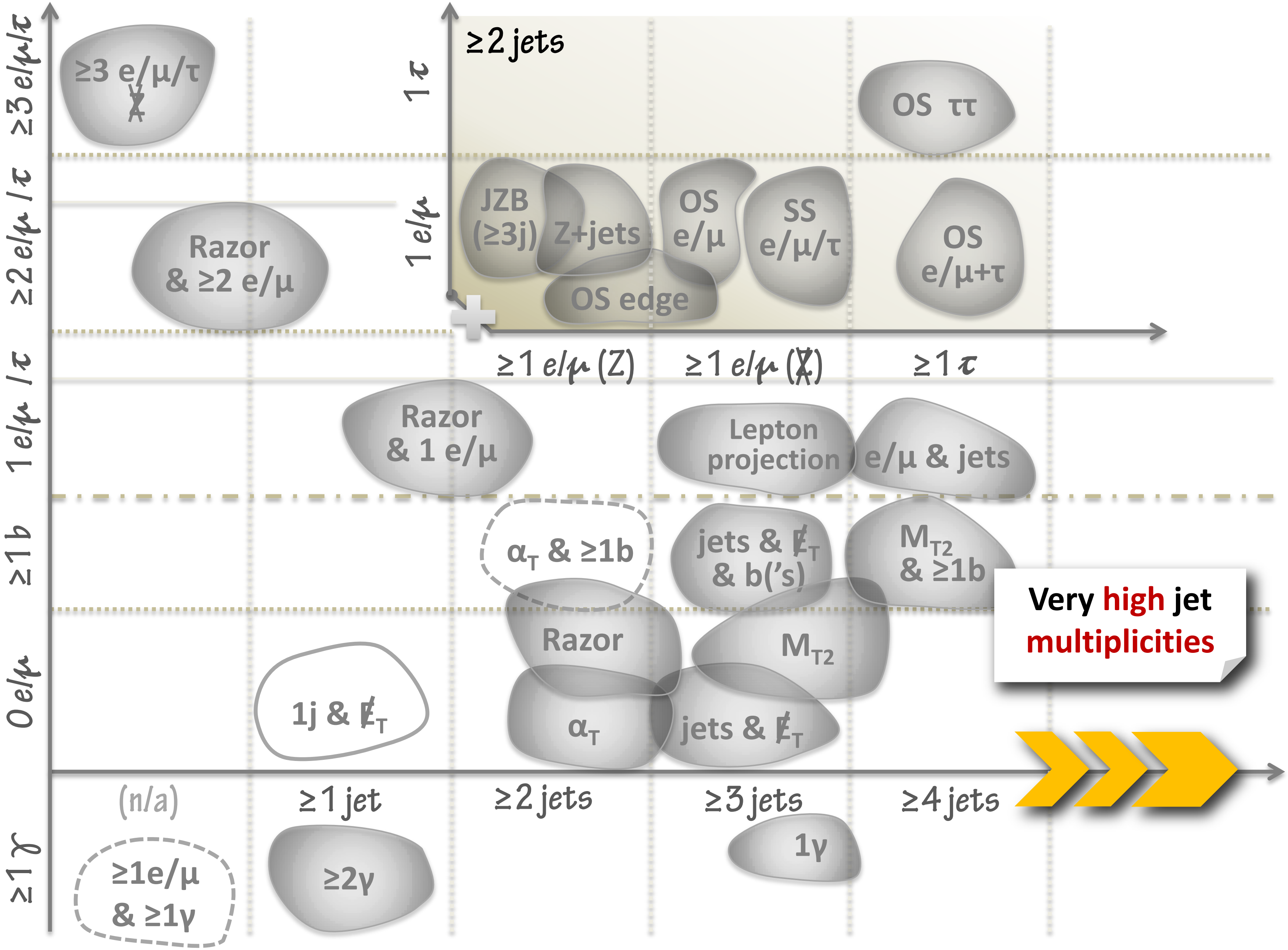

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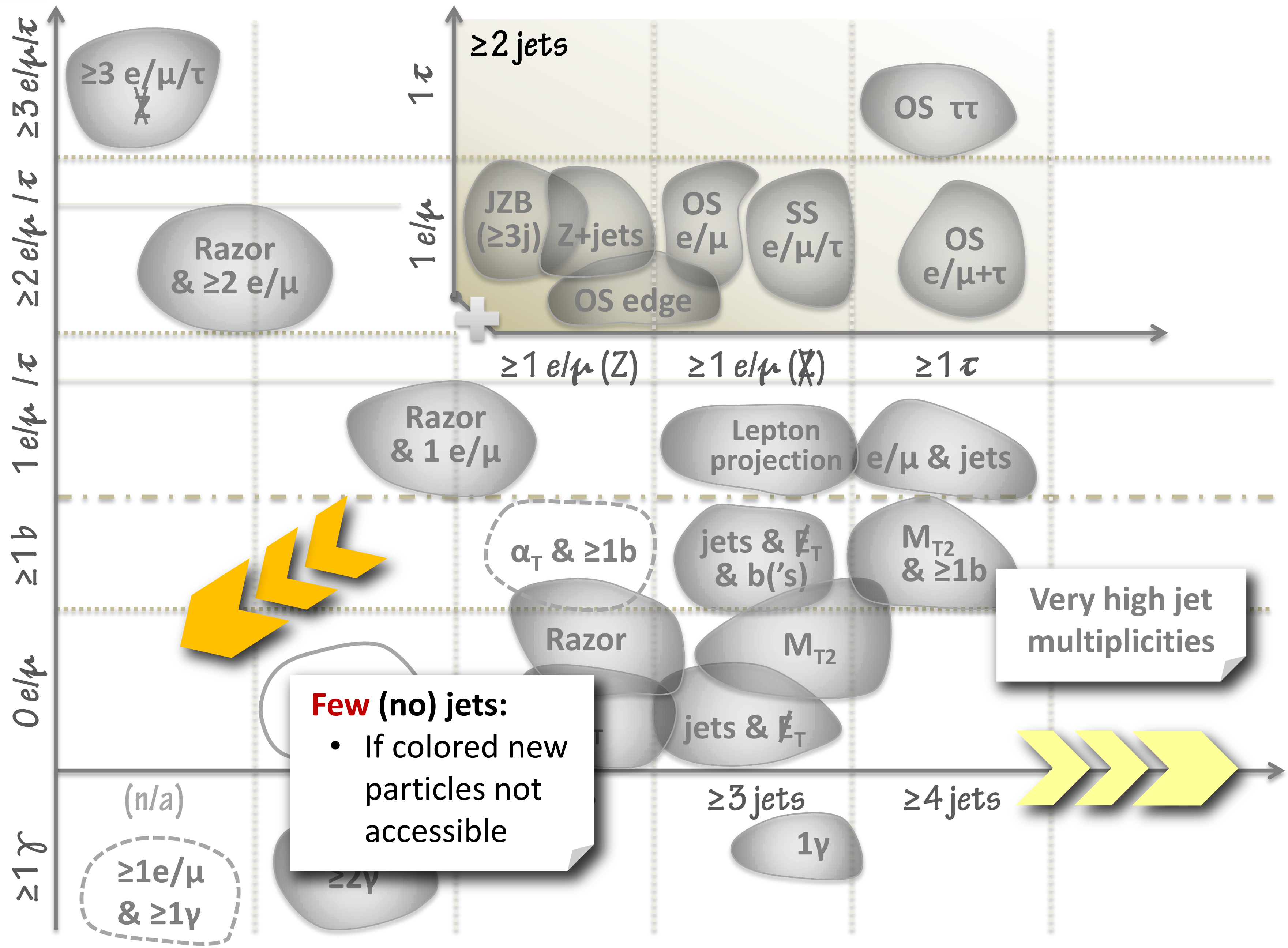

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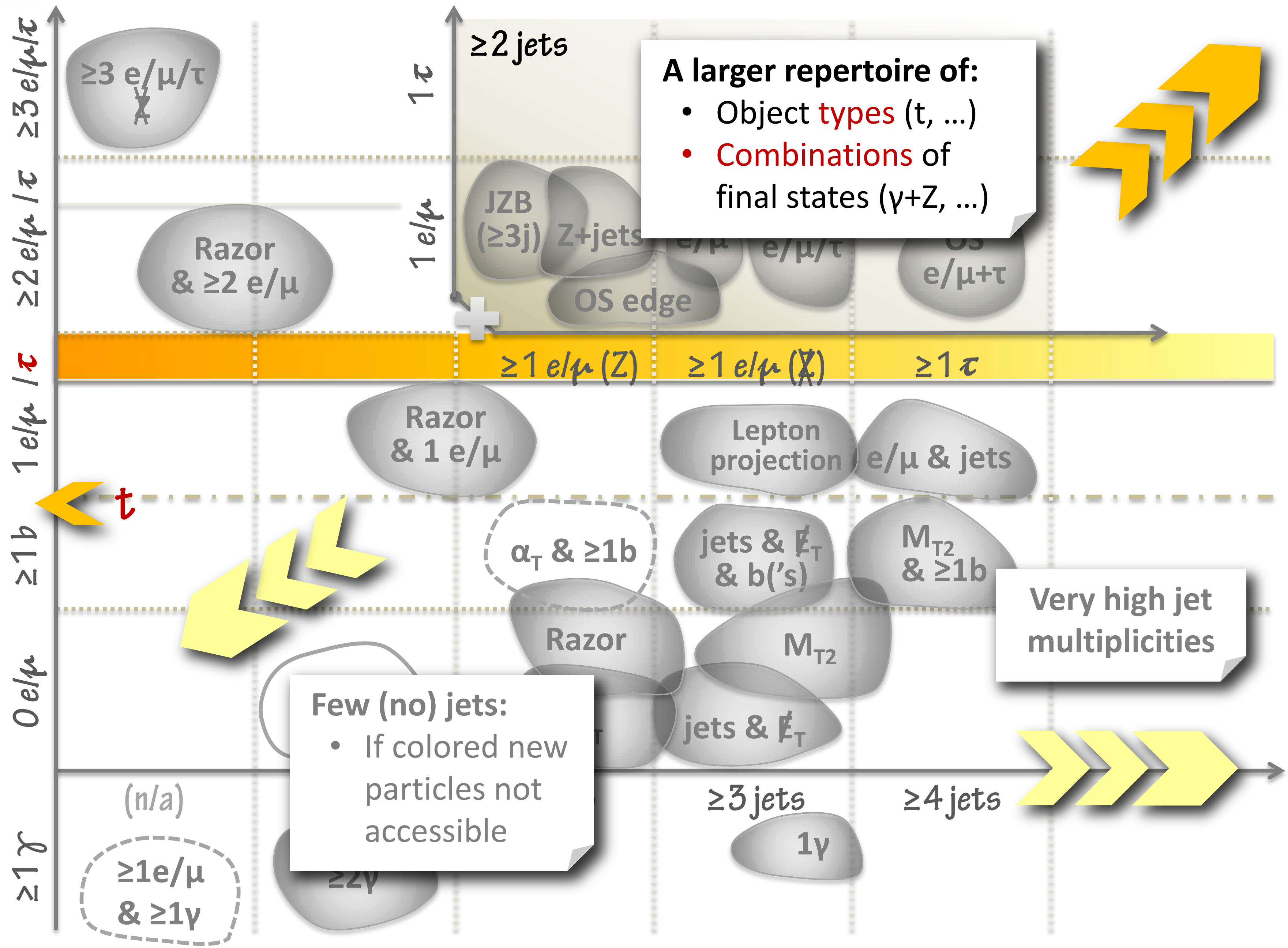

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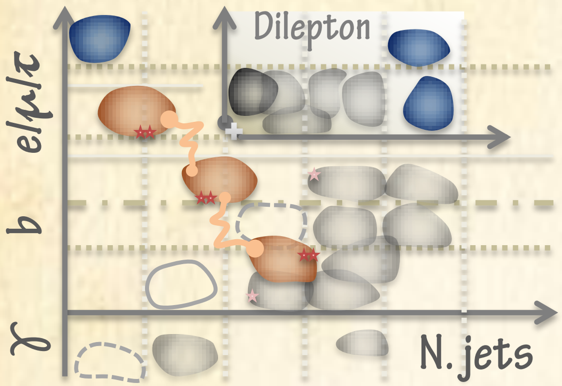
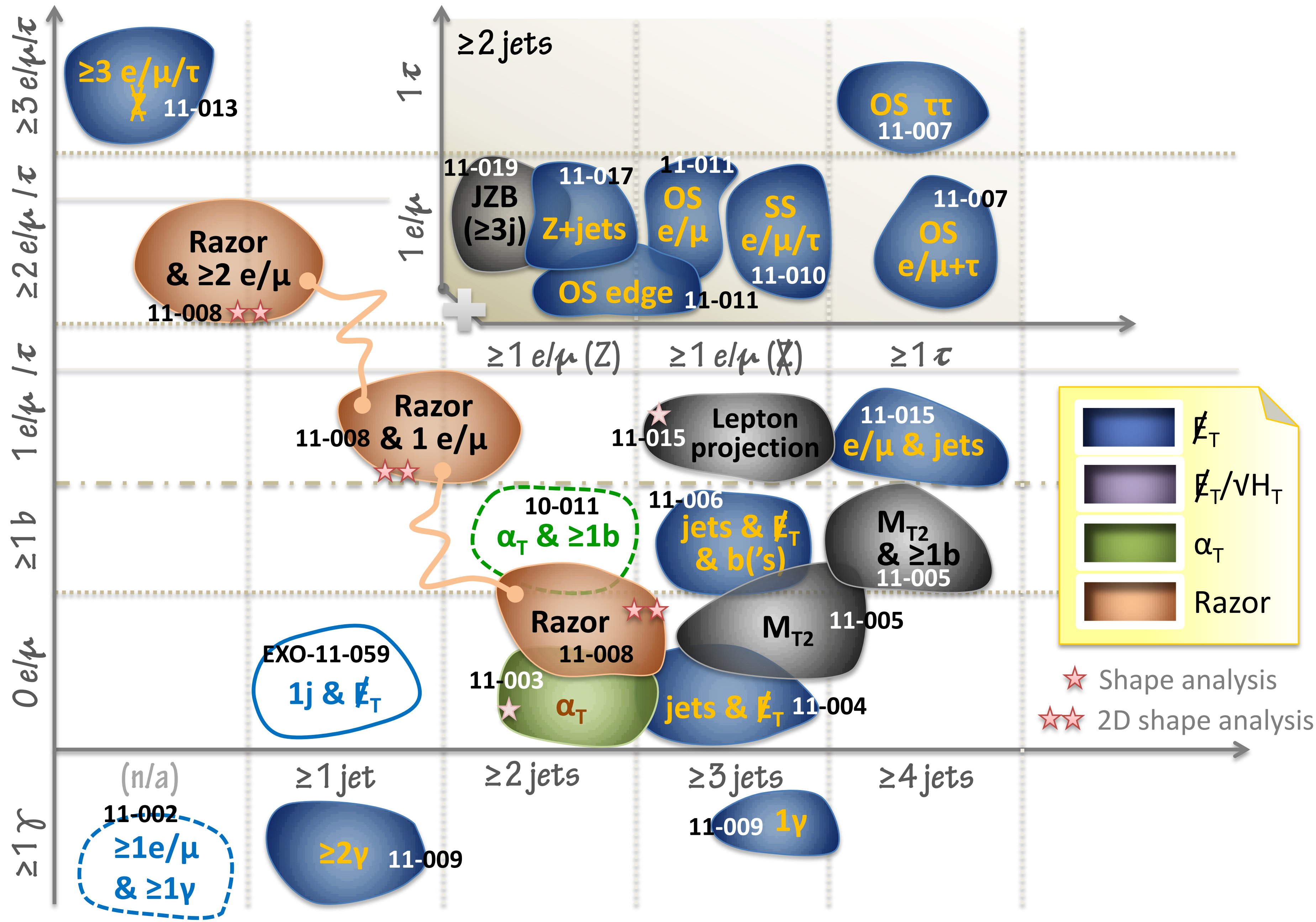


Extra Information

SUSY searches of CMS : PAS numbers (SUS-*)



The Multi-lepton (≥3 e/μ/τ) search

$\begin{pmatrix} 3\ell \\ \geq 4\ell \end{pmatrix} \times \begin{pmatrix} \text{relative} \\ \text{sign} \end{pmatrix} \times \begin{pmatrix} \text{flavor} \end{pmatrix} \times \begin{pmatrix} H_T > 200 \\ H_T < 200 \end{pmatrix} \times \begin{pmatrix} \not{E}_T > 50 \\ \not{E}_T < 50 \end{pmatrix}$

= *52 channels*

(All in good agreement with prediction)

SUS-11-008

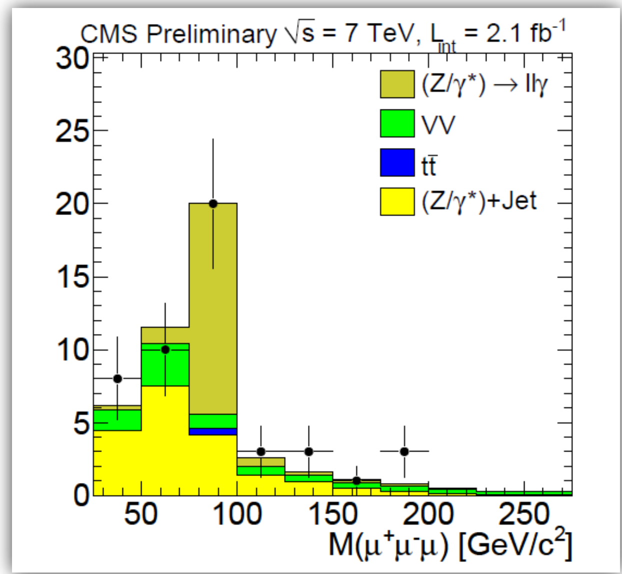
Background predictions:

Data driven

- $\ell\ell$+(jet→ℓ) — Apply P(isolated track → e/μ); Extrapolate τ_h isolation sideband
- $\ell\ell$+(γ→$\ell\ell$) — Conversion rate $N(\ell^+\ell^-\ell^\pm)/N(\ell^+\ell^-\gamma)$ measured on Z peak

- $t\bar{t}$
- Diboson

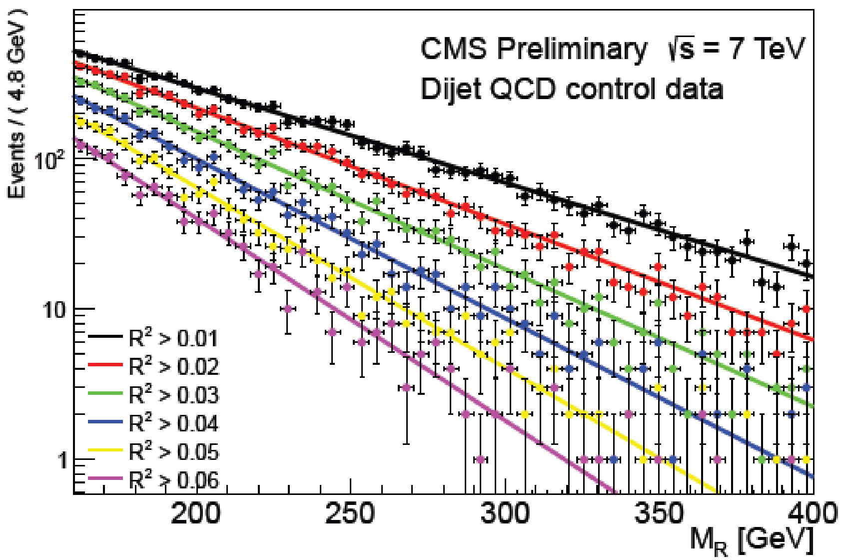
Validated MC

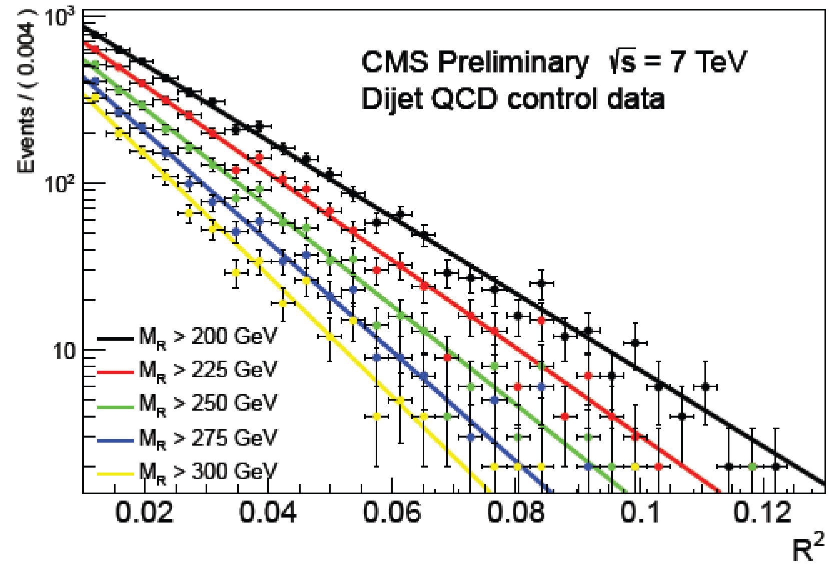


Another Razor advantage

poster N3

- For various cuts on M_R (R), the differential distribution of R (M_R) has a simple exponential (2 exponentials for top/EWK) shape for SM backgrounds:





- This allows one to formulate a simple fit function for the 2D (M_R, R^2) shape.

2

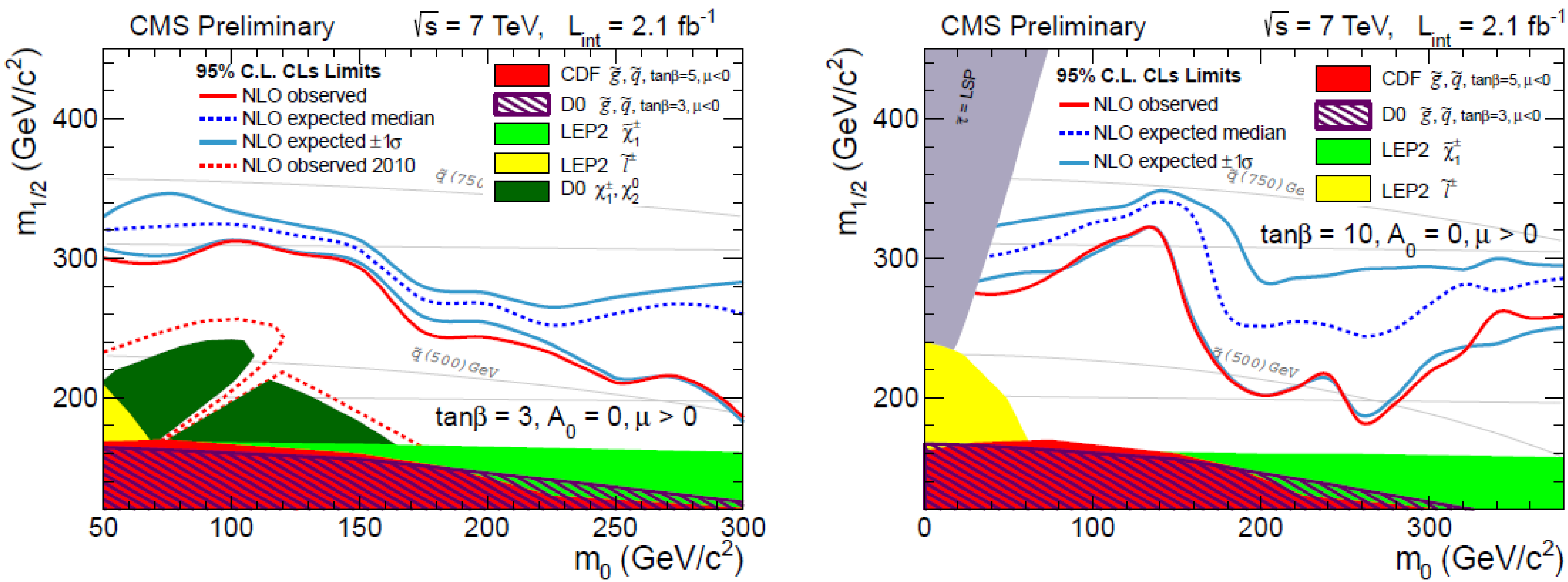
$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

peaks around M_Δ

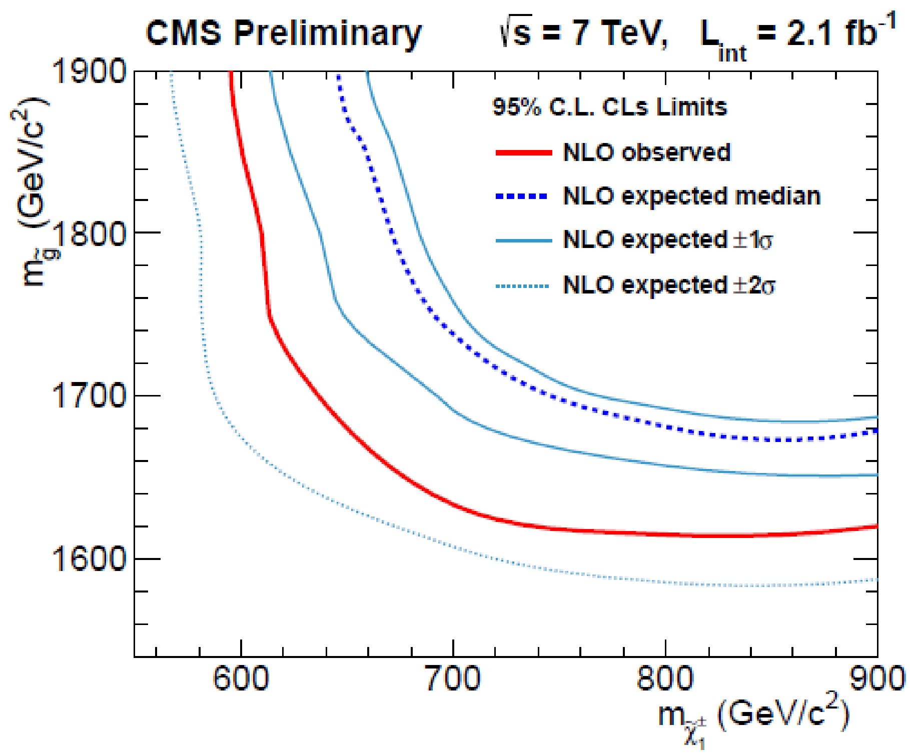
3

$$R \equiv \frac{M_T^R}{M_R}$$

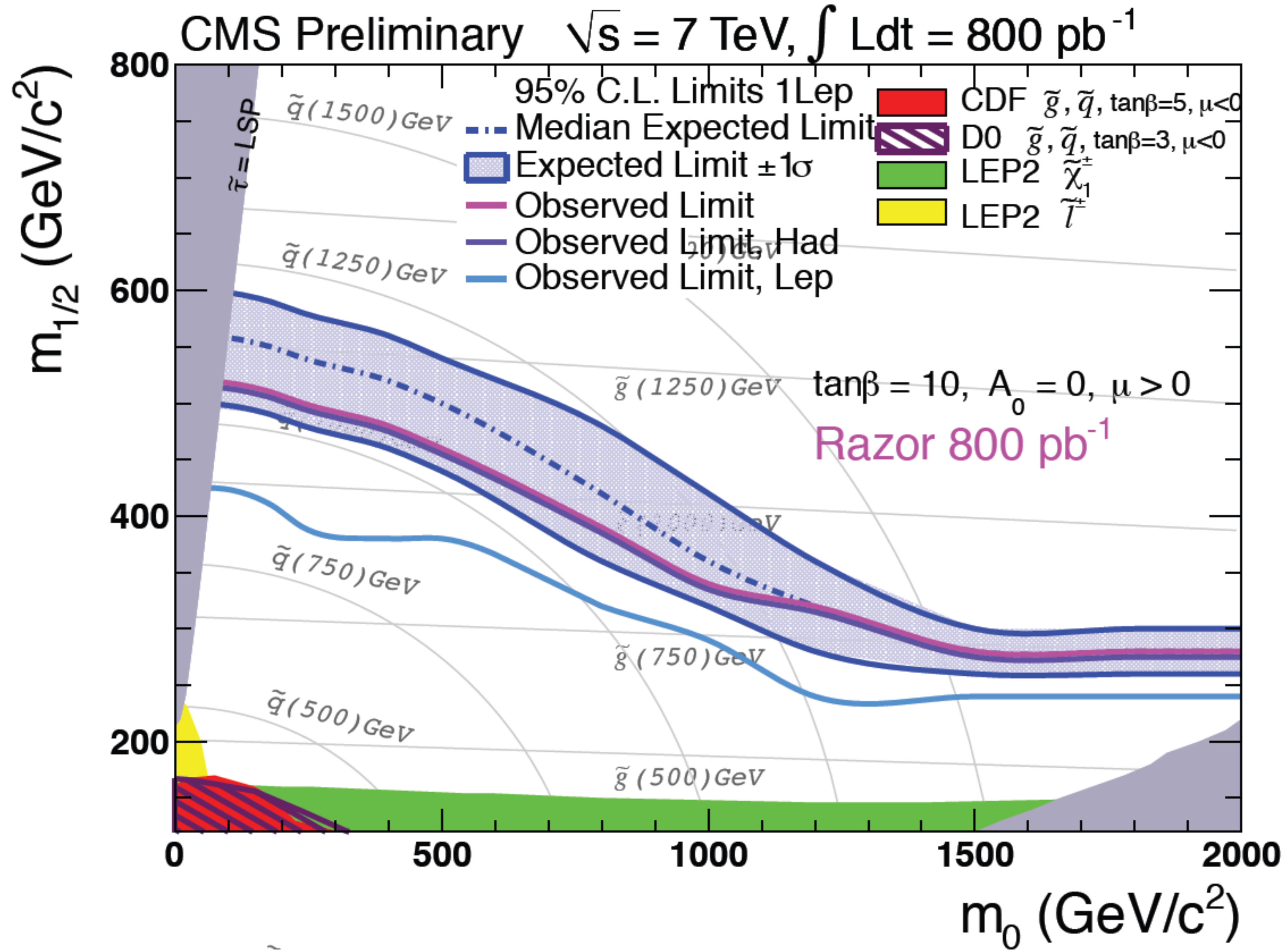
Multi-lepton Exclusions : CMSSM



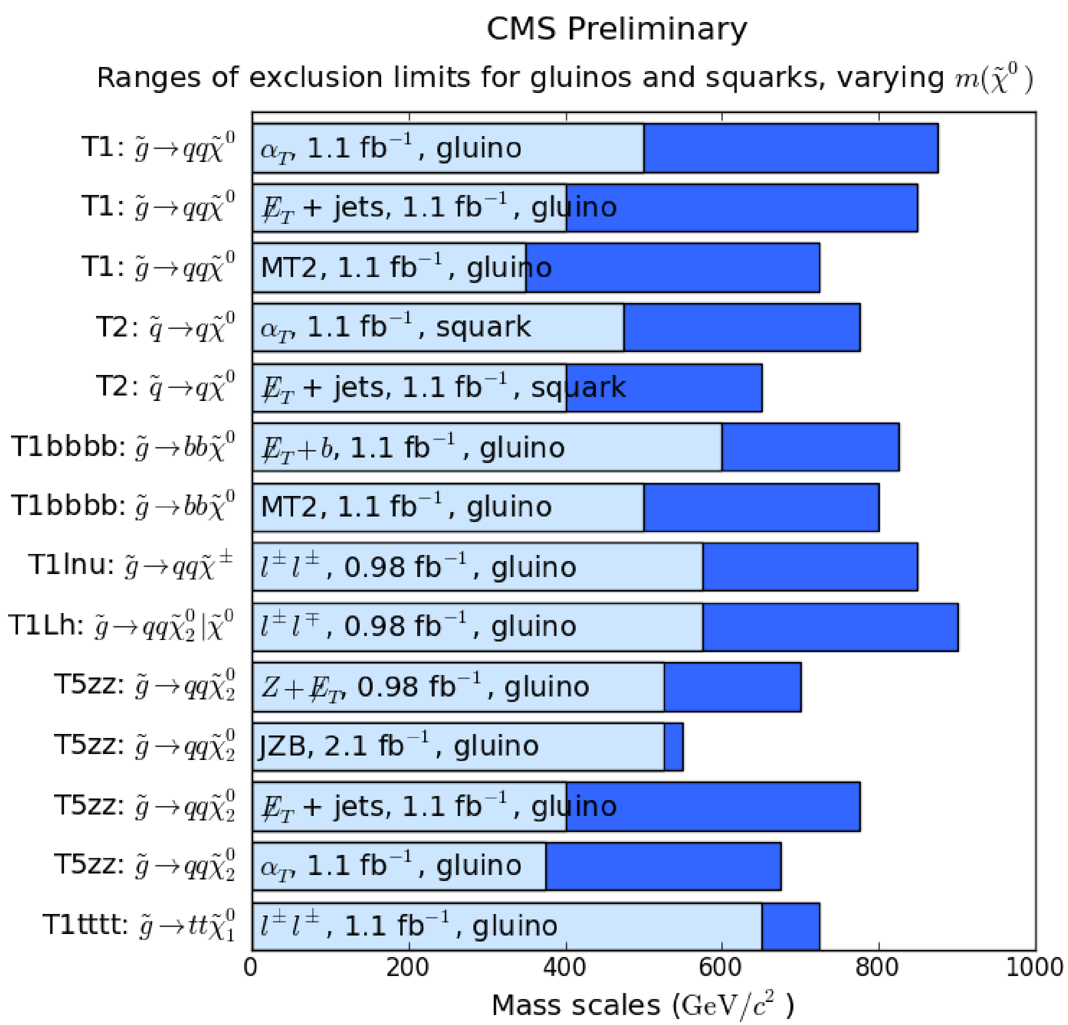
Multi-lepton Exclusions : Slepton co-NLSP



Razor Exclusions



Detailed SMS Summary



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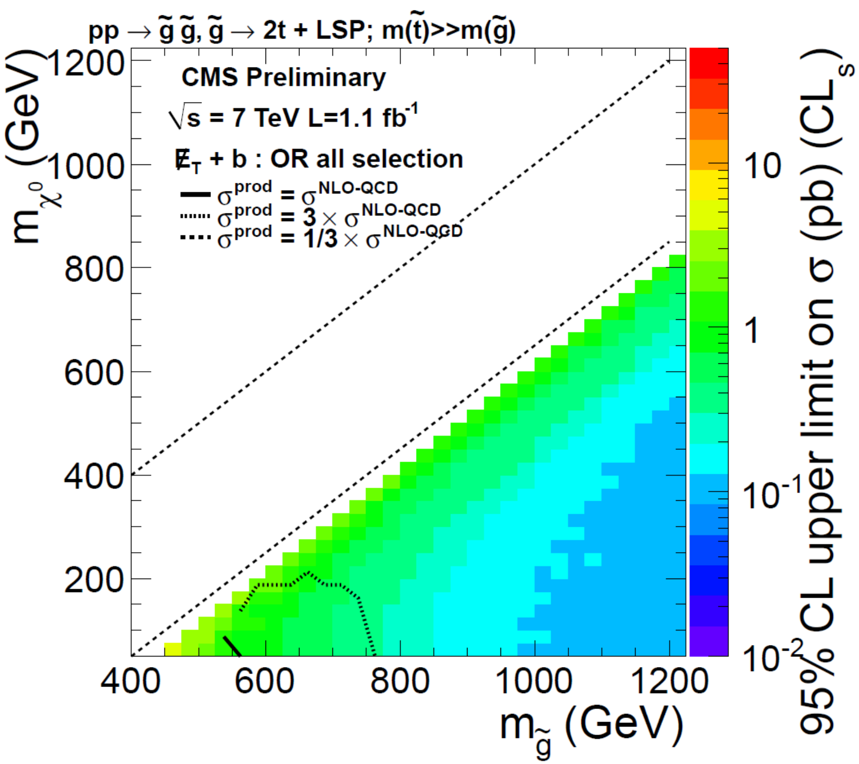
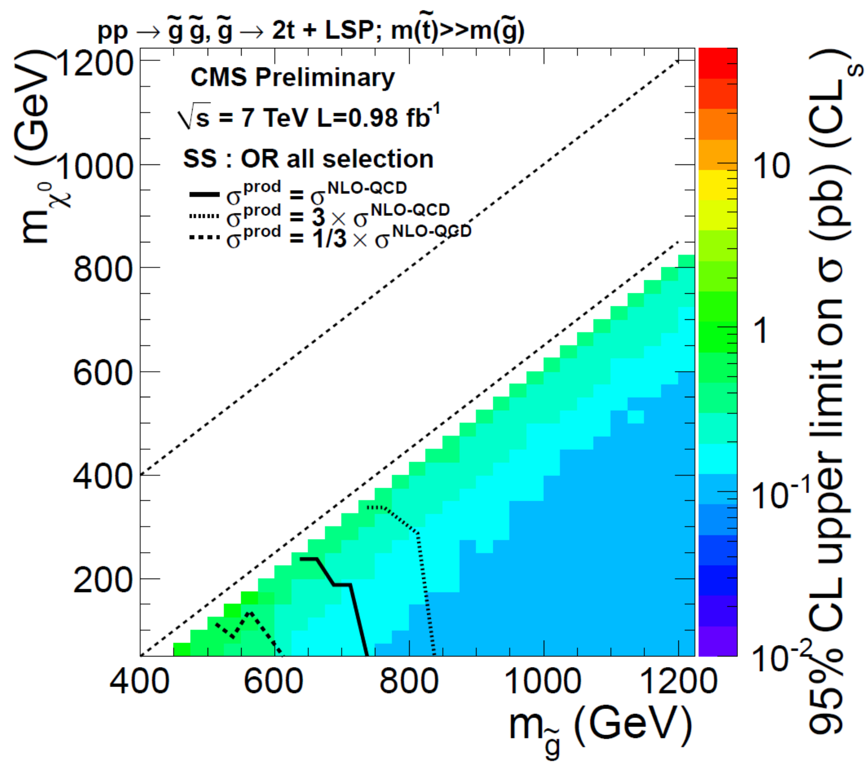
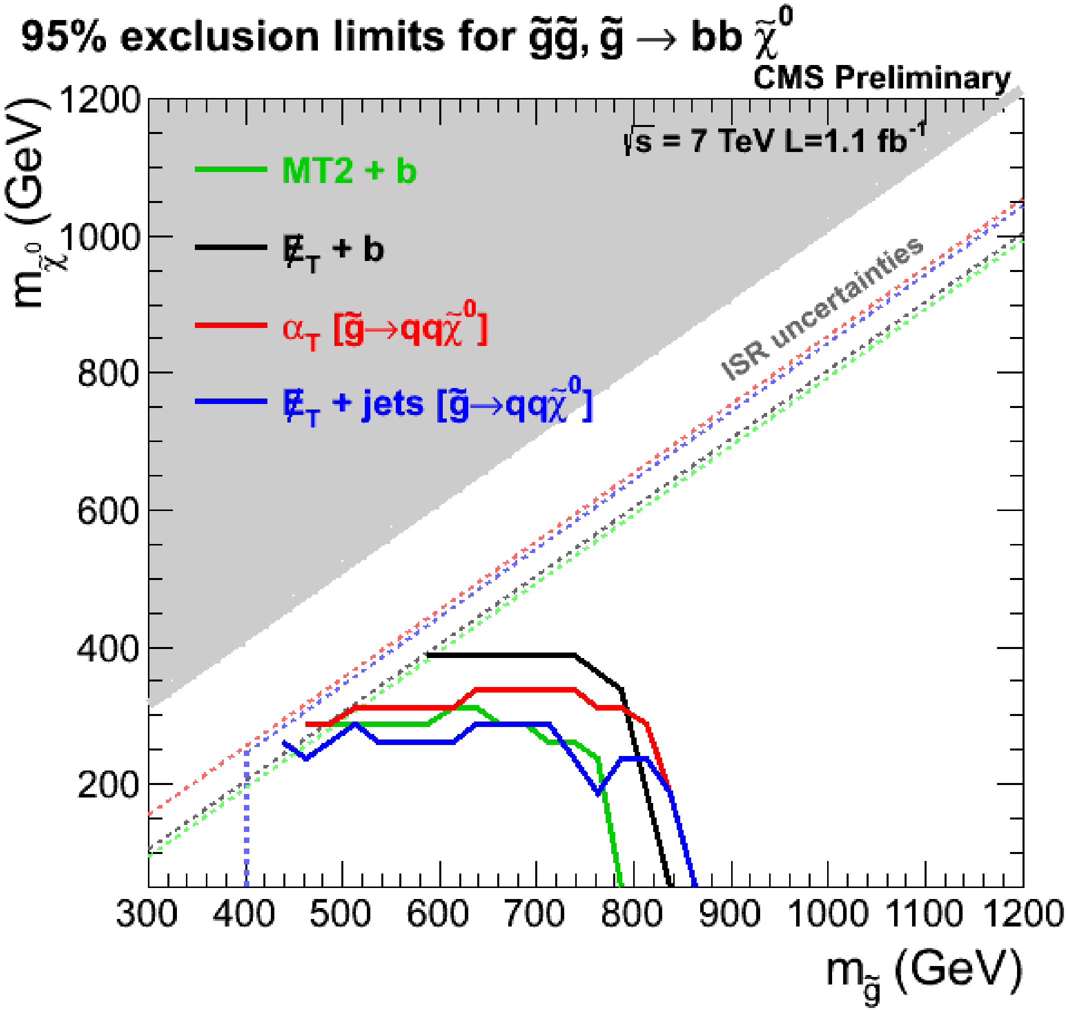
T1bbbb limits





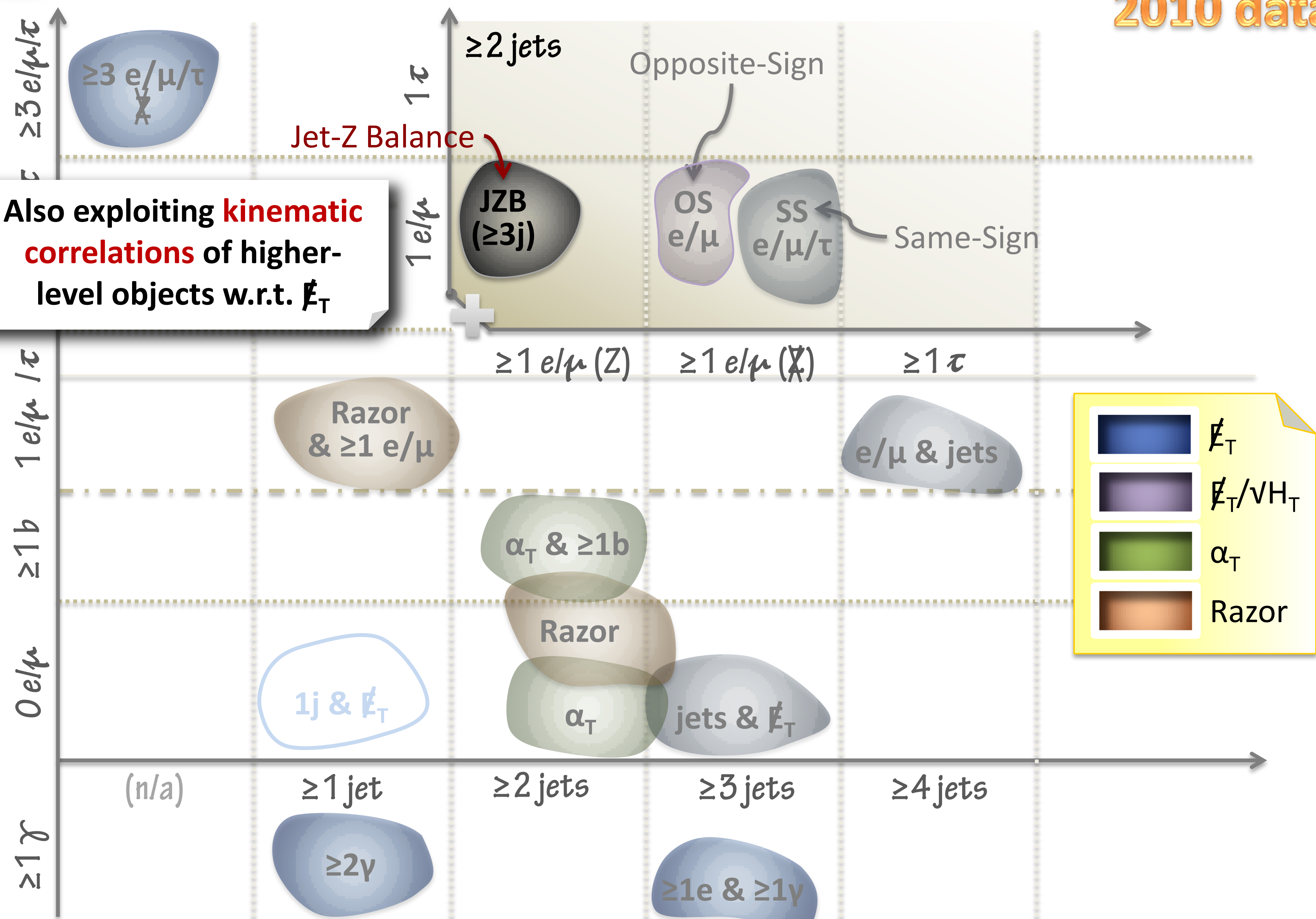
$\tilde{g}\tilde{g}$, $\tilde{g} \to bb\tilde{\chi}^0$ comparisons



Obscure Information

Signatures sought by SUSY searches

~36pb^{-1}
2010 data



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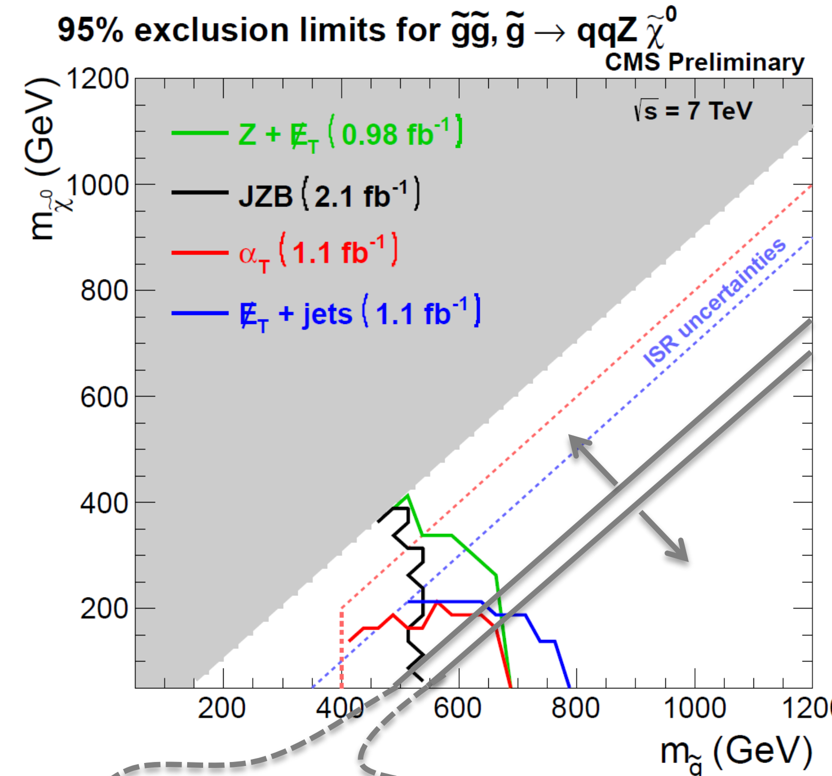
- High-H_T (reduced $\not{E}_T$ requirement) search regions important for signals with long decay chains:
  - Exclusions taken from search region that yields best expected limit.



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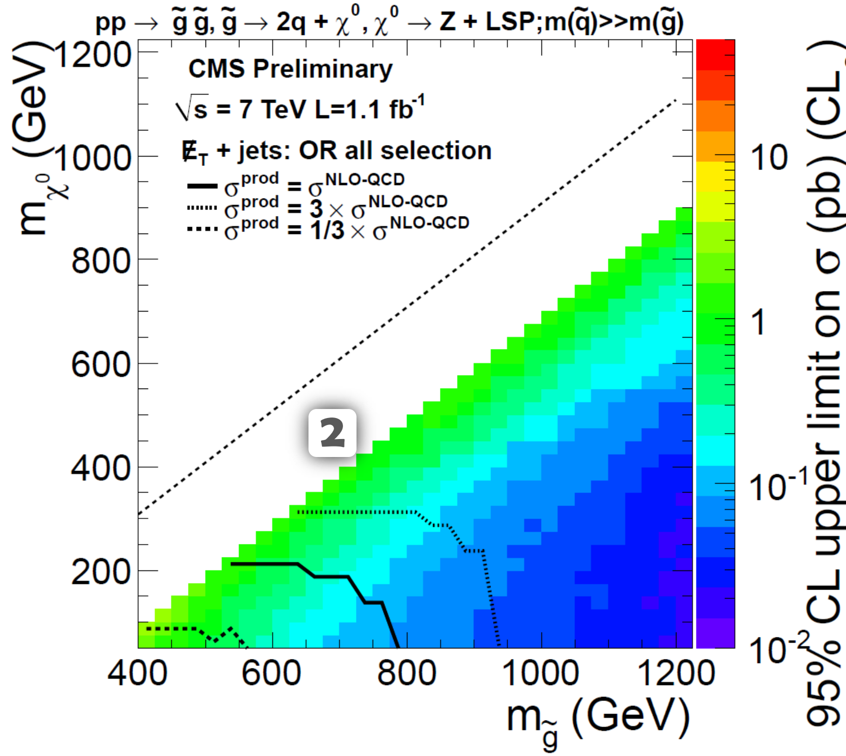

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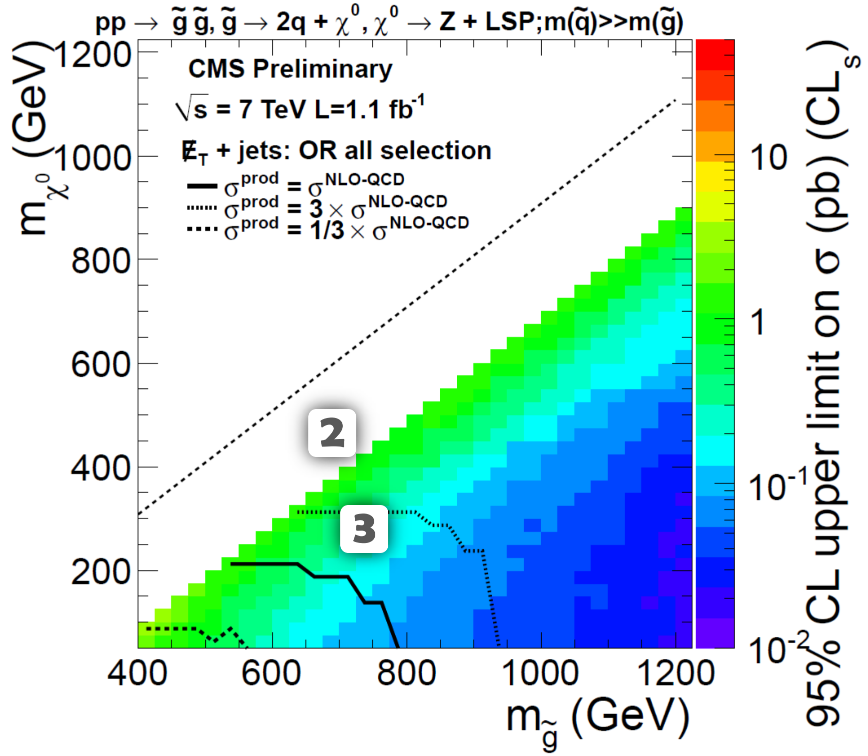

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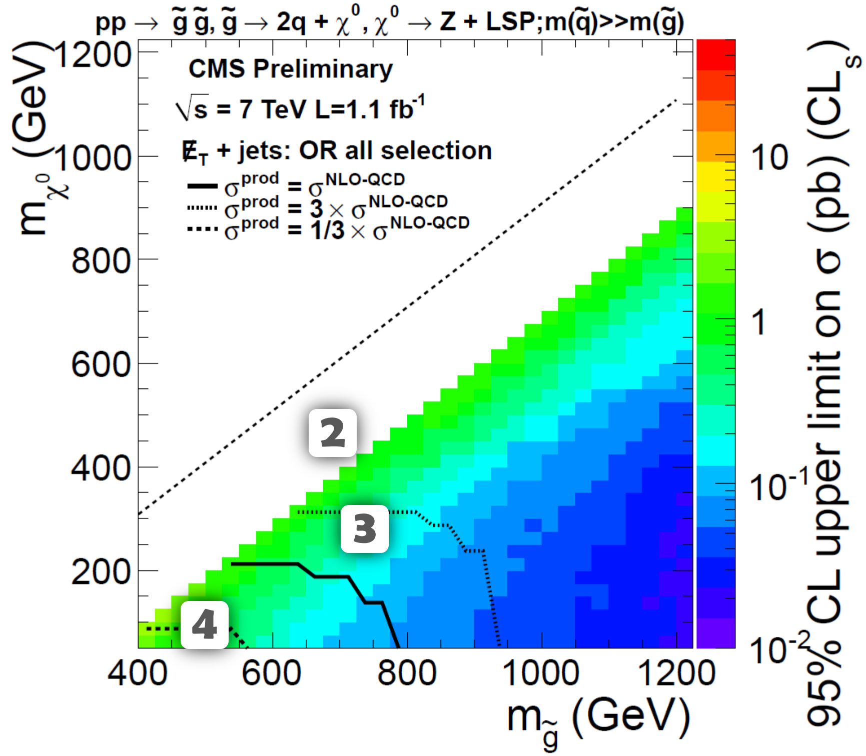

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