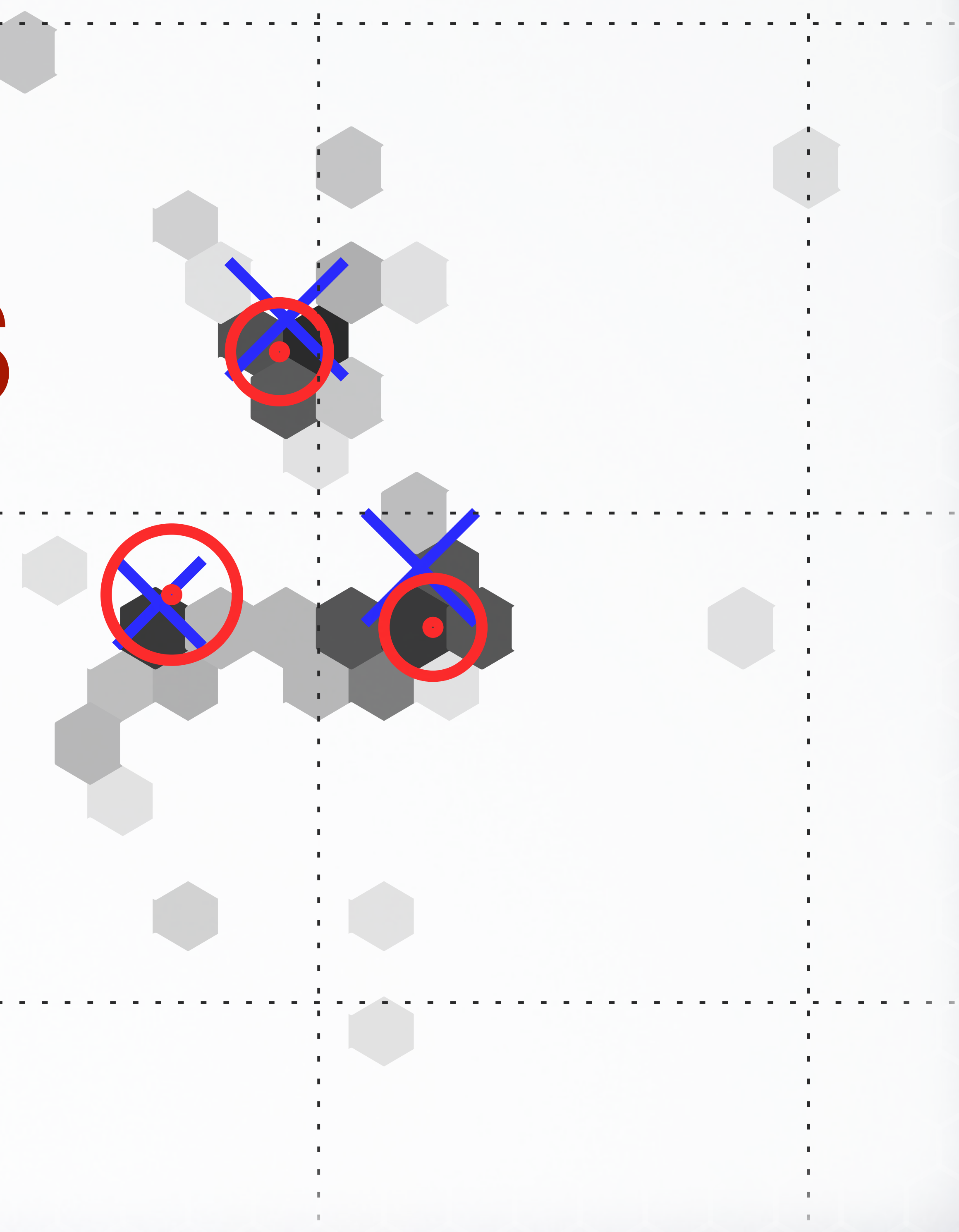
BOOSTED **TOPS** IN THE LHC ERA



Mihailo Backović (WIS)

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

From a theory point of view

Standard Model Higgs is "surprisingly" light.

Whatever the mechanism that "cures" the hierarchy problem is, it seems to have something to do with the **top quark.**

Theory - new dofs. exist which cancel the quadratic divergences of the top loops in the Higgs propagator (**top partners**).

Naturalness

SUSY
(scalar top partners)

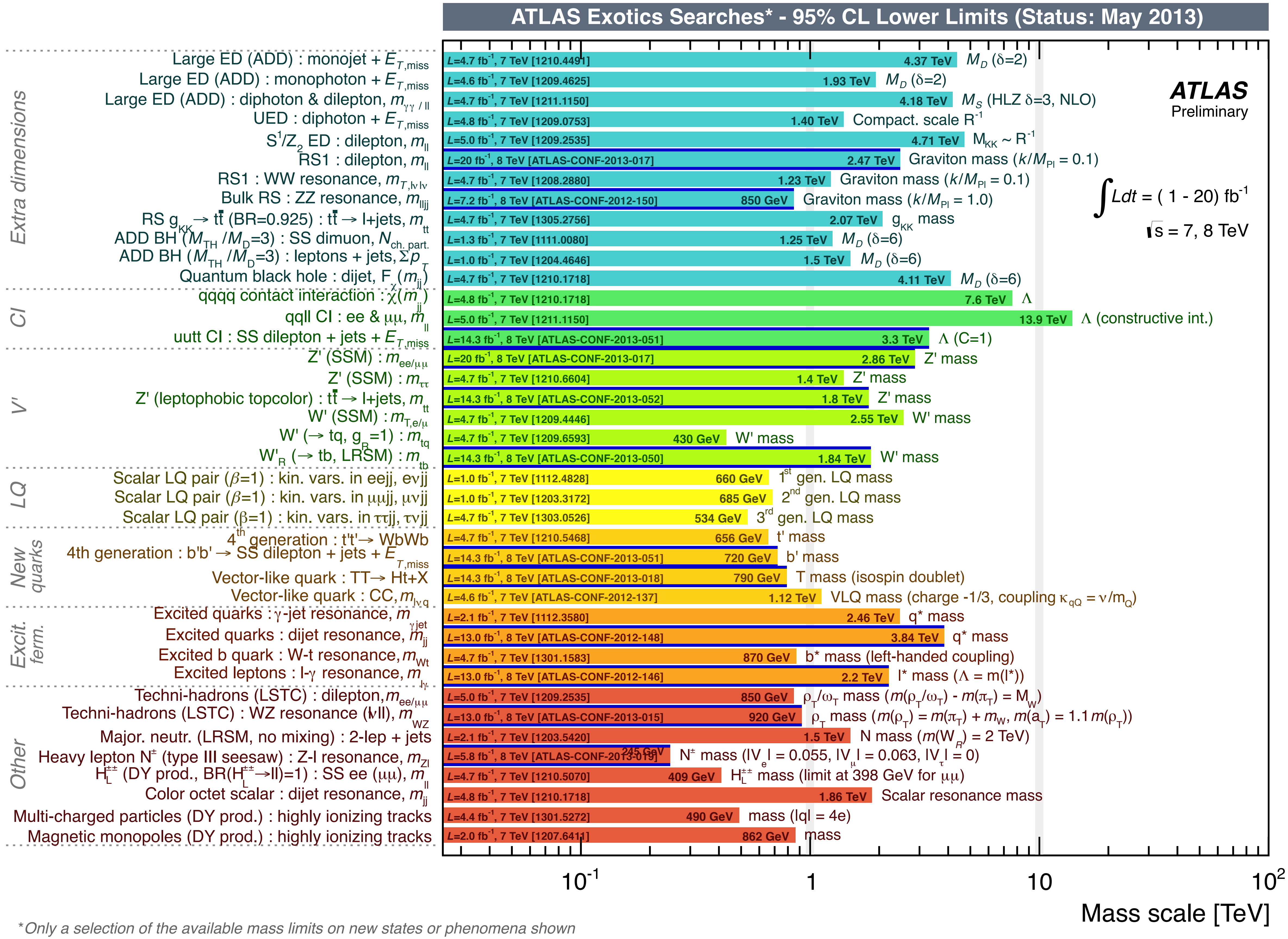
Composite Higgs
(fermionic top partners)

Why **boosted tops**?

1. Standard Model

Measure the high p_{T} tails of the top diff. distributions.

2. New Physics!



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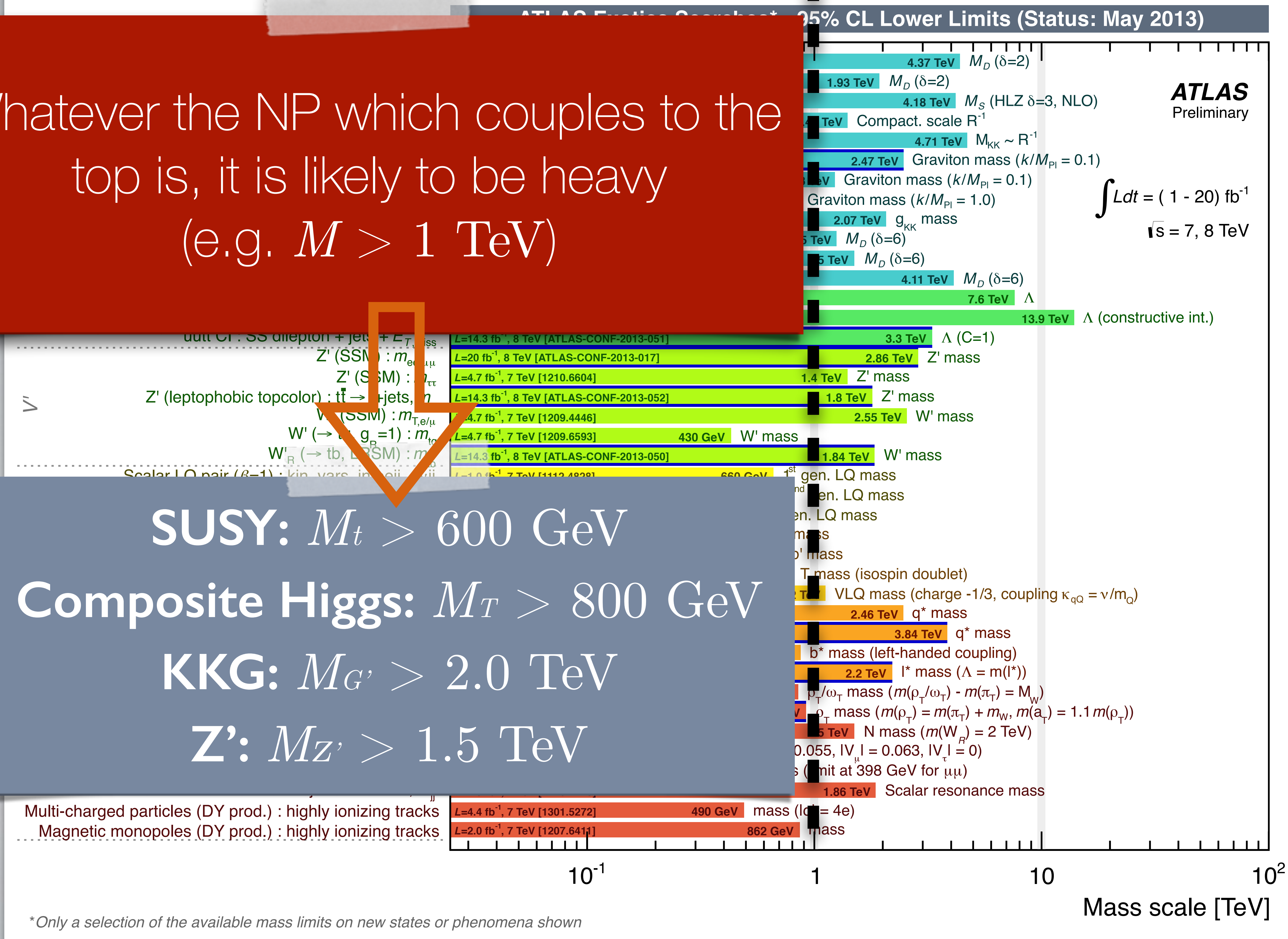
2. New Physics!

Whatever the NP which couples to the top is, it is likely to be heavy (e.g. $M > 1$ TeV)



SUSY: $M_{\tilde{t}} > 600$ GeV

Composite Higgs: $M_T > 800$ GeV

KKG: $M_{G'} > 2.0$ TeV

Z': $M_{Z'} > 1.5$ TeV

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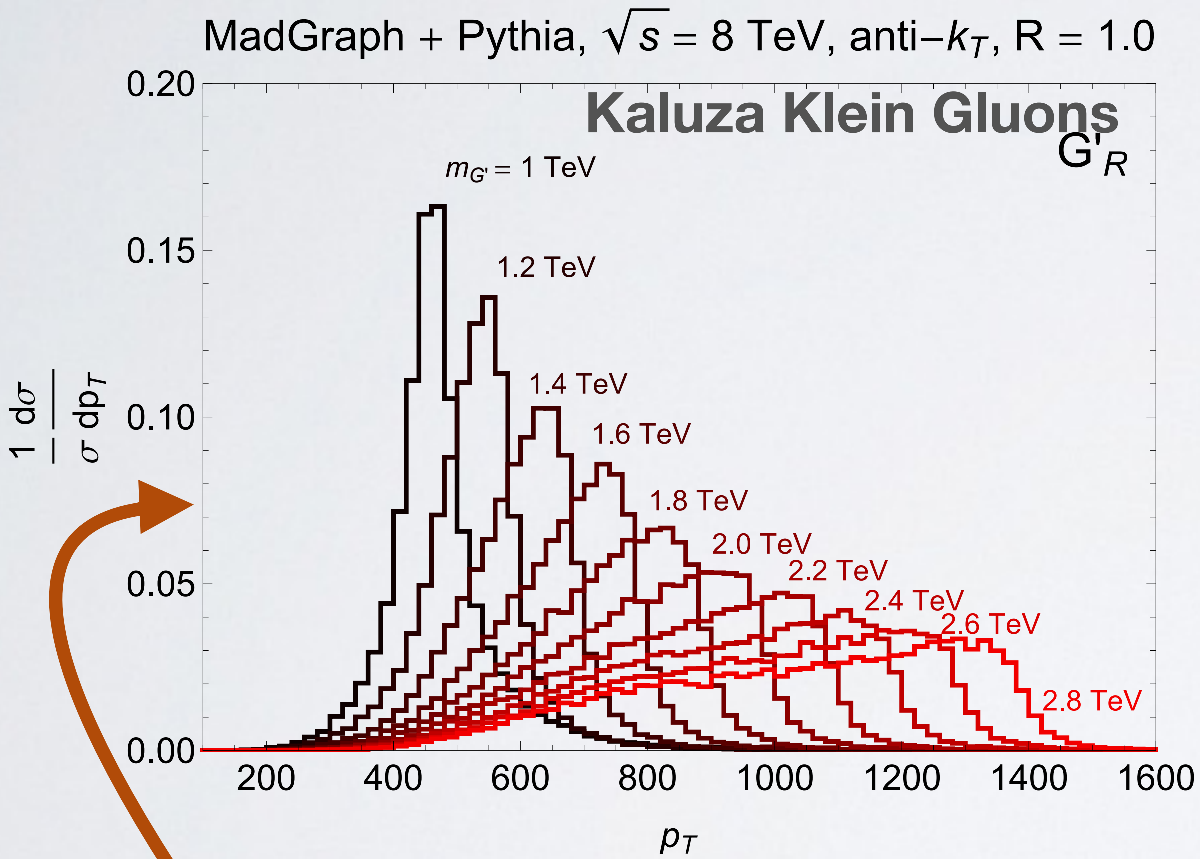
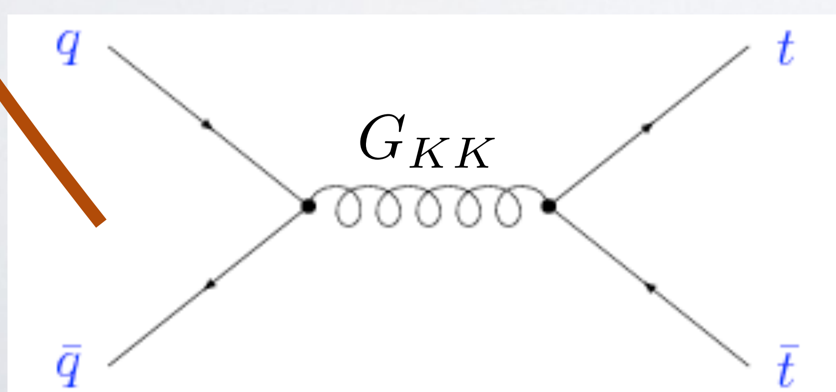
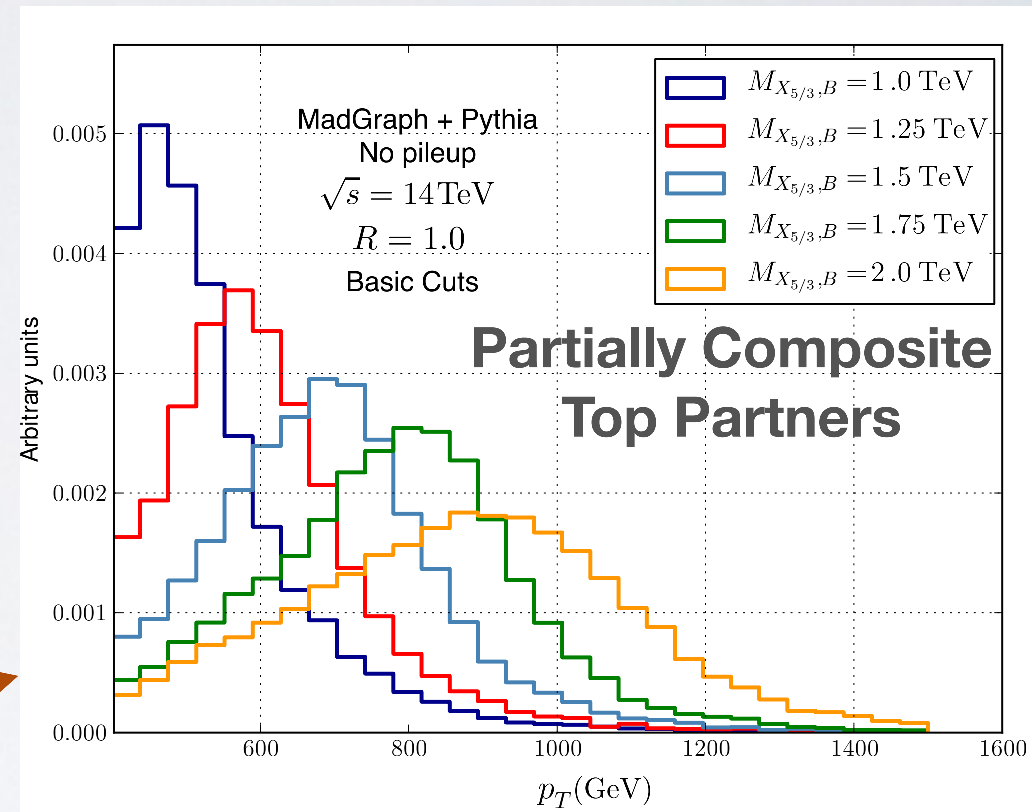
Why **boosted tops** ?

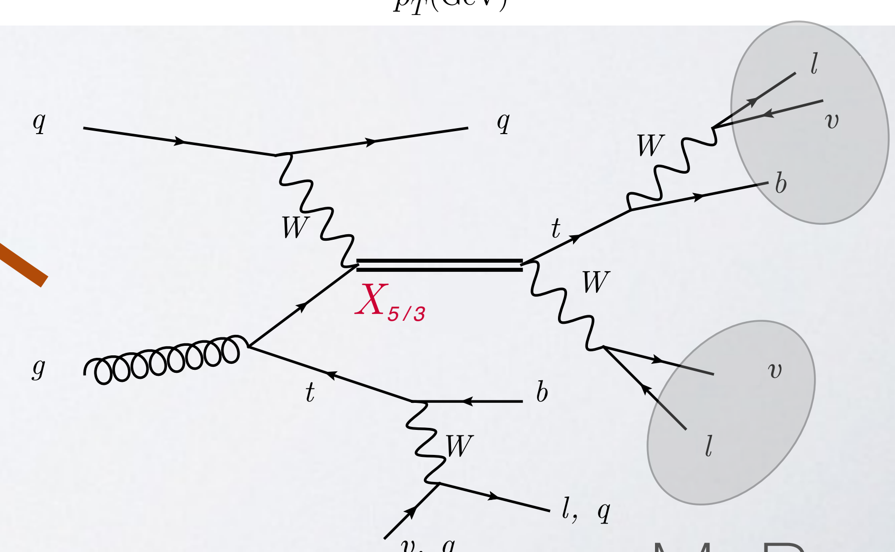
Heavy NP states decay to boosted SM particles.

$$p_T \sim \frac{M}{2}$$









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Why **boosted tops** ?

Future searches for (some) NP models will rely almost exclusively on (highly*) boosted tops.

* "highly" $= p_T > 500\ \text{GeV}$

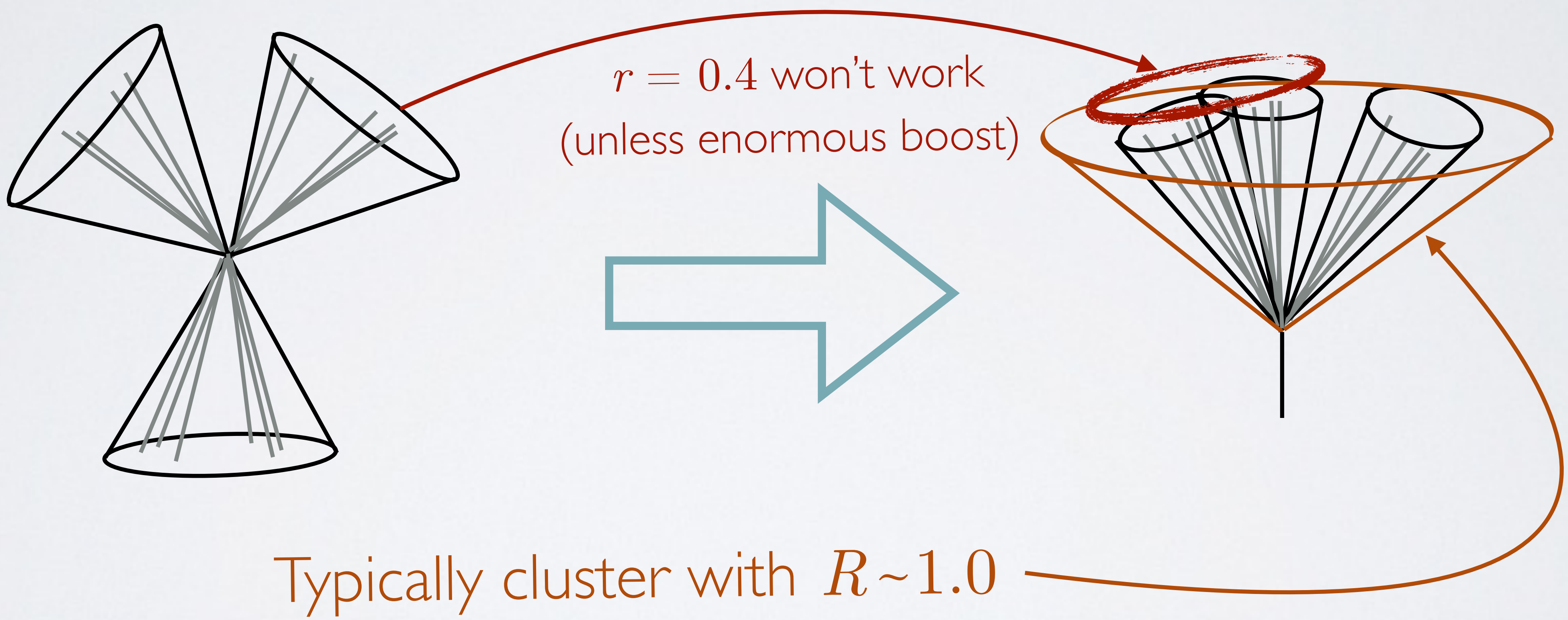
Boosted top **tagging/measuring** comes with it's own set of difficulties:

Top decay (roughly) at rest:

- Decay products isolated
- Possible combinatorial issues

Boosted top decay:

- Typically needs large jet cone
- **Pileup** effects more prominent!
- Simpler combinatorics.
- Backgrounds could be trickier!

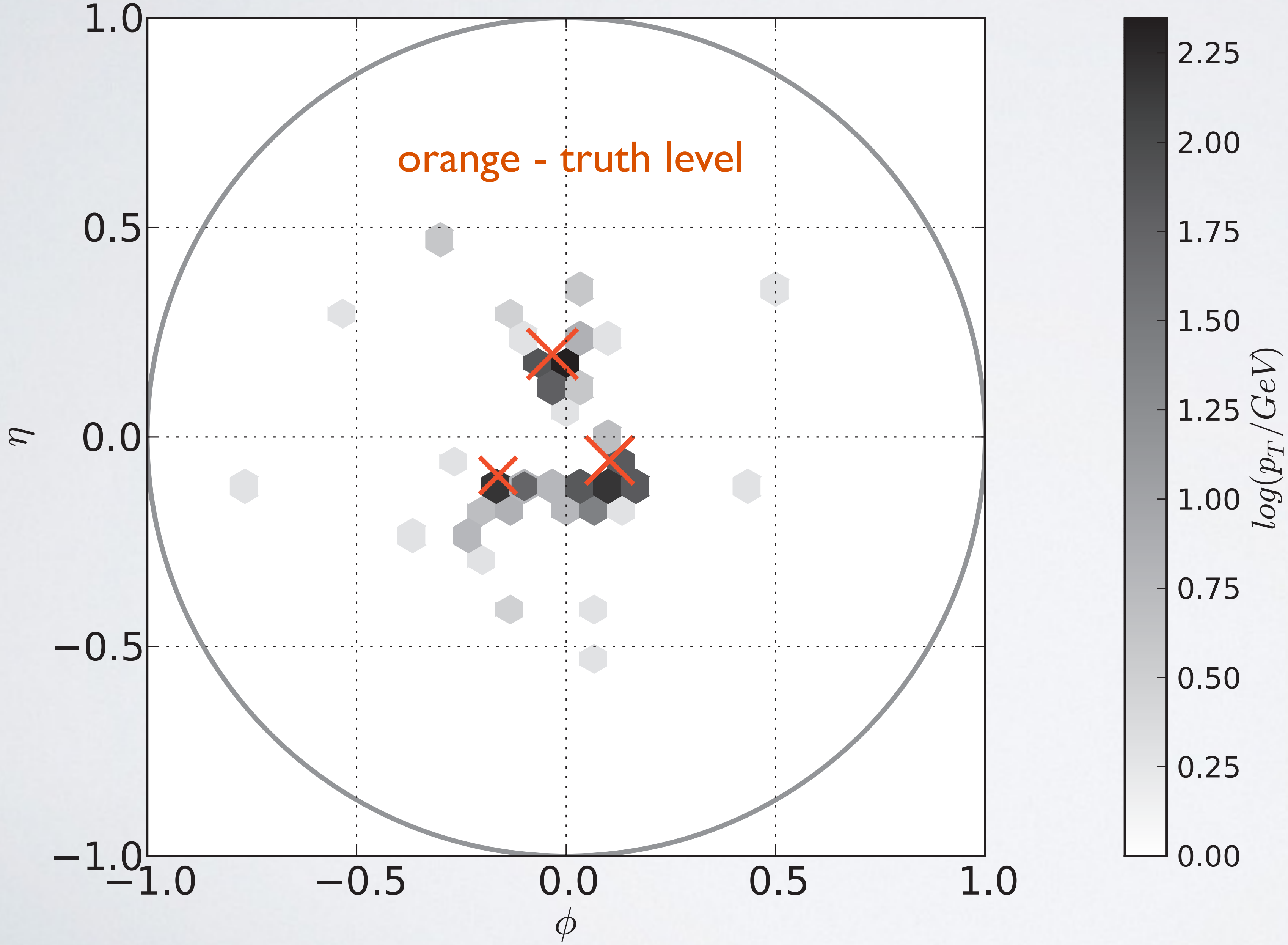


*** Issues also with leptonically decaying boosted tops
(**See Emanuelle's talk**)

A “**fat jet**” is characterized by a “splash pattern” which contains more information than just the jet mass and transverse momentum.

We wish to characterize and categorize these splash patterns

Example: Boosted top jets show a characteristic **three “prong” structure**.



- What are the useful moments of the energy distribution?
- What are the useful correlations?
- How is the energy distributed among the three prongs? (e.g. underlying decay t -> Wb).

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Many Available approaches to boosted top tagging:

Jet Shapes

Planar Flow
Angularities
Di-polarity
Jet Pull
...

Jet De-clustering

HEPTopTagger
CMS Tagger

ATLAS Top Tagger
...

Jet Trimming
Jet Pruning
...

Prong Taggers

N-subjettiness

Matrix Element

Shower Deconstruction

Template Overlap Method (TOM)

See also Emanuele's talk

Very Active Field:
Almeida, Backovic, Butterworth, Cacciari, Chen, Davison, Erdogan, Falkowski, Han, Hook, Jankowiak, Katz, Kim, Kribs, Larkoski, Lee, Martin, Nojiri, Perez, Plehn, Raklev, Rehermann, Roy, Rojo, Rubin, Salam, Seymour, Shelton, Spannowsky, Sreethawong, Son, Soyez, Sung, Schwartz, Seymour, Soper, Sterman, Takeuchi,Thaler, Tweedie, vanTilburg, Virzi, Wacker, Wang, Zhu, etc.

Many Available approaches to boosted top tagging:

Jet Shapes

Planar Flow
Angularities
Di-polarity
Jet Pull

We do not have a complete theoretical understanding of a lot of the tools

Jet De-clustering

HEPTopTagger
CMS Tagger
AS Top Tagger

Jet Trimming
Jet Pruning
…

The variety of the tools is a **huge asset** (different approaches for various boost, pileup levels, etc.)

Matrix Ele

Shower Deconstruction

Template Overlap Method (TOM)

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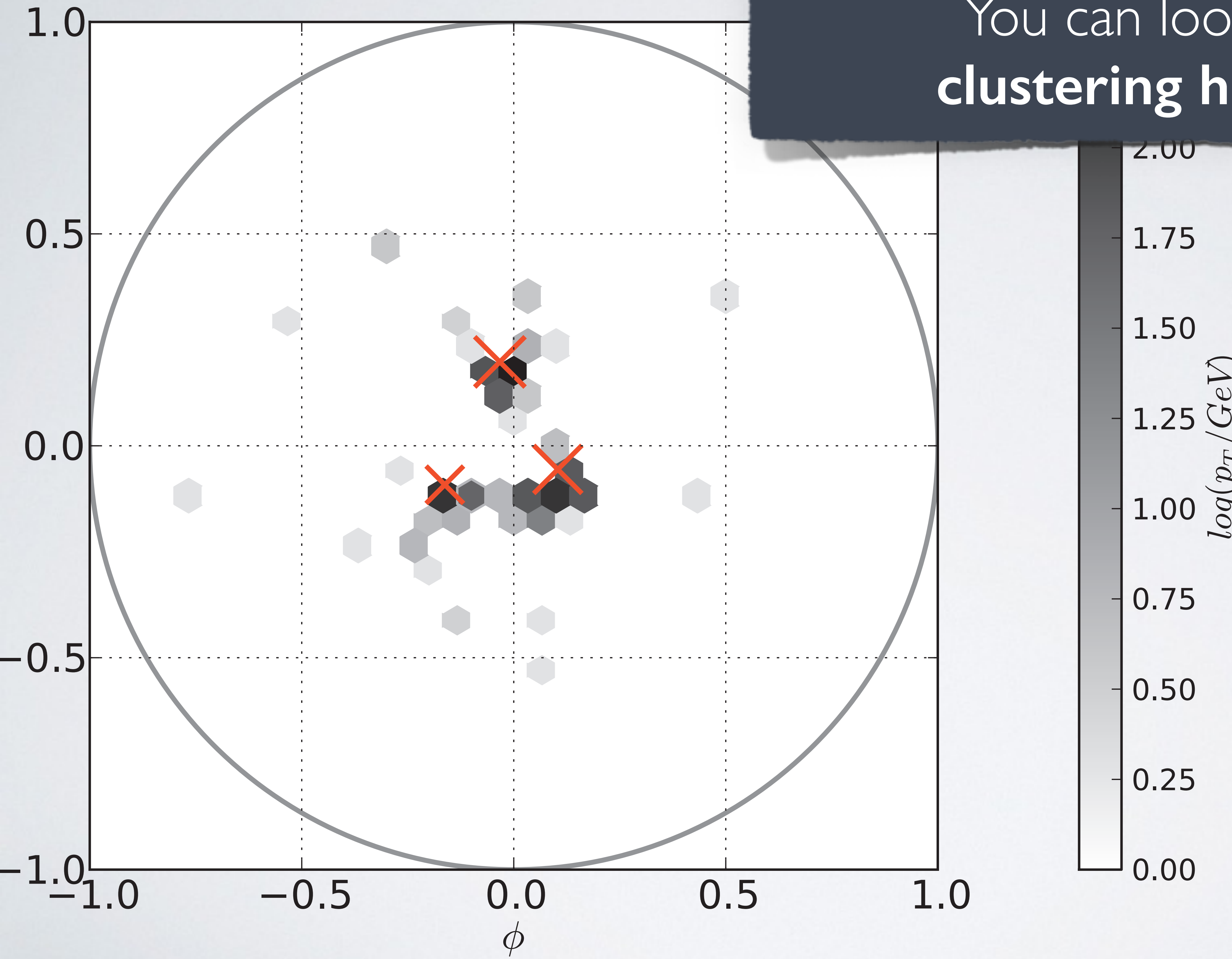
A few heuristic examples…

See also Emanuele's talk



You can look at the **clustering history**…

A few heuristic examples…

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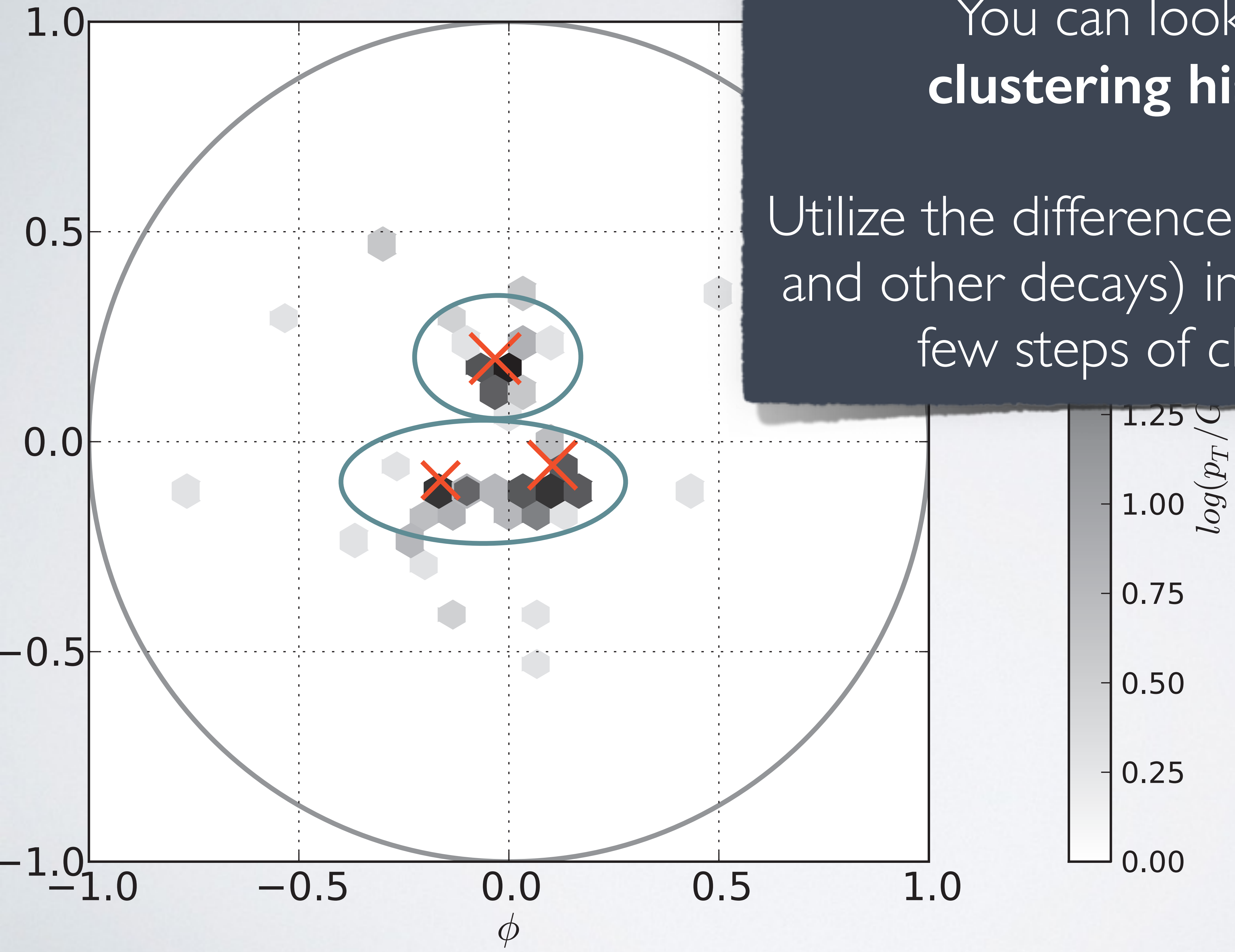

You can look at the **clustering history**…

Utilize the differences (between top and other decays) in the in the last few steps of clustering.

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A few heuristic examples…

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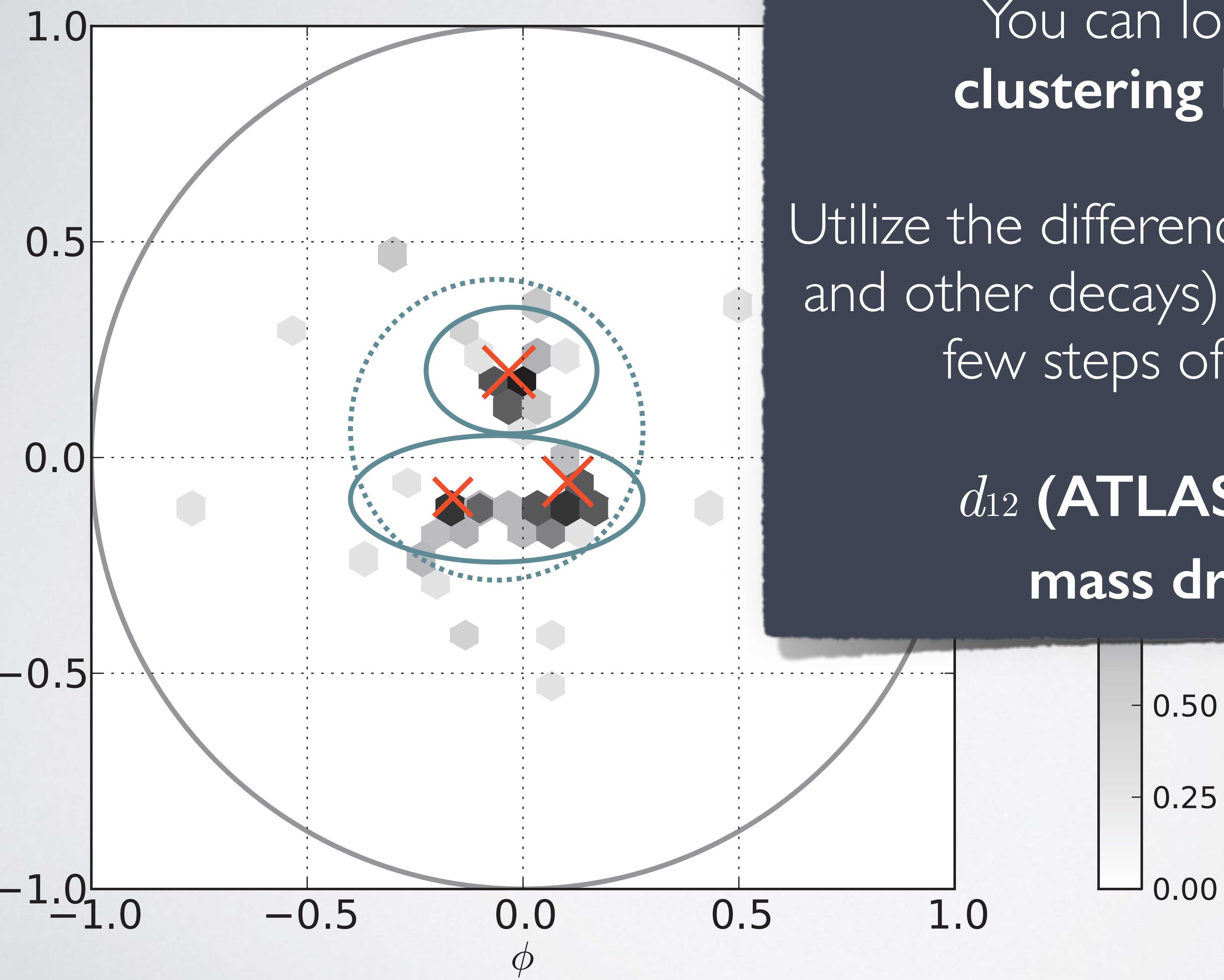


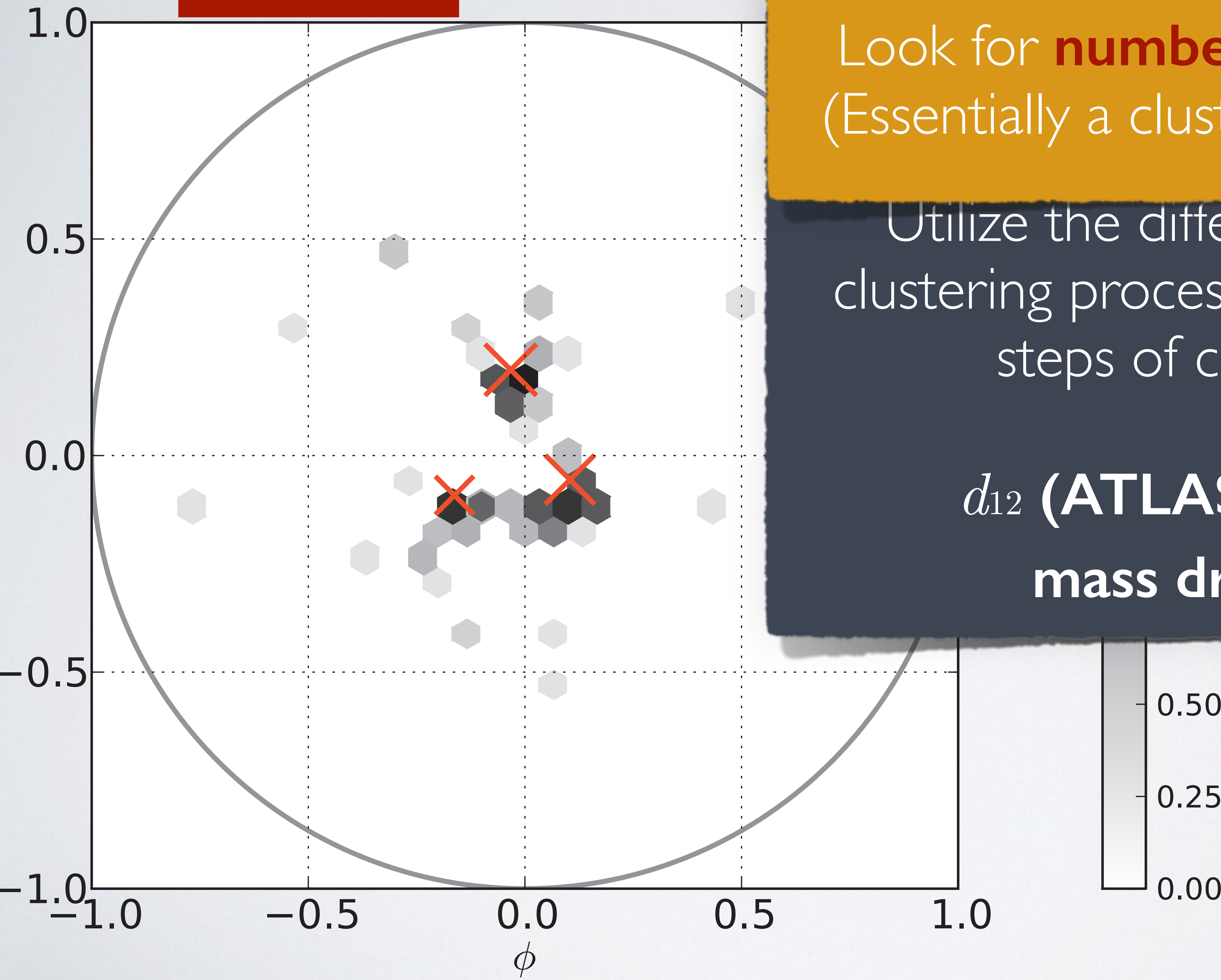
You can look at the **clustering history**…

Utilize the differences (between top and other decays) in the in the last few steps of clustering.

d_{12} (ATLAS tagger), mass drop, …

A few heuristic examples…

Or…

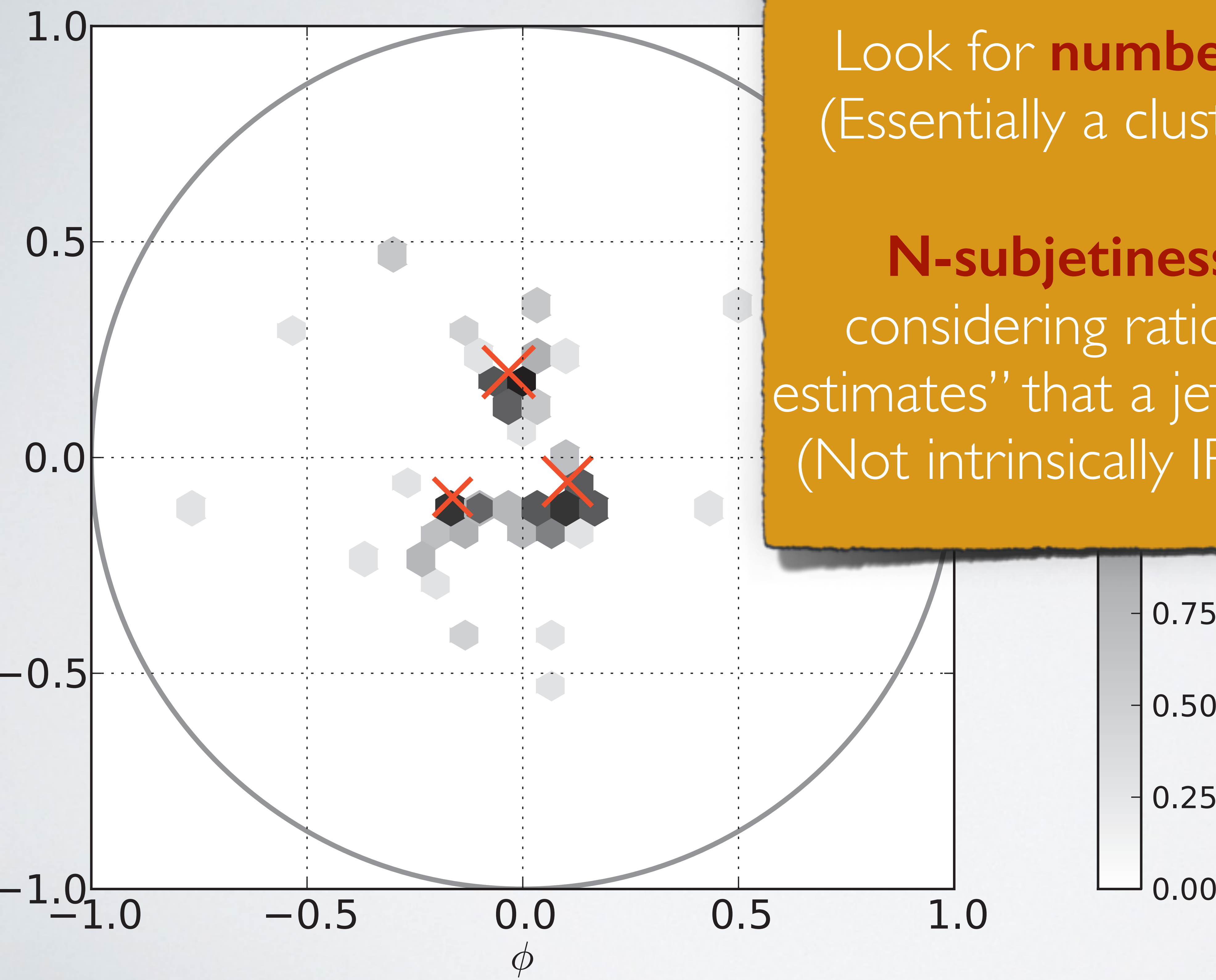


Look for **number of “prongs”.**
(Essentially a clustering algorithm)

Utilize the differences in the clustering process in the last few steps of clustering.

d_{12} **(ATLAS tagger), mass drop, …**

A few heuristic examples…



Look for **number of "prongs".**
(Essentially a clustering algorithm)

N-subjetiness tags tops by considering ratios of "likelihood estimates" that a jet is 2 or a 3 prong.
(Not intrinsically IR safe, but useful!)

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A few heuristic examples…

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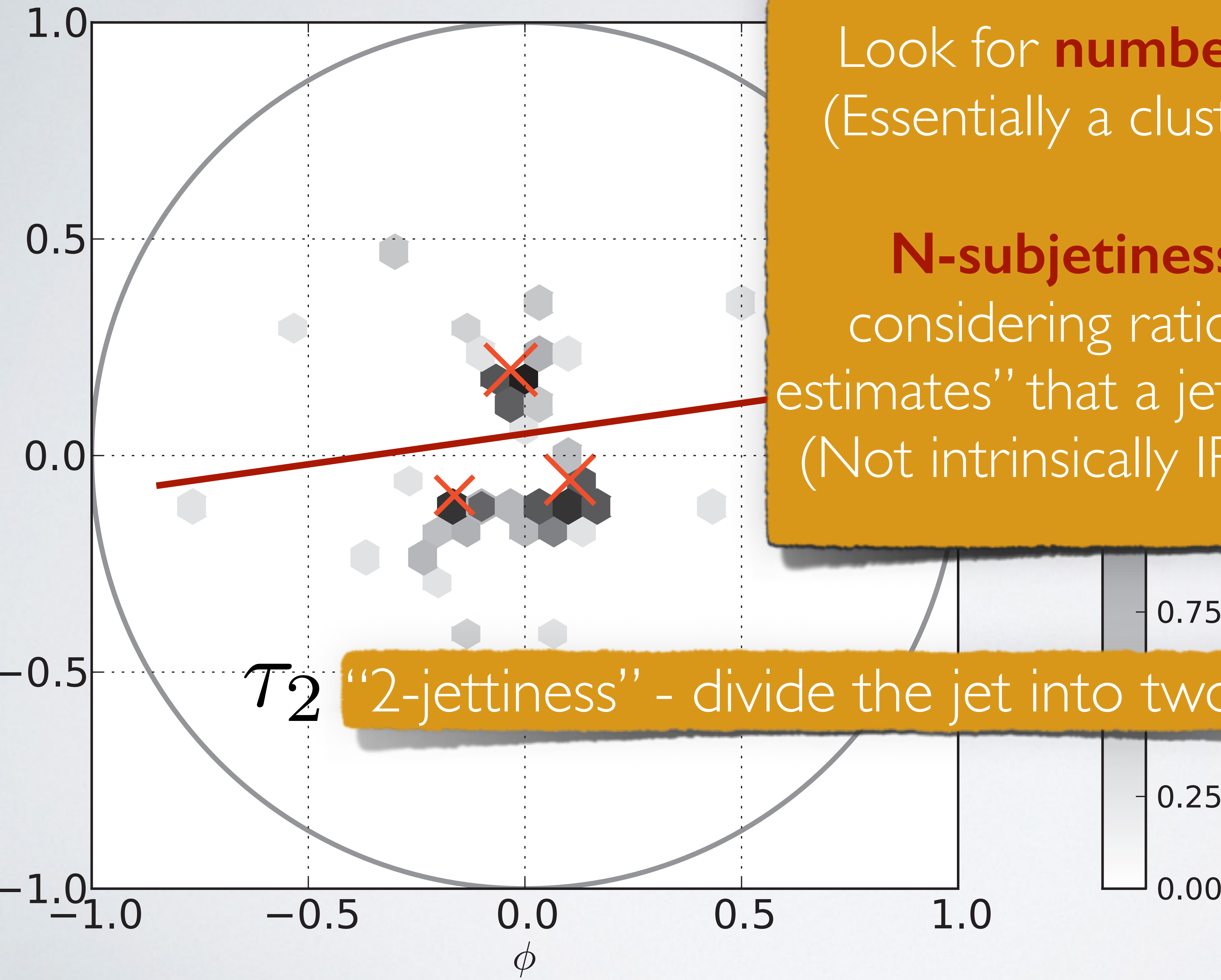
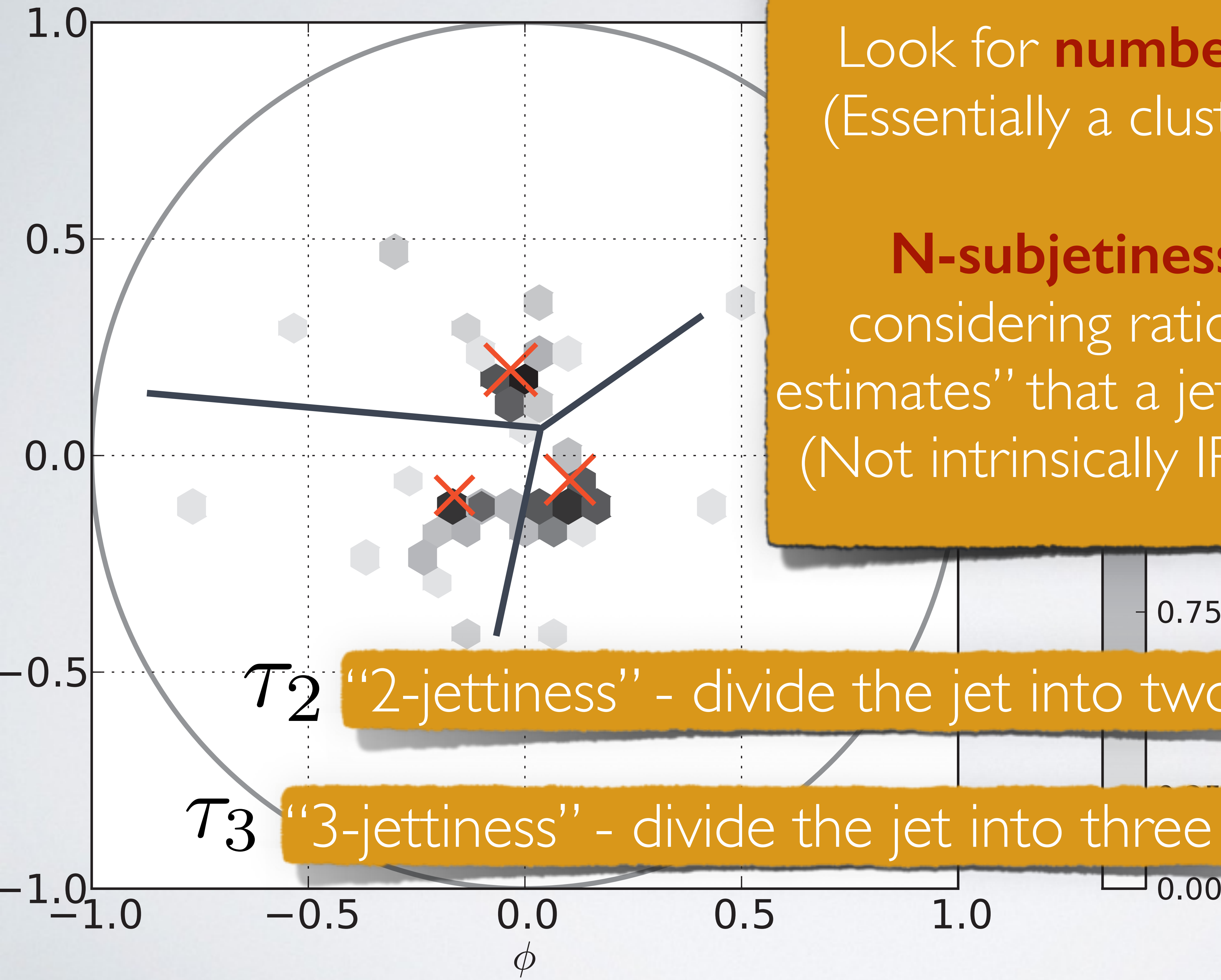


τ_2 "2-jettiness" - divide the jet into two regions

A few heuristic examples…



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τ_2 "2-jettiness" - divide the jet into two regions

τ_3 "3-jettiness" - divide the jet into three regions

A few heuristic examples…

Or…

Try to **match jet energy dist. to a parton structure** of top decay products (**TemplateTagger**).

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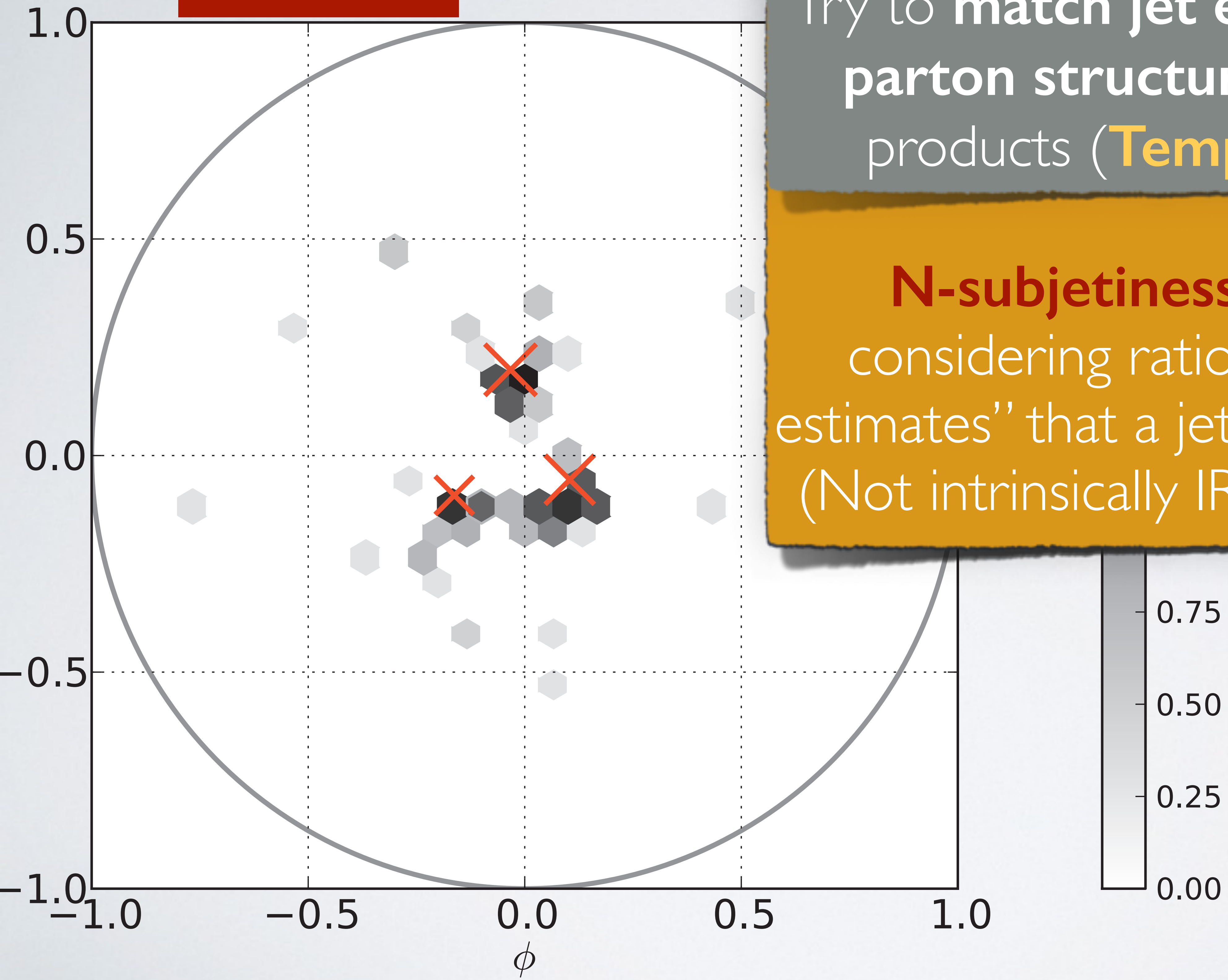

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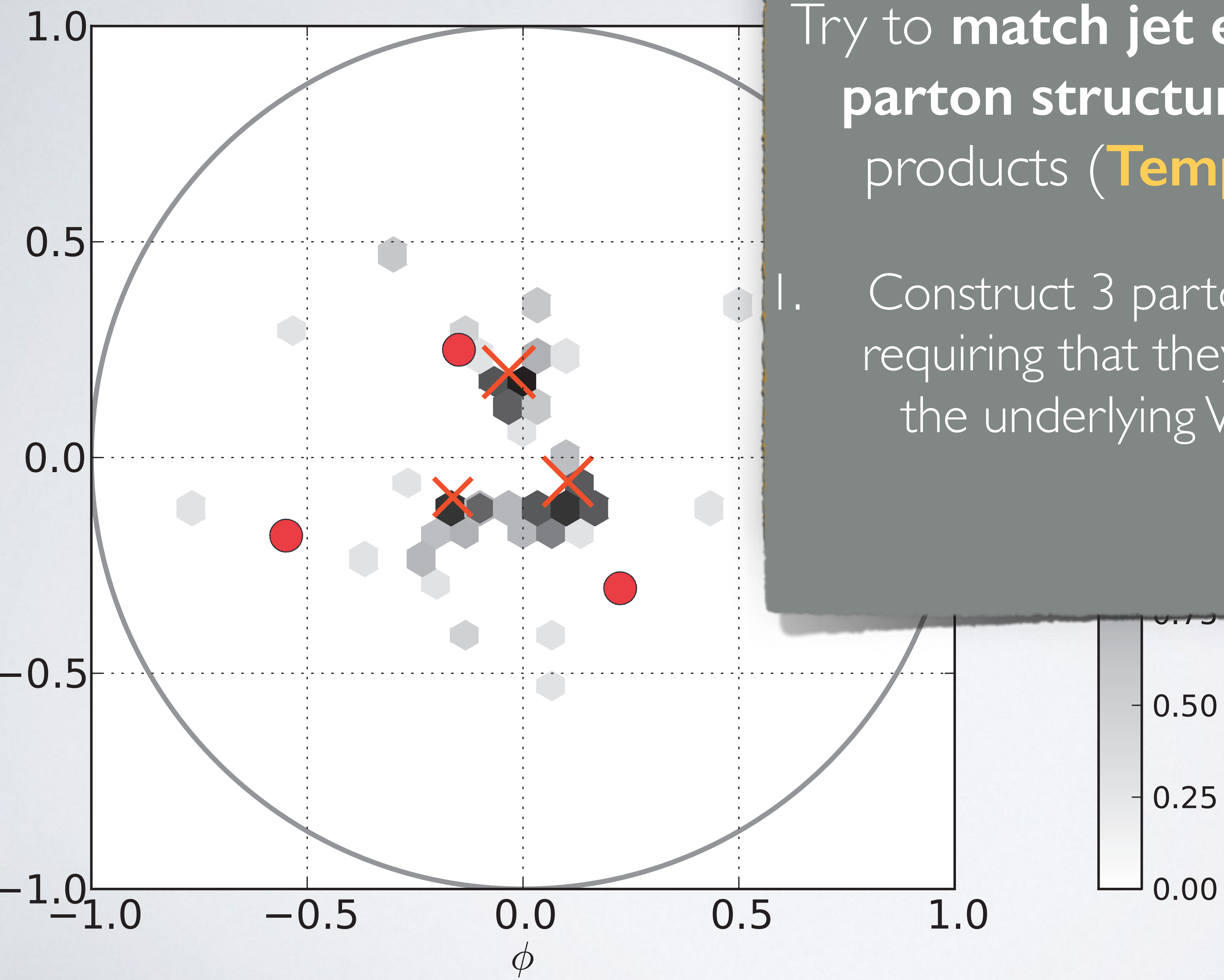

Try to **match jet energy dist. to a parton structure** of top decay products (**TemplateTagger**).

1. Construct 3 partonic 4-momenta by requiring that they reco. the top (and the underlying W) **- "Template"**

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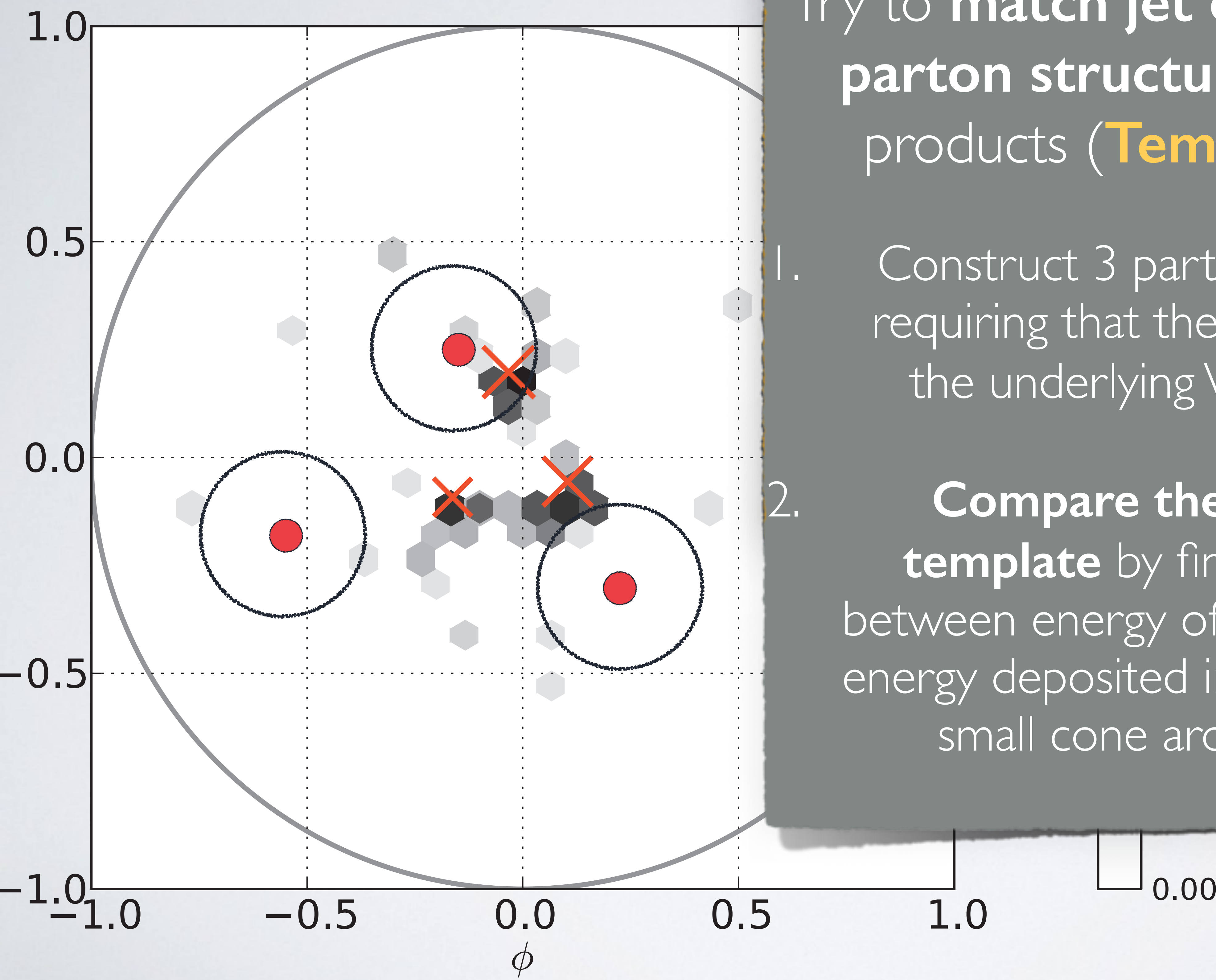

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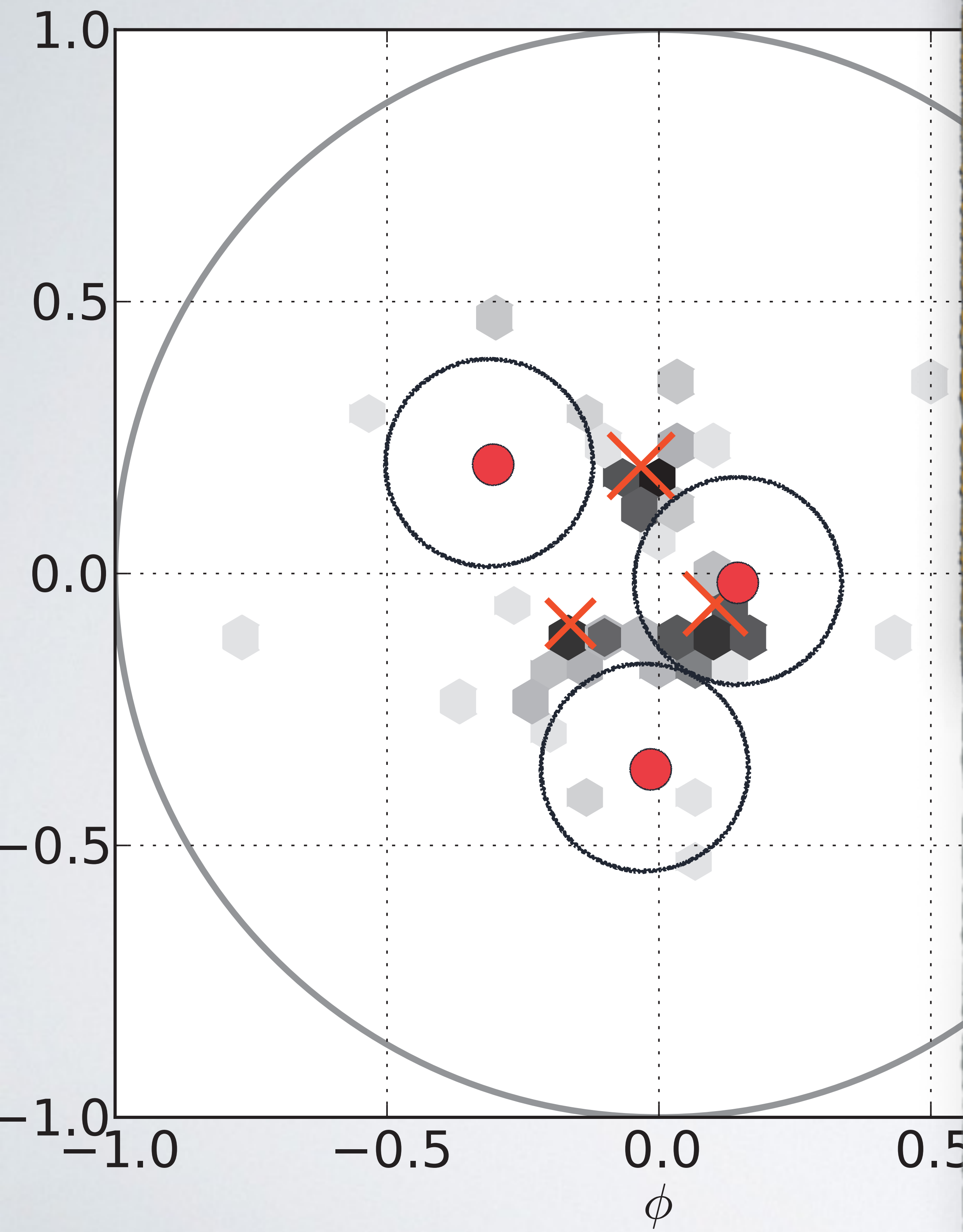

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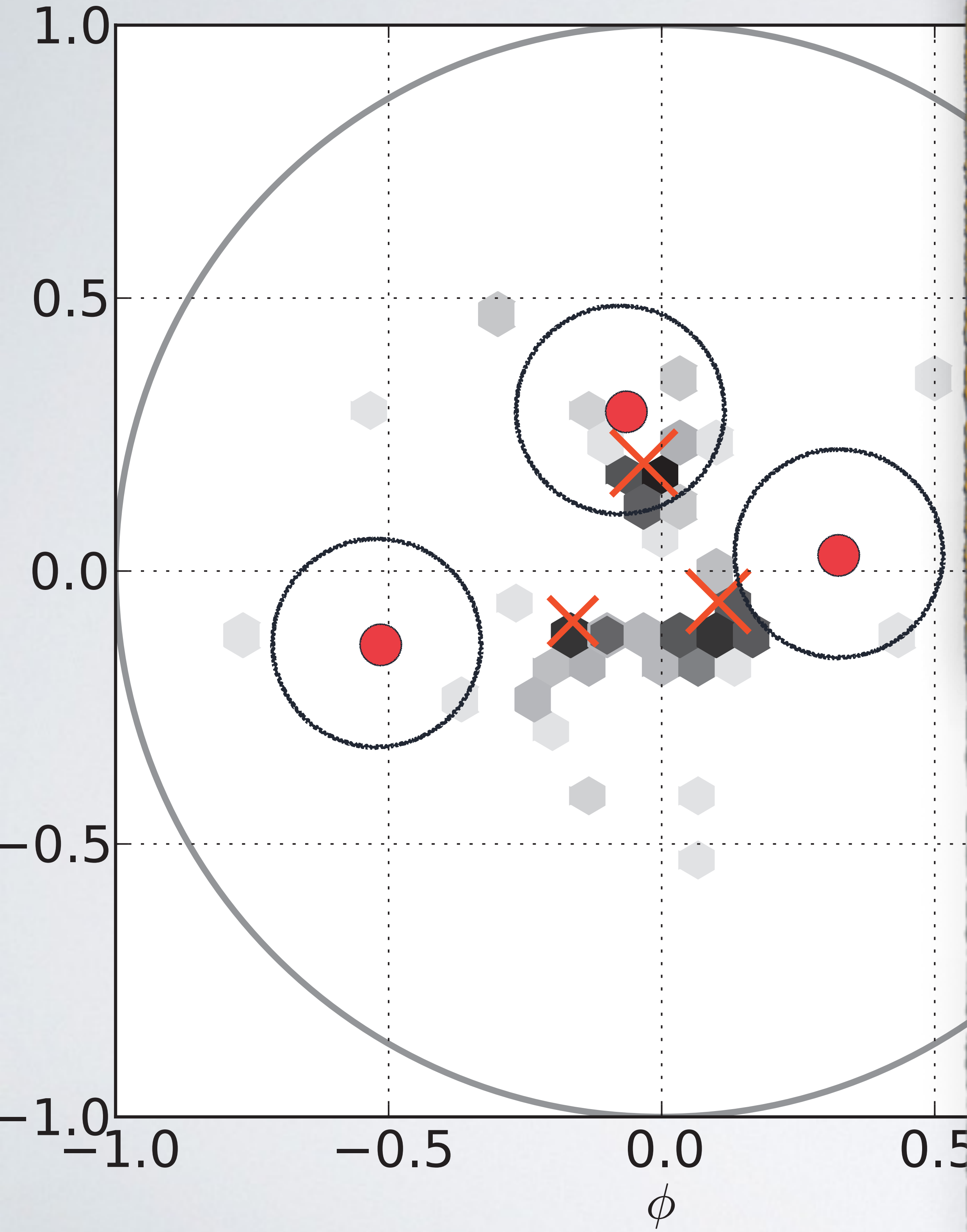

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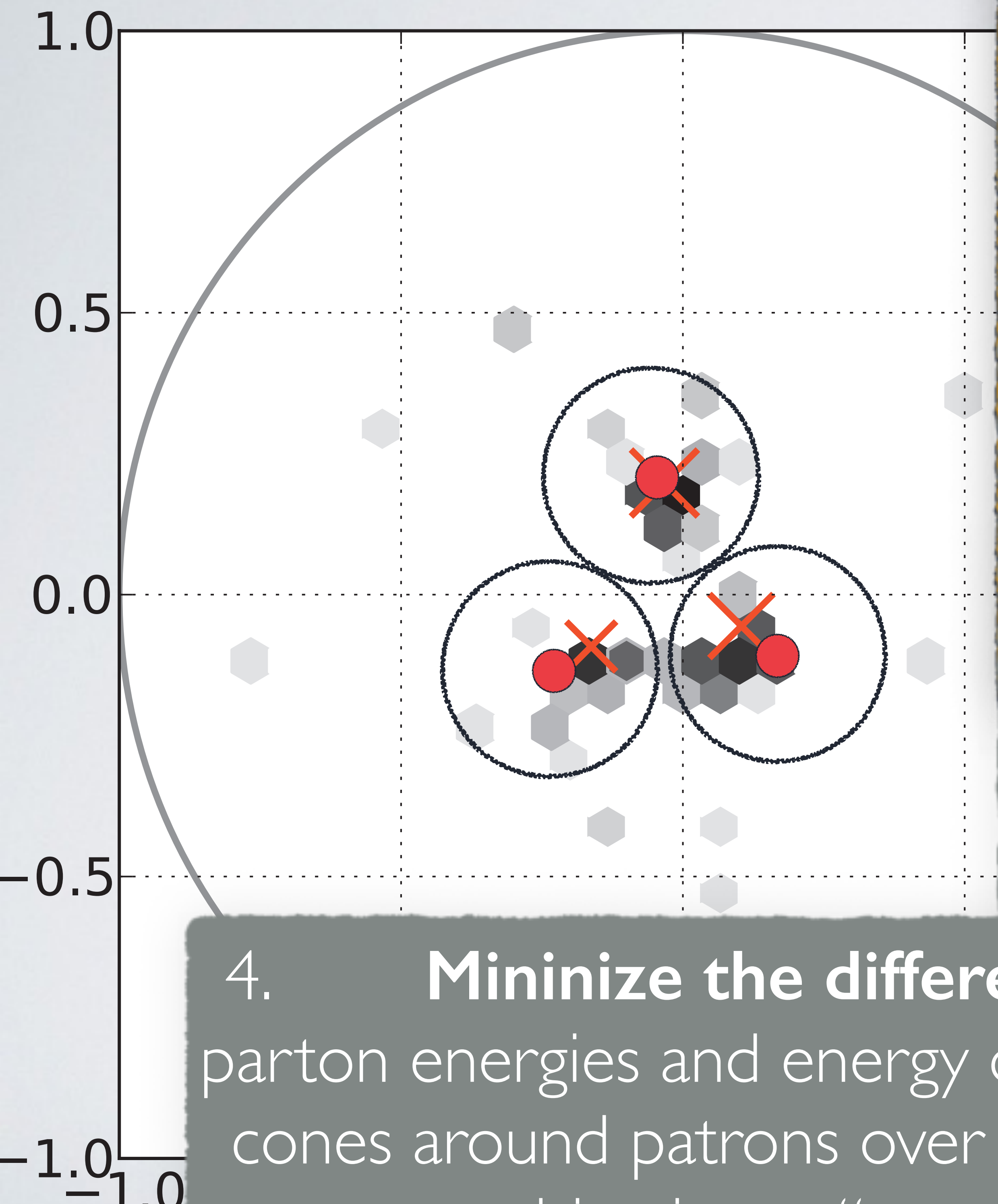

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… kinematically allowed combos.

4. **Mininize the difference** in the parton energies and energy deposited in cones around patrons over all possible combinations - “**overlap**”

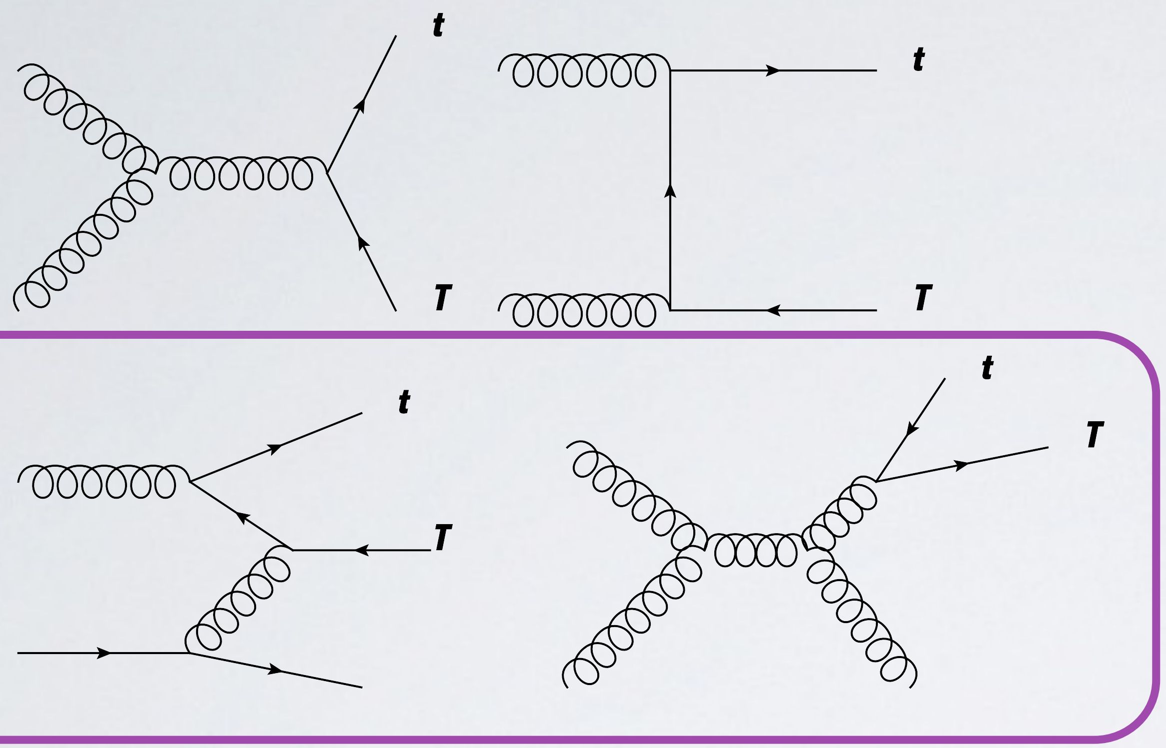
There are a few boosted top tagging **issues** we need to resolve for the future.

- High energy effects
- High Luminosity (pileup)
- - *** "p_T ceiling" -

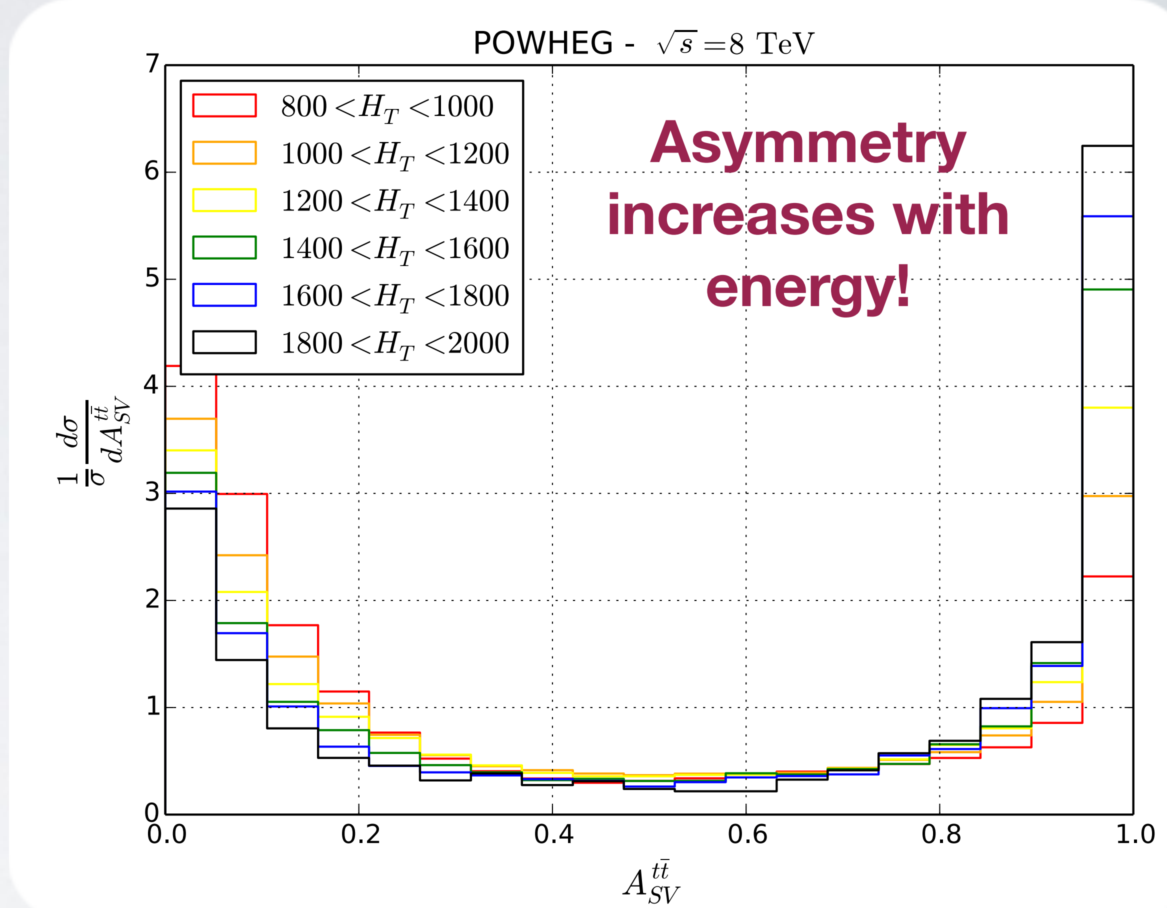
how do you tag a top with $p_T > 1.5$ TeV

*** not very relevant for Run II but interesting to think about

Issues with Top Tagging at High Energies



Important at HE



A significant fraction of top pairs are **not "back to back"** at HE

$$A_{t\bar{t}}^{T} \equiv \frac{|\vec{p}_T^{\,t} + \vec{p}_T^{\,\bar{t}}|}{p_T^t + p_T^{\bar{t}}}$$

defined from truth level tops!

In signal tt events, **the hardest fat jet** can be a **light jet**!

Modeled well in MC tools?!

See also Ofir's poster!

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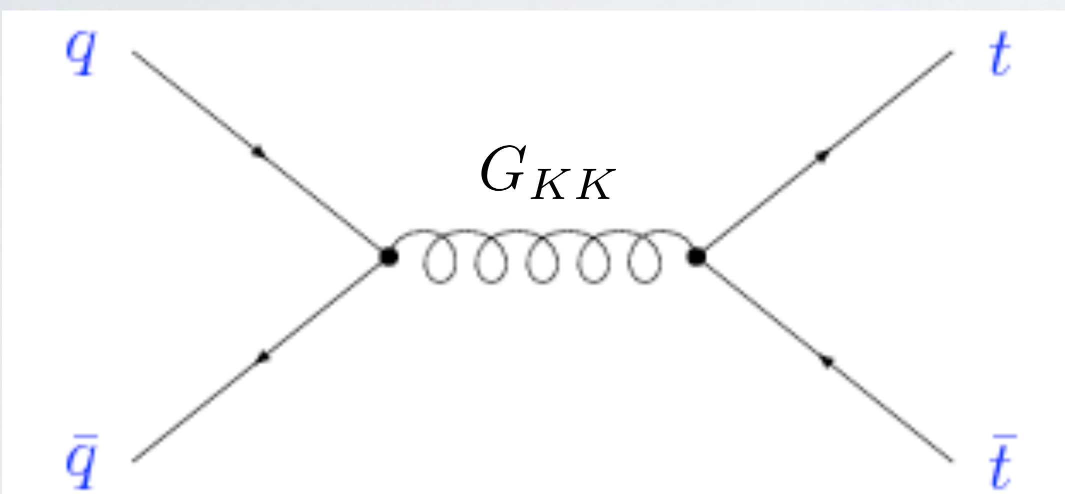
Asymmetric $t\bar{t}$ events are both a **blessing** and a **curse**

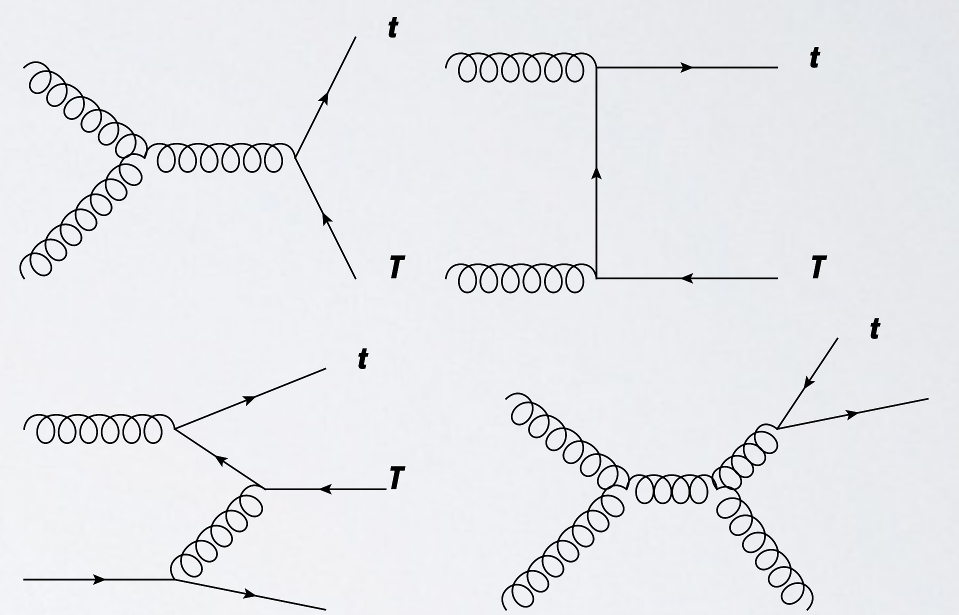
BSM di-top resonance prod.

Less asymmetric!



SM di-top production

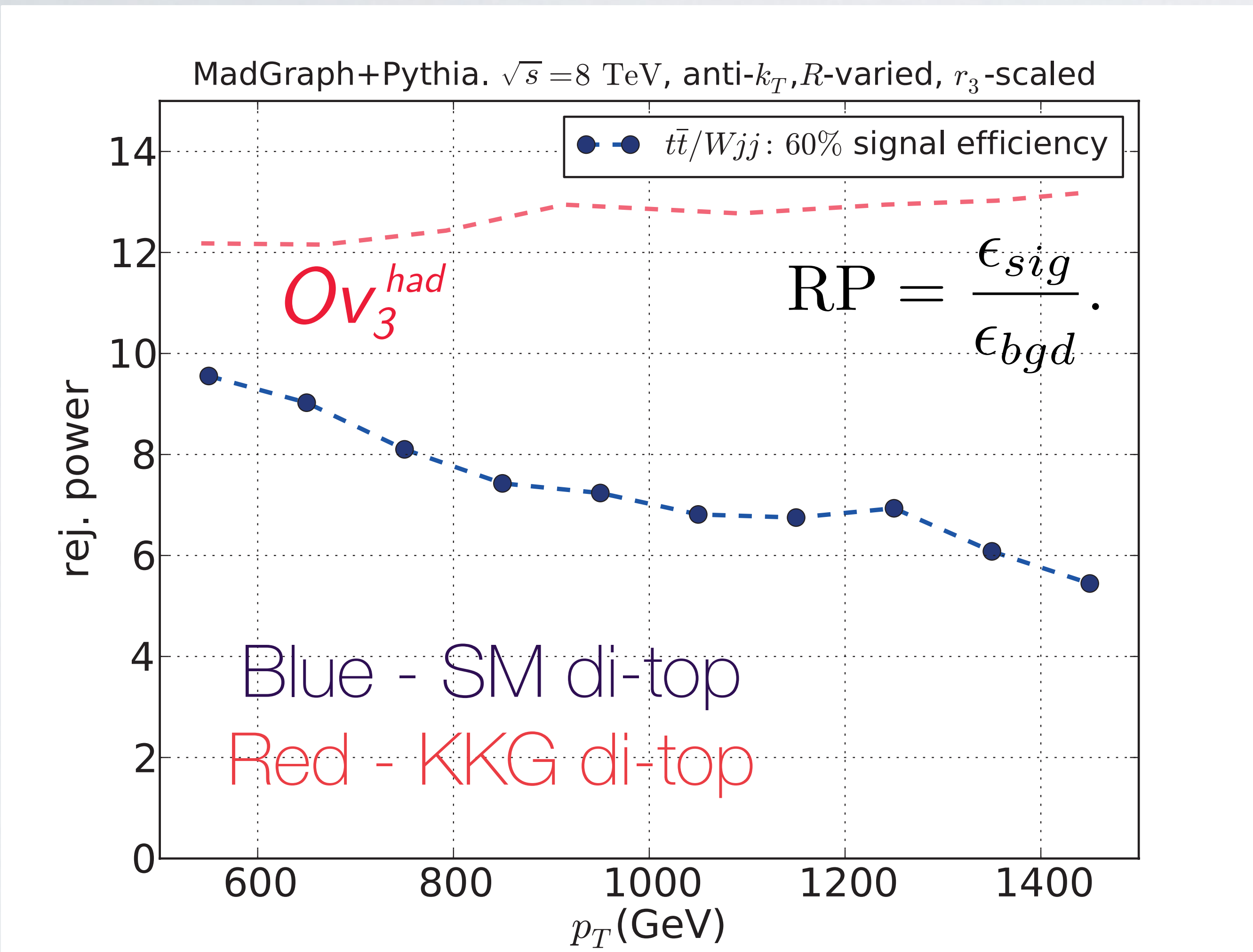
More asymmetric!



:(- if interested in **SM measurements**, signal efficiency will be lower upon boosted top tagging.

:) - if interested in **BSM**, tt is not an irreducible background anymore!

Asymmetric $t\bar{t}$ events are both a **blessing** and a **curse**



Model	$M_{KK} = 2.5$ TeV		$M_{KK} = 3.0$ TeV		EFT	
$m_{t\bar{t}}^{min}$	2125 GeV		2550 GeV		2000 GeV	
Ov_3^{min}	0	0.7	0	0.7	0	0.7
$\sigma_{t\bar{t}}$ (fb)	1.8	0.75	0.43	0.14	2.7	1.1
σ_{W+jets} (fb)	30	0.51	13	0.15	38	0.67
σ_S (fb)	1.4	0.82	0.46	0.16	13.0	12.0
S/B	0.04	0.65	0.04	0.55	0.3	6.8
$S/\sqrt{B}\,(14.3\,\mathrm{fb}^{-1})$	0.9	2.8	0.5	1.1	7.7	34
$S/\sqrt{B}\,(20.0\,\mathrm{fb}^{-1})$	1.1	3.3	0.6	1.3	9.1	40

Eff. (SM tt) - 40%

Eff. (KKG tt) - 60%

Study done at LO + matching, effect more prominent at full NLO

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Pileup effects on top tagging

~ **20 years ago**

~ **7 TeV Run**

~ **8 TeV Run**

~ **Run II**

Pileup effects on top tagging

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"What is this pileup you speak of?"

~ **7 TeV Run**

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"**7** interaction per bunch crossing is difficult"

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"**7** interaction per bunch crossing is easy, but **20 is difficult**"

~ **Run II**

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~ **8 TeV Run**

"**7** interaction per bunch crossing is easy, but **20 is difficult**"

~ **Run II**

"**20** interaction per bunch crossing is easy, but **50 is difficult**"

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Pileup effects on top tagging

~

"What is this pileup you speak of?"

"7

No "silver bullet" solution to pileup

~

We've been very good at coming up with pileup solutions on the go

~

"20

is easy, but

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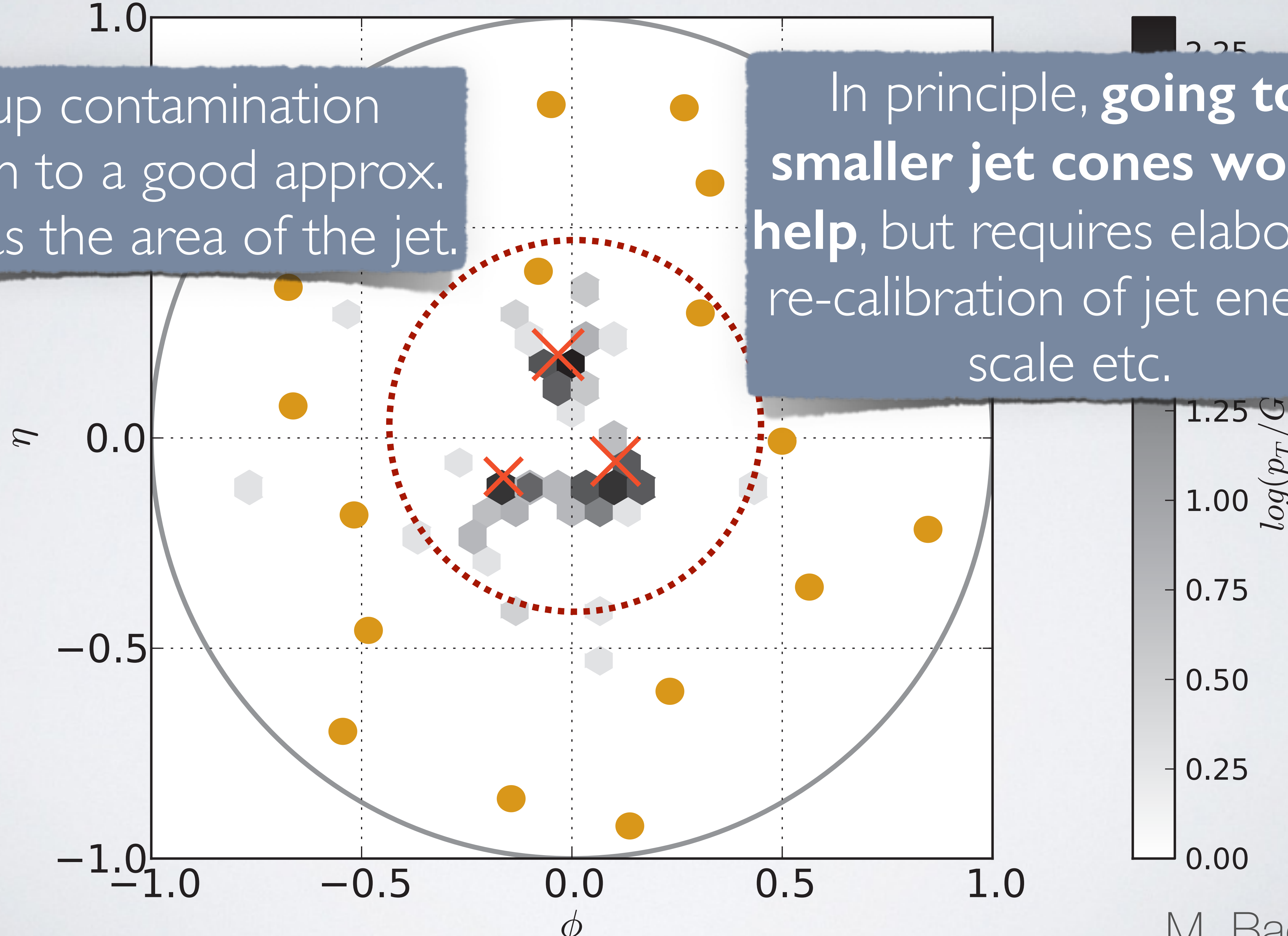
Pileup effects on top tagging

The issue is really the use of large jet cones ($R \sim 1$)



Pileup contamination uniform to a good approx. Scales as the area of the jet.

In principle, **going to smaller jet cones would help**, but requires elaborate re-calibration of jet energy scale etc.

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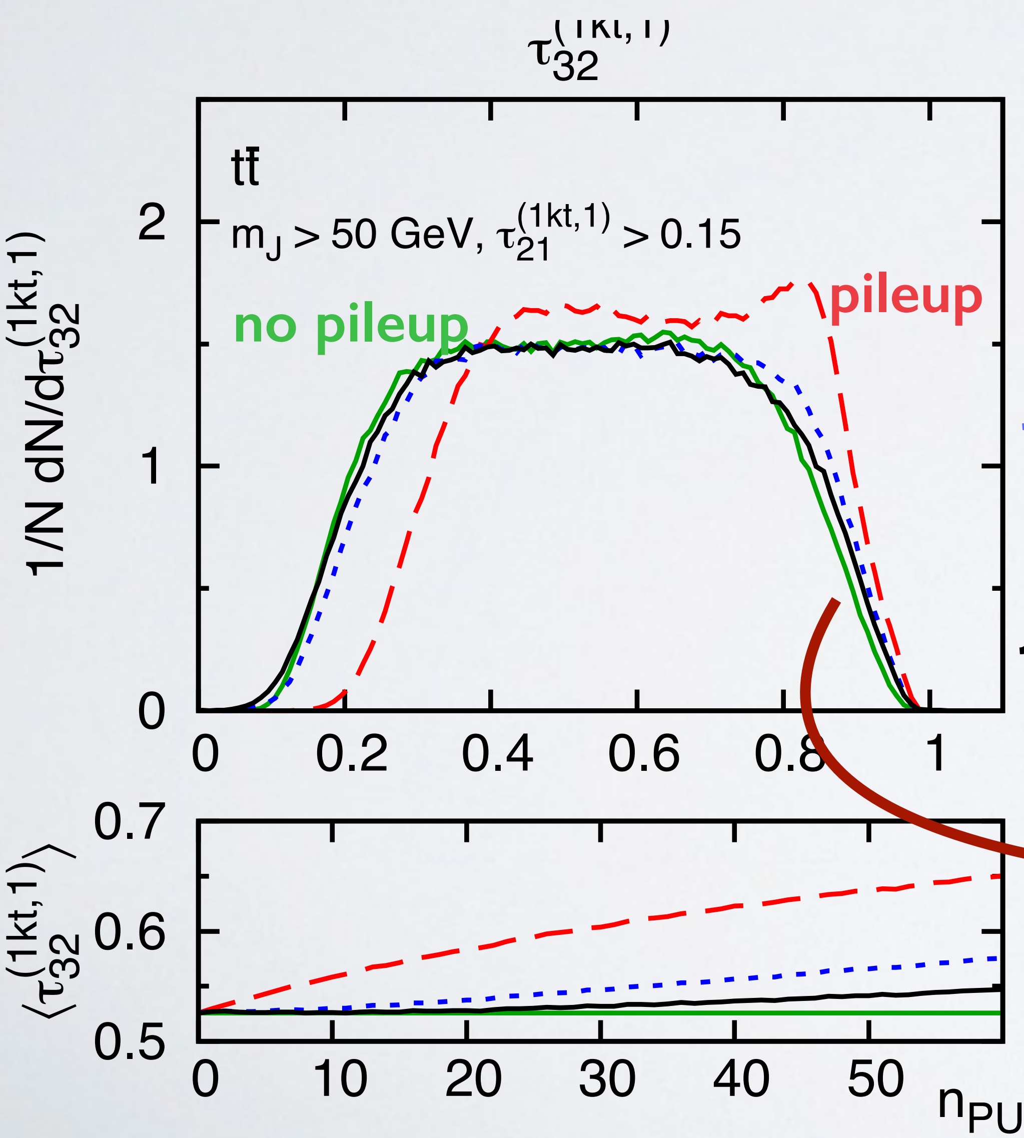
Pileup effects on top tagging

Much progress in **pileup mitigation** for jet substructure:

Jet Area (JA) subtraction methods

(Soyez, Salam, Kim, Dutta, Cacciari,): **arXiv:1211.2811**



1st order JA subtraction

2nd order JA subtraction

$$V_{\rm jet,sub} = V_{\rm jet} - \rho V_{\rm jet}^{[1]} + \frac{1}{2}\rho^2 V_{\rm jet}^{[2]} + \cdots .$$

$$V_{\rm jet}^{[n]} \equiv A_g^n \frac{d^n}{dr_{t,g}^n} V(\{p_i\}_{\rm jet}),$$

derivatives of the substructure observable wrt. soft component pT and mass

Works very well for N-subjettness (for example)

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However…

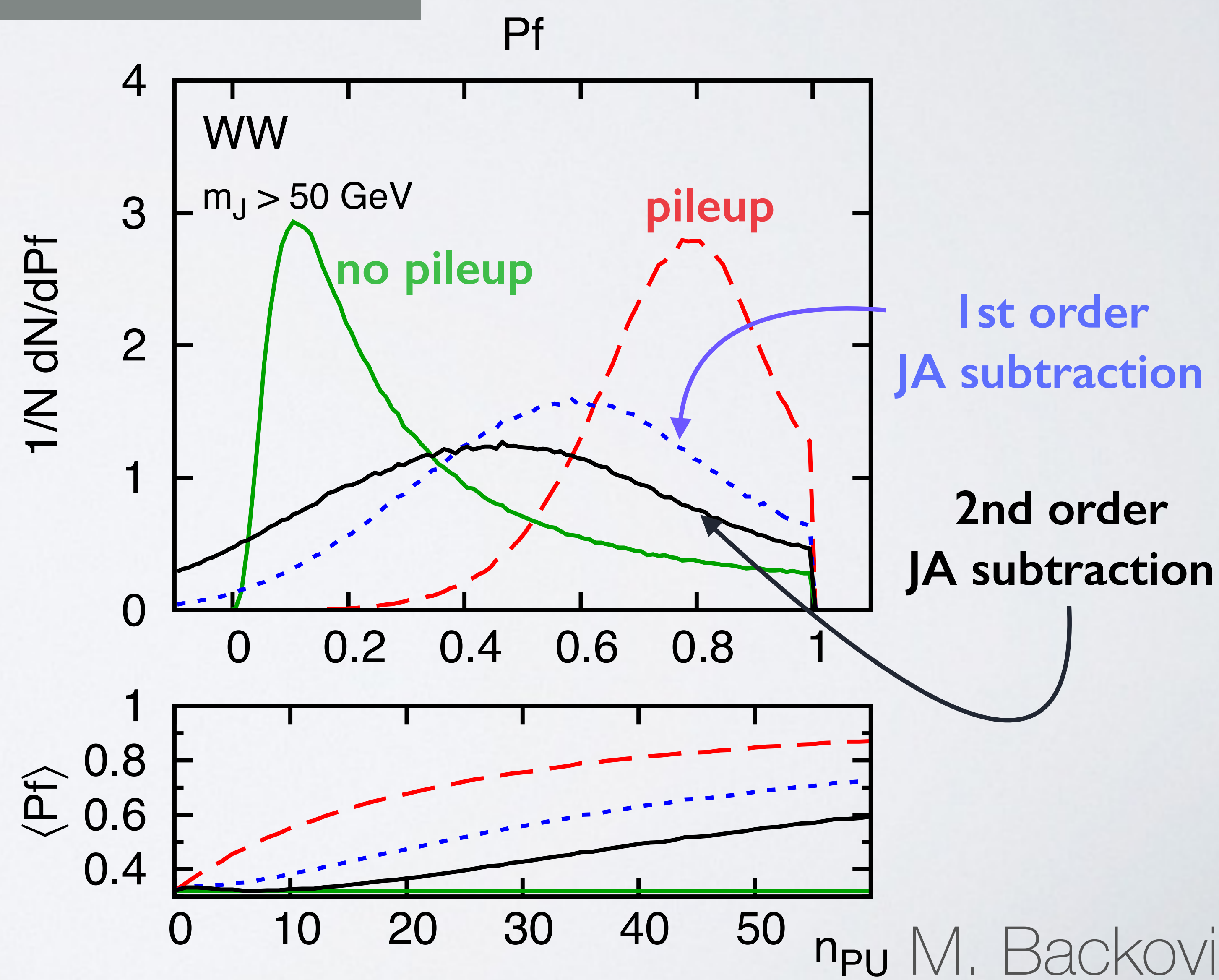
- Pileup mitigation for jet substructure can be complicated!
- There still are observables which we **don't know how to correct for pileup.**

An extreme example is jet planar flow

$$Pf = \frac{4\det(I_\omega)}{\mathrm{tr}(I_\omega)^2},$$

$$I_\omega^{kl} = \frac{1}{m_J}\sum_i \omega_i \frac{p_{i,k}}{\omega_i}\frac{p_{i,l}}{\omega_i},$$

Measure of how well the jet energy dist. fits on a line (0 - line, 1-"uniform")



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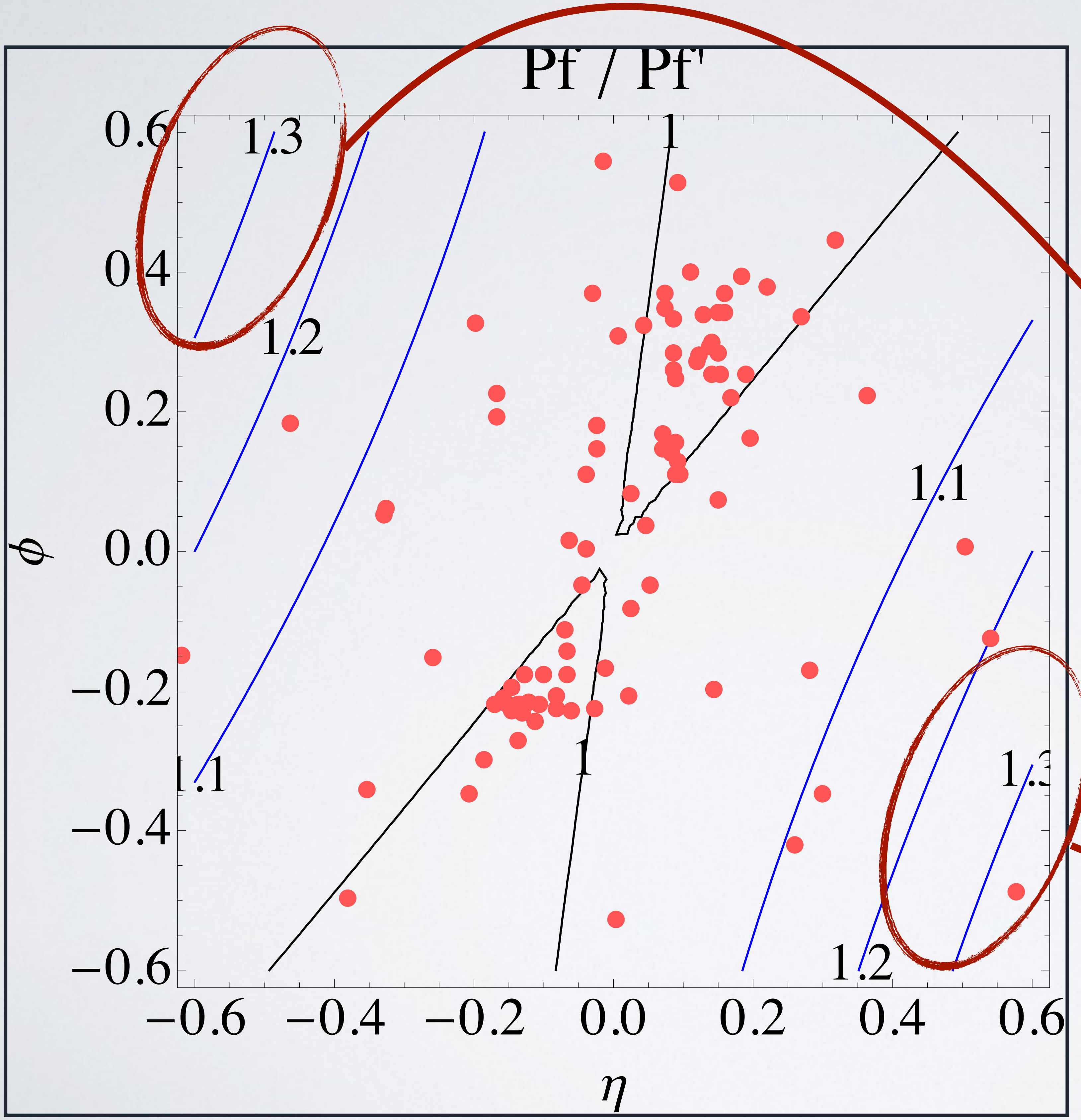
Effect of **one 3 GeV pion** on the numerical value of **jet planar flow**

$$Pf = \frac{4\,\det(I_\omega)}{\mathrm{tr}(I_\omega)^2},$$

Pf is a very non-linear variable (it correlates every jet constituent to all other ones)



One 3 GeV pion can change the Pf value by **~ 30%**

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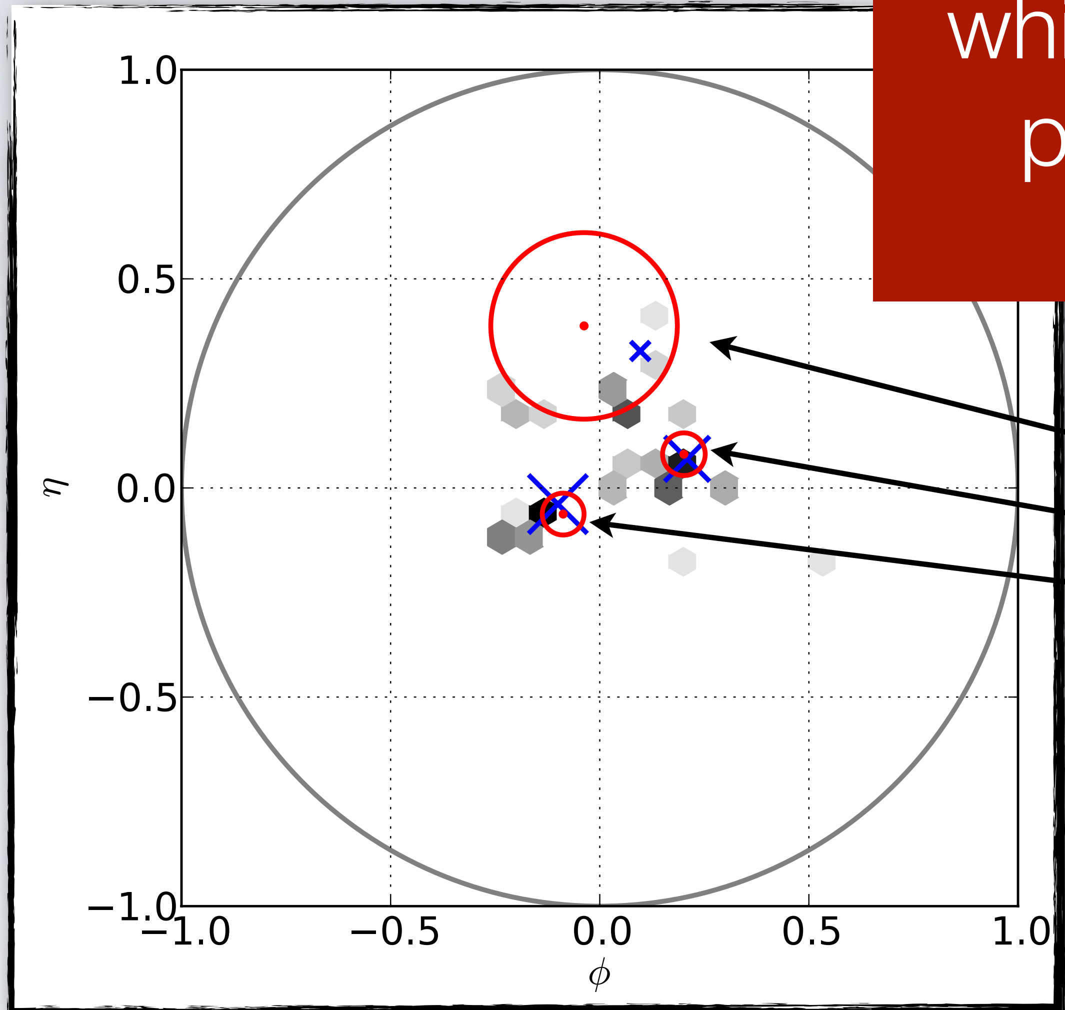
Pileup effects on top tagging

We can also think about observables which are **weakly susceptible** to pileup **by design**. TOM is one example.



Templates are sensitive ***only*** to the energy deposition inside the template sub-cones.

Pileup contribution to a template relative to the fat jet

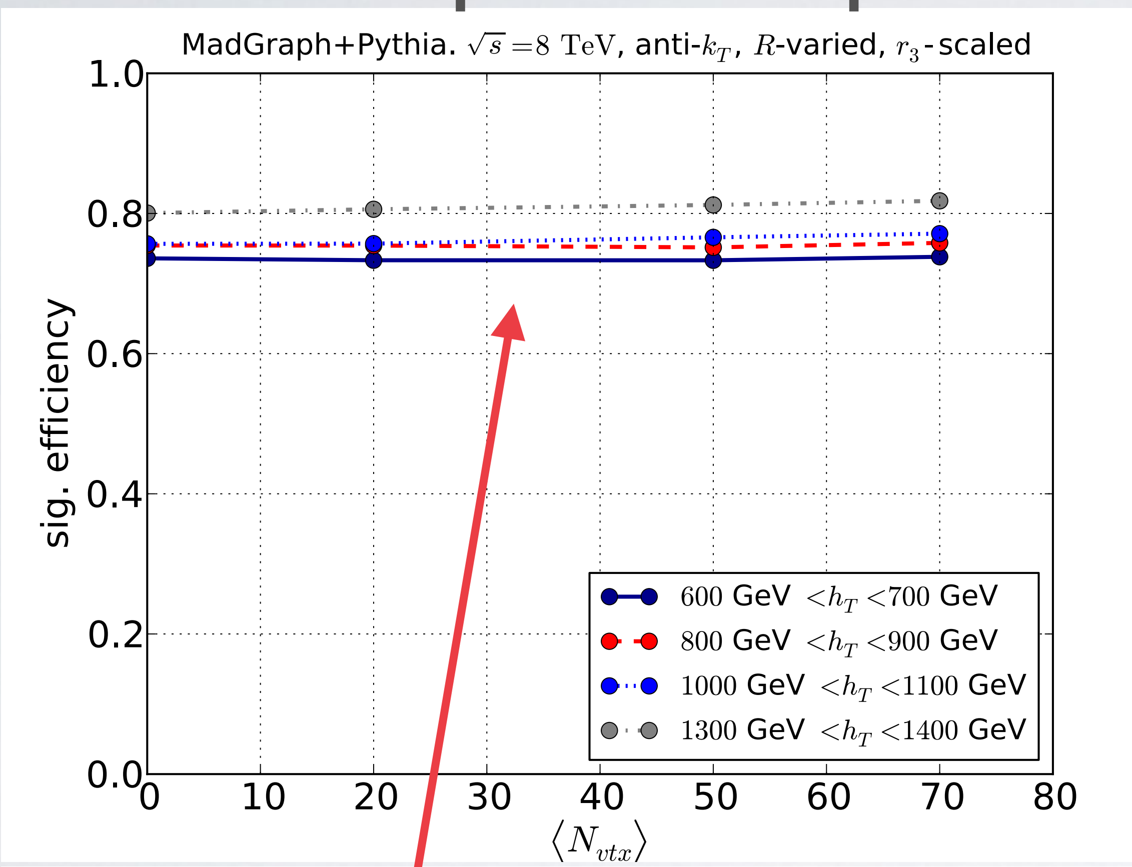
For fat jets: $\delta p_T^{pileup} \sim R^2$

For templates: $\delta p_T^{pileup} \sim r^2$

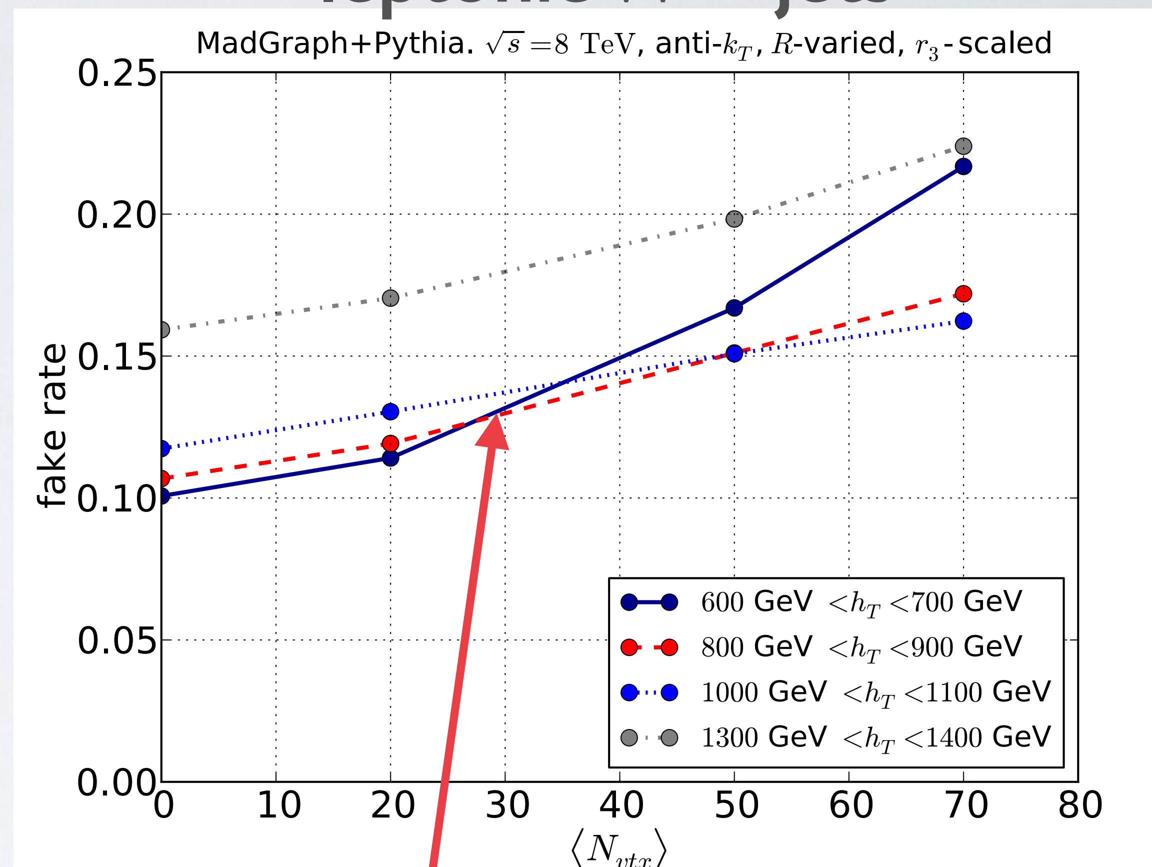
e.g.: $n_{temp} \times r^2/R^2 \sim n_{temp} \times 0.1^2/1.0^2 = 0.01 \times n_{temp}$

Pileup effects on boosted top tagging

semi-leptonic di-tops



leptonic W + jets



Signal efficiency of TOM for $t\bar{t}$ almost unaffected by pileup

Still significant effects on the fake rate of W+jets.

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Boosted tops for Run II BSM physics

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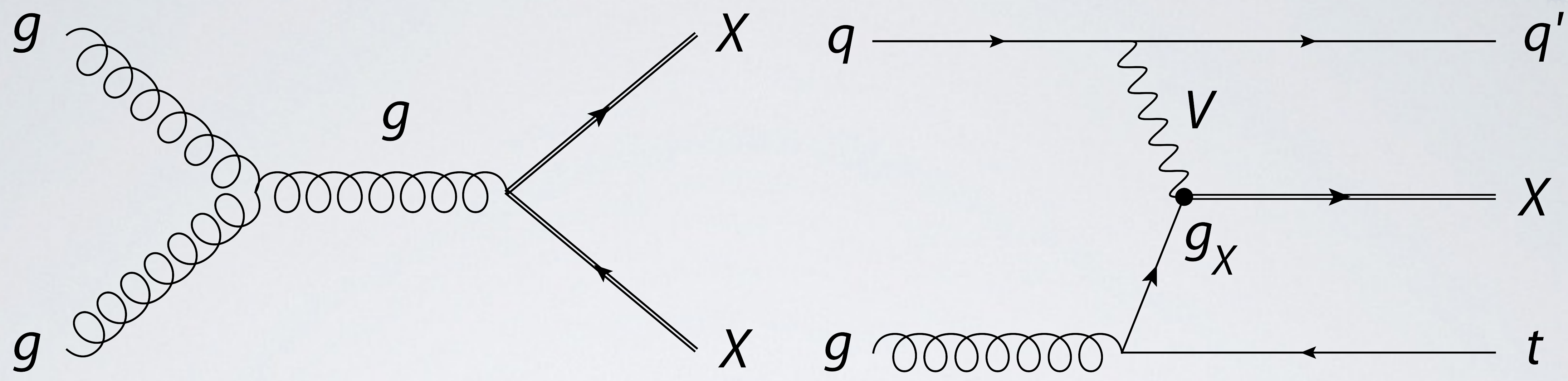
Fermionic Top Partner Searches (Comp. Higgs)



Lightest top partner typically **charge 5/3** which decays to tW

SSDL

- Very clean.
- Suppressed rate.
- Sensitive only to 5/3 partner.

Lepton + jet

- Large tt and W+jets bgd.
- Much higher rate.
- Sensitive to partners other than 5/3.

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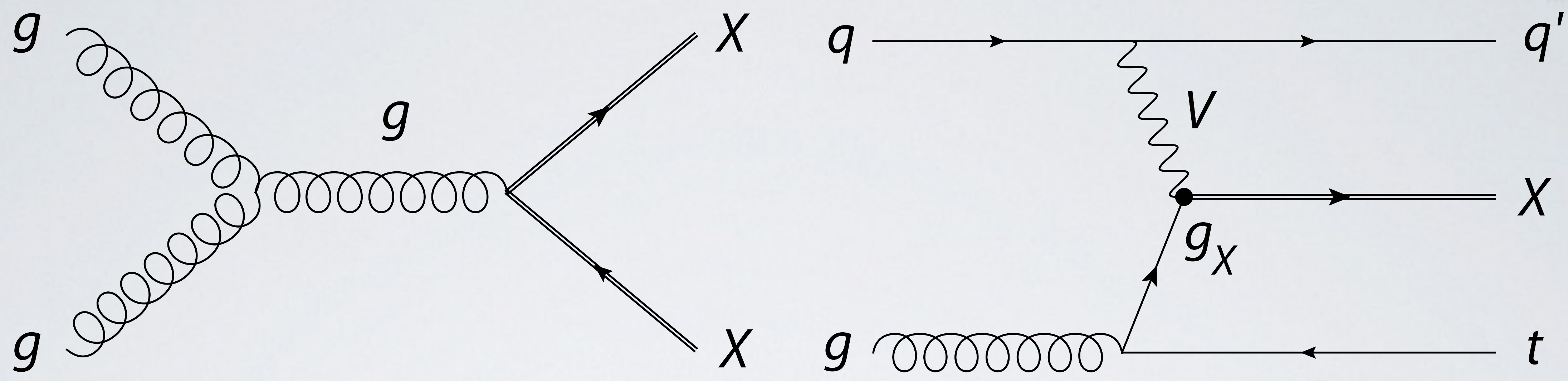

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Focus of the exp. effort so far

Lepton + jet

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- Much higher rate.
- Sensitive to partners other than 5/3.

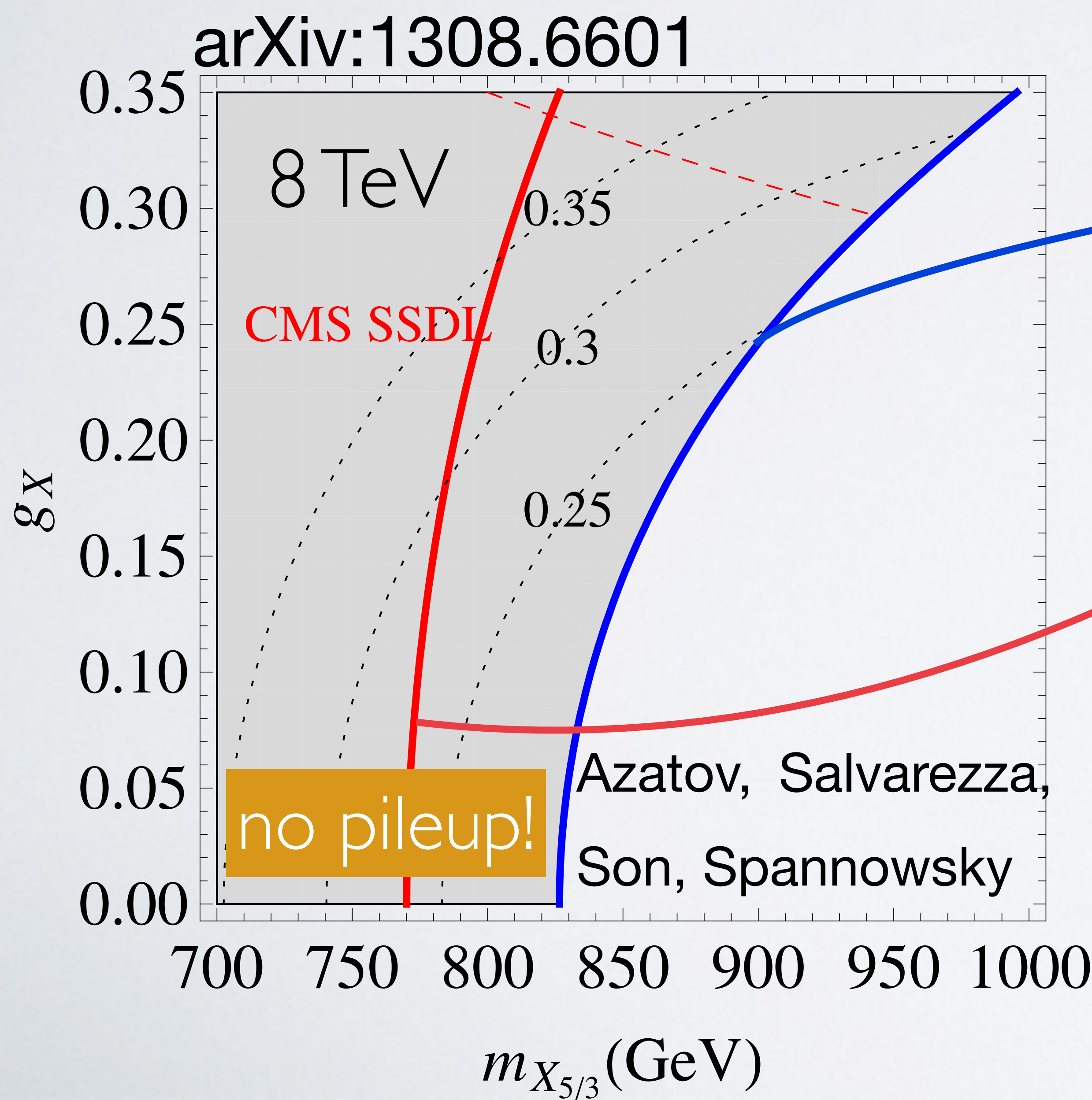
M. Backović

Fermionic Top Partner Searches (Comp. Higgs)

- Lepton + Jet channels can (in principle) **do better than SSDL**!

Many handles on SM backgrounds: boosted t, boosted W, $2b$-tags, hard leptons, forward jet.

See Emanuele's talk for details on b-tagging of fat jets



Limit using the lepton+jet cutflow (**HEPTopTagger** for boosted regime)

CMS limit using SSDL

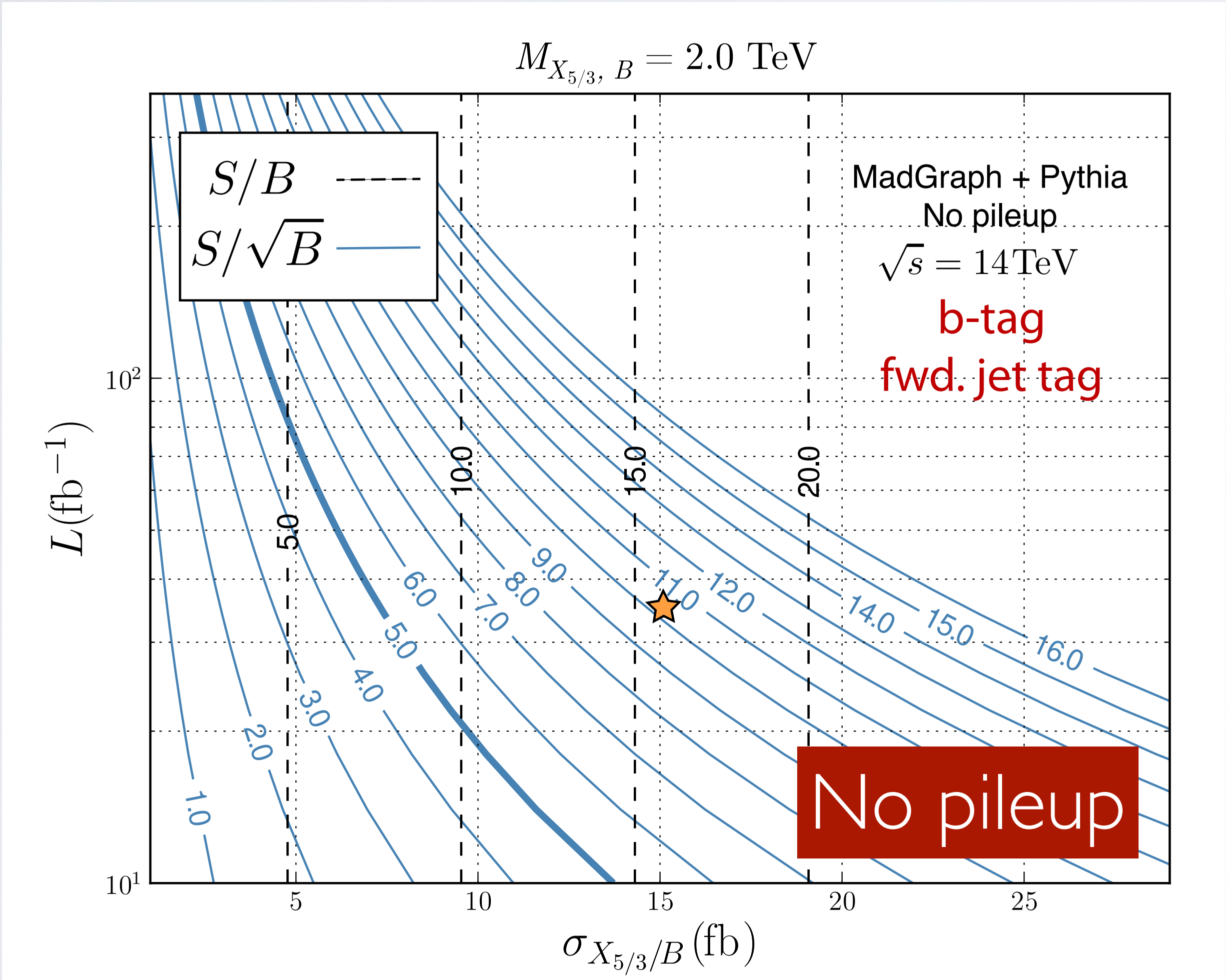
"Proof of concept" that boosted jet tagging techniques could be becoming as powerful as fully leptonic channels!

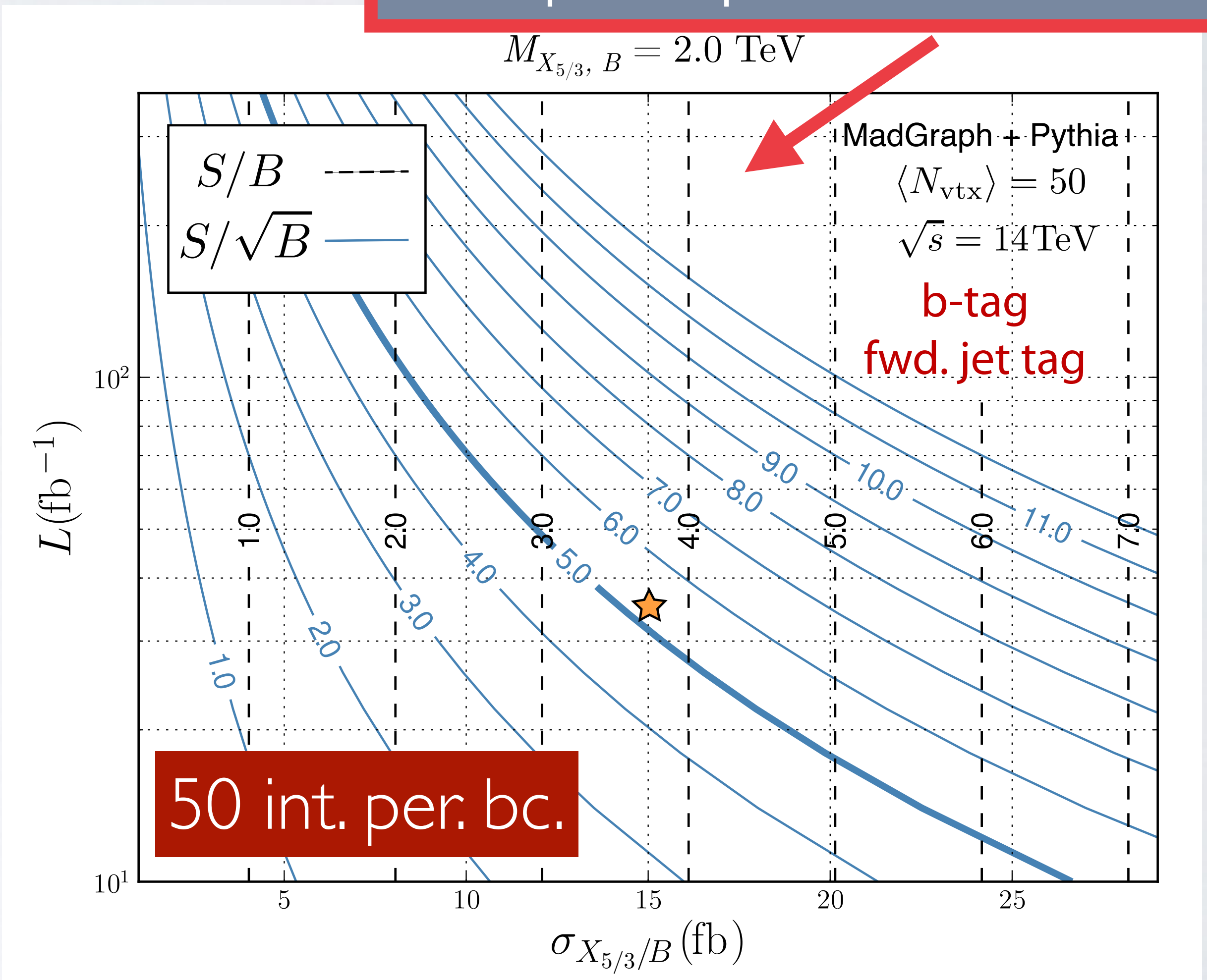
M. Backović

Fermionic Top Partner Searches (Comp. Higgs)

- Similar proposal: **lepton + fat jet + fwd. jet + b tagging** for Run II.
- Analysis tailored for **very heavy states** (i.e. ~ 2 TeV)
  (Utilizes the **TemplateTagger**)

No pileup subtraction!





MB, Flacke, Lee, Perez: **arXiv:1409.0409**

Fermionic Top Partner Searches (Comp. Higgs)

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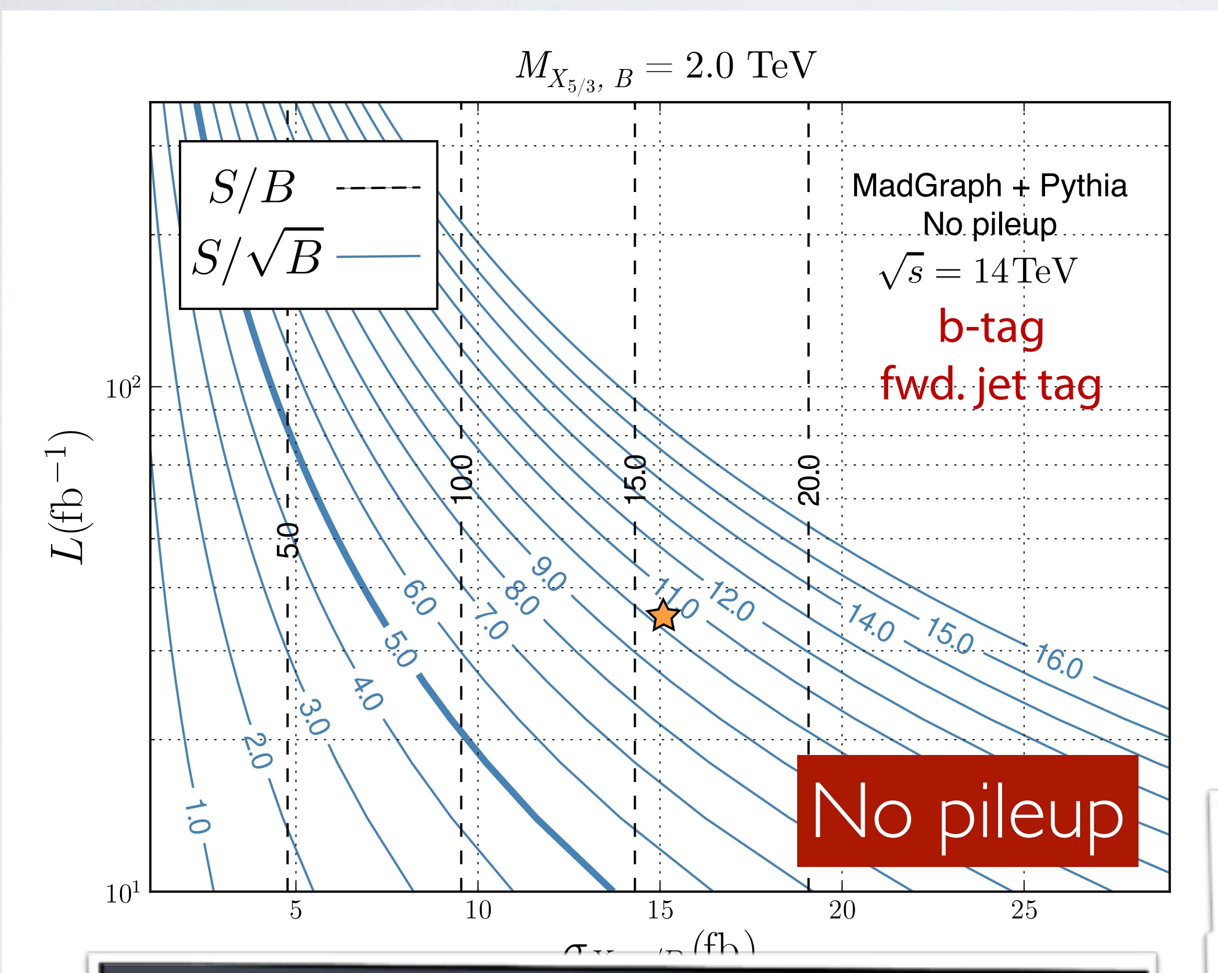
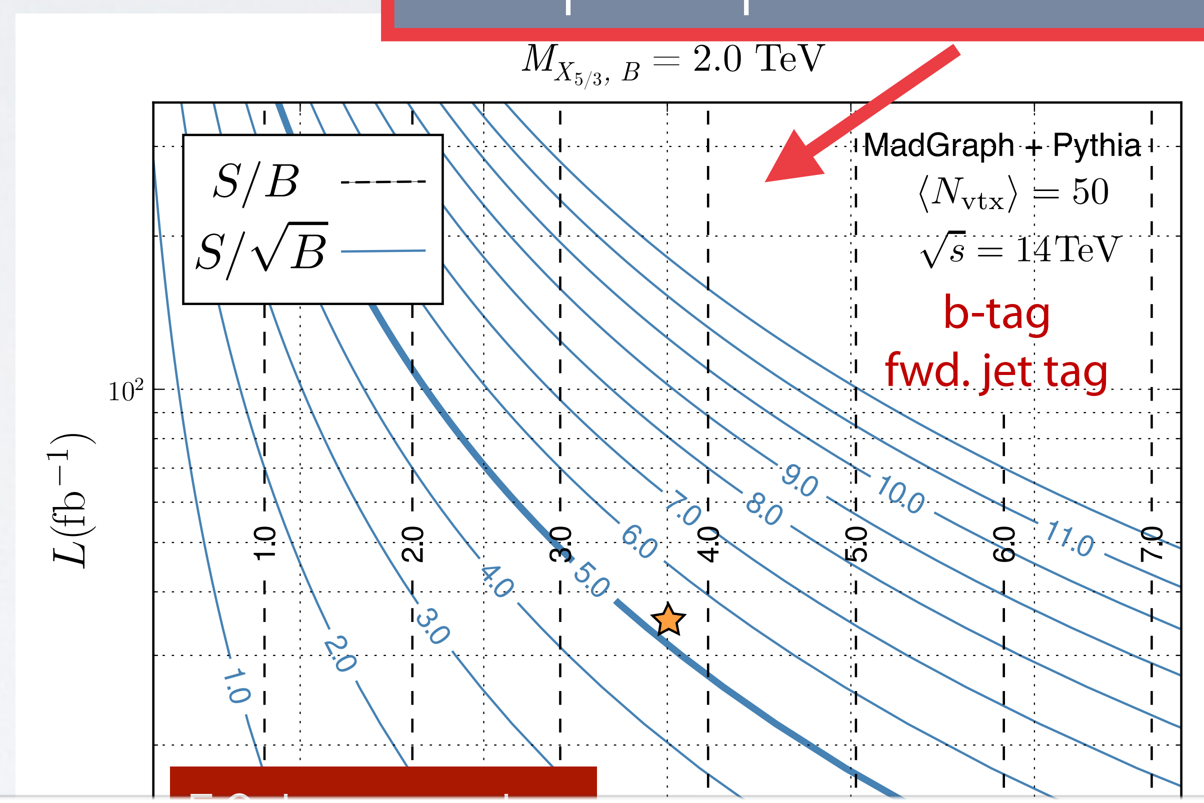


Signal cross section > SSDL after the cutflow



No pileup subtraction!

Some effects of pileup, but the "most pessimistic" scenario shows that no aggressive pileup subtraction should be necessary.

Fermionic Top Partner Searches (Comp. Higgs)

Other proposals for top partners searches in boosted channels appeared recently:

Top Partner Discovery in the $T \to tZ$ channel at the LHC

Jürgen Reuter and Marco Tonini

arXiv:1409.6962

Search Strategies for Top Partners in Composite Higgs models

Ben Gripaios,[a] Thibaut Müller,[a] M. A. Parker[a] and Dave Sutherland[a]

arXiv:1406.5957

Looks like "exotics" searches in boosted top channels are in a good shape!

We have several obstacles to overcome

before Run II …

… but LHC Run I has taught us that we are

very good at solving problems on the run!

Let’s hope we find something **new and exciting**!