Top quark reconstruction

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Overview reconstruction at Tevatron and early LHC

Most tops produced at threshold

Address physics questions where $m_{t\bar{t}} \simeq 2\ m_t$

Hadronic top reconstruction

- Often simple χ^2 -fit with $m_W^2 = m_{j_1 j_2}^2$ and $m_t^2 = m_{b,j_1,j_2}^2$
- Kinematic fitter (HitFitter, KinFitter, …)
- Matrix Element Method $P(\mathbf{x},\alpha) = \frac{1}{\sigma}\int d\phi(\mathbf{y})|M_\alpha|^2(\mathbf{y})W(\mathbf{x},\mathbf{y})$

Leptonic top reconstruction

- Full reconstruction by estimating $p_{Z,\nu}$
  using $m_W^2 = (p_l + p_\nu)^2 = m_l^2 + 2(E_l E_\nu - \vec{p}_l \vec{p}_\nu)$
- Templating, exploiting e.g. $m_{lb} \sim 140\ \mathrm{GeV}$
- Mini-isolation criteria for high-pT, see e.g. [Rehermann, Tweedie '10]

Motivation to reconstruct tops at LHC 13/14

Top and Higgs most interesting particles of SM

Window to elw. symmetry breaking

Due to large y_t

- In SM, top largest contributor to destabilising the elw. scale $\longrightarrow$ can turn λ negative
- Radiative elw. sym. breaking in e.g. SUSY or composite Higgs models

[See talk by M. Peskin]

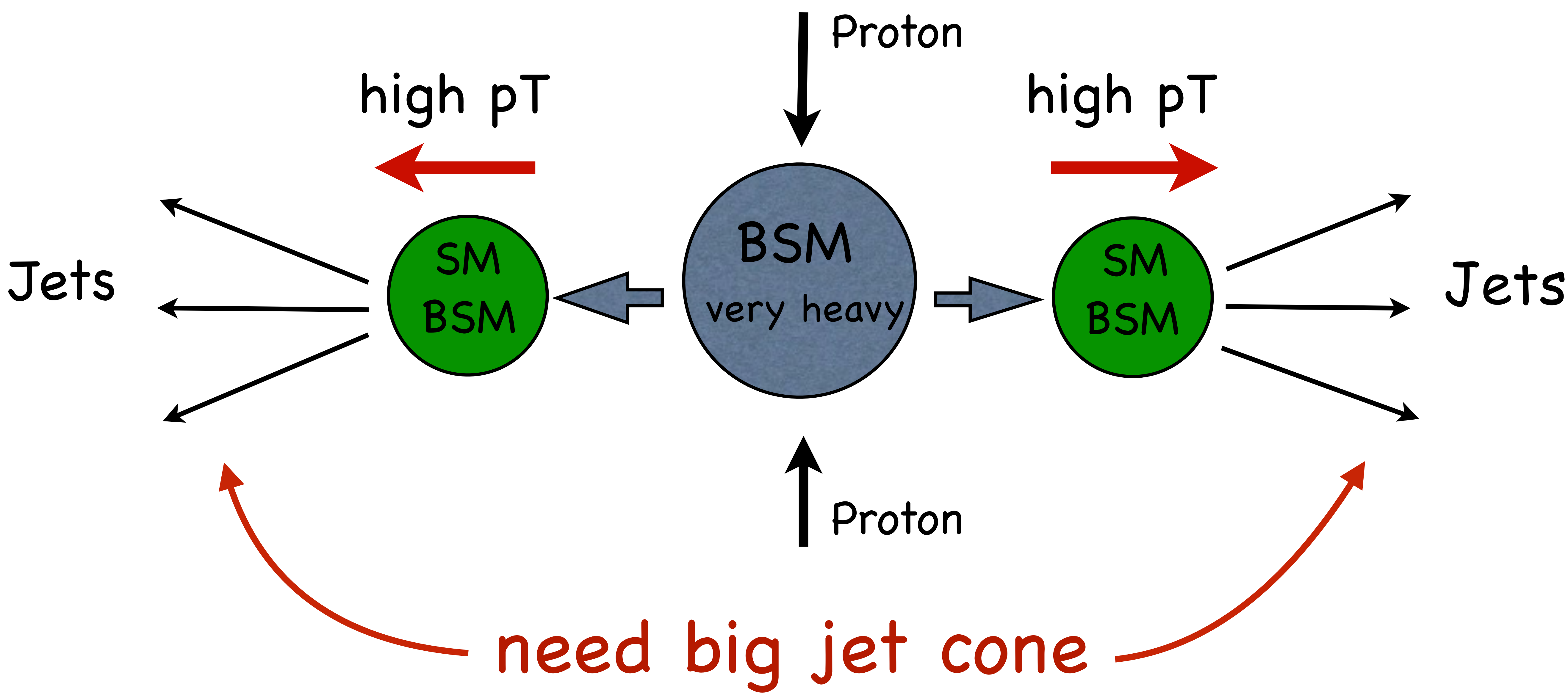
An incomplete list of important searches and measurements:

- Higgs-top coupling
- top-partner searches (stop, vector-like quarks)
- New particles in association with tops
- Resonance searches
- Afb
- Anomalous top couplings and effective operators

Benefit from energetic top quarks

Sensitivity for New Physics kicks in at high energy scales

Generic kinematic in New Physics search

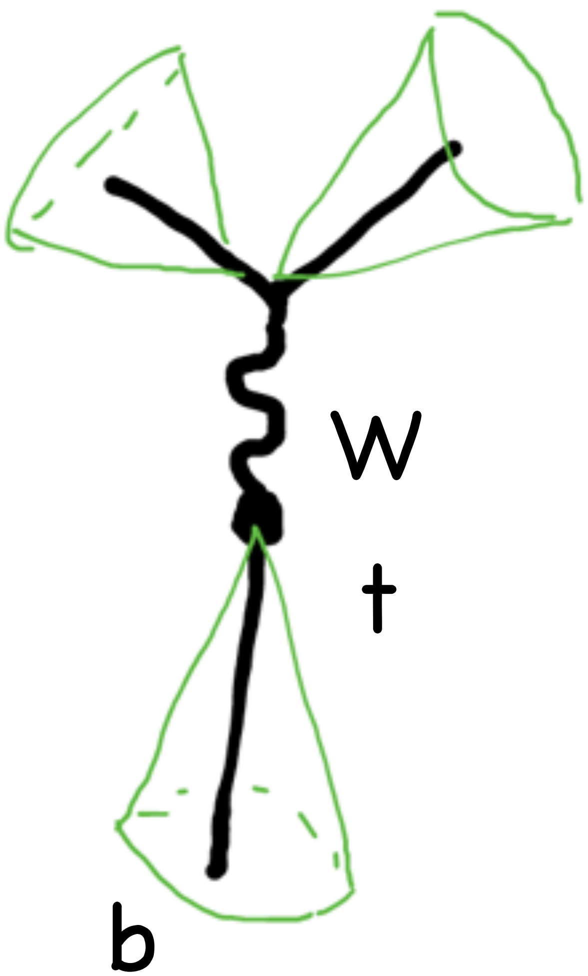


jet substructure =  for resonance properties

Different scenarios based on pT vs mass

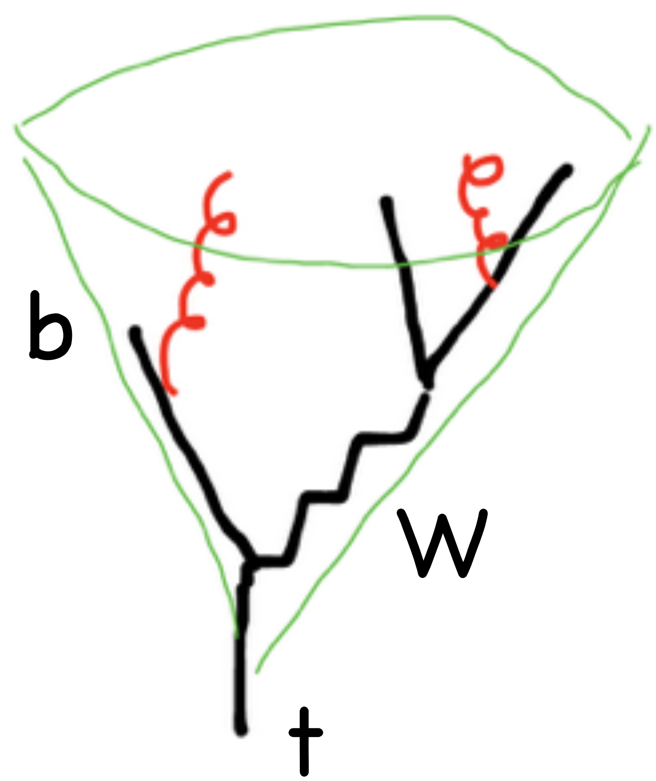
Scenario 1

$$m_{t\bar{t}} \simeq 2\ m_t$$



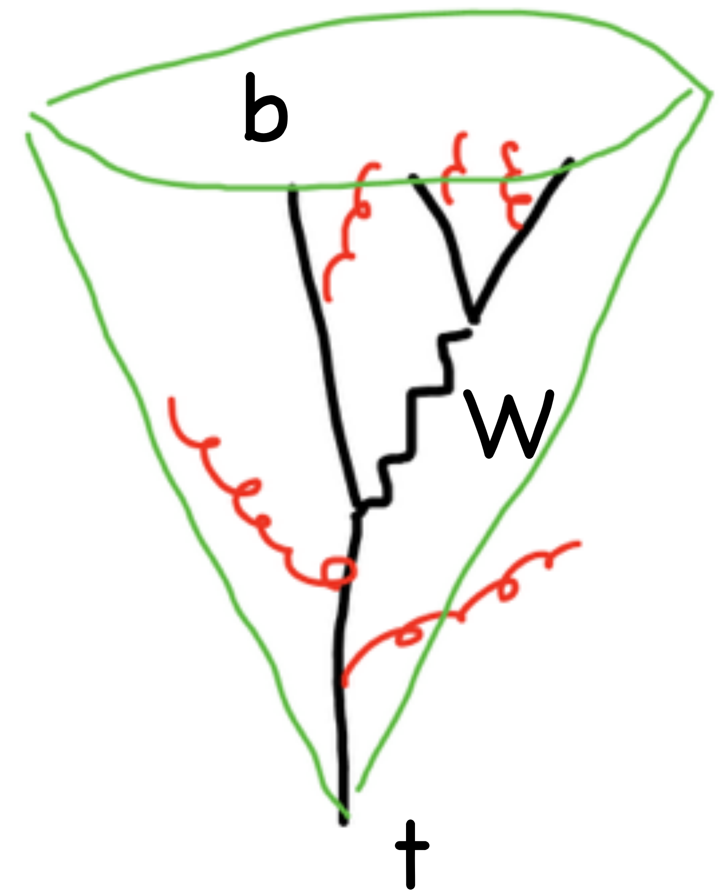
Scenario 2

$$m_{t\bar{t}} > 2\ m_t$$



Scenario 3

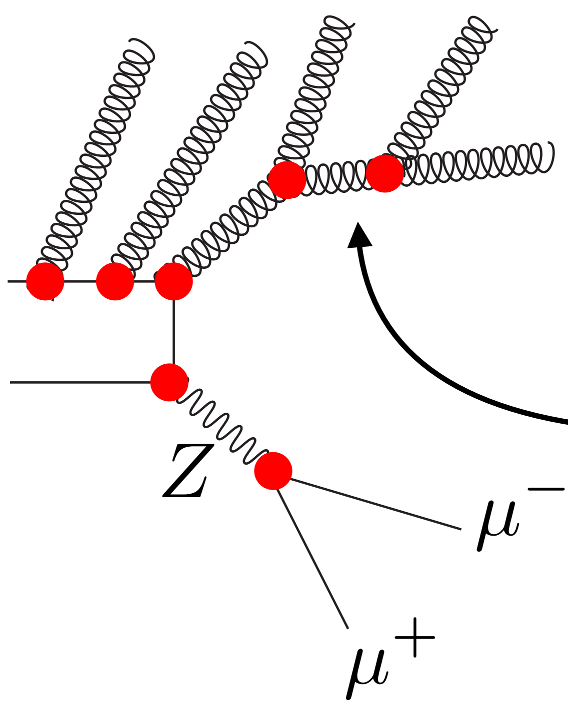
$$m_{t\bar{t}} \gg 2\ m_t$$



Standard reconstruction (templating, MEM, ...) focuses on Scenario 1

Physics cases require Scenarios 2 and 3

The parton shower bridges the gap from the hard interaction scale down to the hadronization scale O(1) GeV



partons from the hard interaction emit other partons (gluons and quarks)

These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

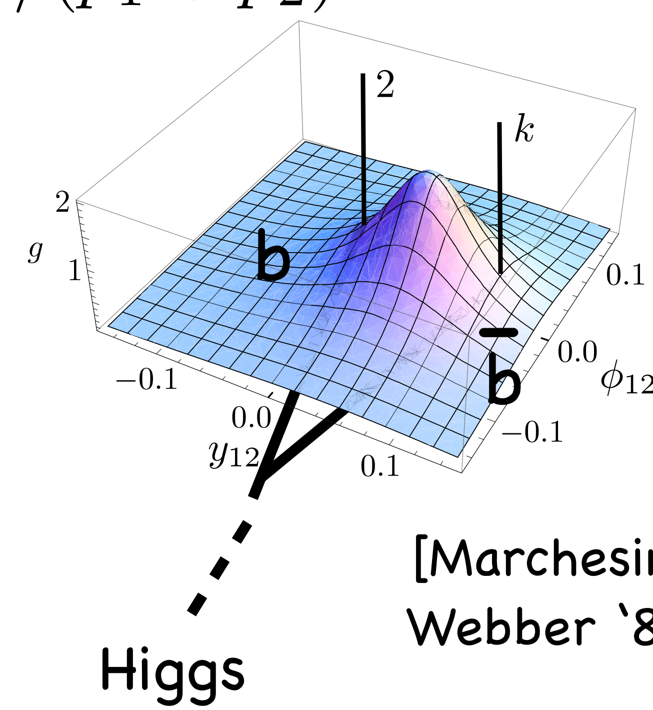
Probability enhanced in soft and collinear region due to ~ $1/(p_1 + p_2)^2$

Collinear limit: $$d\sigma_{ee\to 3j} \approx \sigma_{ee\to 2j} \sum_{j\in\{q,\bar{q}\}} \frac{\alpha_s}{2\pi} \frac{d\theta_{jg}^2}{\theta_{jg}^2} P(z)$$

$e^+e^- \to \bar{q}qg$ factorizes (Eikonal Current)

Soft limit: ↓ dipole

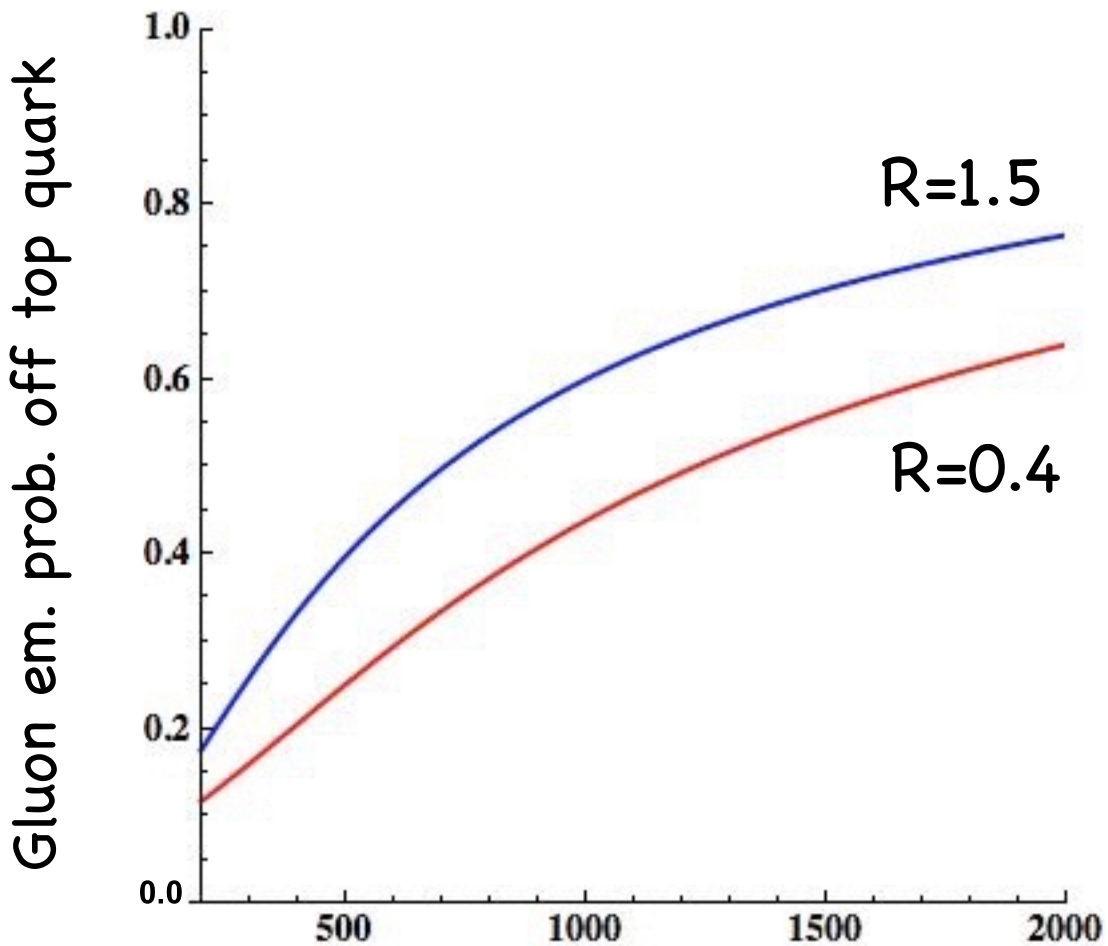
large Nc $$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 g_s^2 C_F \frac{2p_1 \cdot p_2}{p_1 \cdot k \ p_2 \cdot k}$$



[Marchesini, Webber '84]

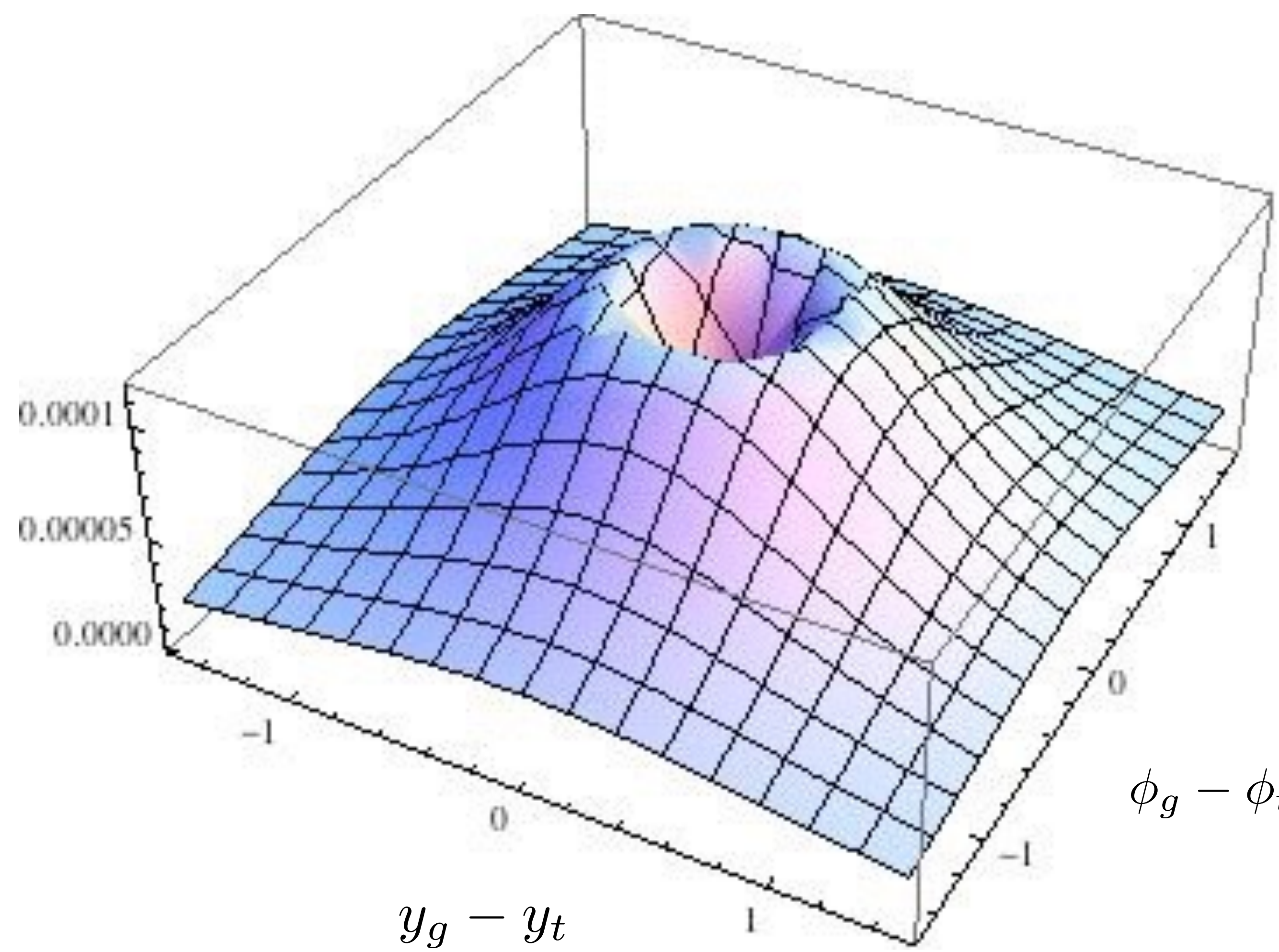
One can be slightly more quantitative...

$$\mathcal{P} = 1 - e^{-S_{ttg}}$$



pT top quark [GeV]

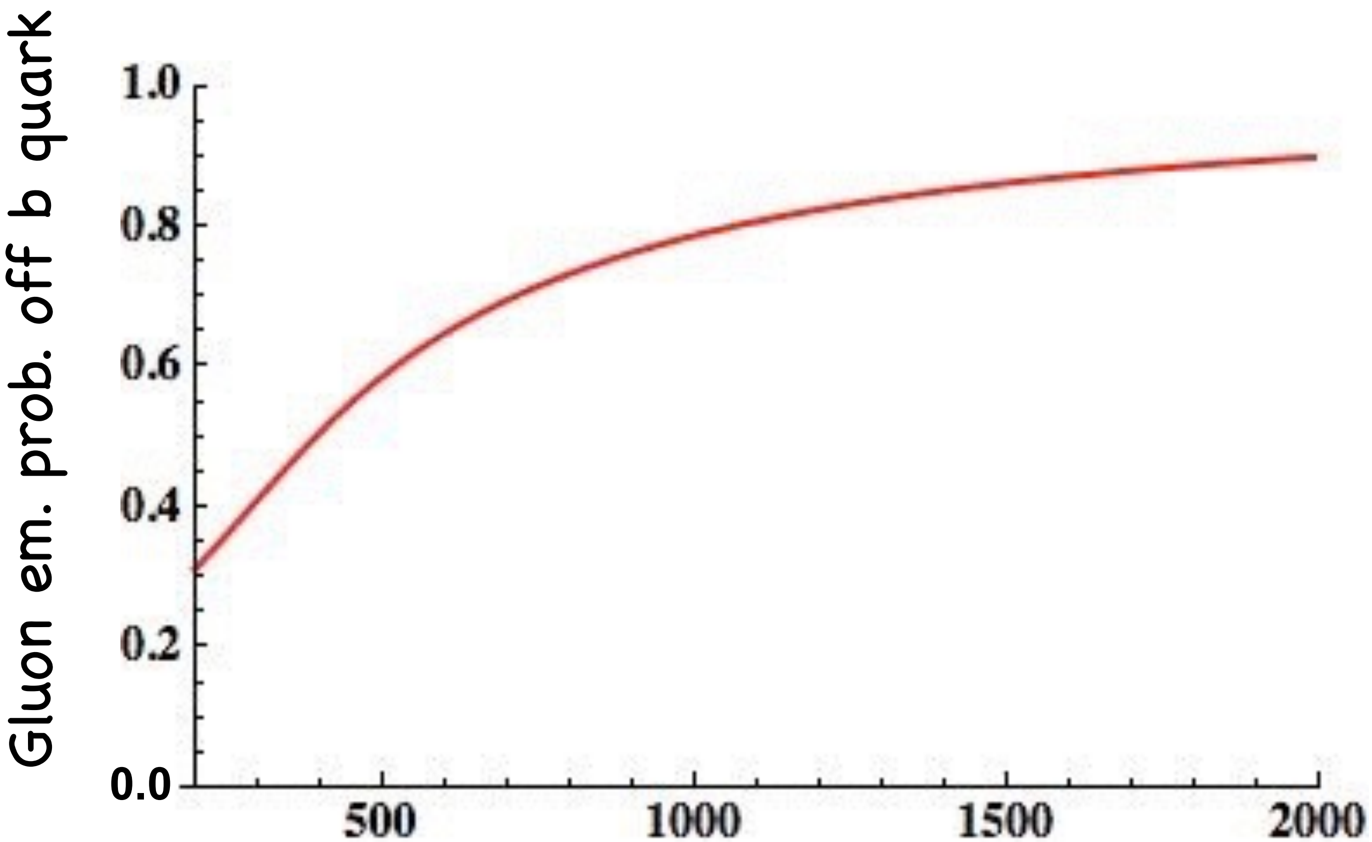
Dead region around top



pT top 500 GeV, pT gluon 20 GeV

Radiation off bottom quark down to hadronization scale

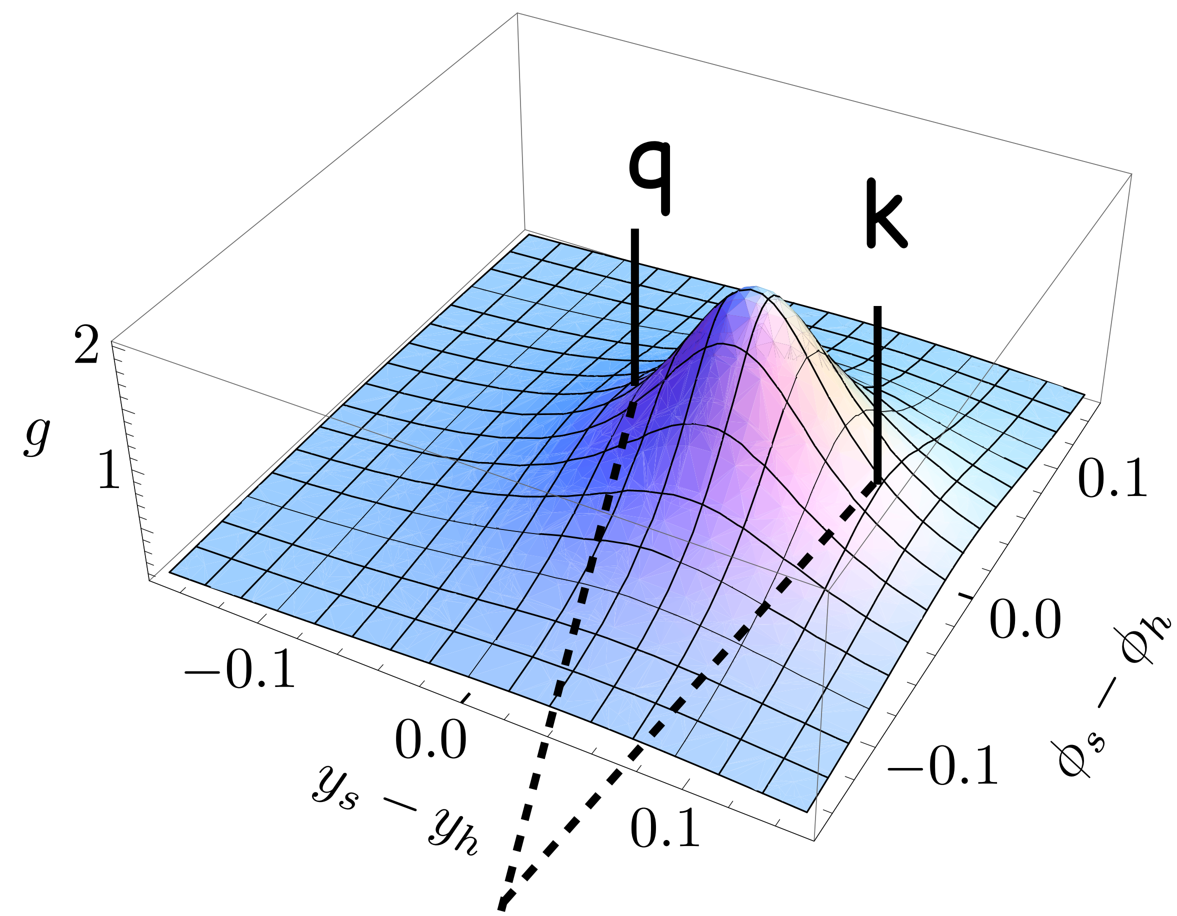
$$\mathcal{P} = 1 - e^{-S_{bbg}}$$



pT top quark [GeV]

pT bottom = pT top / 3

angular distribution for radiation off W decay products



W decay products

However, at the LHC many sources of radiation:

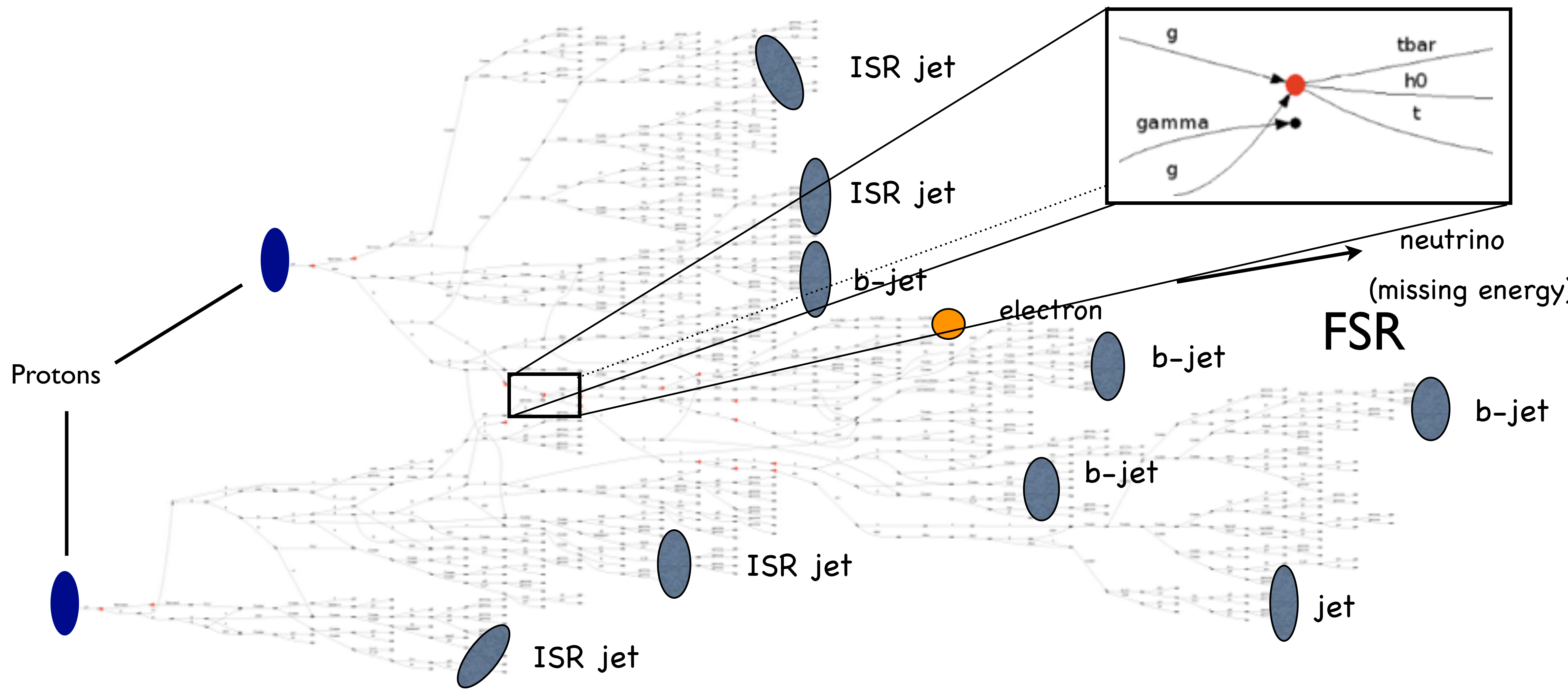
[Cacciari, Salam, Sapeta JHEP 1004]

- **Pileup** → Can add up to 100 GeV of soft radiation per unit rapidity
- **Underlying Event** → $\langle \delta m_j^2 \rangle \simeq \Lambda_{\rm UE}\, p_{T,j} \left(\frac{R^4}{4} + \frac{R^8}{4608} + \mathcal{O}(R^{12}) \right)$ with $\Lambda_{\rm UE} \sim \mathcal{O}(10)$ GeV

[Dasgupta, Magnea, Salam JHEP 0802]

- **Initial state radiation (ISR)**
- **Hard radiation from many resonances in event**

→ Jet mass and internal structure will be affected by these sources



"Mano sinistra e destra del diavolo"

Groomers clean up jet from soft uncorrelated radiation

reduce active area of jet

↕

reduce sensitivity to pileup/UE

Taggers aim to identify objects based on their properties

Quantum numbers

↕

Radiation profile

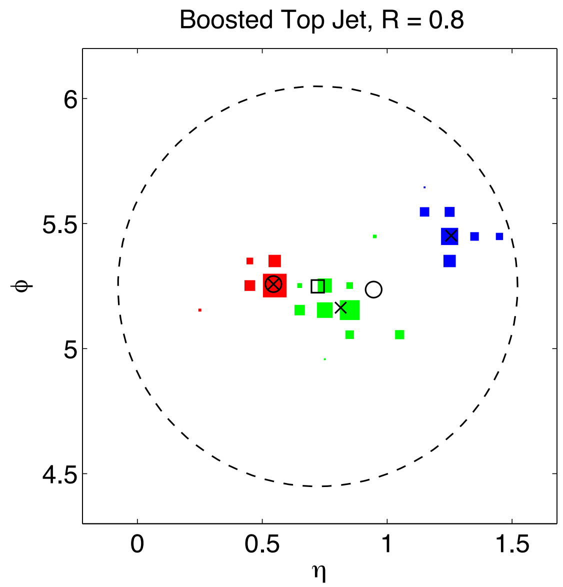
Jet grooming procedures	Filtering	[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]
	Pruning	[Ellis, Vermilion, Walsh PRD 80 (2009)]
	Trimming	[Krohn, Thaler, Wang JHEP 1002 (2010)]
2-pronged resonances	Mass-drop/Filtering and variations	[Butterworth, Davison, Rubin, Salam PRL 100 (2008)] [Plehn, Salam, MS PRL 104 (2010), Kribs, Martin, Roy, MS PRD 81 (2010)]
3-pronged resonances	y-splitter Top Tagger	[Butterworth, Cox, Forshaw PRD 55 (2002)] [Broijmans ATL-COM-PHYS-2008-001]
	energy flow	[Thaler, Wang JHEP 0807]
	Johns Hopkins Tagger	[Kaplan, et al. PRL 101 (2008)]
	HEP Top Tagger	[Plehn, MS, Takeushi, Zerwas JHEP 1010]
	tree-less approach	[Jankowiak, Larkoski JHEP 1106]
General methods	Template method	[Almeida et al. PRD 82 (2010)]
	N-subjettiness	[Kim PRD 83 (2011)] [Thaler, Van Tilburg JHEP 1103]
	Multi-variate (BDT, NN)	[Gallicchio et al. JHEP 1104] [Almeida et al. JHEP 1507]
	Shower deconstruction	[Soper, MS PRD 84 (2011)] [Soper, MS PRD 87 (2013)]

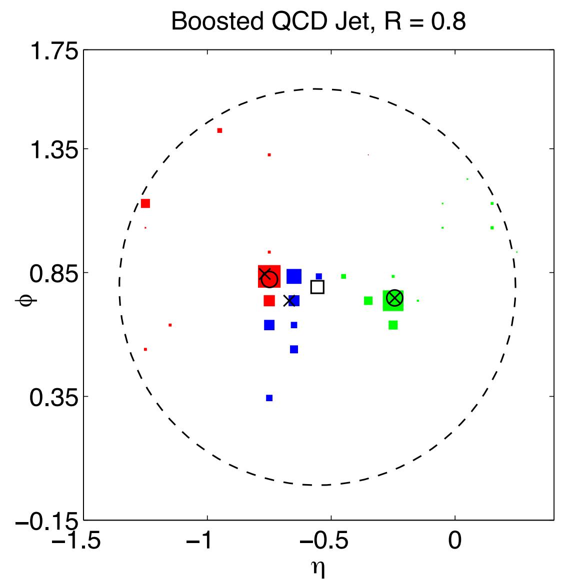
Jet-shape tagger: N-subjettiness

Degree to which a jet has N subjets

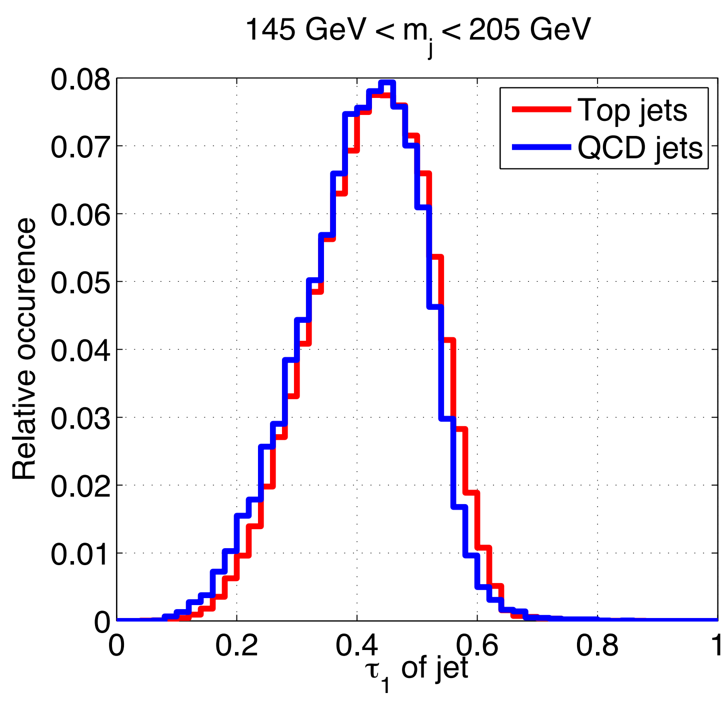
[Kim PRD 83 (2011)] [Thaler, Van Tilburg JHEP 1103] [Thaler, Van Tilburg JHEP 1202]

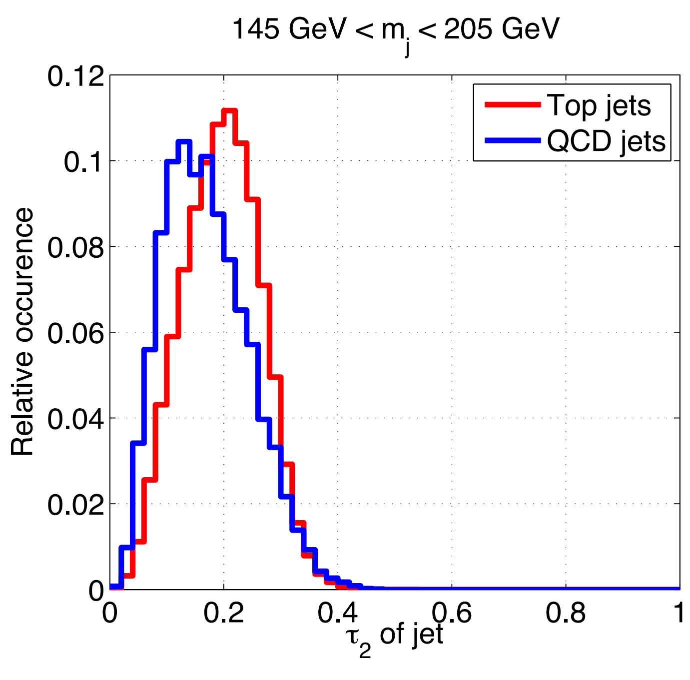
Top tagging by eye:

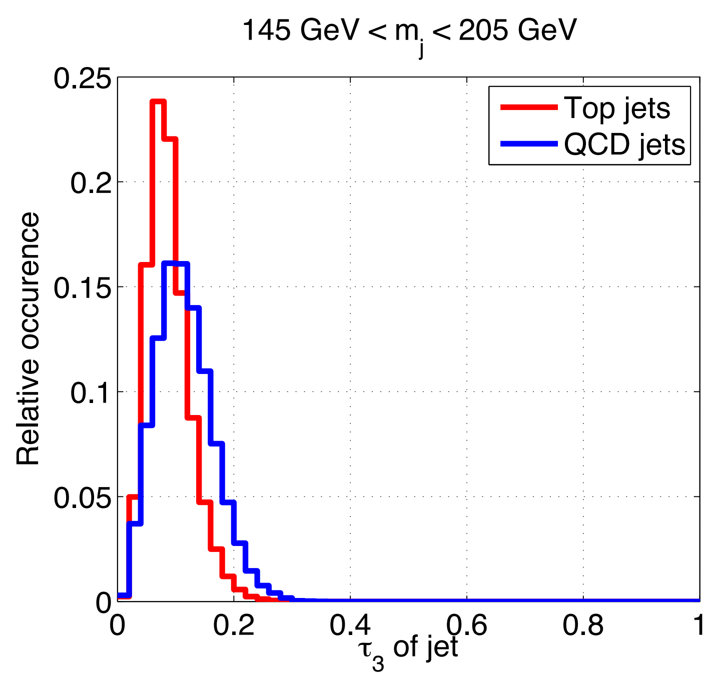




τ_1, τ_2 and τ_3 no good discriminators:

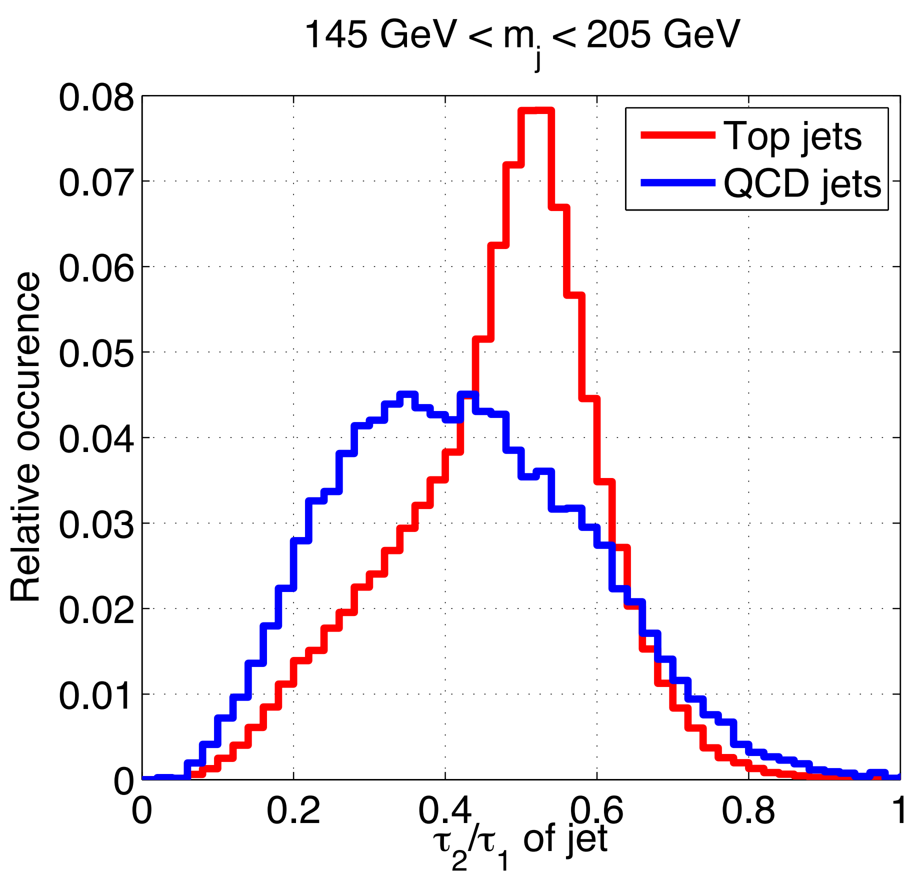


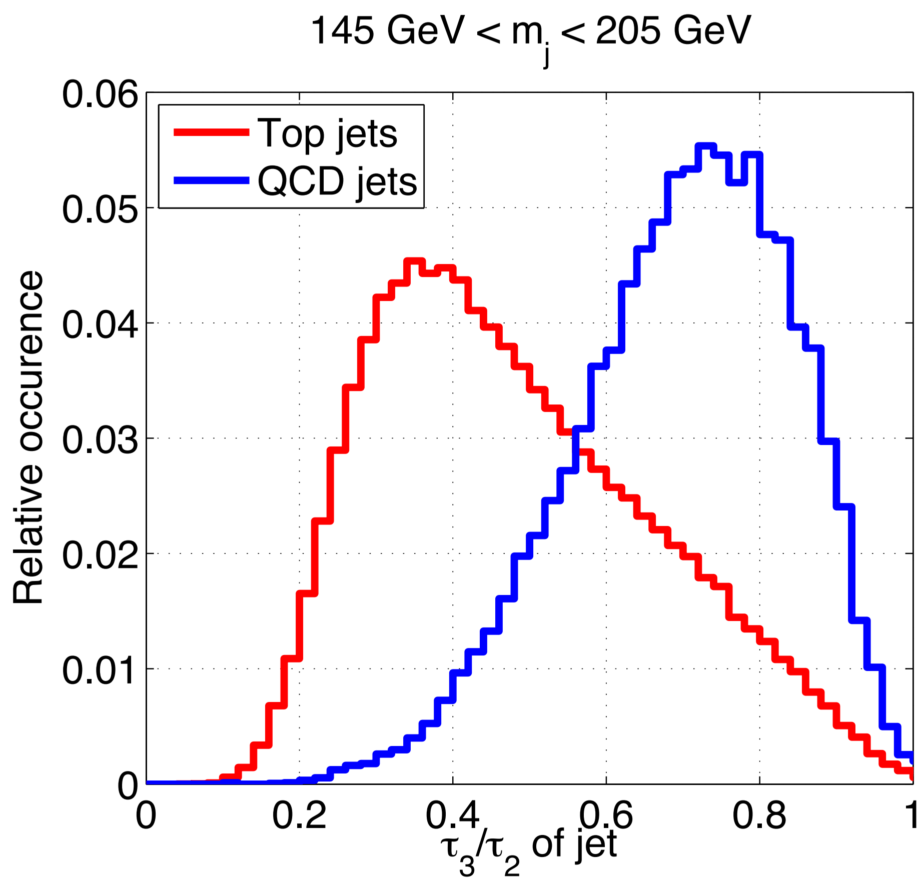




N-subjettiness: Degree to which a jet has N subjets

However, ratio of taus is good discriminator:





- τ_3/τ_2 is best discriminator for boosted tops
- In ratio effects from soft/uncorrelated radiation cancel

Mass-drop Tagger: HEPTopTagger

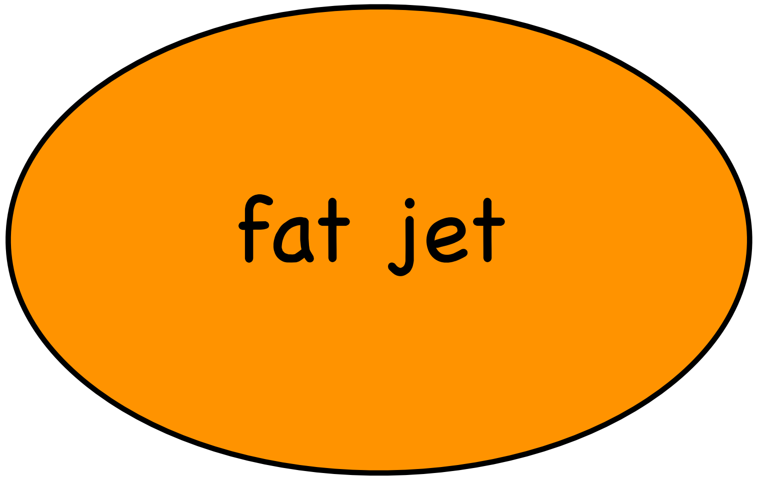
[Plehn, Salam, MS '09]

[Plehn, MS, Takeuchi, Zerwas '10]

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

II. Find hard substructure using mass drop criterion

Undo clustering, $m_{\mathrm{daughter}_1} < 0.8\, m_{\mathrm{mother}}$ to keep both daughters



How does the HEPTopTagger work?

I. Find fat jets (C/A, R=1.5, pT>200 GeV)

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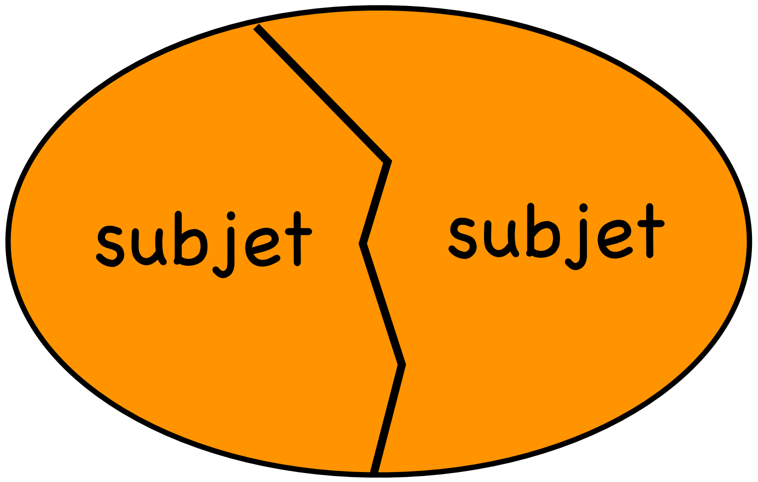

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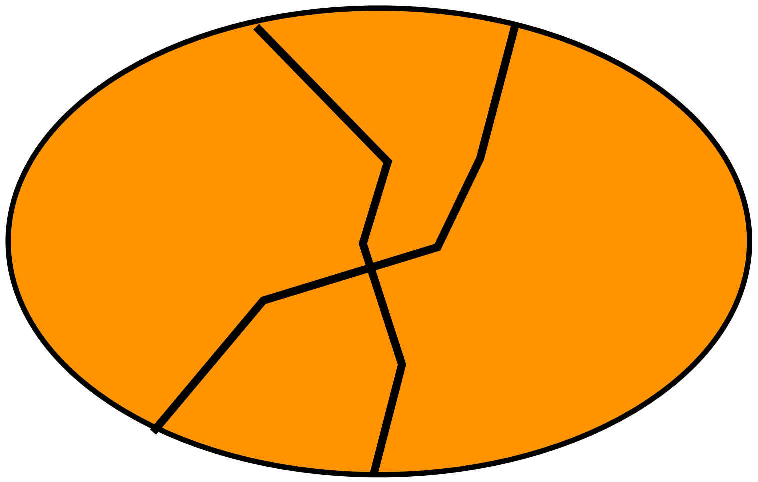

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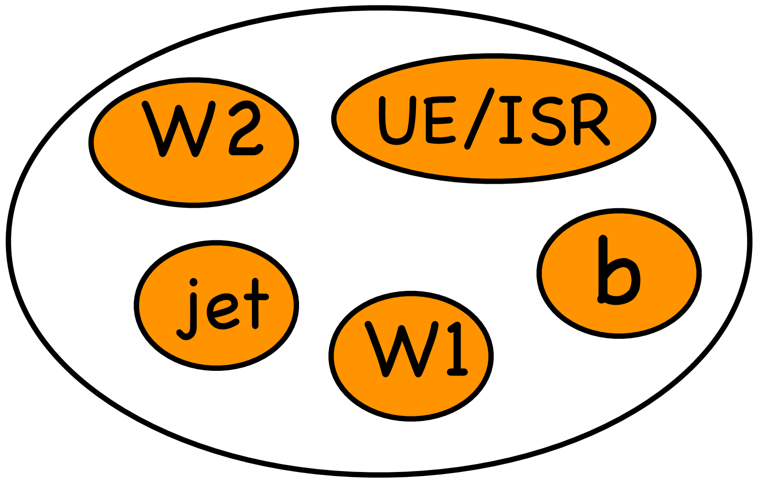

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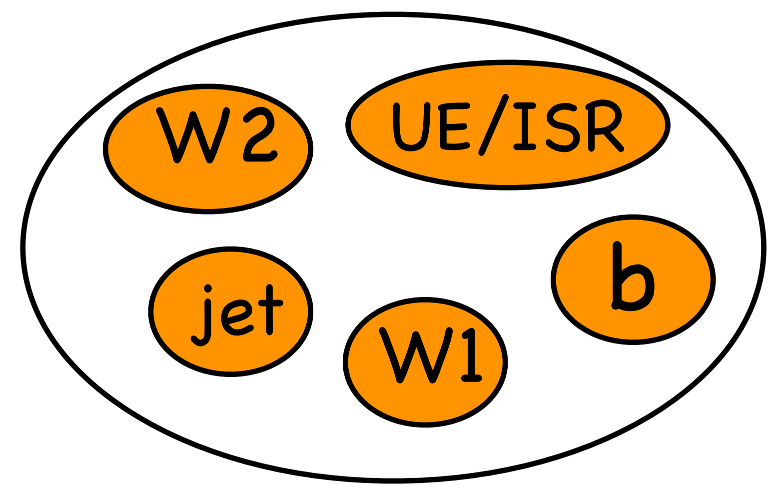
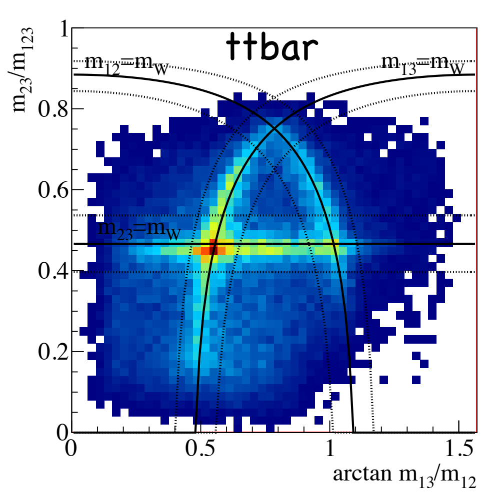
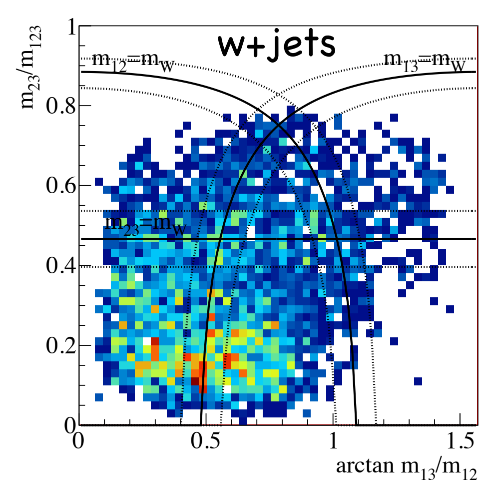
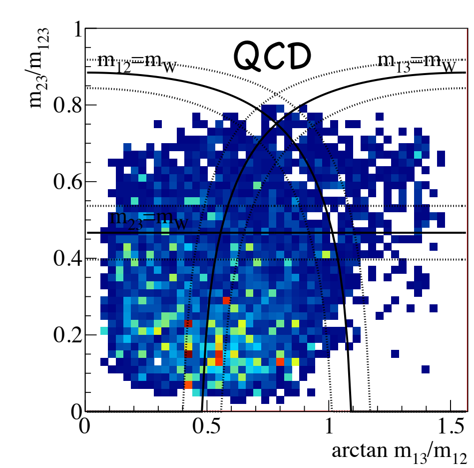


IV. Choose pairing based on kinematic correlation, e.g. top mass, W mass and invariant subjet masses

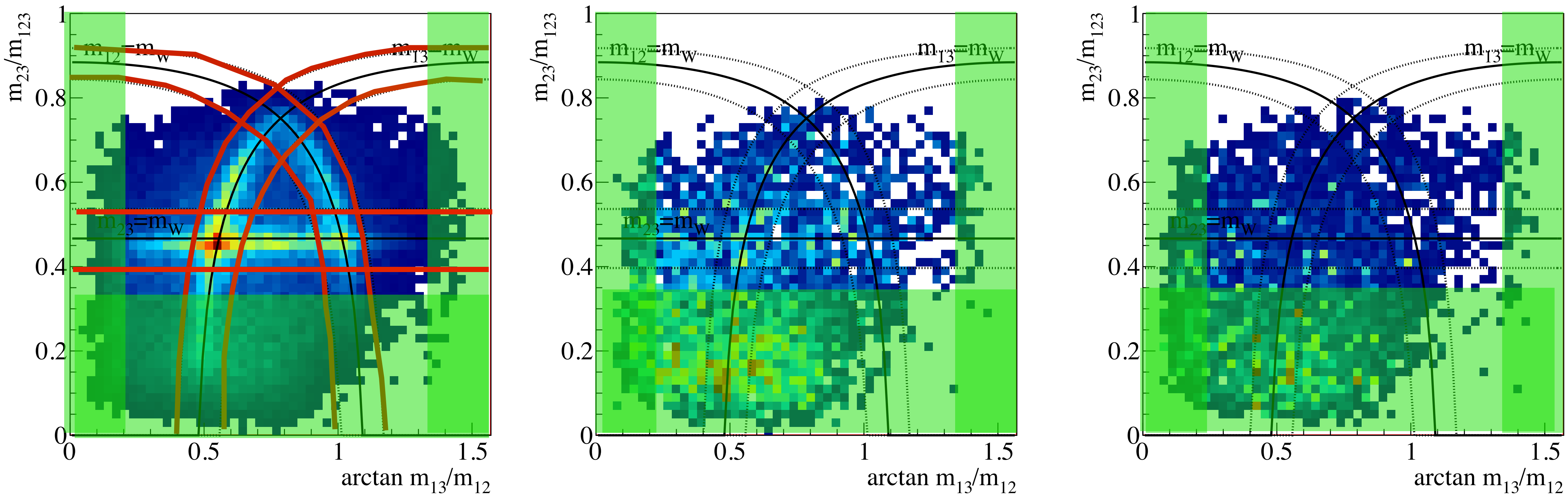






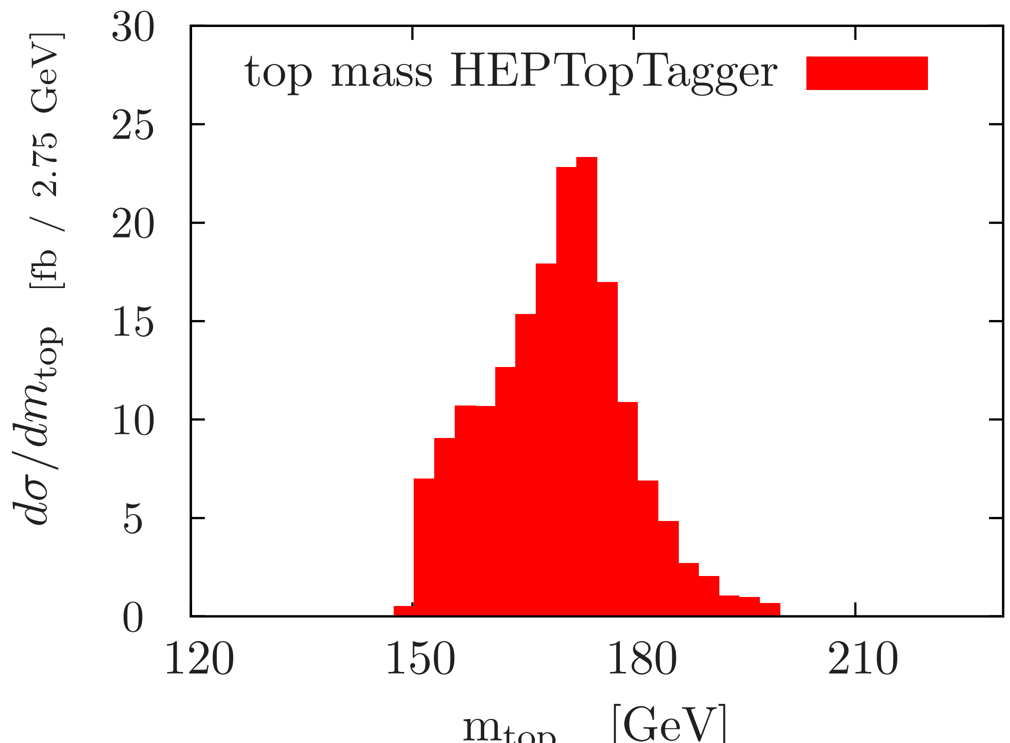
IV. check mass ratios

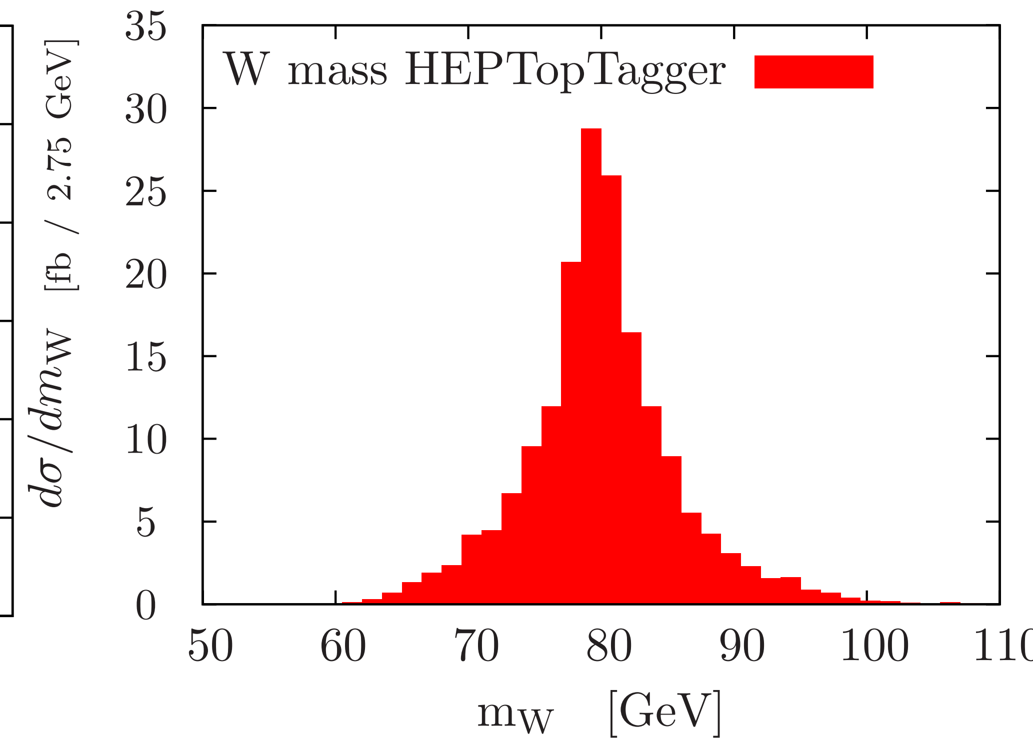
Cluster top candidate into 3 subjets j_1, j_2, j_3



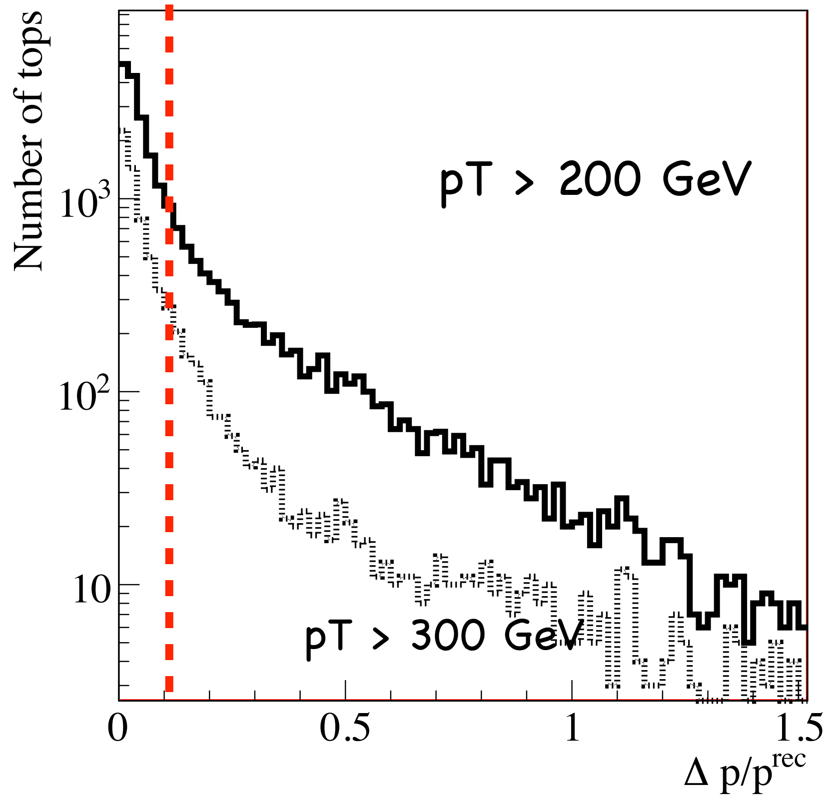
No fix pairing for W mass reconstruction

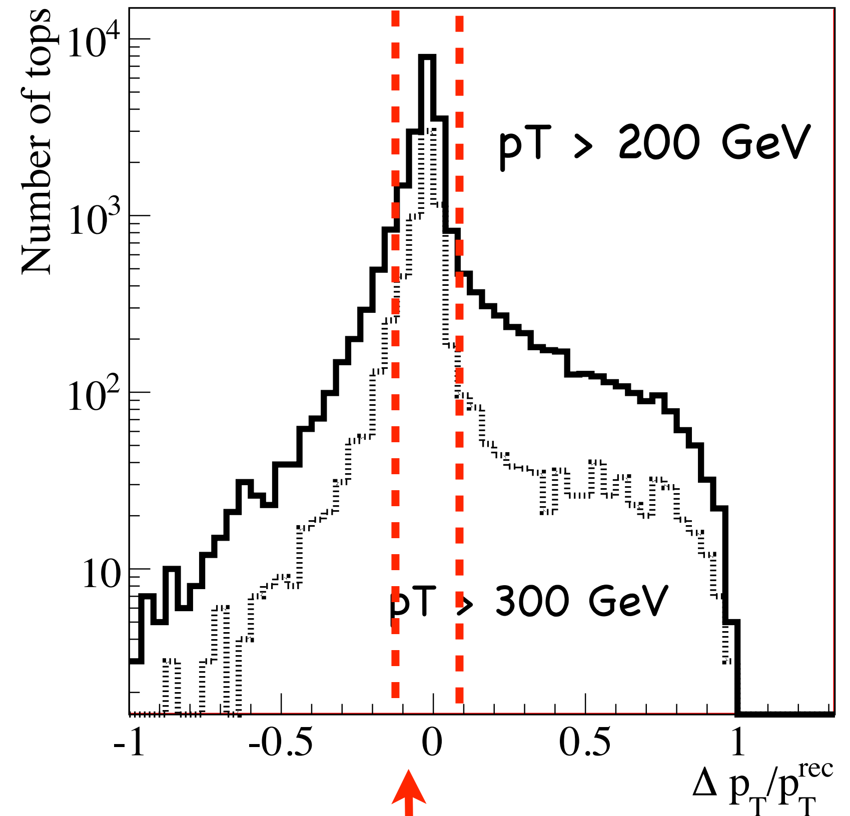
Only invariants for reconstruction

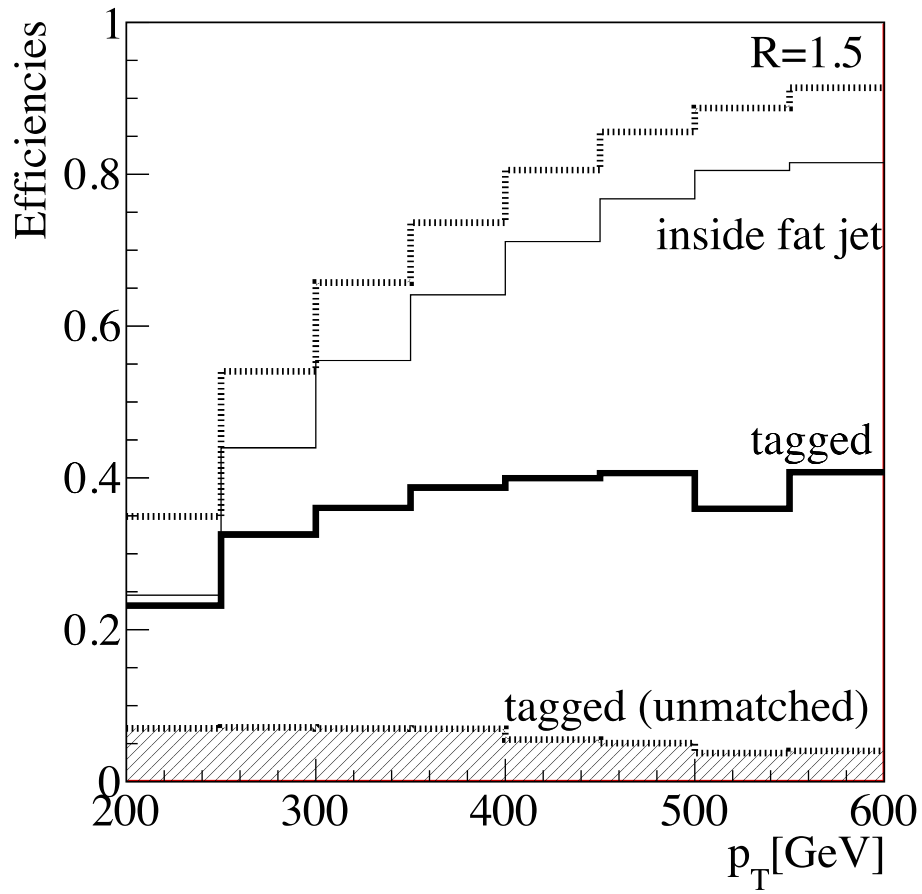




Top quark momentum reconstruction







- Great reconstruction of top quark momentum
- 35% tagging efficiency
  2% W+jets fake rate

All taggers are trying to access the matrix element as directly as possible, so why not calculate the matrix element weight directly for given final state?

[Soper, MS `11]
[Soper, MS `12]

Idea of **Shower Deconstruction**:

Calculate analytically the perturbative part,
fit to data the non-perturbative (universal) part

Shower Deconstruction

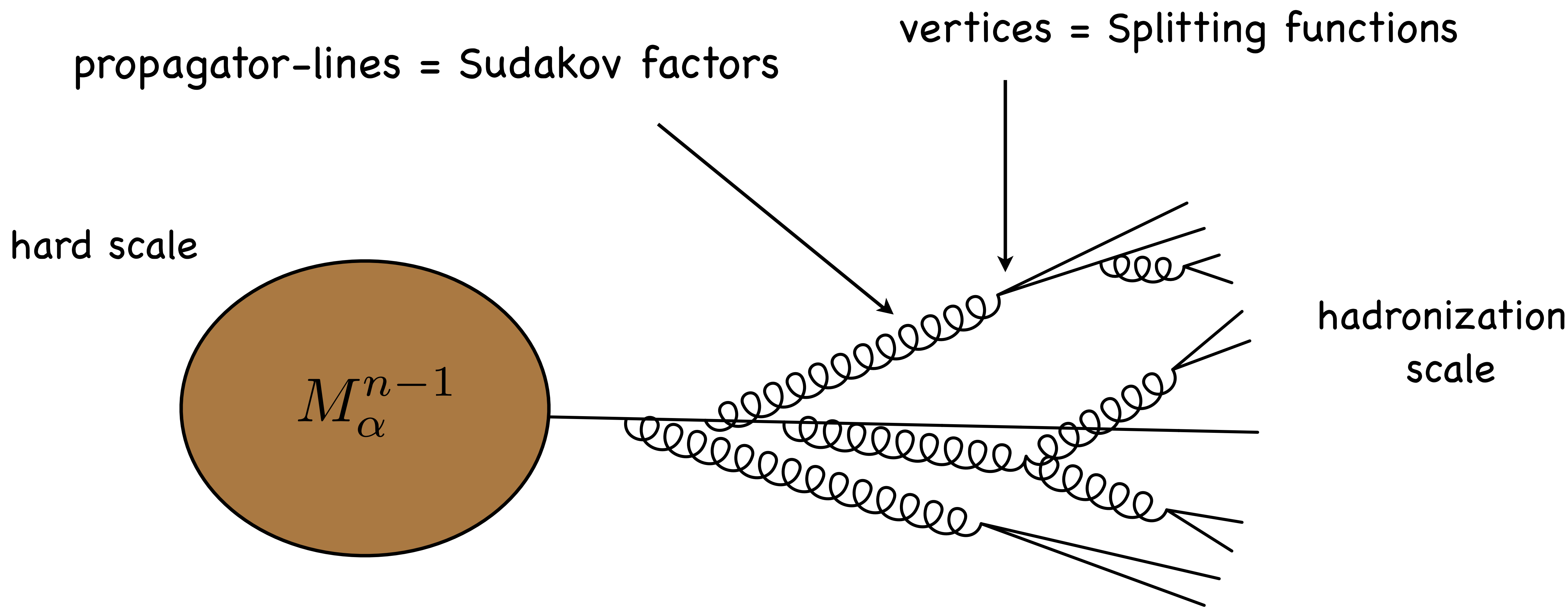
=

Matrix Element method for (many) small objects

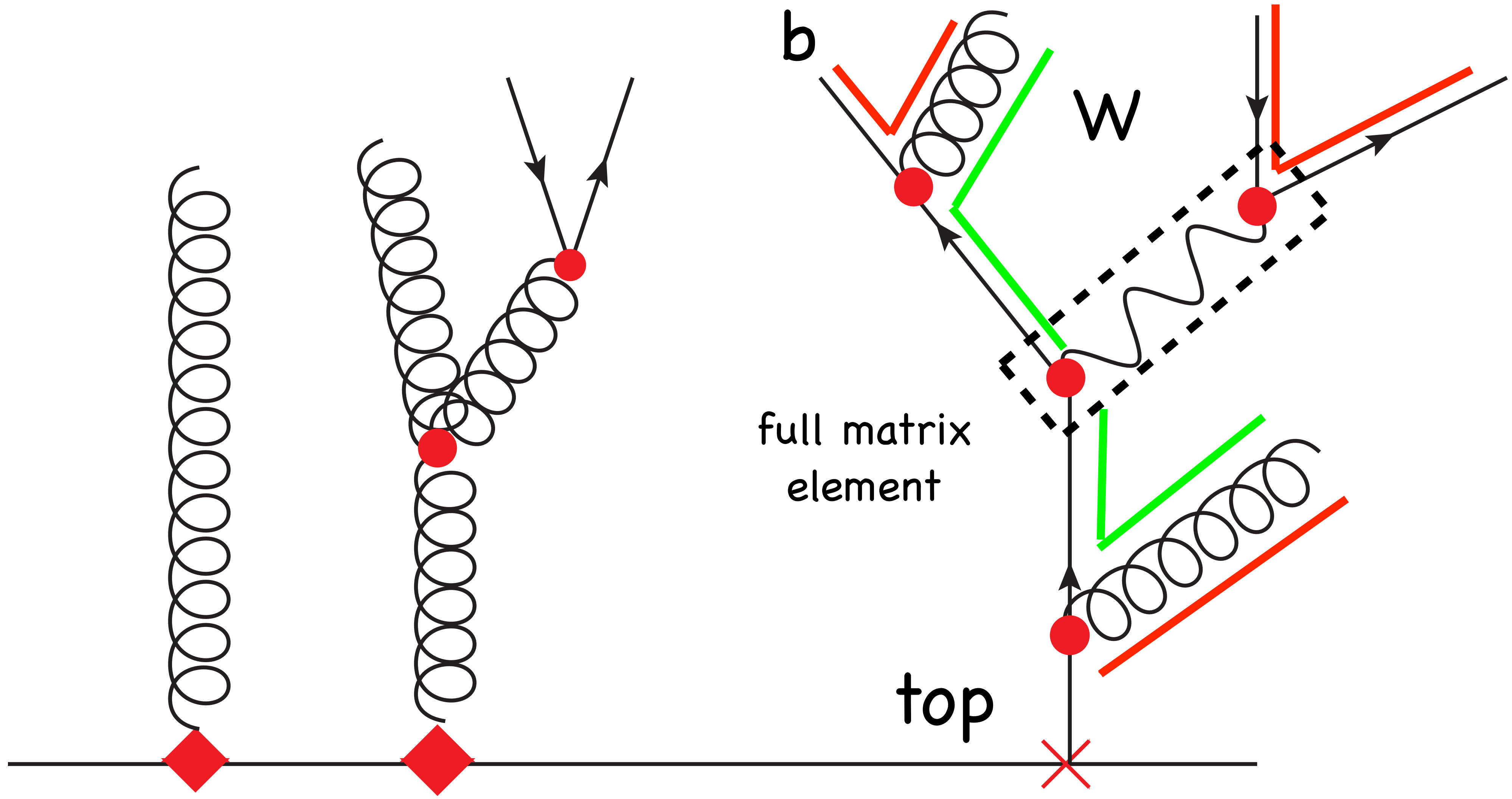
Summary of Method:

Perform resummation calculation to discriminate between signal and background

The probability weights in the evolution from the hard interaction scale to the hadronization scale are given by Sudakov factors and splitting functions.



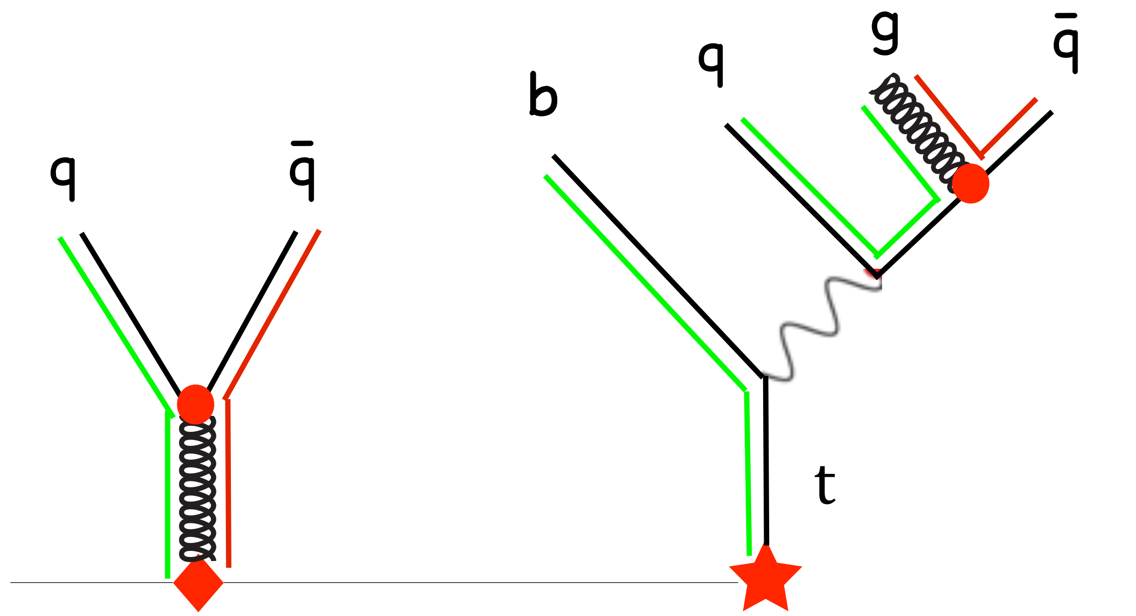
Example: Top decay

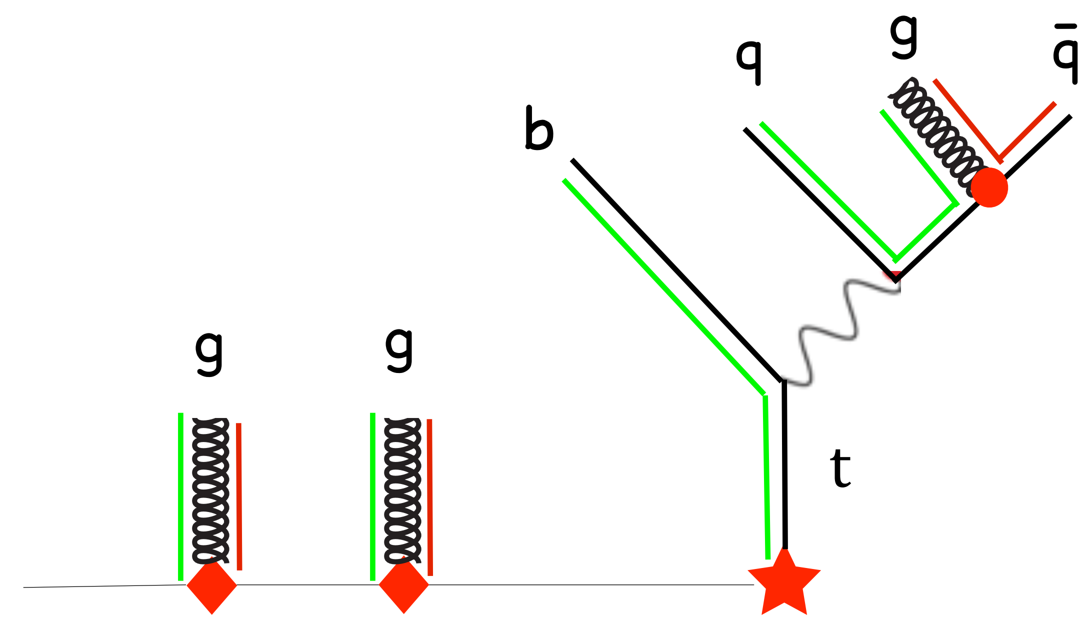


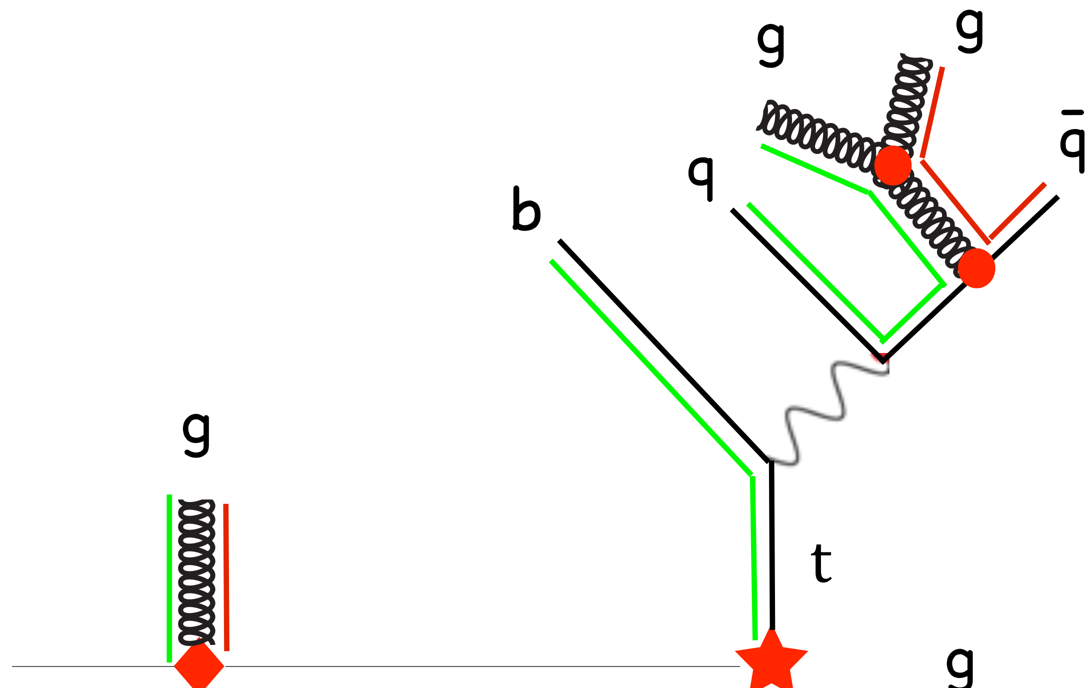
Conceptional difference compared to Higgs from last year:

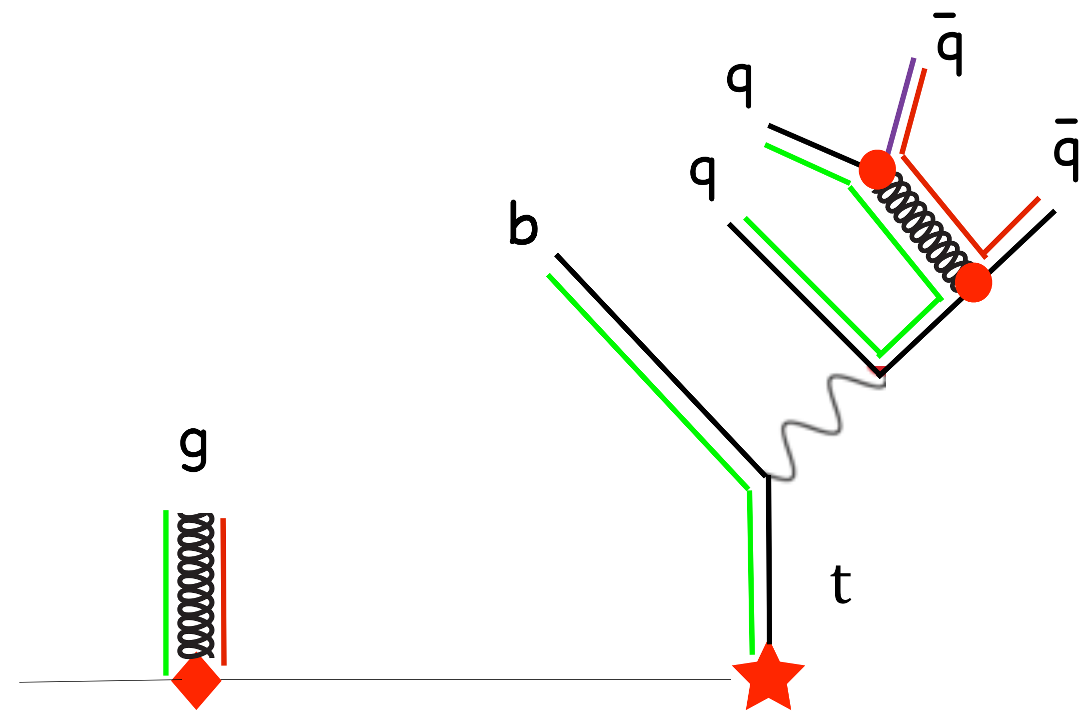
- Splitting functions for massive emitter and spectator
- Full matrix element for top decay

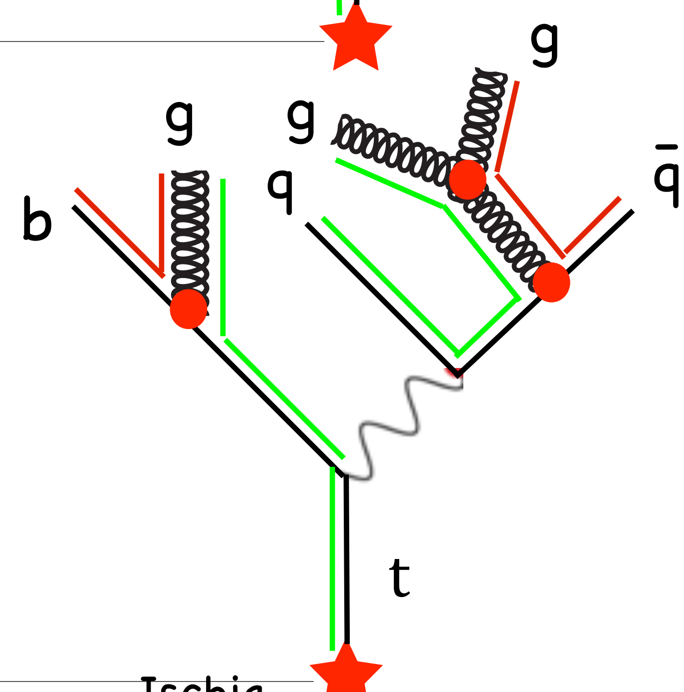
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} |\mathcal{M}|^2 H_{\text{top}} e^{-S_{t_1}} H^s_{tg} e^{-S_g} \ldots}{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} H^b_g e^{S_g} H_{ggg} \cdots}$$





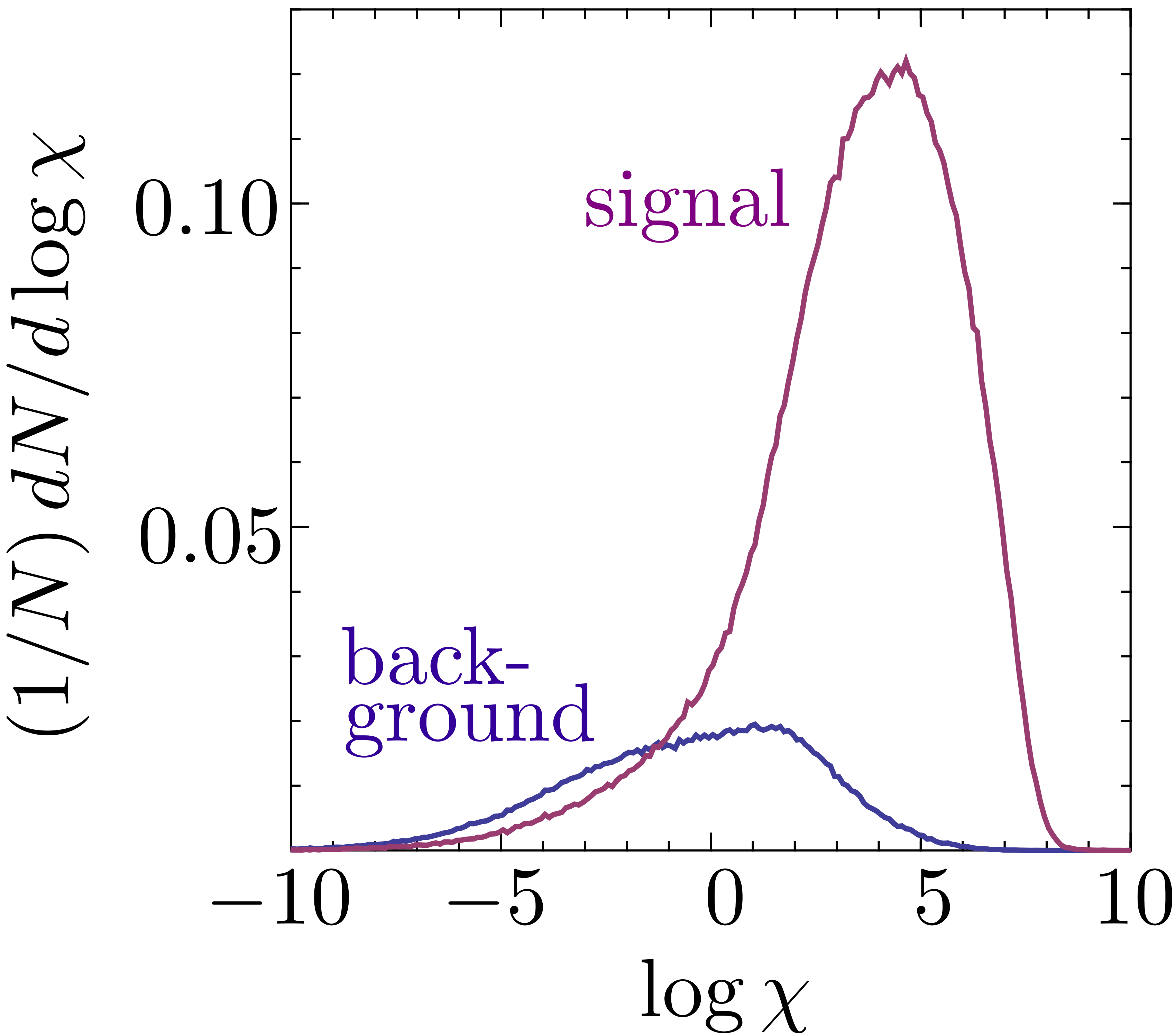


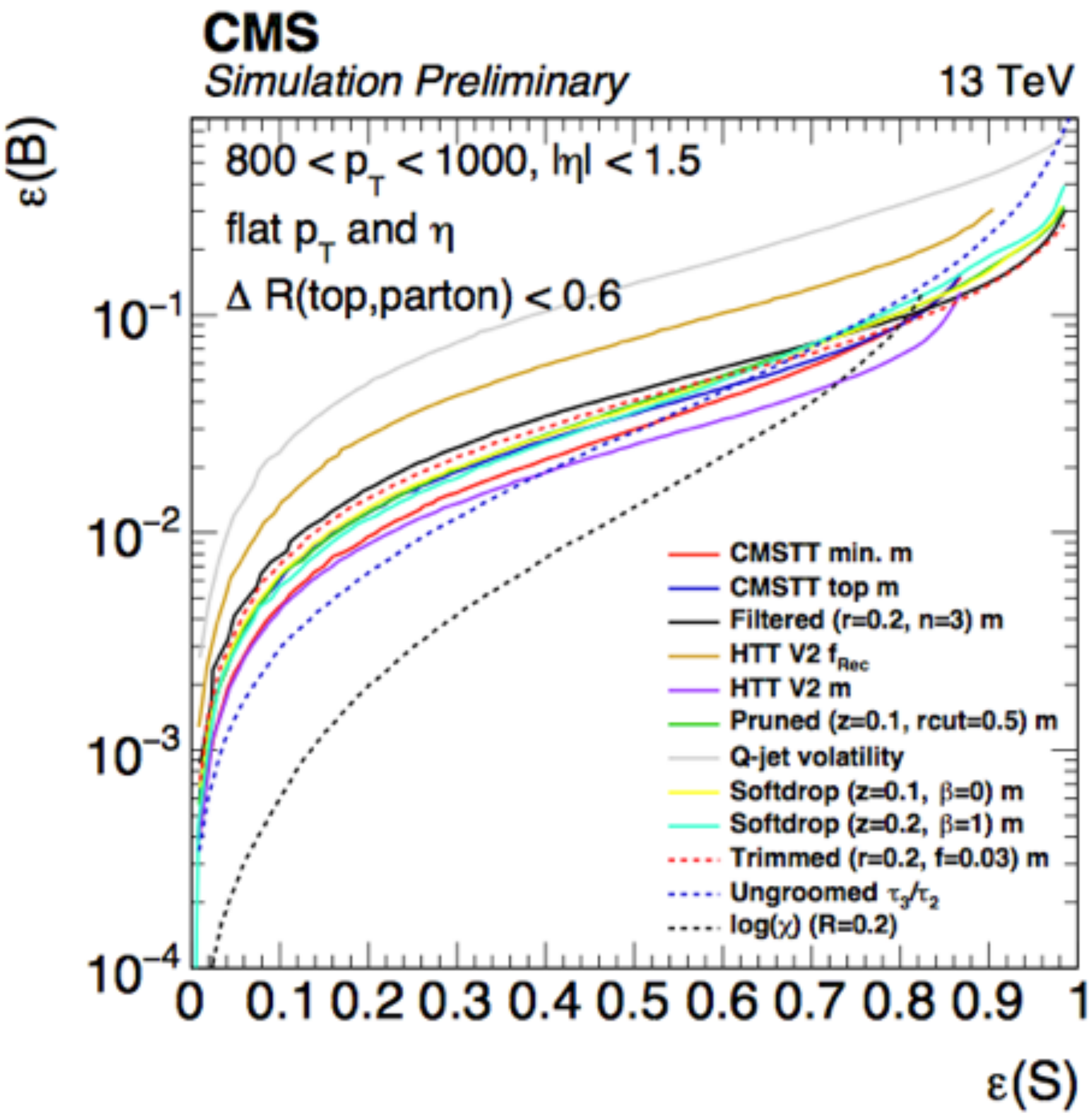


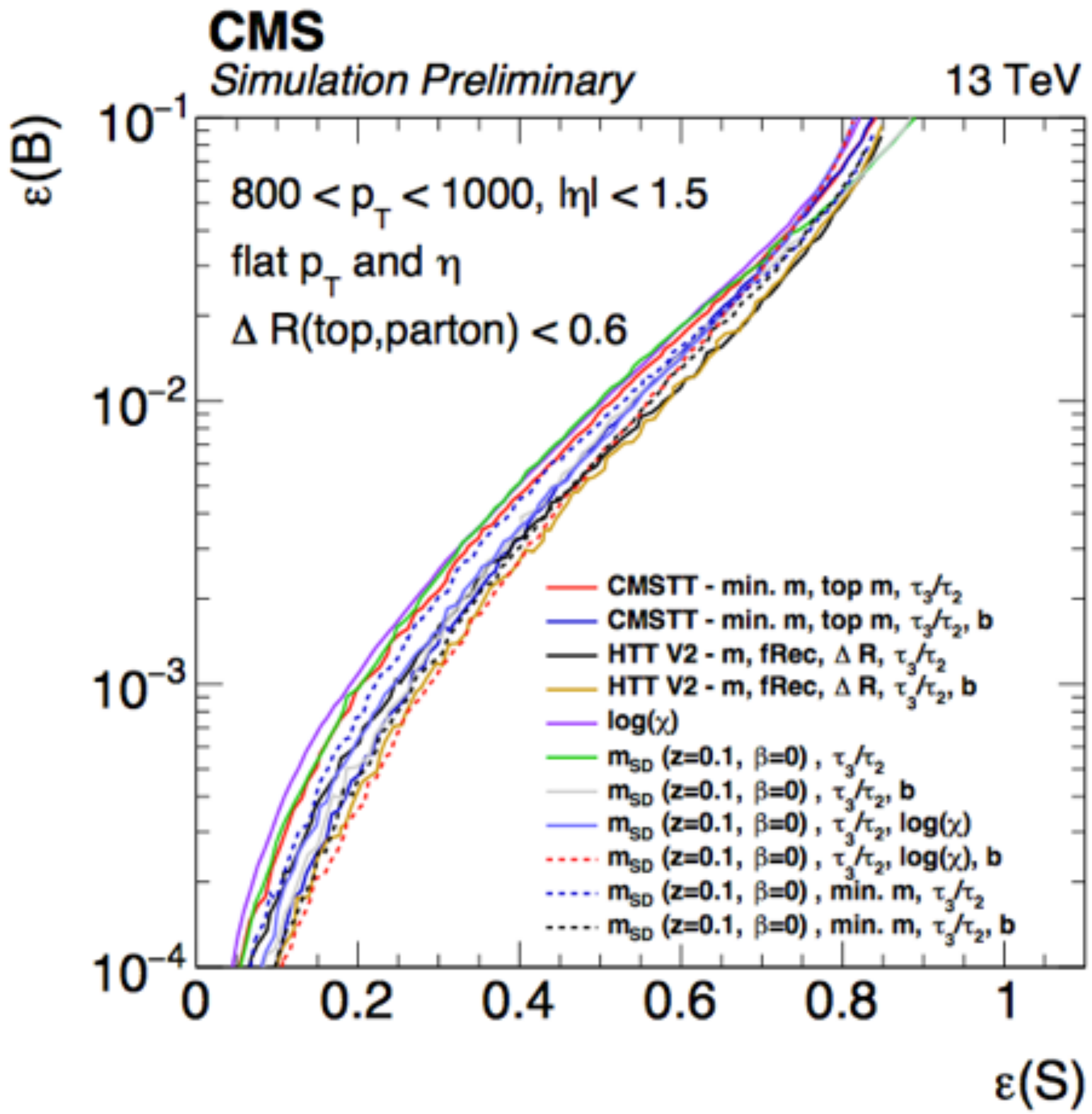


- And many more...
- And for all backgrounds...

χ distribution for top vs QCD







Shower Deconstruction best single discriminative observable,
but when different methods combined same information can be accessed

Reconstructing highly boosted tops

- LHC and beyond -

[Katz, Son, Tweedie '10]

[Schaetzel MS '13]

[Larkoski, Maltoni, Selvaggi '15]

[MS, Stoll '15]

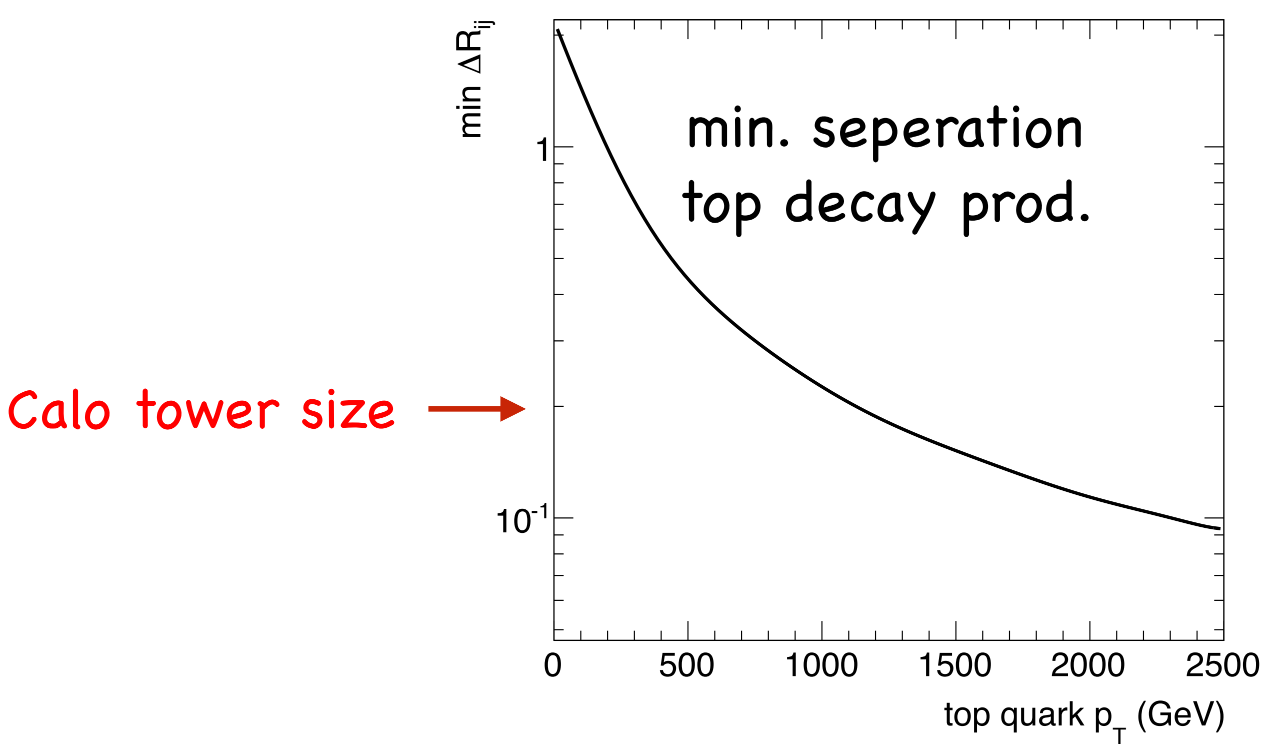
[Bressler, Flacke, Kats, Lee, Perez '15]

We want to search for very heavy resonances, e.g. Z' with 5 TeV

→ Have to reconstruct tops with $p_{T,t} \geq 2$ TeV

Such tops decays cannot be resolved by Hcal

Issue with granularity unavoidable 13/14 or 100 TeV



Energy of jet: 60% charged particles

25% photons (mostly π^0)

15% neutral hadrons

→ $85\% \pm 15\%$ energy in Tracker and Ecal

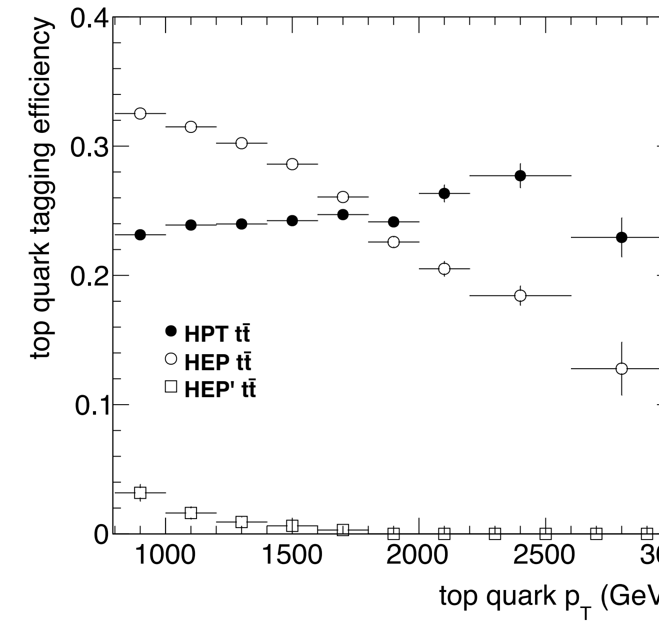
When the calorimeter is just not enough: Tracks-only HPTTopTagger

[MS, Stoll '15]

Idea:

[Schaetzel, MS PRD 89 (2014)]

- Perform top tagging based on tracks only
- Do local recalibration -> stretch track. mom by $\alpha_j = \frac{E_{\rm jet}}{E_{\rm tracks}}$
- Run High-pT TopTagger
- W/Z/top tagger available at https://www.ippp.dur.ac.uk/~mspannow/webippp/HPTTaggers.html



Problem: [Bressler, Flacke, Kats, Lee, Perez '15]

- jet-energy rescaling does not protect from subjet fluctuations

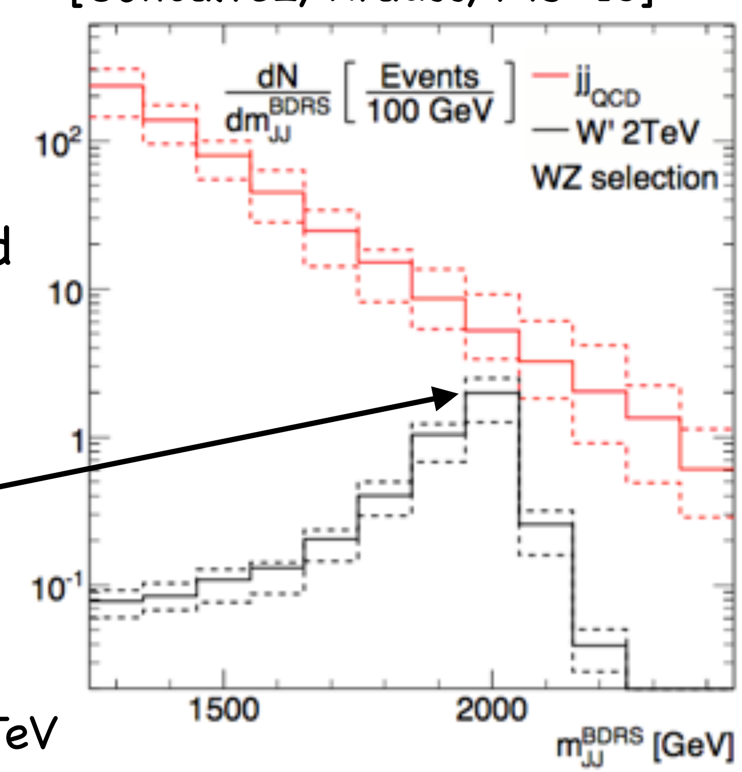
$$R_{\rm subjet} = (3/4)\, m_W/p_T\,, \text{40\% larger}$$

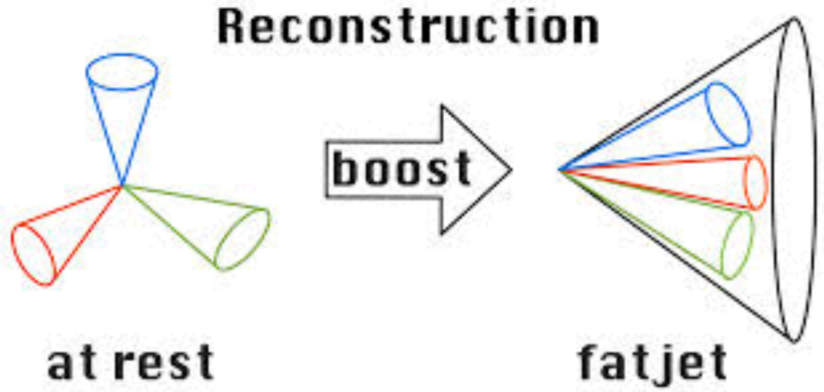
- jet (not subjet) correction applied using α_j leaves reconstructed MW to fluctuate by O(25)%
- Mass not so different from y-cut in BDRS reconstruction used in current ATLAS excess:

$$y = \min(p_{T,j_1}, p_{T,j_2}) \frac{\Delta R_{(j_1,j_2)}}{m_{j_1+j_2}} \geq y_f$$

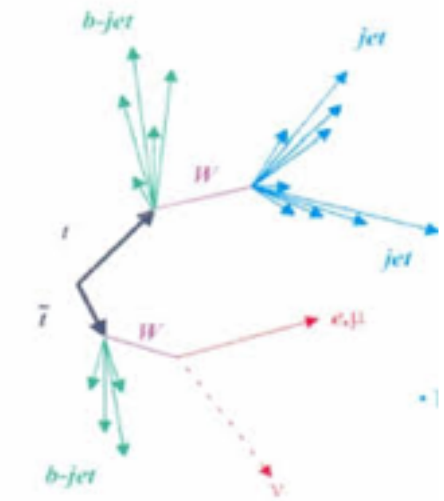
ΔR -dependent ycut uncertainty increases tail at ~ 2 TeV

[Goncalvez, Krauss, MS '15]





Summary



Top physics at core of upcoming LHC program

Many reconstruction approaches of top

The boosted regime is of particular importance

jet substructure not optional

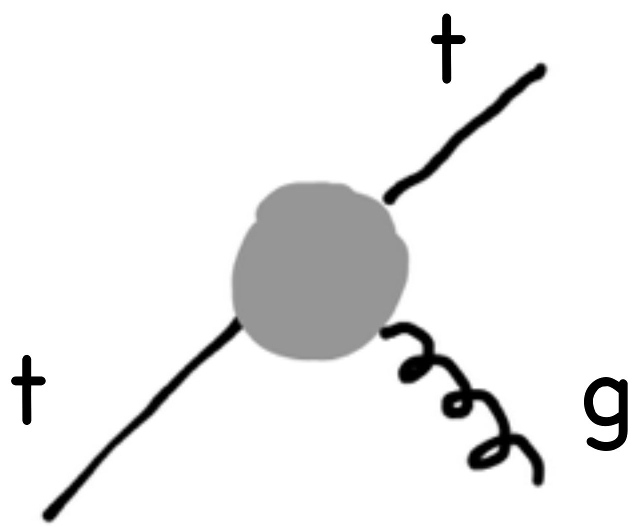
ongoing research for several years now

Highly-boosted regime requires still more work

Better understanding of input objects (topo-cluster) necessary

Anomalous top gluon couplings

(Scenario 2 or 3)



Top-compositeness can induce magnetic moment and radius

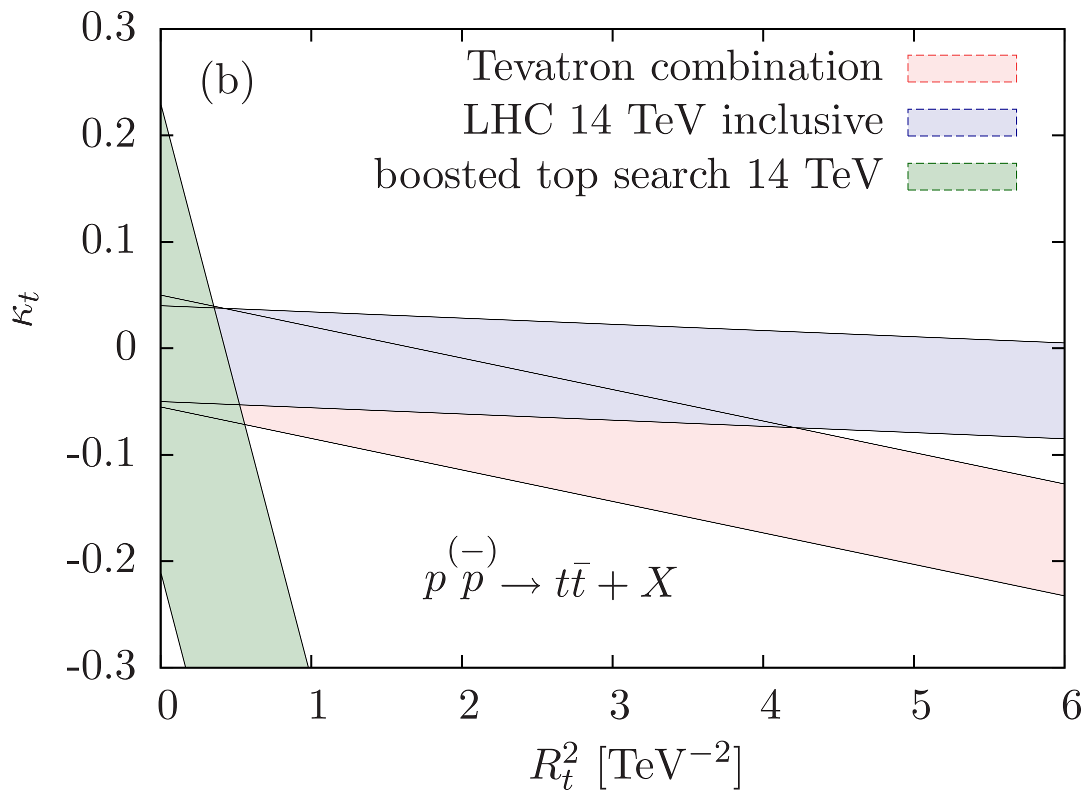
Effect of non-pointlike top structure via

$$\mathcal{L}_R = -g_s \frac{R_t^2}{6} \bar{t}\gamma^\mu \mathcal{G}_{\mu\nu} D^\nu t + \text{h.c.},$$

$$\mathcal{L}_\kappa = g_s \frac{\kappa_t}{4m_t} \bar{t}\sigma^{\mu\nu} \mathcal{G}_{\mu\nu} t \,,$$

gluon-fusion induced top production does not depend on R_t at leading order

Use large $m_{t\bar{t}}$ to increase quark contribution in production



	R_t	$\lvert\kappa_t\rvert$
Tevatron ⊕ LHC[7 TeV]	2.9 TeV^{-1} $\sim 0.57 \times 10^{-16}$ cm	0.17
Tevatron ⊕ LHC[14 TeV]	2.1 TeV^{-1} $\sim 0.41 \times 10^{-16}$ cm	0.07
LHC[14 TeV]: inclusive ⊕ boosted top	0.7 TeV^{-1} $\sim 0.14 \times 10^{-16}$ cm	0.05

Combination of Tevatron, incl. LHC and boosted LHC gives good measurement

[Englert, Freytas, Spira, Zerwas]

Event Deconstruction = Matrix. Method + Shower Deconstruction