A first attempt towards
Event Deconstruction

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1402.1189

Nature:
Symmetries, Forces, Particles

Result in measurable objects, e.g.
Jets, stable leptons, photons

Experiments measure radiation

Theory assumption:
Symmetries, Forces, Particles

Encoded in Lagrangian Density

$$\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{Higgs}}$$

Event Generators predict radiation

Comparison

Signal vs Background using Event Deconstruction

= fully automated event pattern matching method

[Soper, MS '11]
[Soper, MS '12]
[Soper, MS '14]

In quantum process the probability of a radiation pattern to occur is described by the matrix element

↕

All reconstruction methods (observables) are trying to access

matrix element

as directly as possible

↓

Idea: why not calculate the matrix element weight directly for given final state and perform hypothesis test on full radiation profile? (face recognition for LHC events)

In other words: Perform calculation to discriminate signal from background

Observable to calculate: $\chi(\{p,t\}_N) = \dfrac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$

Nature:
Symmetries, Forces, Particles

Theory assumption:
Symmetries, Forces, Particles

Result in measurable objects

Encoded in Lagrangian Density

$$\mathcal{L} = \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{Higgs}}$$

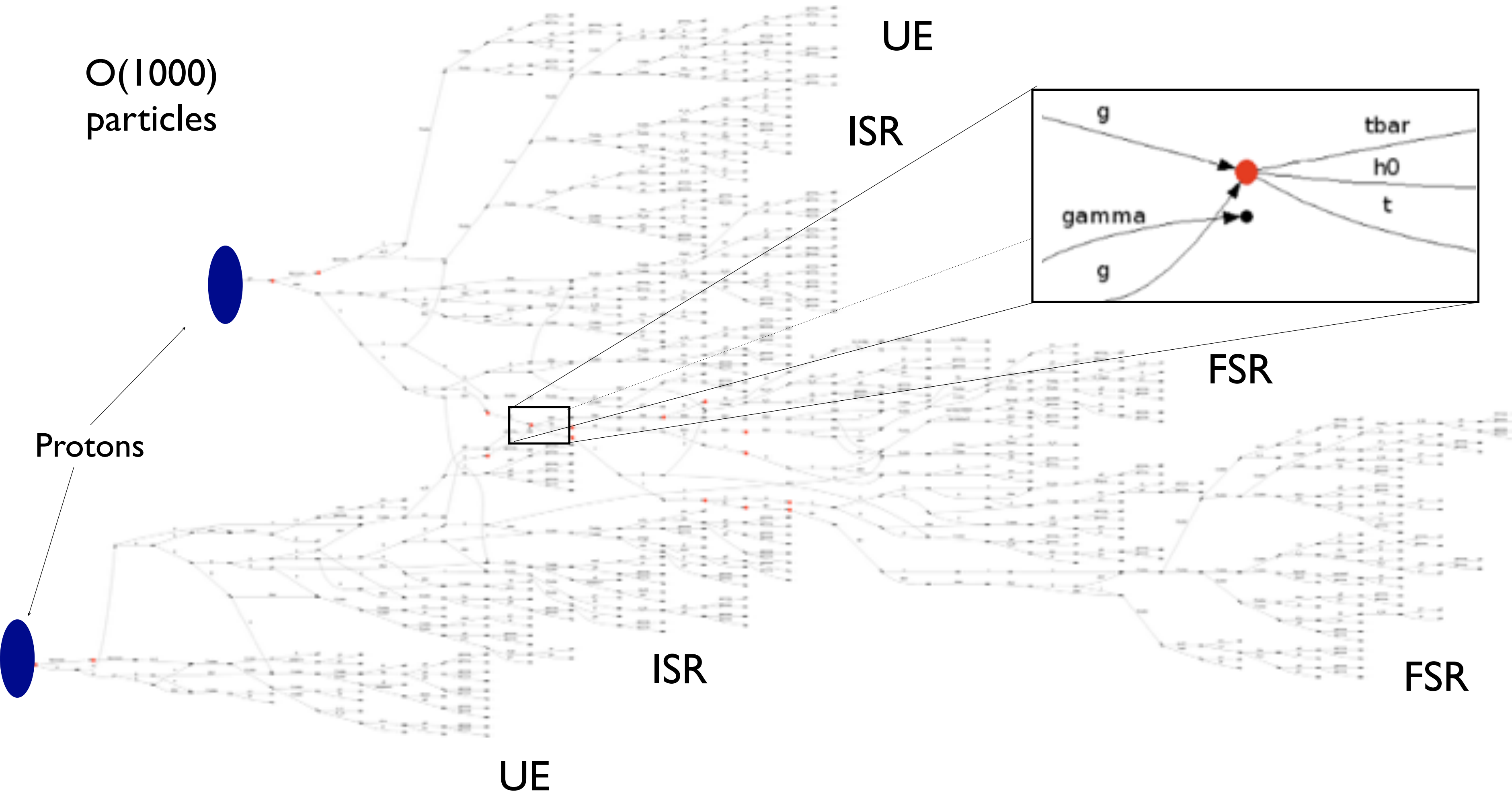
event dec.

Experiments measure radiation

Event Generators predict radiation

Comparison

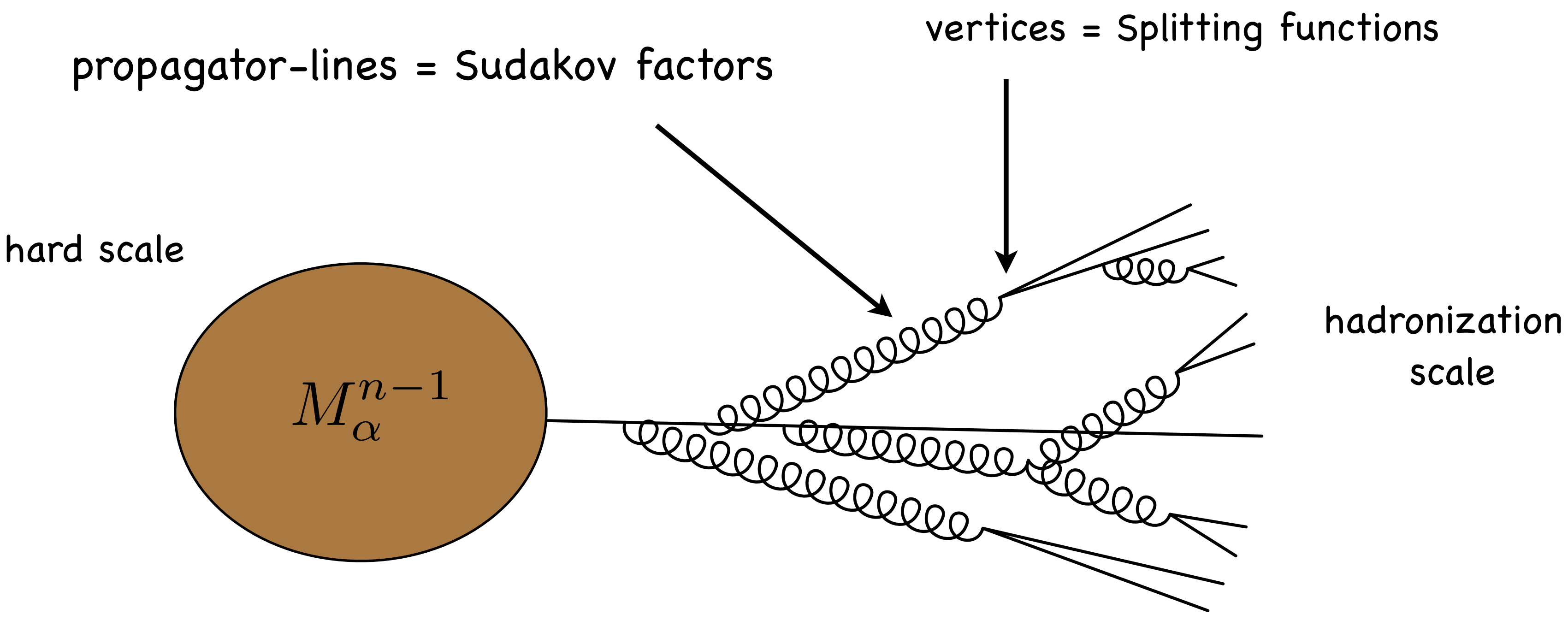
Is it possible to perform such hypothesis test given complexity of LHC events?

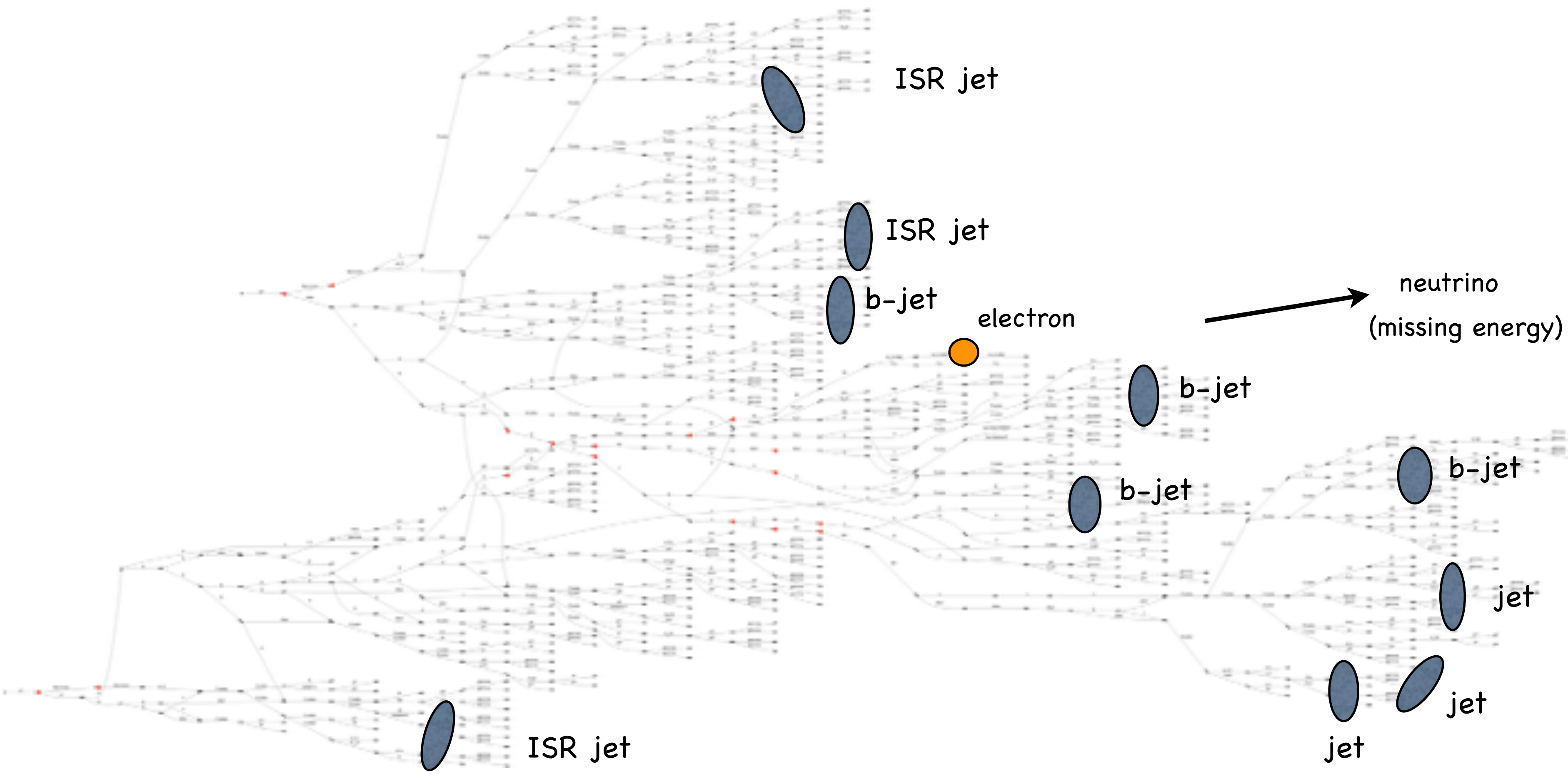


At least full event generators do a good job reproducing data...

Summary of shower approximation:

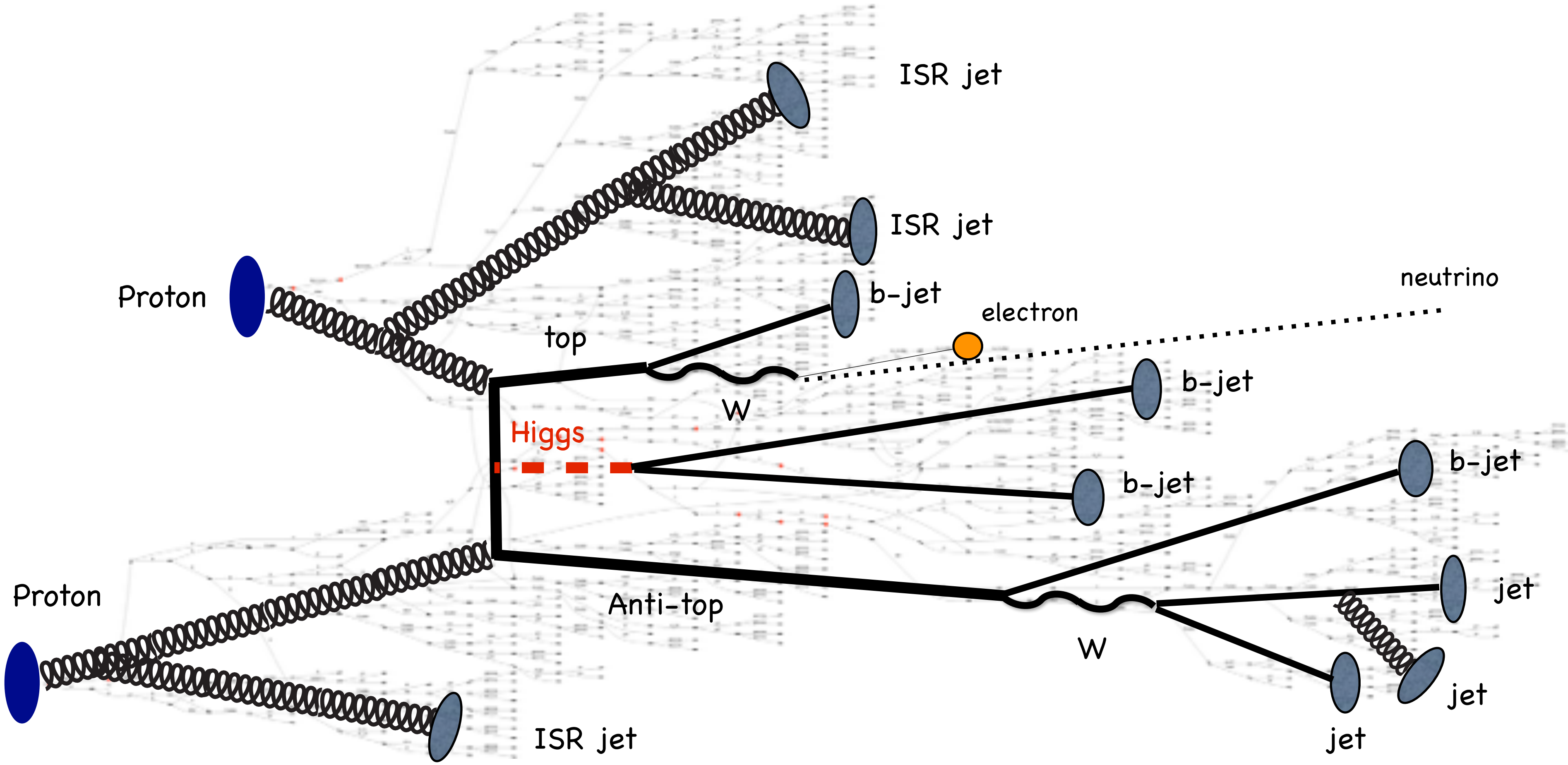
The probability weights in the evolution from the hard interaction scale to the hadronization scale are given by Sudakov factors and splitting functions.





To obtain a weight which indicates if a specific final state was more likely to be initiated by signal or background we have to

sum over all possibilities



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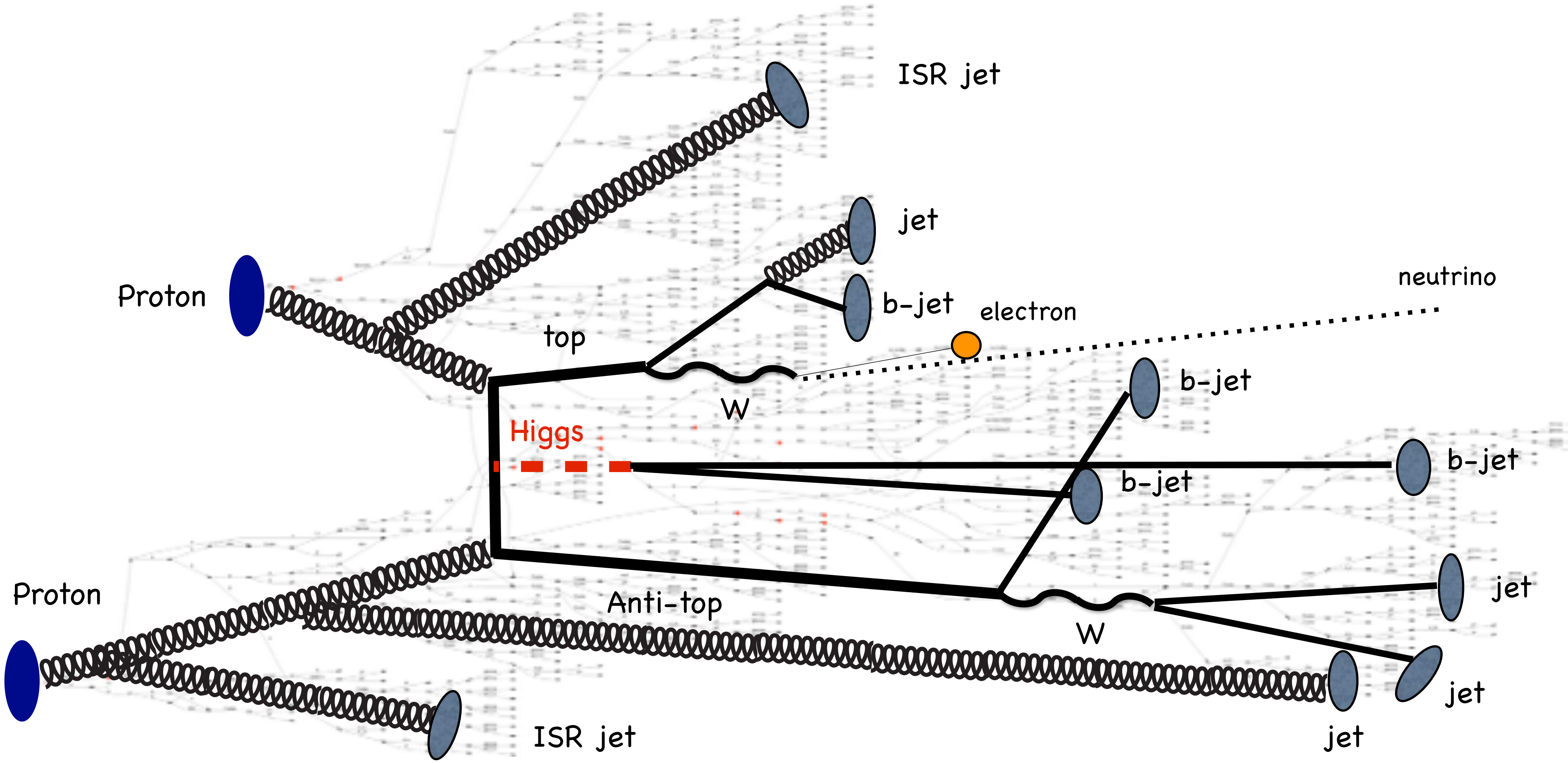

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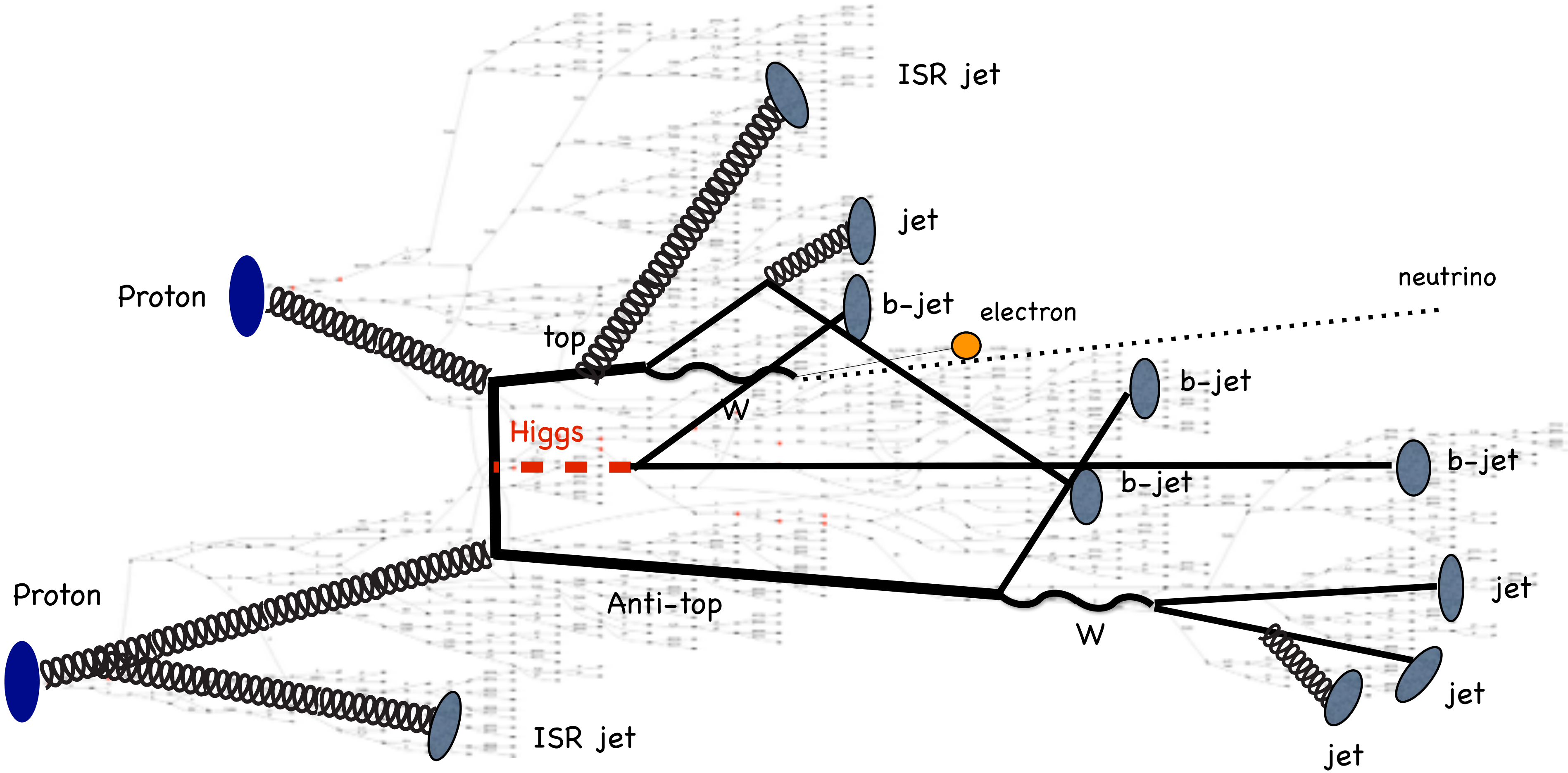

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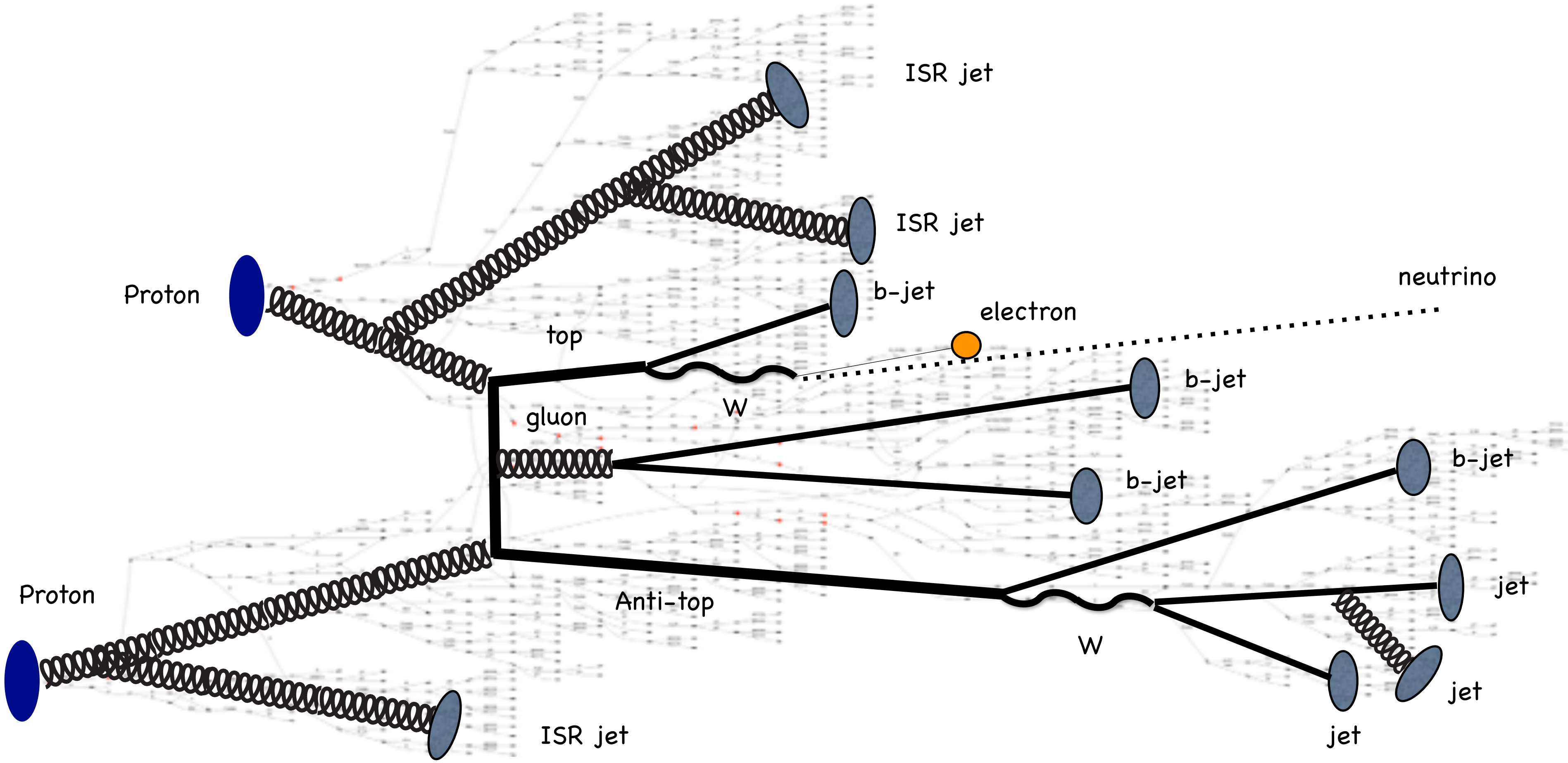

To obtain a weight which indicates if a specific final state was more likely to be initiated by signal or background we have to

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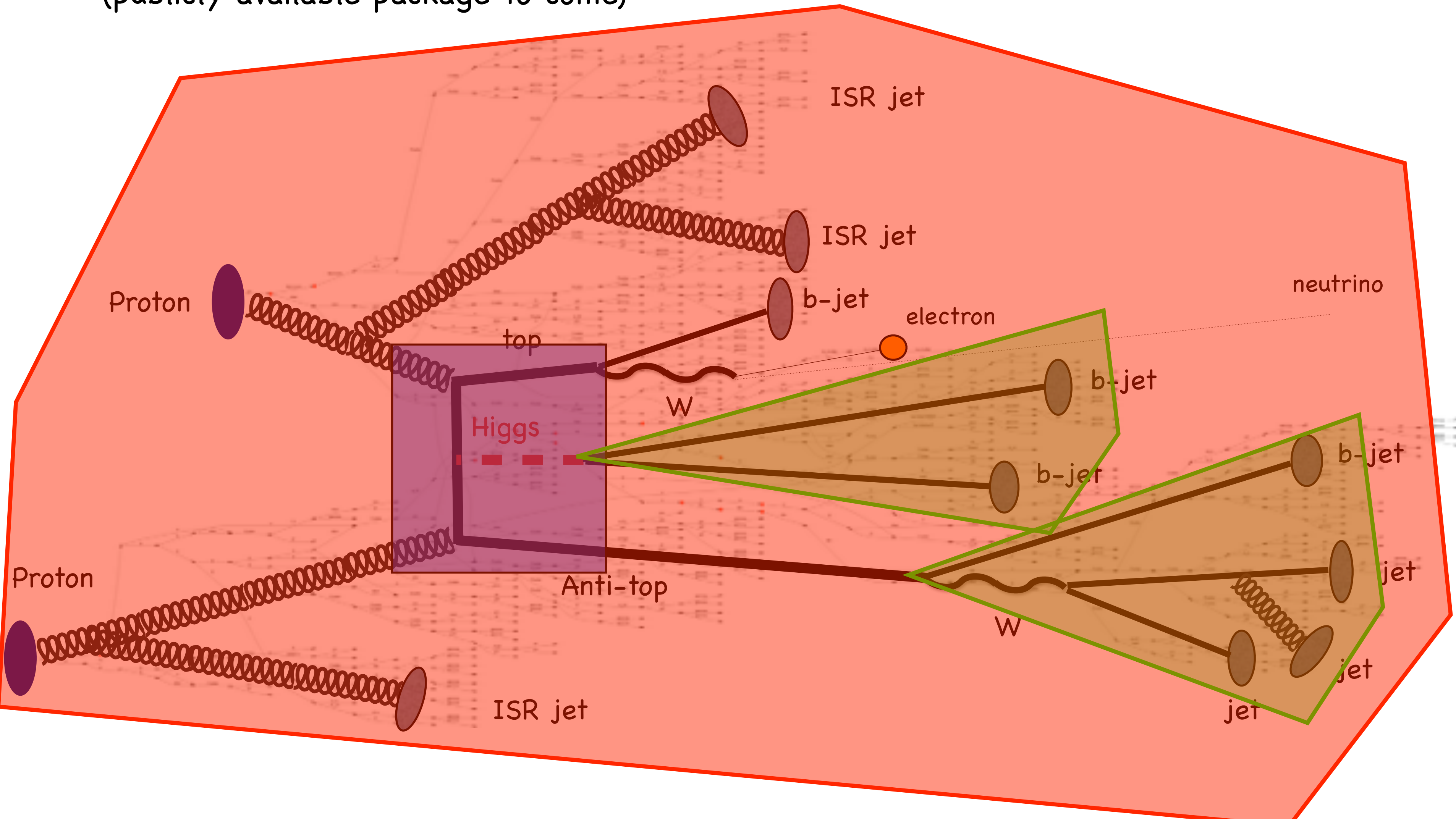
Event Deconstruction = Matrix. Method + Shower Deconstruction

(publicly available package to come)



Event Deconstruction vs matrix element method

(or 'the performance enhancing power of a shower')

The matrix element method in a nutshell:

Given a theoretical assumption α, attach a weight $P(\mathbf{x},\alpha)$ to each experimental event **x** quantifying the validity of the theoretical assumption α for this event.

$$P(\mathbf{x},\alpha) = \frac{1}{\sigma}\int d\phi(\mathbf{y})|M_\alpha|^2(\mathbf{y})W(\mathbf{x},\mathbf{y})$$

$|M_\alpha|^2$ is squared matrix element

$W(\mathbf{x},\mathbf{y})$ is the resolution or transfer function

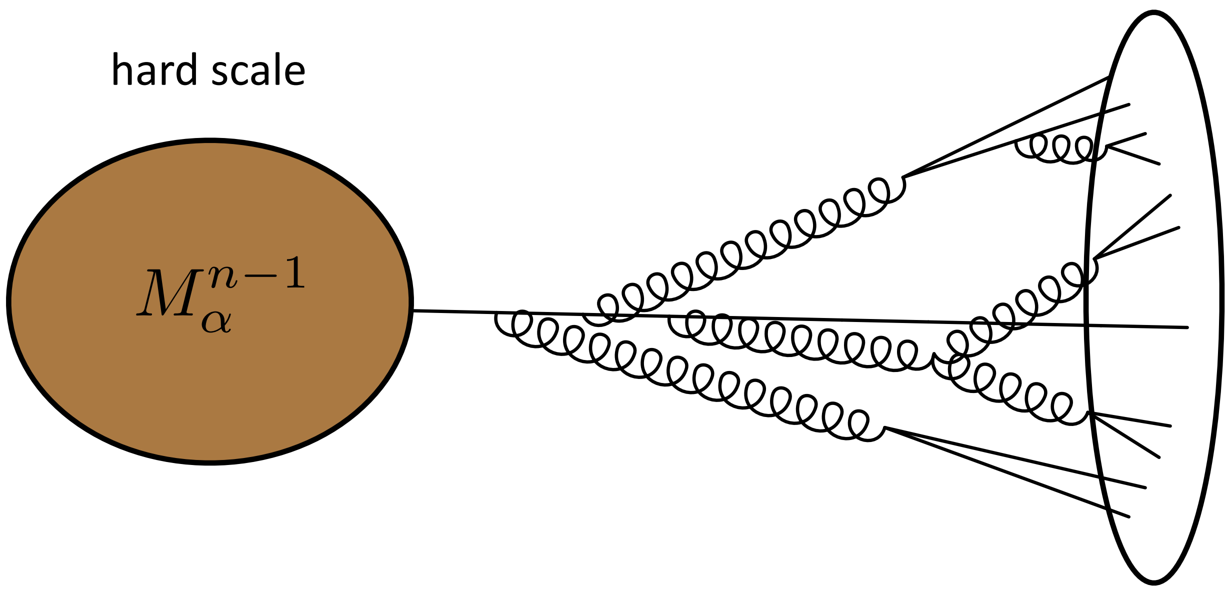
$d\phi(\mathbf{y})$ is the parton-level phase-space measure

The value of the weight $P(\mathbf{x},\alpha)$ is the probability to observe the experimental event **x** in the theoretical frame α

Event Deconstruction vs matrix element method

(or 'the performance enhancing power of a shower')

Purpose of the transfer function is to match jets to partons



Probability density function: $\int d\mathbf{y}\ W(\mathbf{x},\mathbf{y}) = 1$

Event Deconstruction vs matrix element method

(or 'the performance enhancing power of a shower')

The form of the transfer function:

resolution in

$$W(\mathbf{x},\mathbf{y}) \approx \Pi_i \frac{1}{\sqrt{2\pi}\sigma_{E,i}} e^{-\frac{(E_i^{rec}-E_i^{gen})^2}{2\sigma_{E,i}^2}}$$

Energy

$$\times \quad \frac{1}{\sqrt{2\pi}\sigma_{\phi,i}} e^{-\frac{(\phi_i^{rec}-\phi_i^{gen})^2}{2\sigma_{\phi,i}^2}}$$

azimuthal angle

$$\times \quad \frac{1}{\sqrt{2\pi}\sigma_{y,i}} e^{-\frac{(y_i^{rec}-y_i^{gen})^2}{2\sigma_{y,i}^2}}$$

rapidity

Complex, high-dimensional gaussian distribution!

Transfer function introduces new peaks on top of propagators

Shower deconstruction vs matrix element method

(or 'the performance enhancing power of a shower')

Shortcomings/Problems of the matrix element method:

- A hadronized final state has to be matched to a parton level matrix element
  - ➡ Number of final state objects limited to fixed order ME (exclusive)
  - ➡ Limited and fix number of final state objects (jets, leptons, ...)
  - ➡ Transfer function fit dependent (input from experiment)
- transverse boost used to reduce jet sensitivity
  - ➡ Large systematic uncertainty + loos information from jets
- Extremely time consuming calculation
  - ➡ The more particles the higher-dimensional the MC integration

➡ **All problems solved by putting** $W(\mathbf{x},\mathbf{y}) = \delta(\mathbf{x}-\mathbf{y})$

Difference between both methods:

Remove dependence on transfer function $W(\mathbf{x},\mathbf{y}) = \delta(\mathbf{x}-\mathbf{y})$

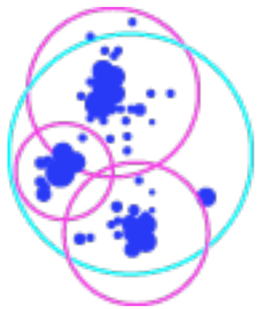
- ➡ Only needed when matrix element varies quickly
- ➡ replace physical Breit-Wigner with experimental
- ➡ Huge gain in speed!

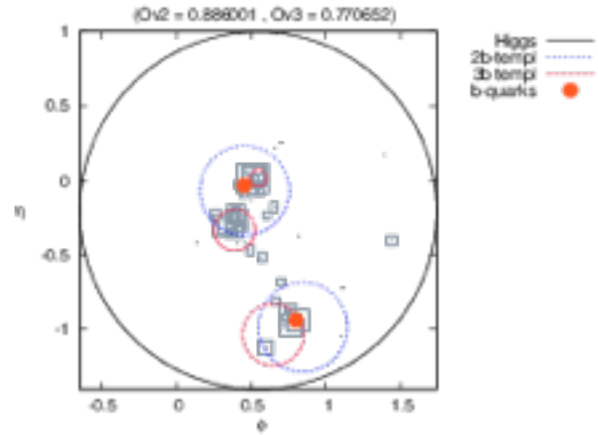
Allow for arbitrary number of final state objects

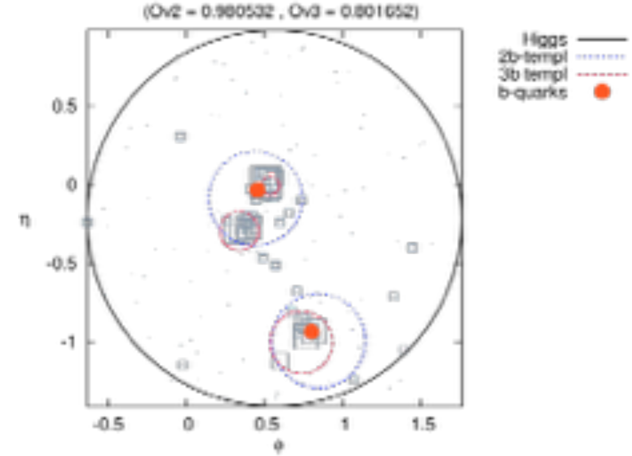
- ➡ Shower approximation removes final state object limitation
- ➡ For hard matrix element <-> final state object matching needed

Use smallest reconstructable objects in event

- ➡ More information
- ➡ Retains sensitivity in boosted final states
- ➡ Radiation collimated/soft -> need Sudakov factors







Numerical approach to Event Deconstruction (unpractical)

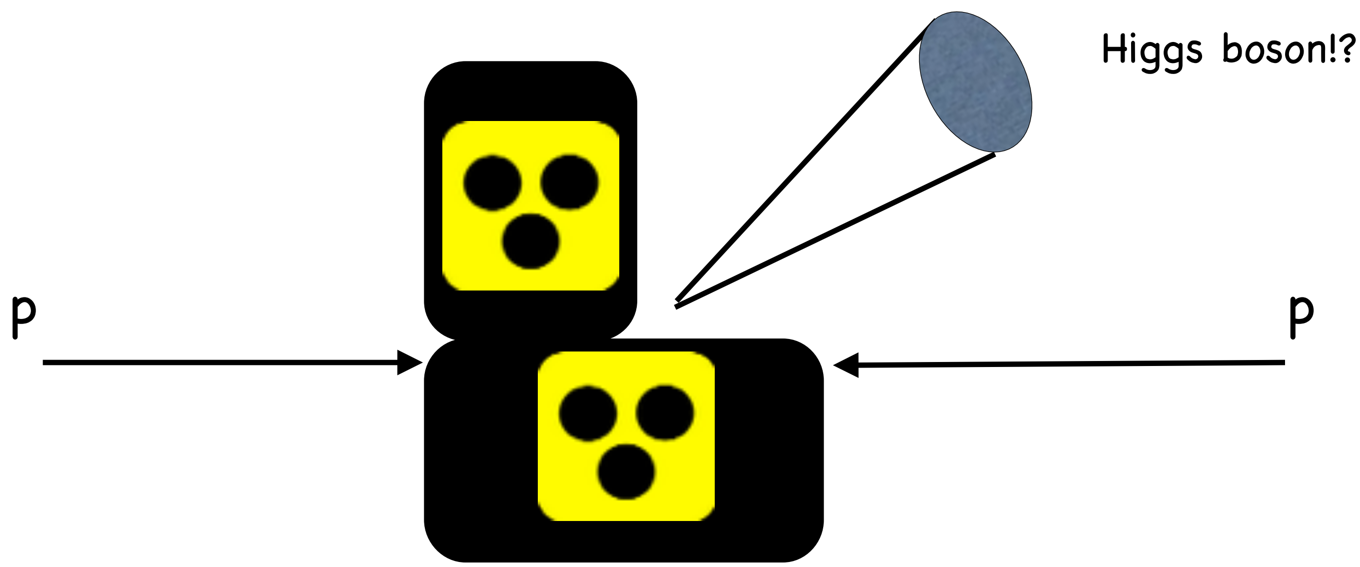
- Run MC for all possible 4-momenta combinations of final state particles and compare observed event with prediction

- Time estimate:

  7 microjets, each 4 momentum components divided into only 10 bins $\rightarrow 10^{28}/7! \sim 10^{24}$ configurations

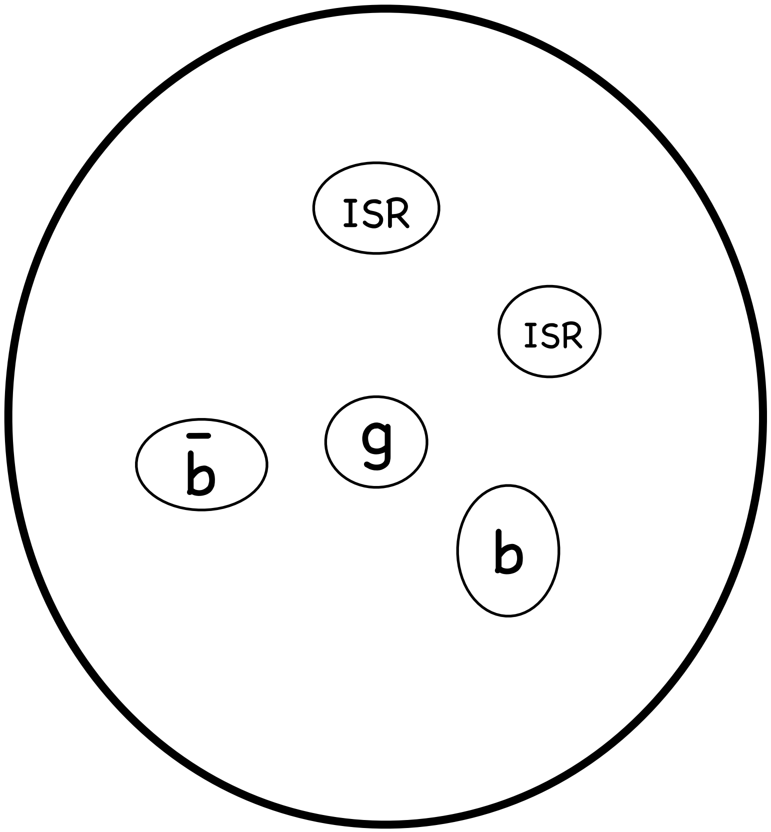
If MC takes 1 ms per event -> 10^{13} years to have 1 hit per config.

How can Event Deconstruction be used to tag a boosted electroweak-scale resonance and improve on BDRS?

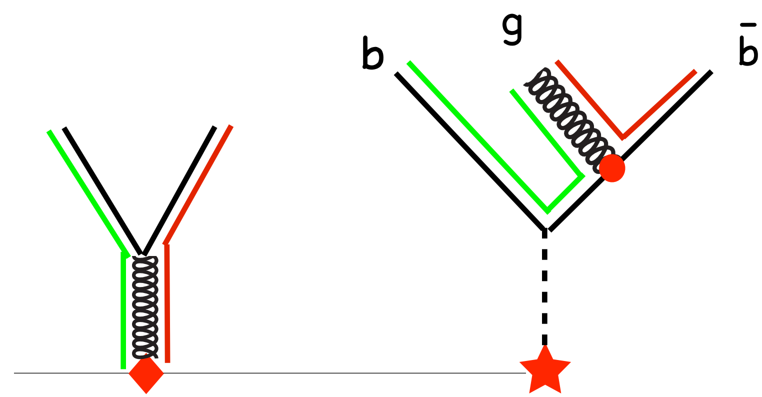


Tagger implicitly ignores rest of event, i.e. production mechanism (strictly not correct)

Fat jet: R=1.2, anti-kT



microjets

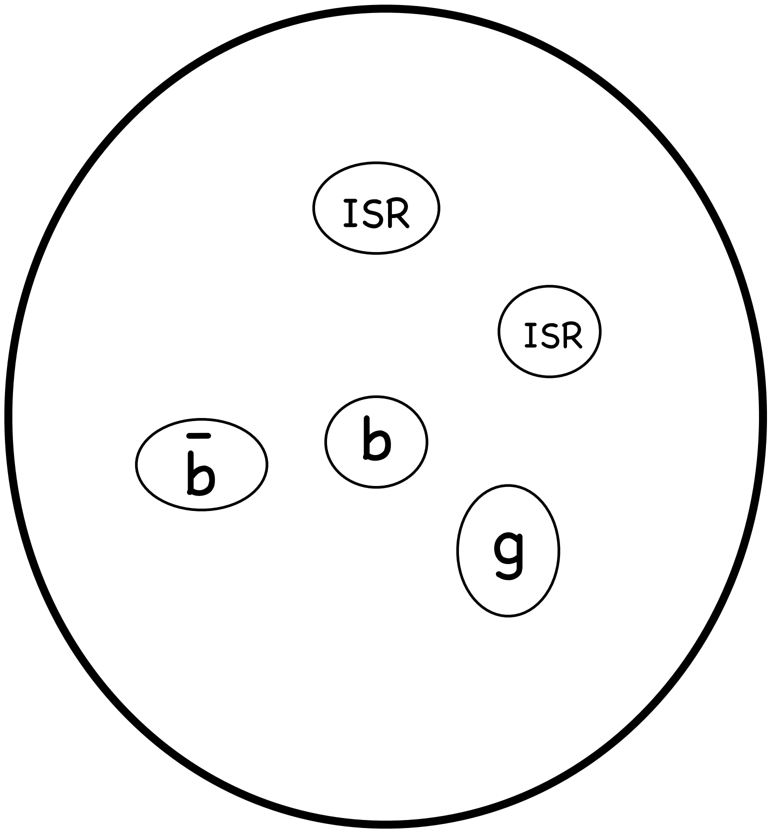


Build all possible shower histories

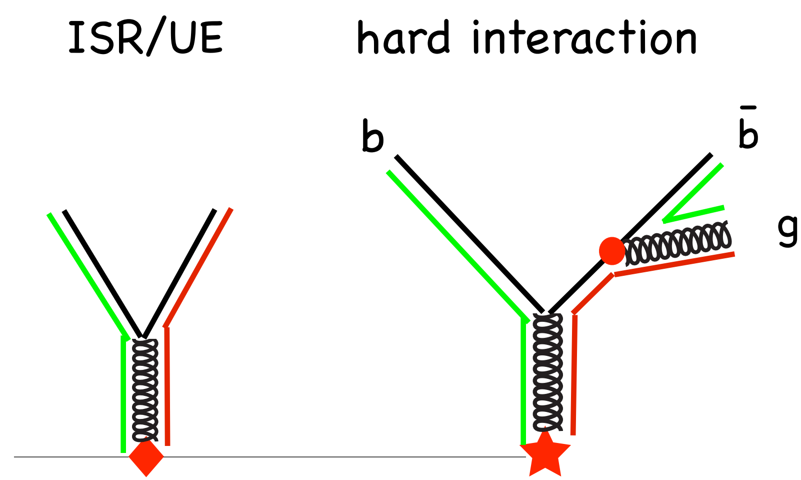
signal vs background hypothesis based on:

- Emission probabilities
- Color connection
- Kinematic requirements
- b-tag information

Fat jet: R=1.2, anti-kT



microjets



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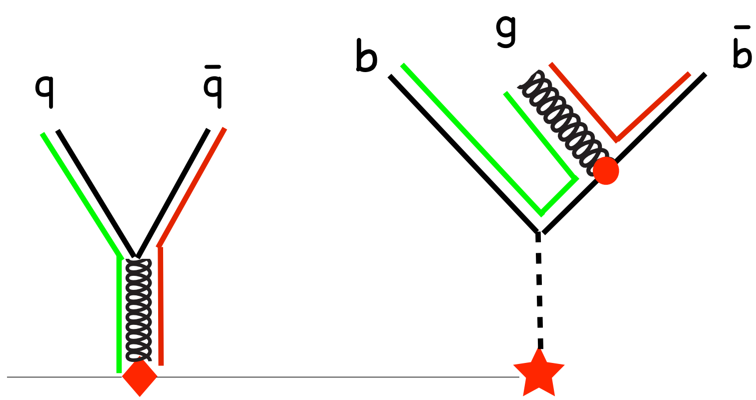
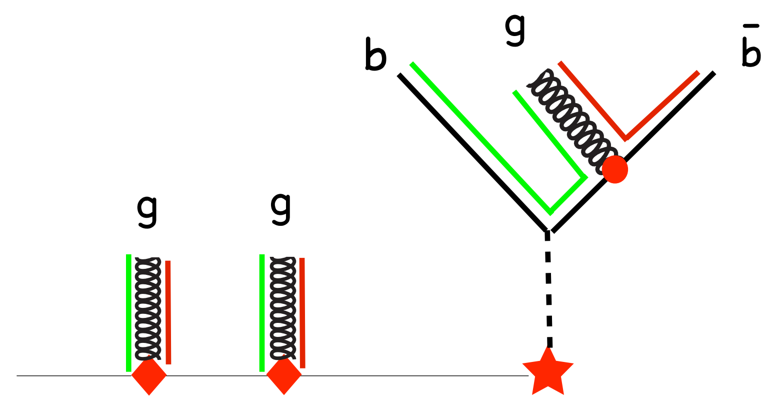
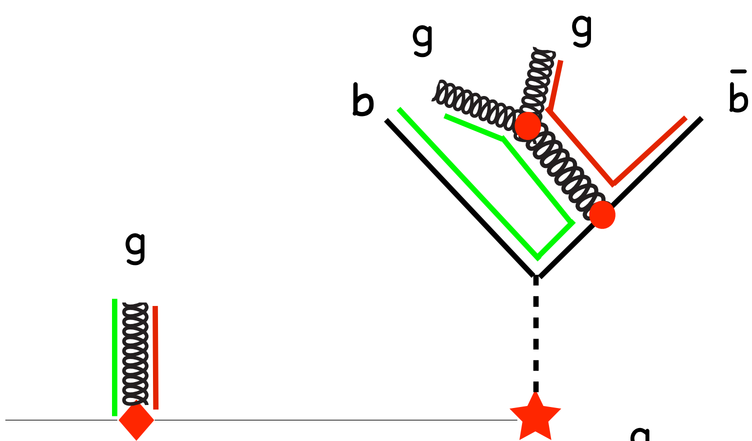
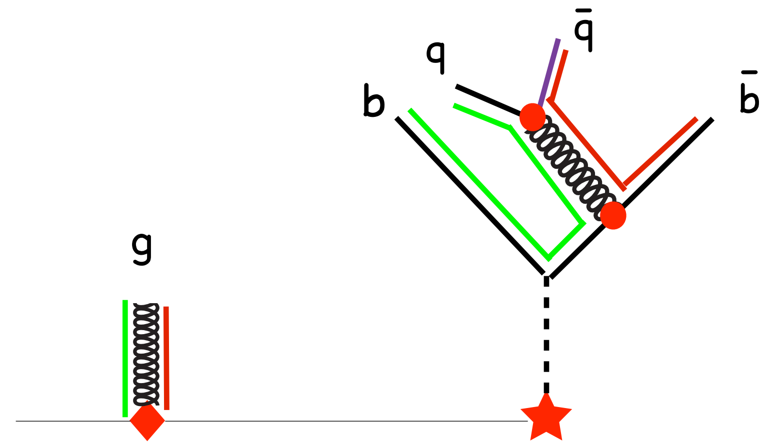
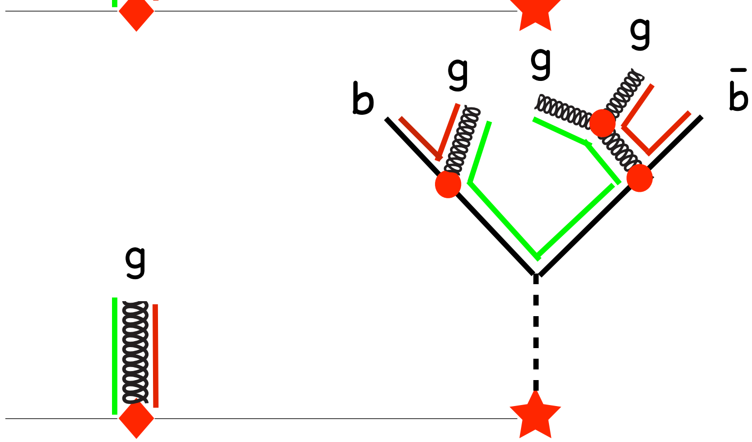








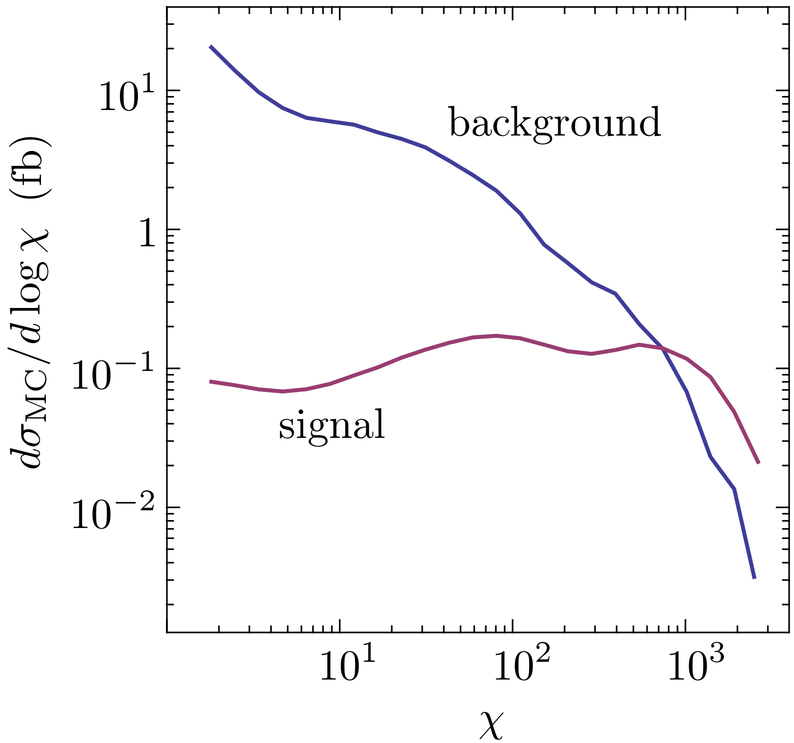


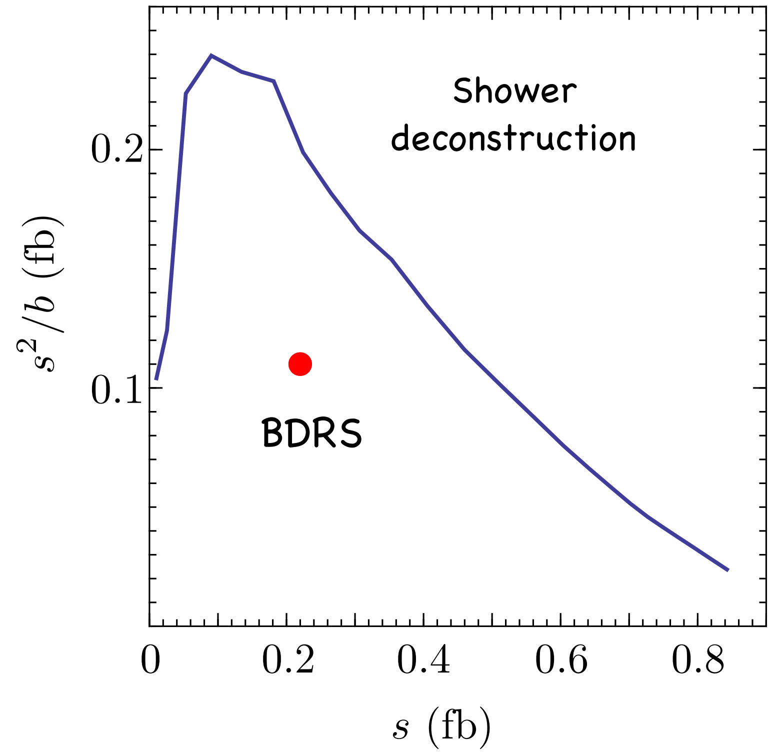
- And many more...
- And for all backgrounds...

Results for Higgs boson:

$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$$

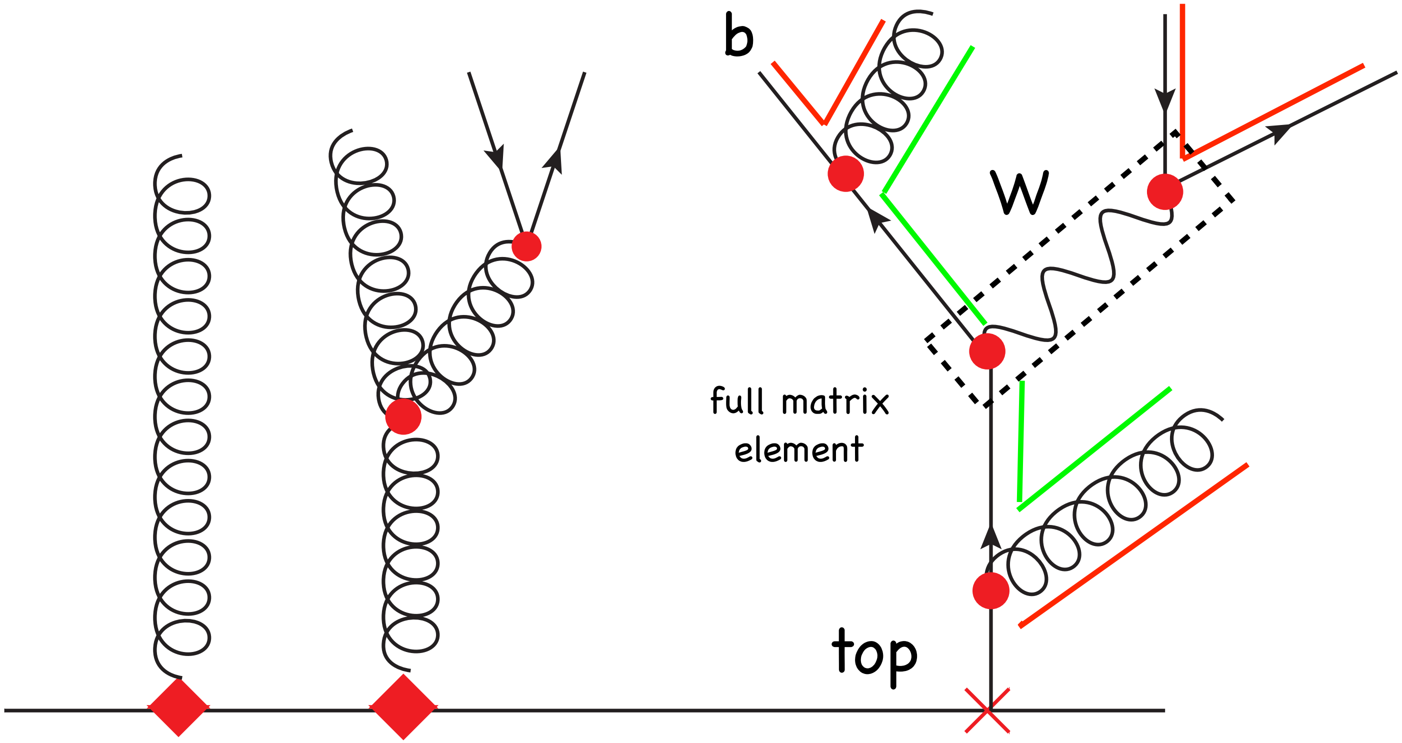
imperfect b-tagging (60%,2%)





Exploited in HH -> 4b [de Lima, Papaefstathiou, MS]

Analogously for the top decay (more involved as top colored)

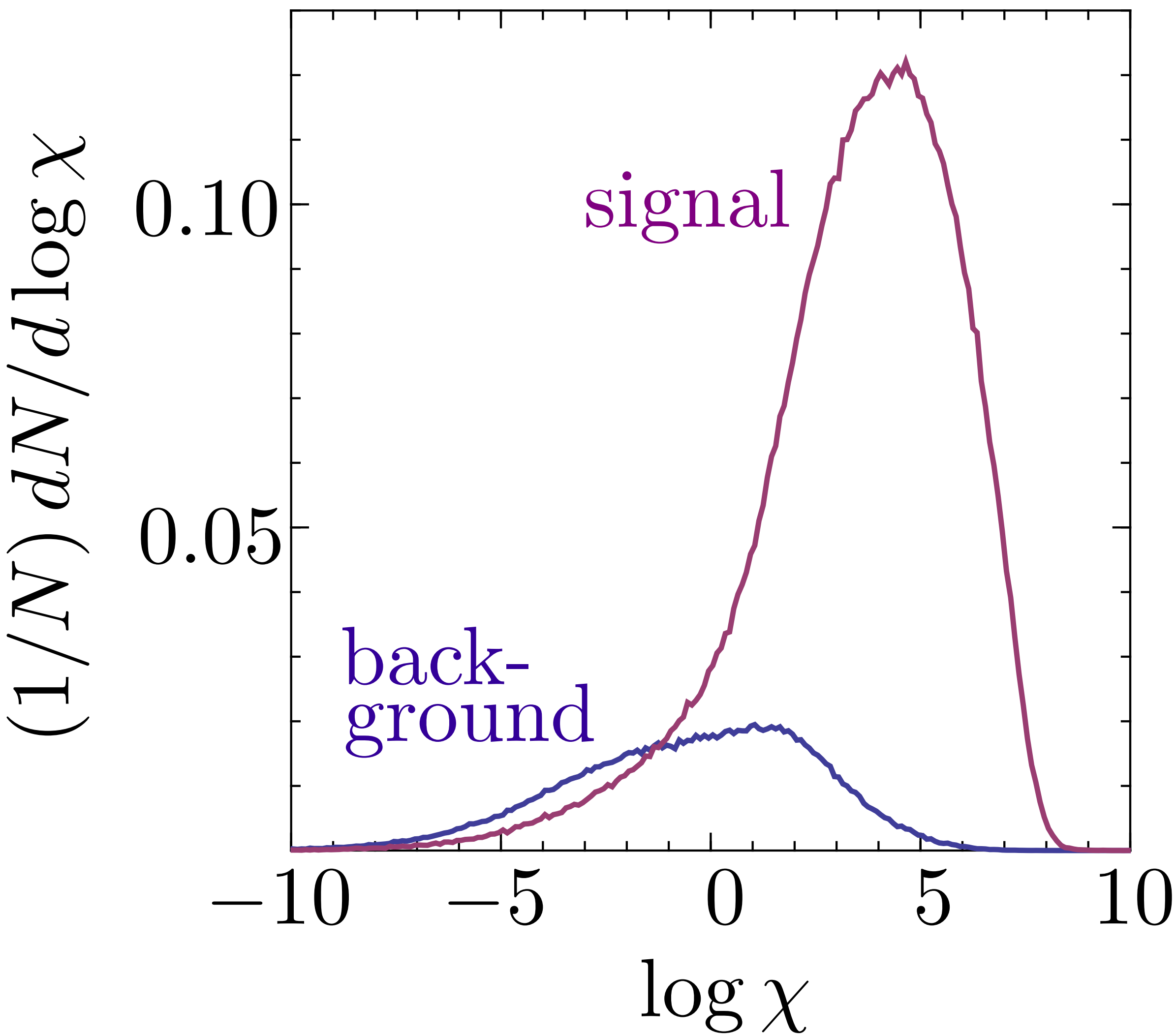


Conceptional difference compared to Higgs from last year:

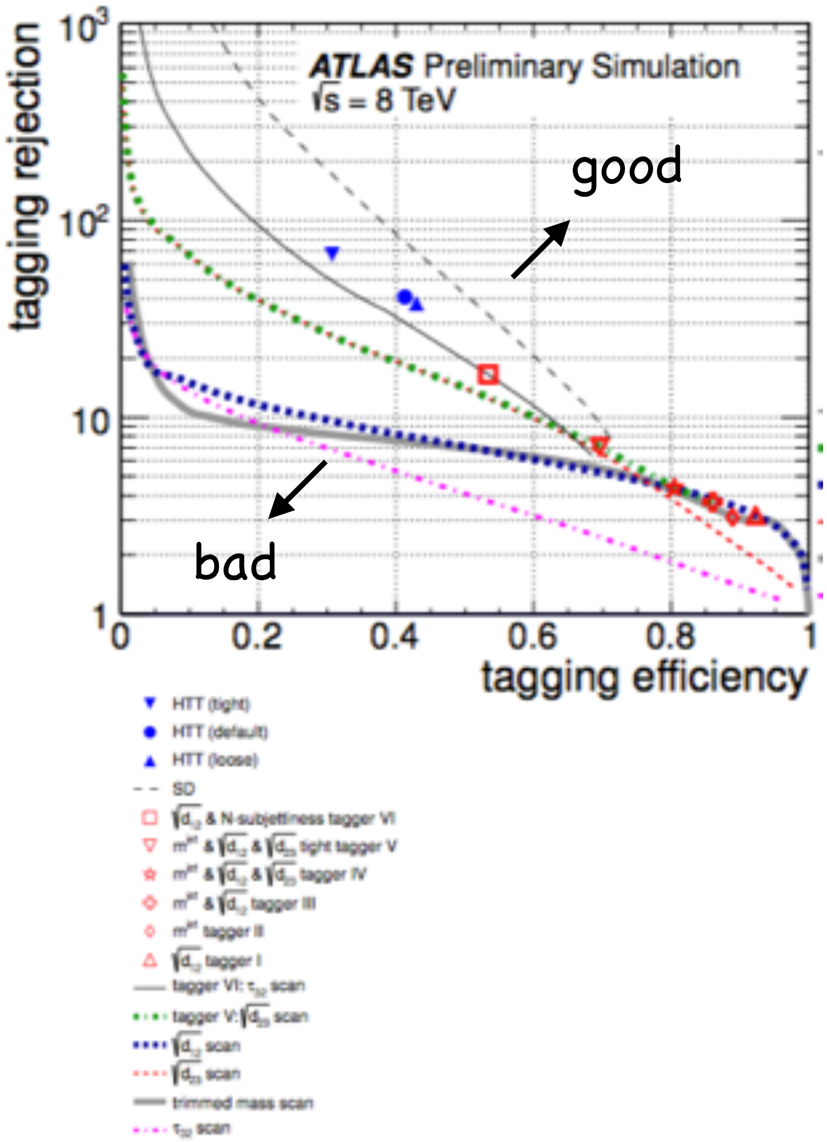
- Splitting functions for massive emitter and spectator
- Full matrix element for top decay

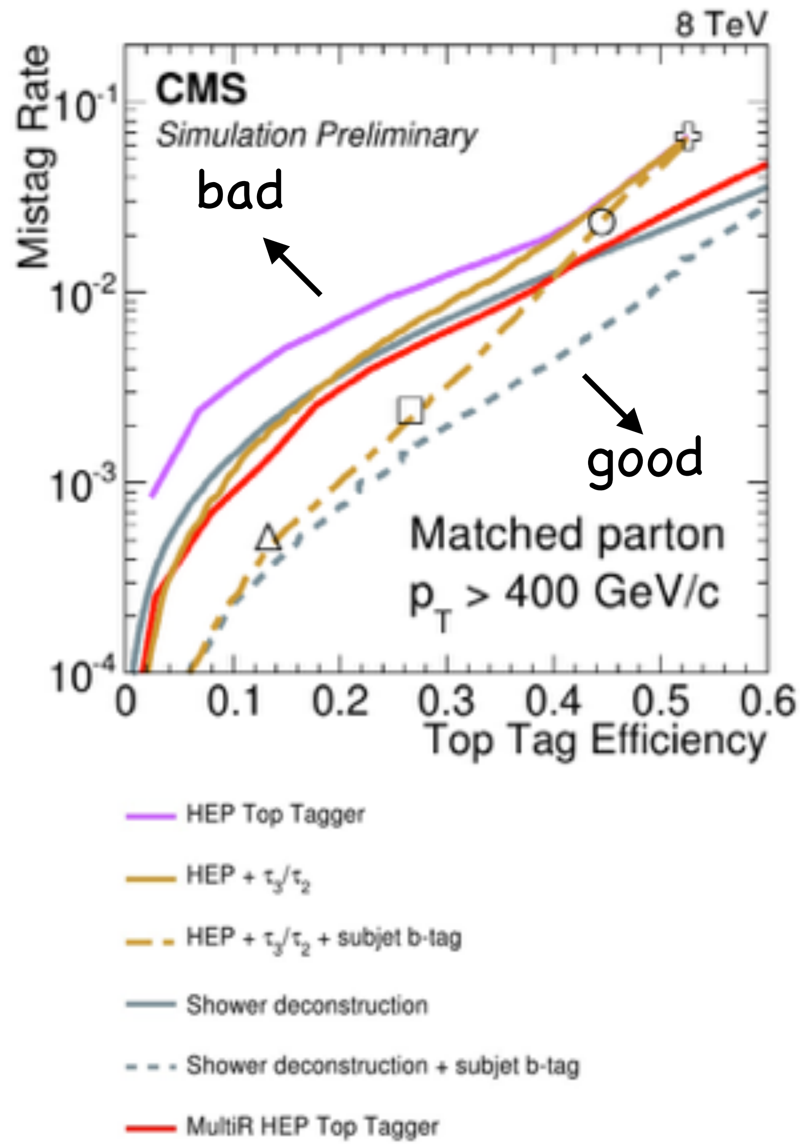
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} |\mathcal{M}|^2 H_{\text{top}} e^{-S_{t_1}} H^s_{tg} e^{-S_g} \ldots}{\sum_{\text{histories}} H_{ISR} \cdots \sum_{\text{histories}} H^b_g e^{S_g} H_{ggg}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

chi distribution for top vs QCD



Results for top quark tagging:

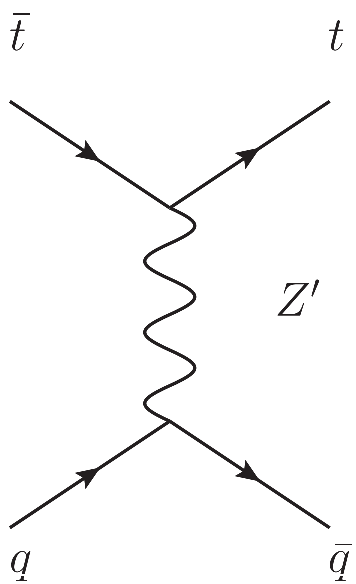




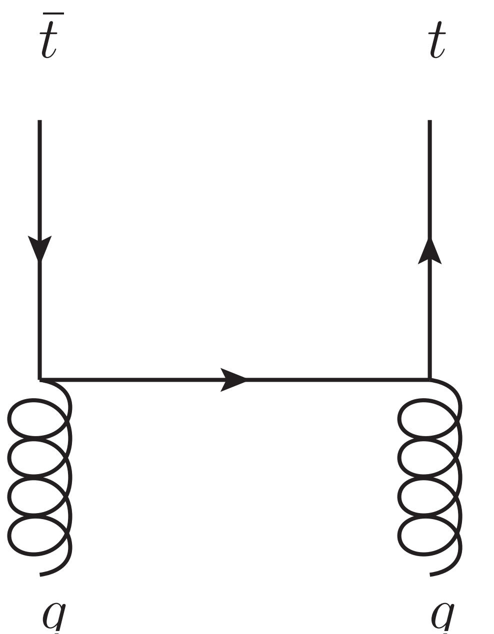
First application of Event Deconstruction

fully hadronic Z' -> tt

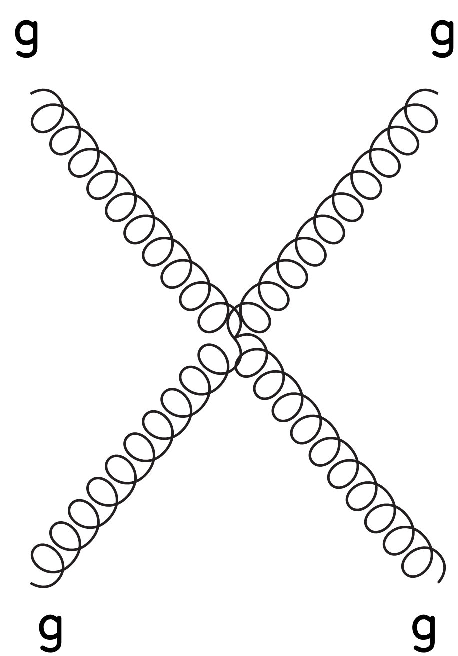
Signal



$t\bar{t}$



dijets



Model: mass Z′ = 1500 GeV with width = 65 GeV

Event selection:

2 fat jets with pT > 400 GeV

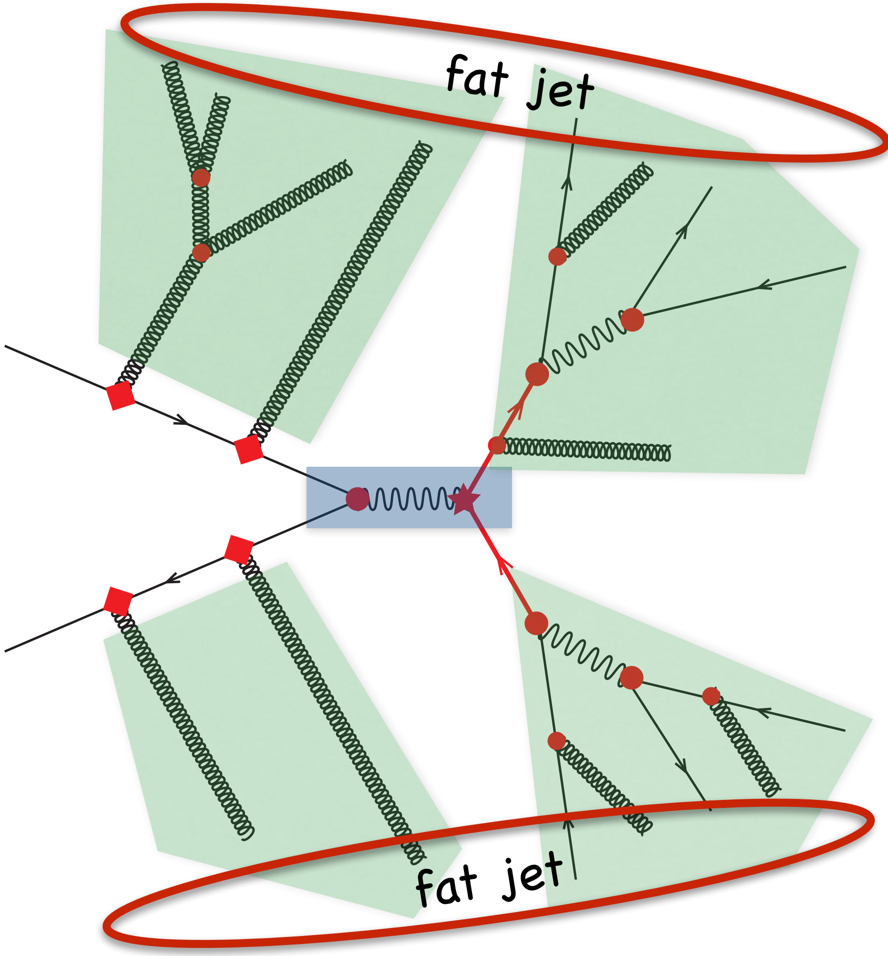
jet algorithm CA R=1.5

Cross section after ES:

dijets	1.73 nb
ttbar	2.27 pb

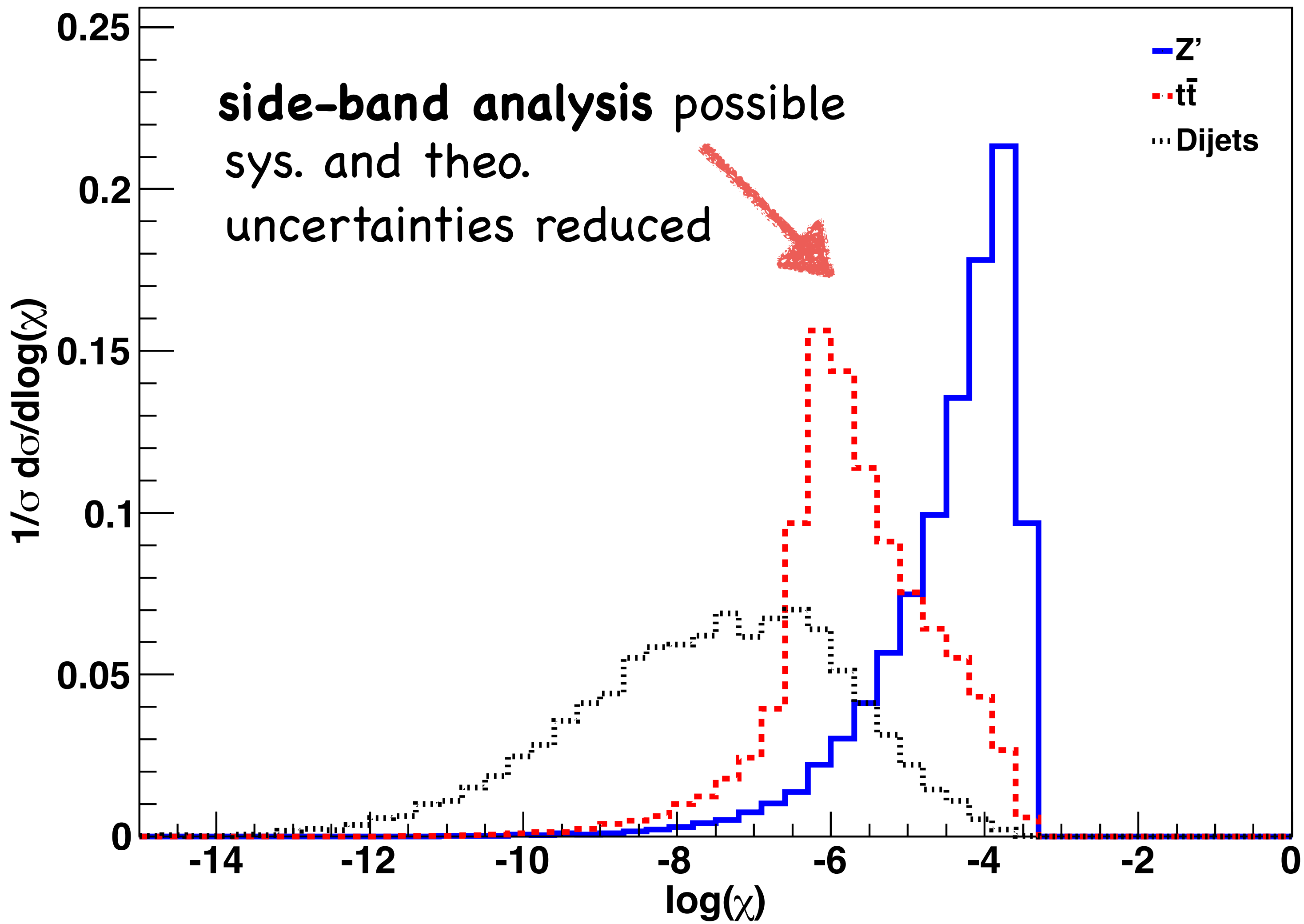
Recluster fatjet constituents using microjets kT R=0.2 pT>10 GeV

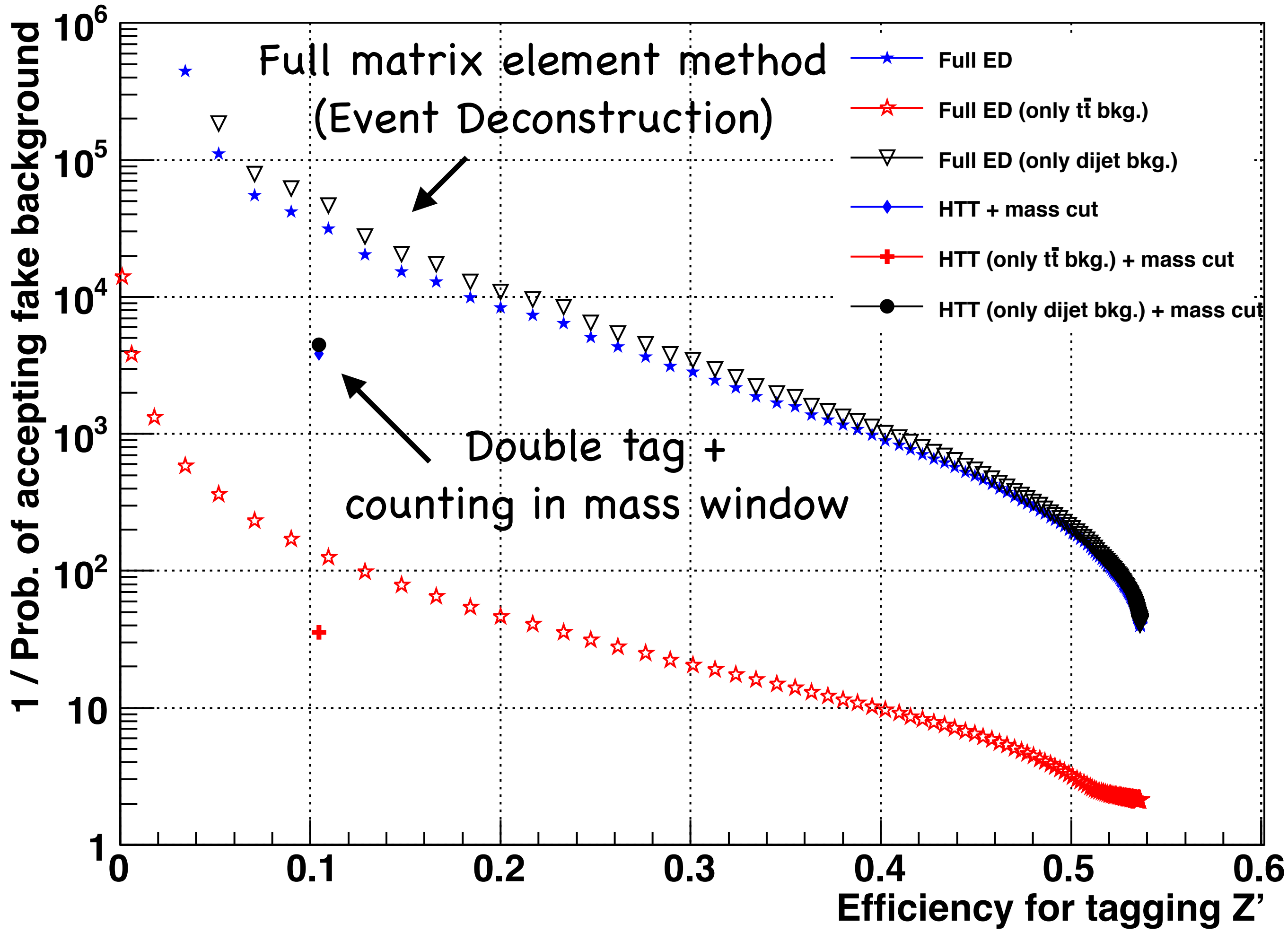
Z′ width in Event Dec. 130 GeV



Hard matrix element generated with MadGraph5

$$\chi = \frac{P(X|Z')}{P(X|t\bar{t} + \mathrm{dijets})}$$





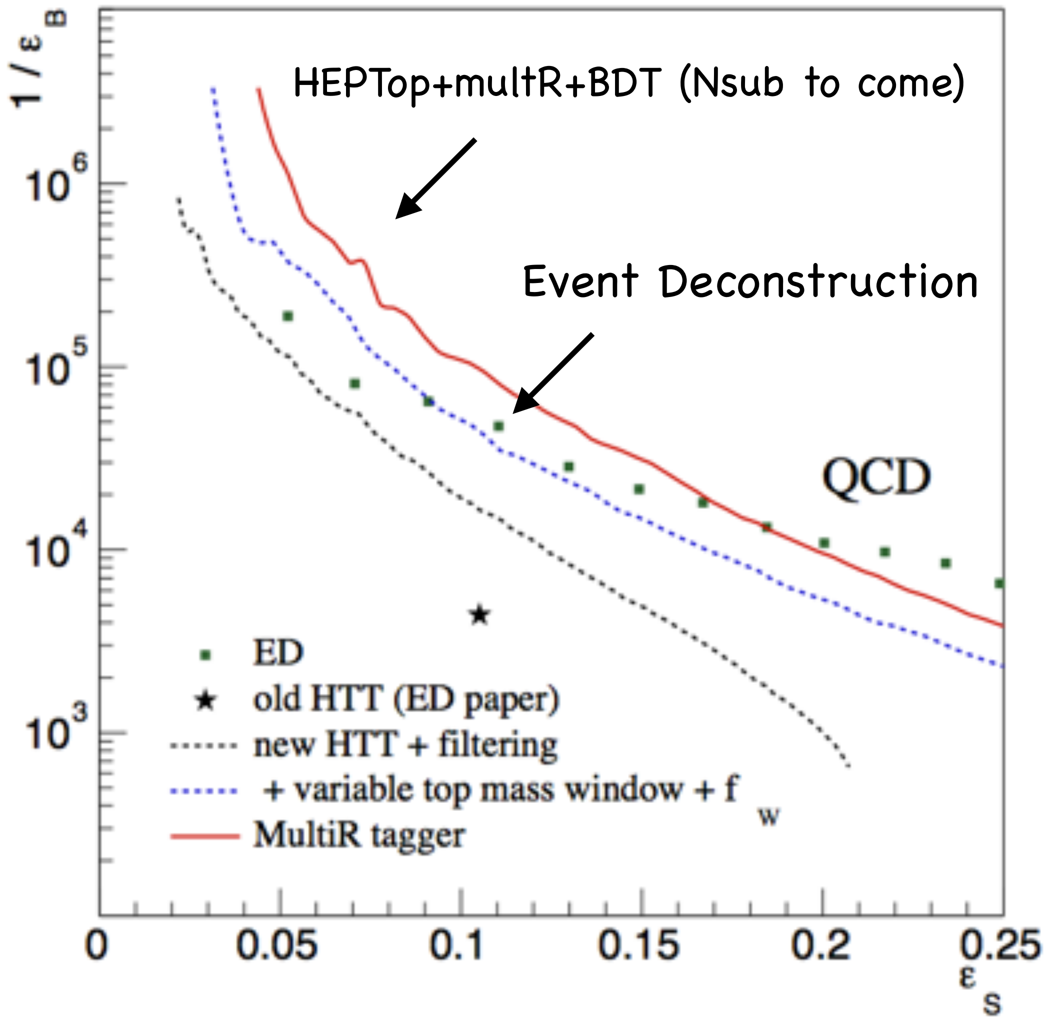
Event Dec: eff : 0.109538
fkr : 3.20063e-05
1/fkr : 31243.8

HTT: eff: 0.104659
fkr: 0.000259946
1/fkr: 3846.95

[Talk by Schell at BOOST]

News from the HEPTopTagger

arXiv:1312.1504 & work with C. Anders, C. Bernaciak, G. Kasieczka, T. Plehn, G. Salam, and T. Strebler



[See Tilman's talk]

Comparison not quite 1:1

- HEPTopTagger at 13 TeV
  ED at 14
- HEP no Detector response
  ED exp. resonance width

still

Different methods can access same amount information,

but Event Deconstruction in first crude implementation achieves very high standard

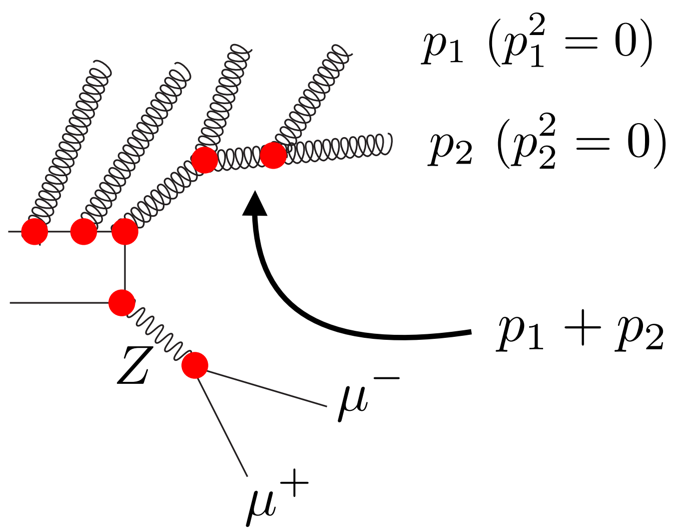
Conclusions

- Matrix Element Methods -> Shower Deconstruction -> Event deconstruction = Maximum information approach
- Shower/Event deconstruction modular structure: Can be fully automated
- Method being tested in data by ATLAS and CMS
- Future improvements:
    - Give up fatjet limitation
    - Real calculation of ISR
    - Trace color flow through hard interaction
    - Matrix Elements with larger jet multiplicities (CKKW)

Backup

Parton shower in a nutshell

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)

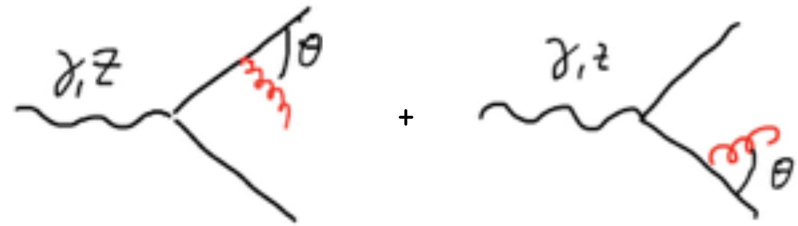
These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

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

- If $p_1 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to 0$, then $1/(p_1+p_2)^2 \to \infty$
- If $p_2 \to \lambda p_1$, then $1/(p_1+p_2)^2 \to \infty$

Example

$e^+e^- \to 3$ jets



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

$$P_{q\to qg} = C_F \frac{1+z^2}{1-z} \qquad P_{g\to gg} = C_A \frac{(1-z(1-z))^2}{z(1-z)} \qquad P_{g\to q\bar{q}} = T_R n_f (z^2+(1-z)^2)$$

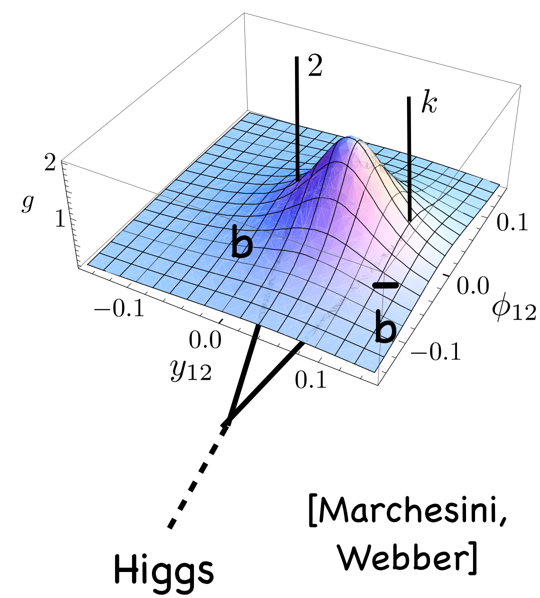
Soft limit: $E_g \to 0 \qquad k^\mu \ll p_i^\mu$ the matrix element for

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

↓ dipole

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

In the large Nc limit most radiation occurs in a cone between colour partners



[Marchesini, Webber]

Factorization of emissions and Sudakov factors allow semiclassical approximation of quantum process:

Sudakov form factor:

$$\mathcal{P}_{\text{nothing}}(0 < t \leq T) = \lim_{n->\infty} \Pi_{i=0}^{n-1} \mathcal{P}_{\text{nothing}}(T_i < t \leq T_{i+1})$$

$$= \lim_{n\to\infty} \Pi_{i=0}^{n-1} \left(1 - \mathcal{P}_{\text{something}}(T_i < t \leq T_{i+1})\right)$$

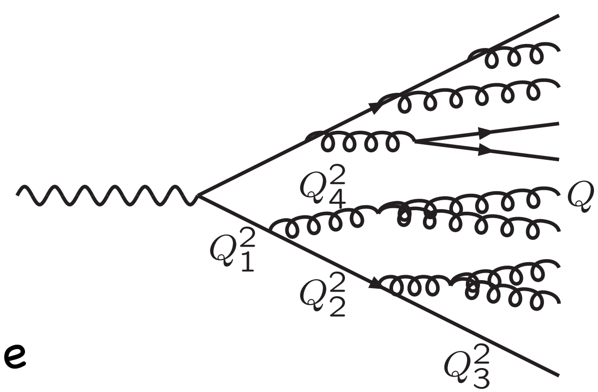
$$= \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

$$\Rightarrow \quad d\mathcal{P}_{\text{first}}(T) = d\mathcal{P}_{\text{something}}(T) \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

Sudakov form factor provides "time" ordering of shower:

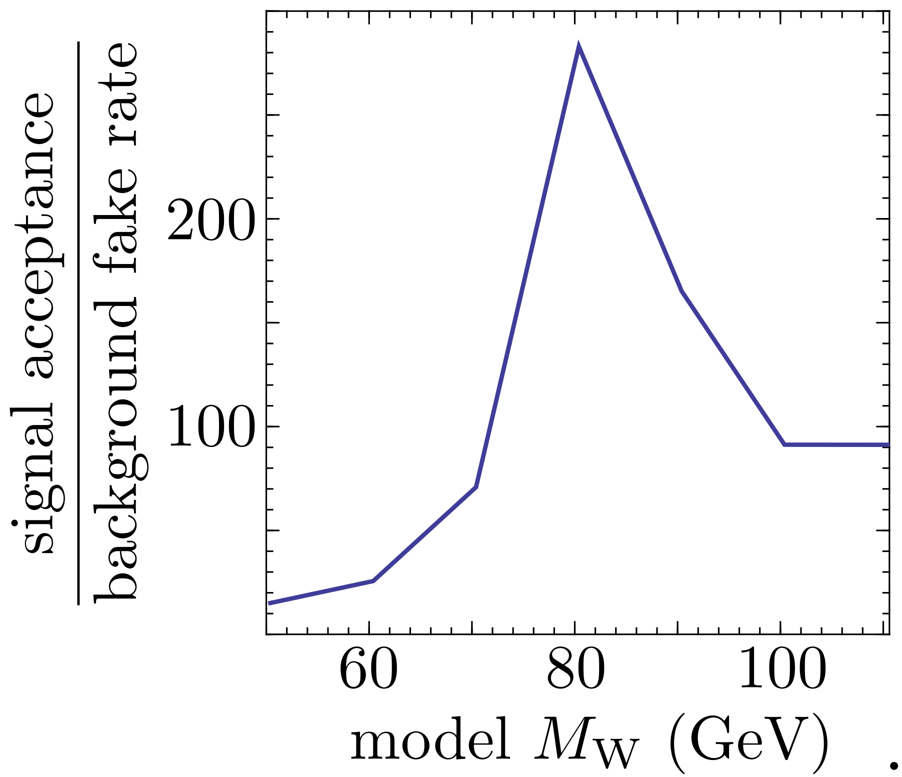
$$Q_1^2 > Q_2^2 > Q_3^2$$

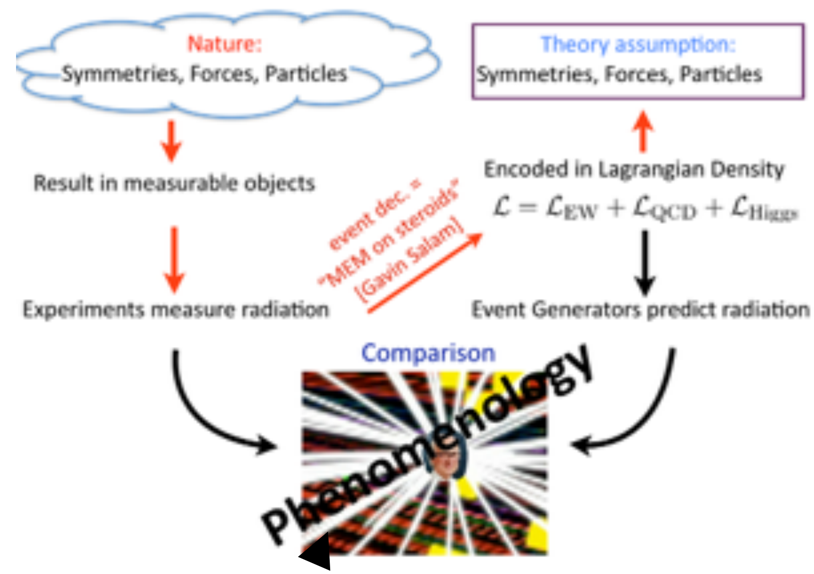
low Q^2 ⬌ longer time



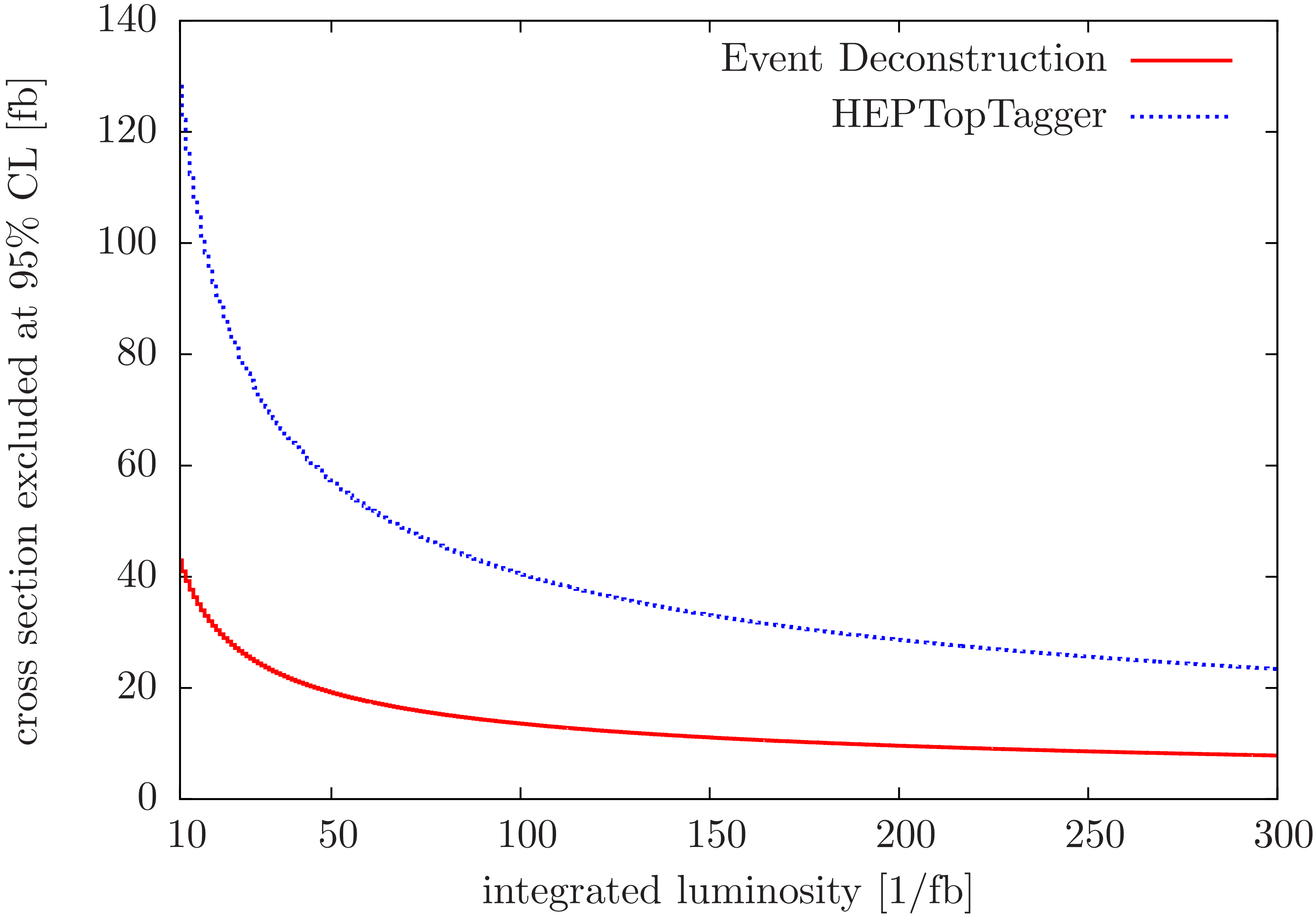
Event Deconstruction can be used to measure parameter of the theory, e.g. W mass.

Significance for different hypotheses for Mw:

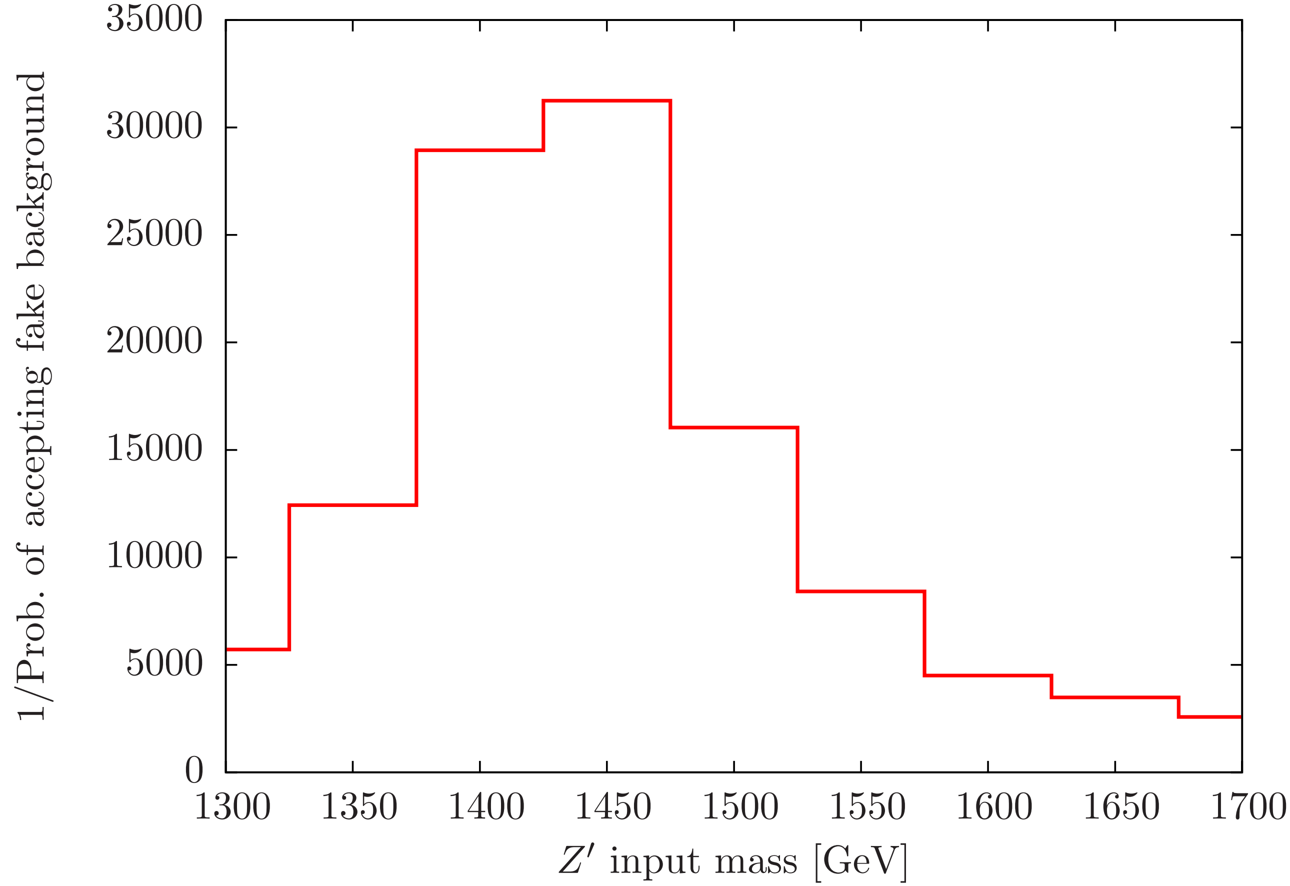




Proofs that Event Deconstruction provides direct link between Lagrangian and radiation profile


Event Deconstruction
HEPTopTagger
cross section excluded at 95% CL [fb]
integrated luminosity [1/fb]
0
20
40
60
80
100
120
140
10
50
100
150
200
250
300

Vary Z′ mass in Event Deconstruction (keep width fix = 130 GeV)



True Z′ mass is 1500 GeV

Invariant mass for fatjets j1+j2

→ Difference between true and tested Z′ mass understandable