Matrix Element Method

in

Higgs Phenomenology

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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

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Matrix Element Method

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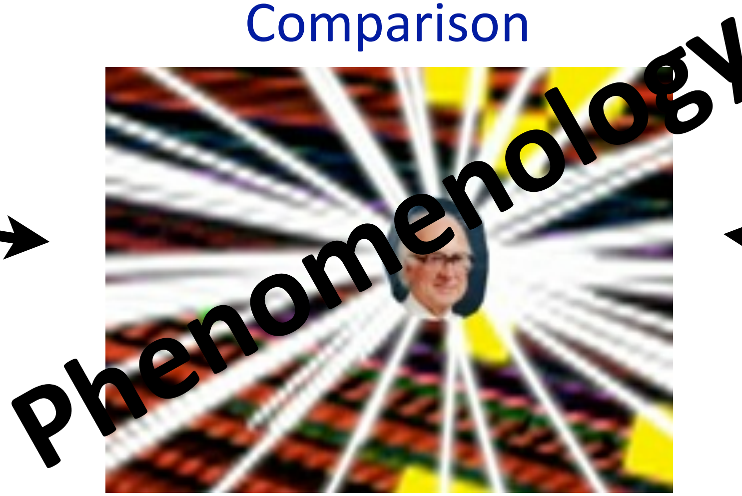
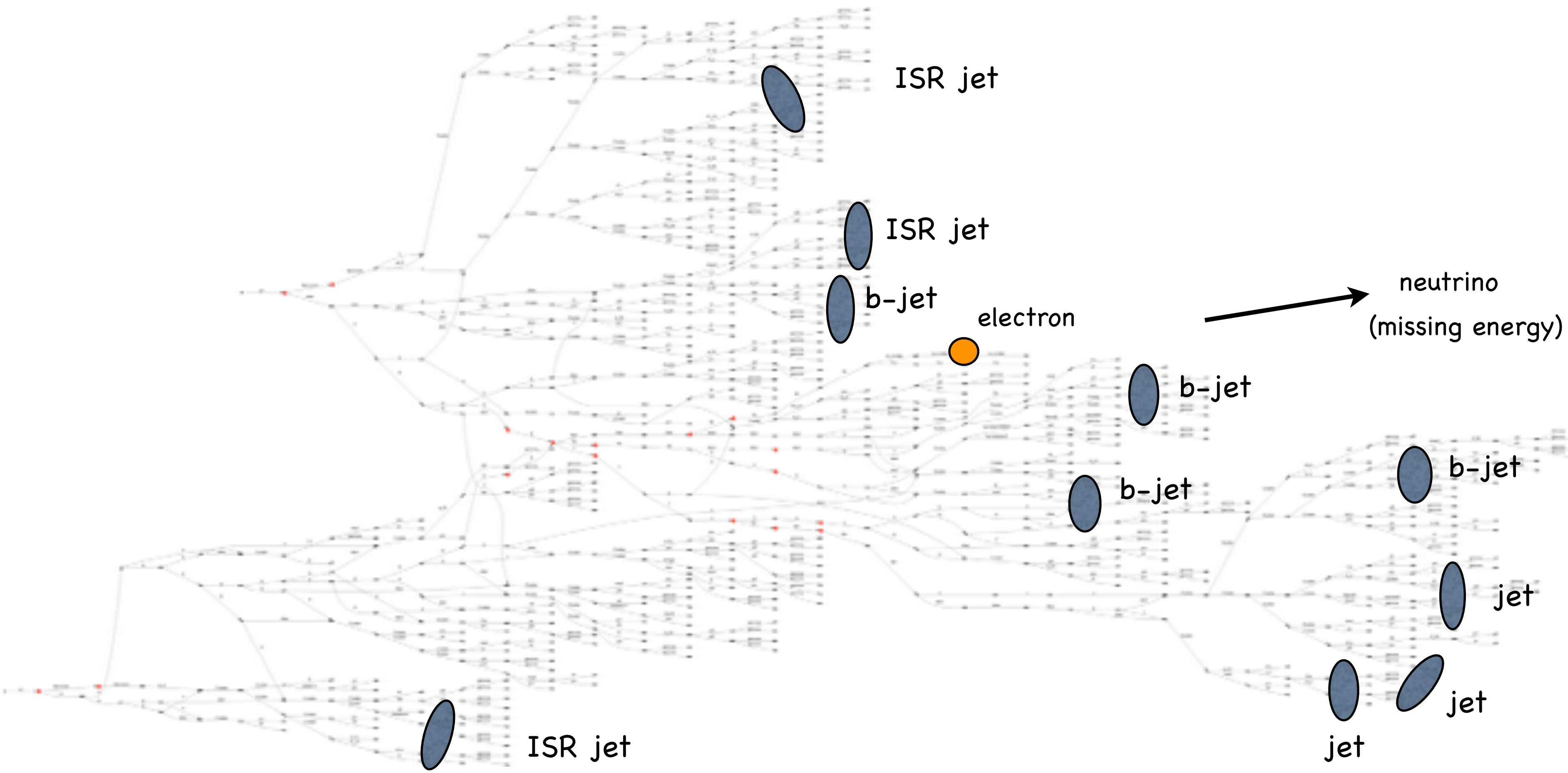
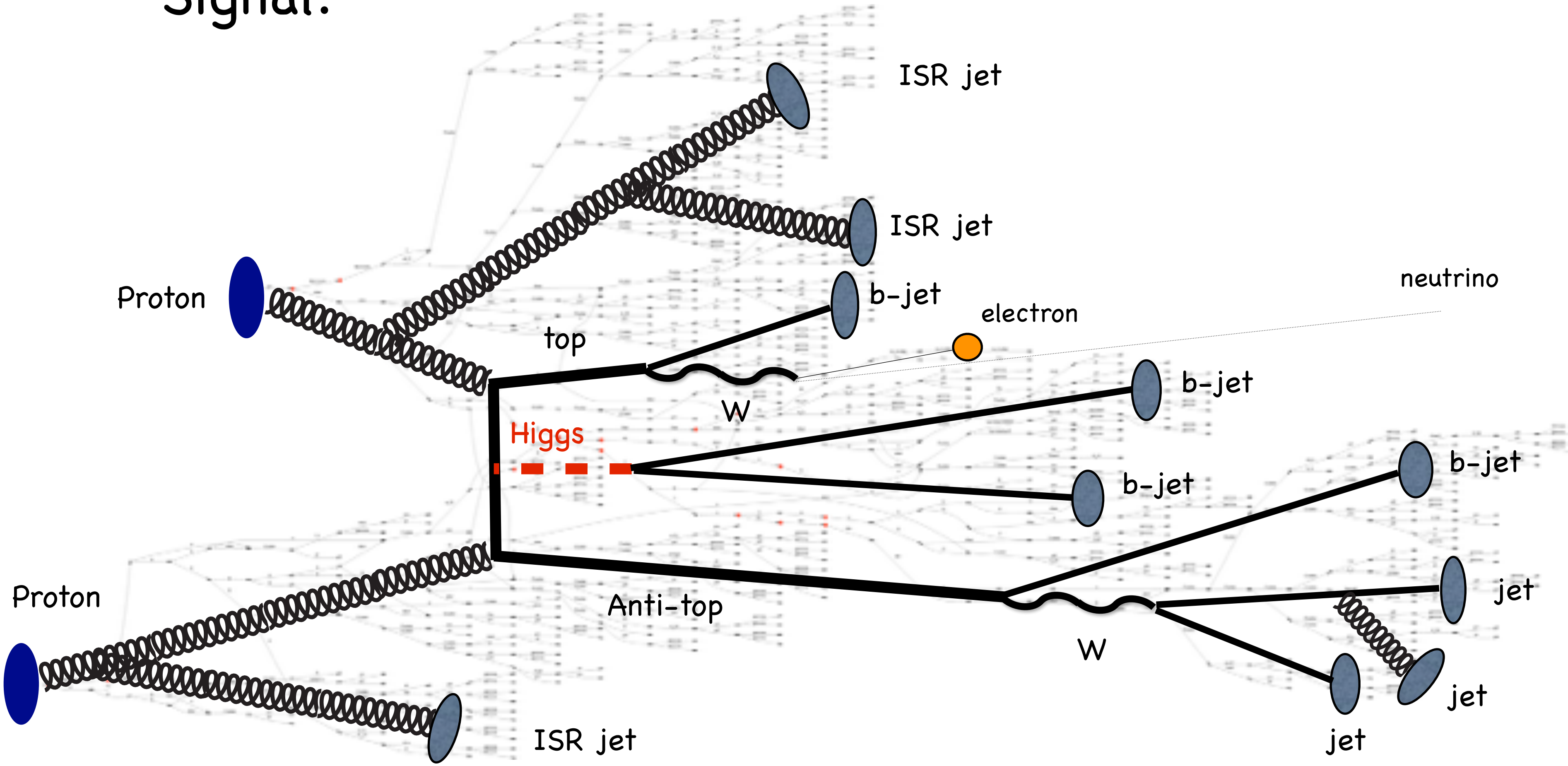


Inverse Problem: Final state measured ('phase space point chosen')



Give final state radiation distinctive meaning in terms of hypothesis

Signal:



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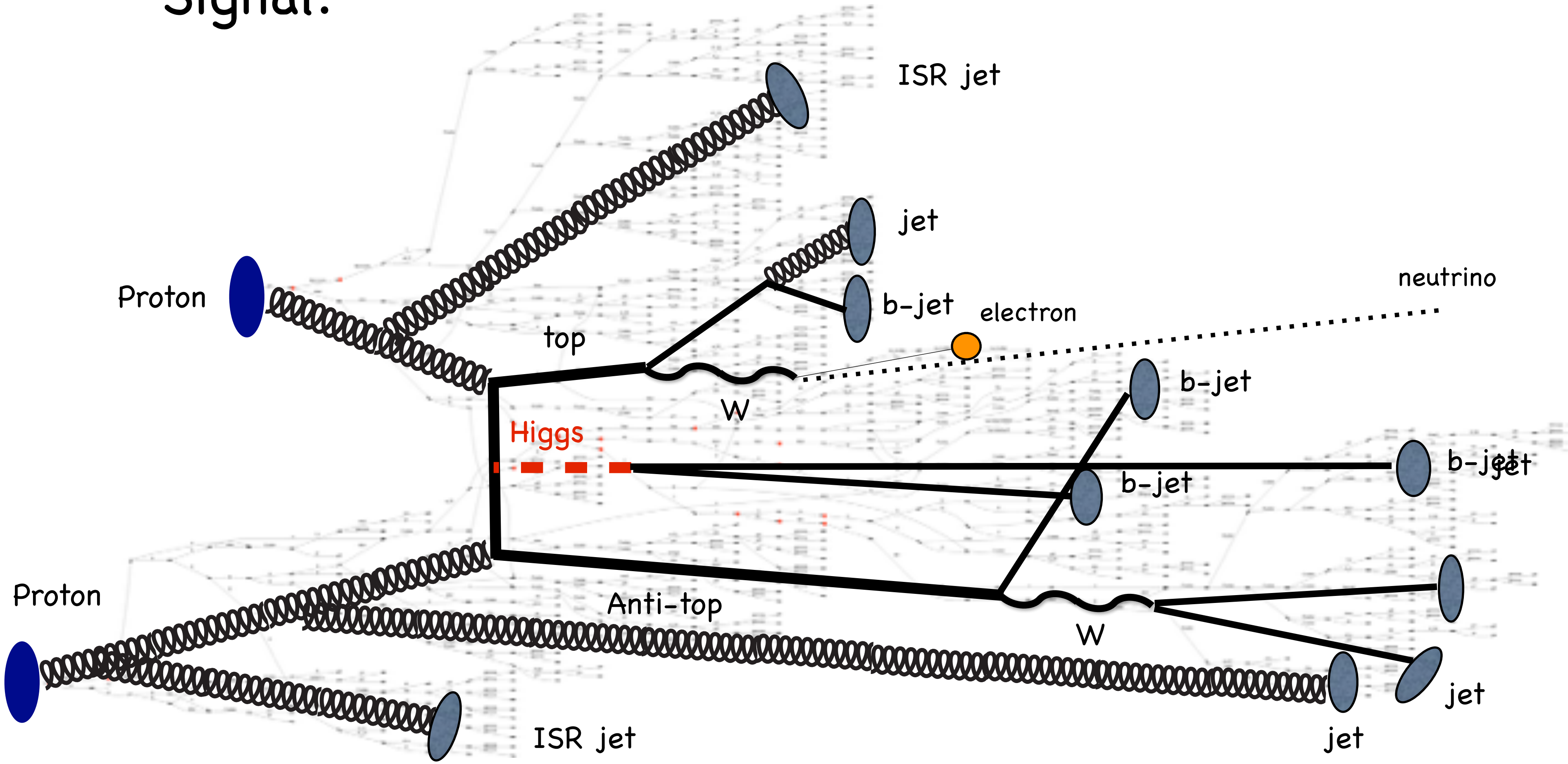

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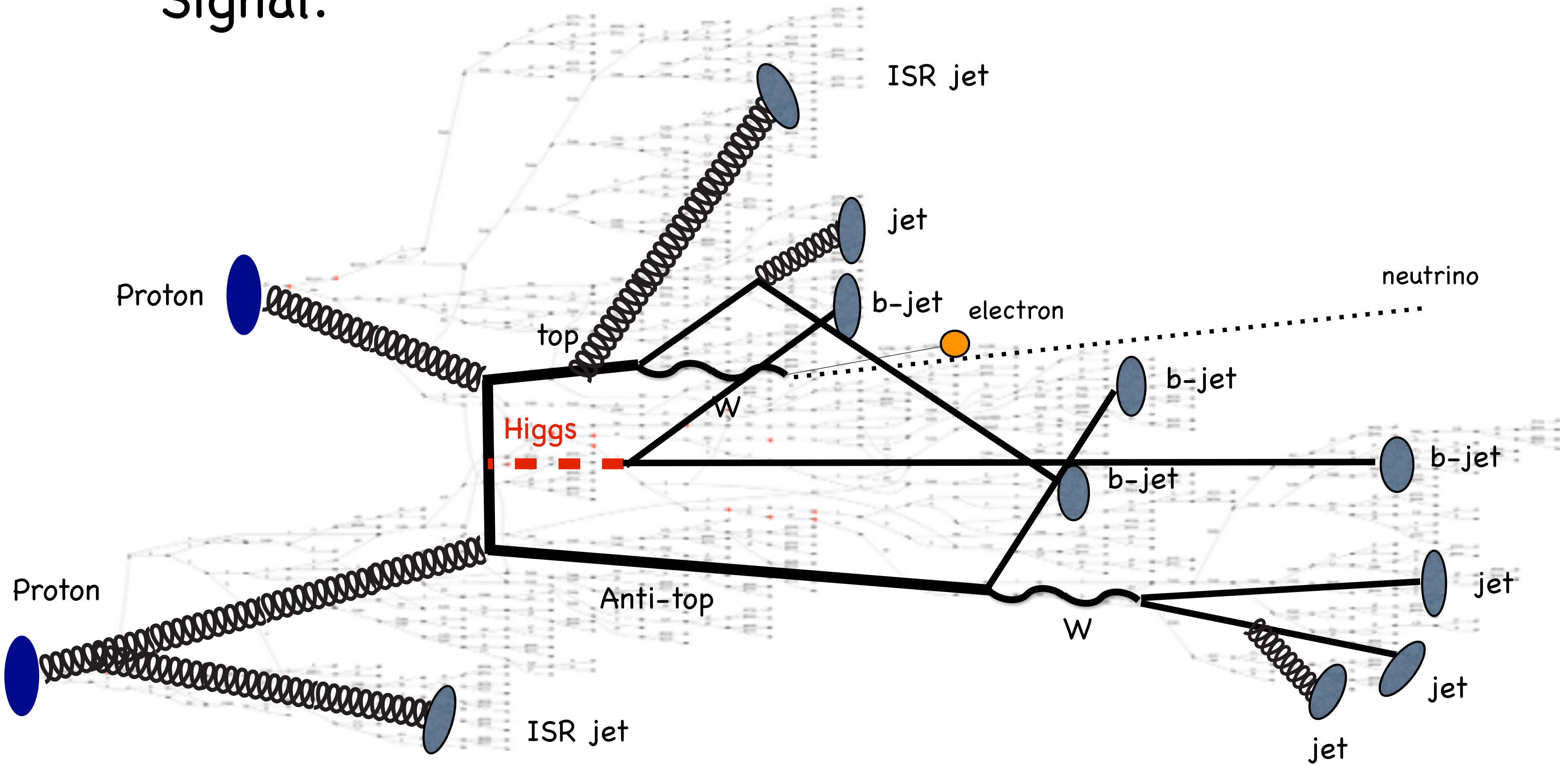
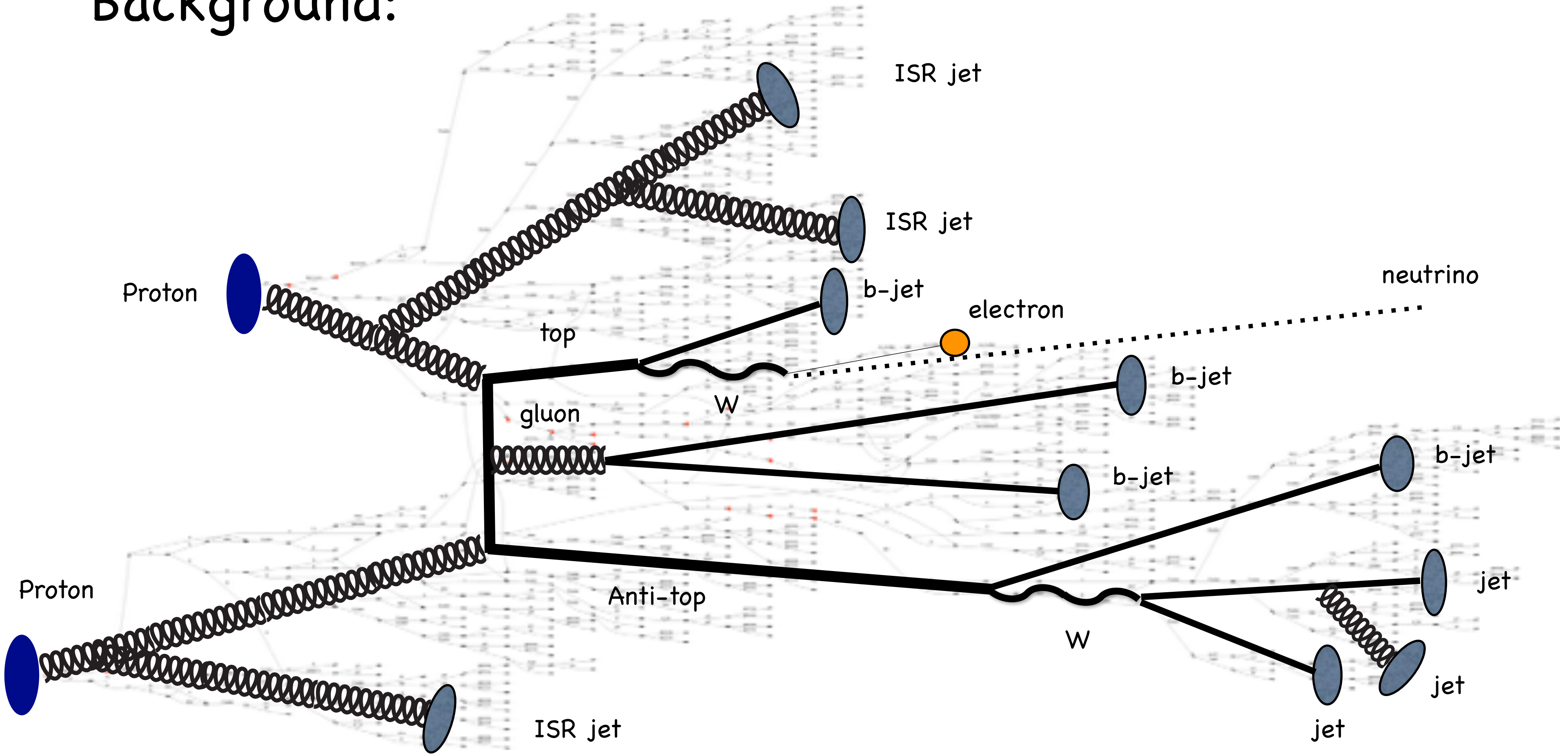
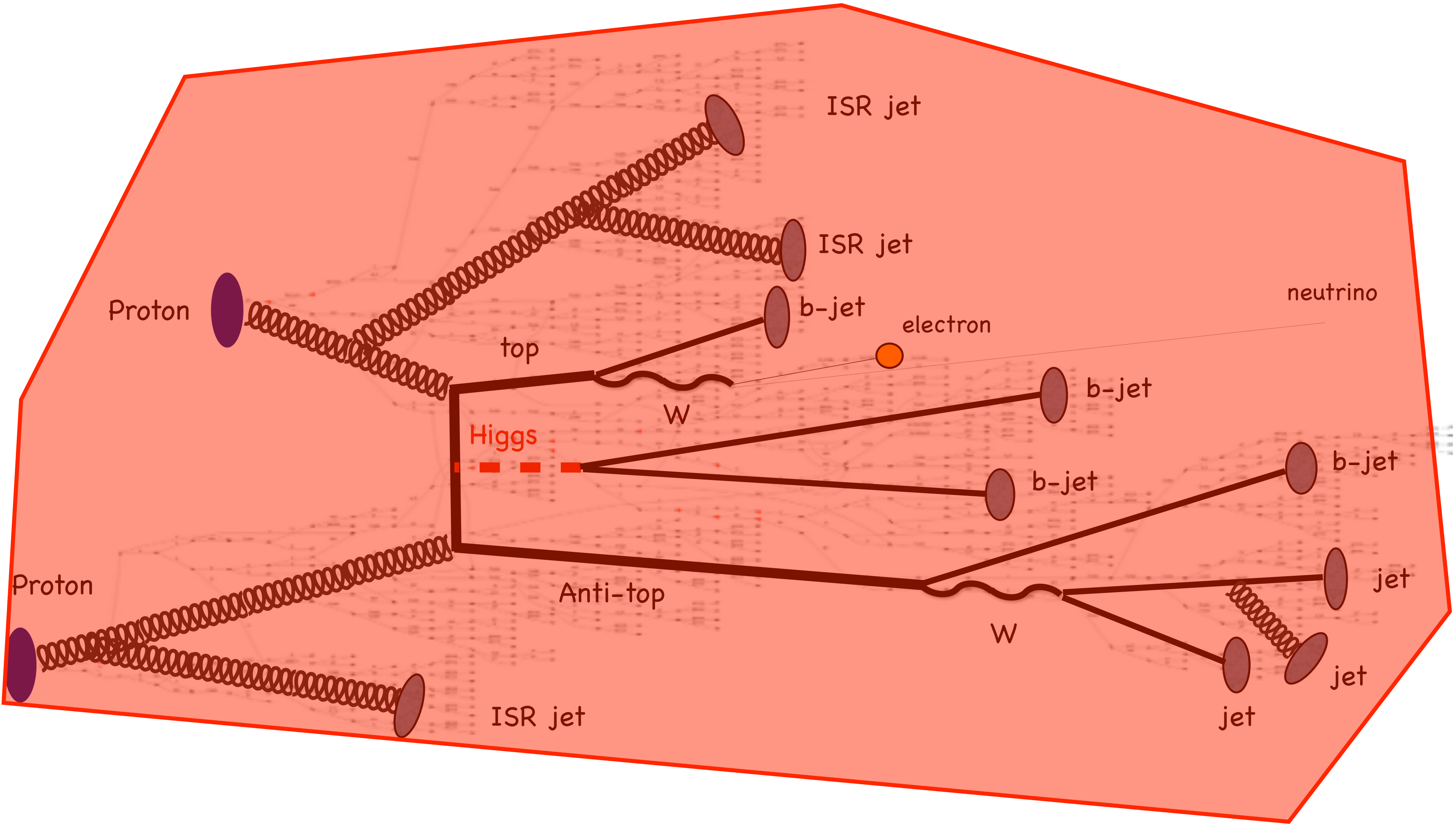


Give final state radiation distinctive meaning in terms of hypothesis

Background:



Ideally one would like to use all radiation related to hard process to discriminate signal from background



Applications of Matrix Element Method:

1988 Rec. of events with MET [Kondo, J.Phys.Soc.Jap. (1988)]

1998 Anomalous gauge couplings [Diehl, Nachtmann Eur. Phys. J. C1 (1998)]

2005 top quark physics [Abazov et al., Nature (2004), D0 Collab.]
[Abulencia et al., PRD 73 (2005), CDF Collab.]
[Abazov et al., PLB 617 (2005), D0 Collab.]

2010 Automated implementation in MadWeight
[Artoisenet et al, JHEP 1012 (2010)]

Plenty of recent applications in Higgs physics:

$H \to \mu^+\mu^-$ [Cranmer, Plehn EPJC 51 (2007)]

$H \to b\bar{b}$ [Soper, MS PRD 84 (2011)]

$H \to \gamma\gamma$ [Andersen, Englert, MS PRD 84 (2013)]

$pp \to t\bar{t}H$ [Artoisenet et al. PRL 111 (2013)]

$H \to ZZ^*/WW^*/Z\gamma$ [Campbell et al JHEP 1211 (2012)]
[Freitas et al PRD 88 (2013)] [Campbell et al PRD 87 (2013)]

Spin/Parity [Avery, et al. PRD 87 (2013)] [Gao et al. PRD 81 (2010)]

The matrix element method in a nutshell:

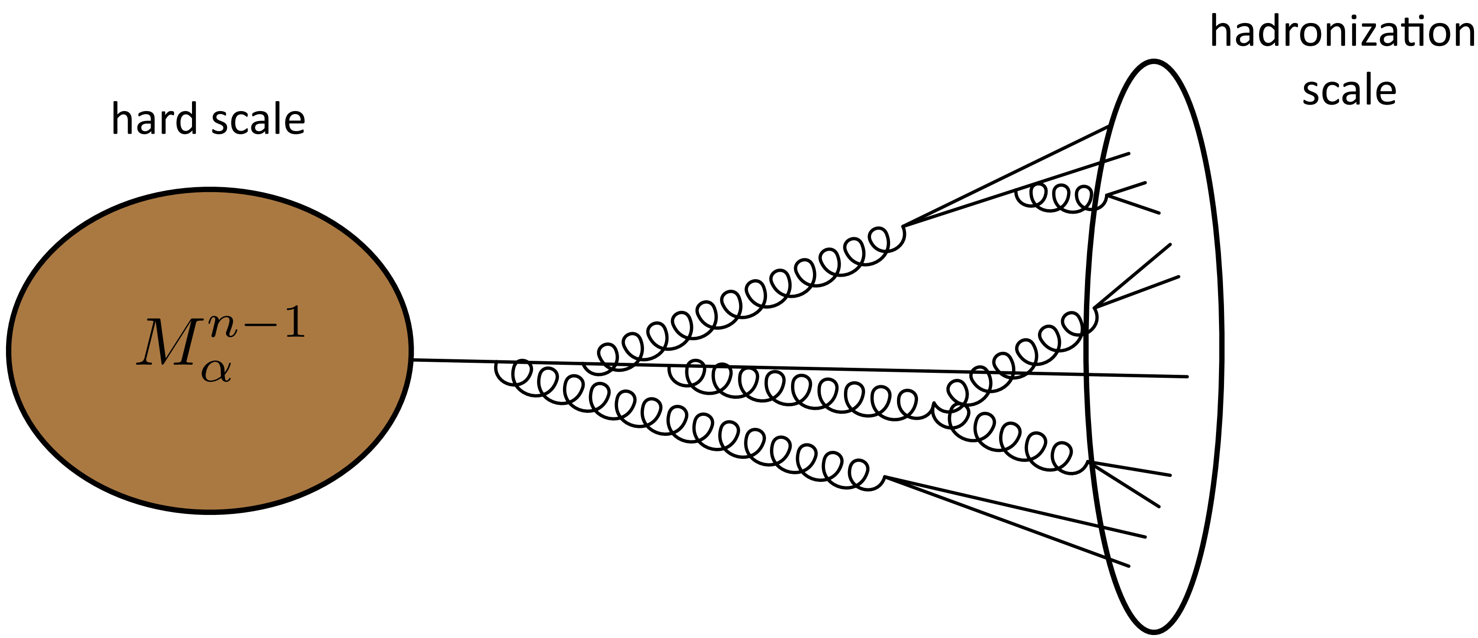
Given a theoretical assumption α, attach a weight $P(\mathbf{x},\alpha)$ to each experimental event **x** quantifying the validity of the theoretical assumption α for this event.

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

$|M_\alpha|^2$	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

Purpose of the transfer function is to match jets to partons



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

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

Subtleties of the convolution $|M(y)|^2 \times W(y,x)$

1) $|M(y)|^2$

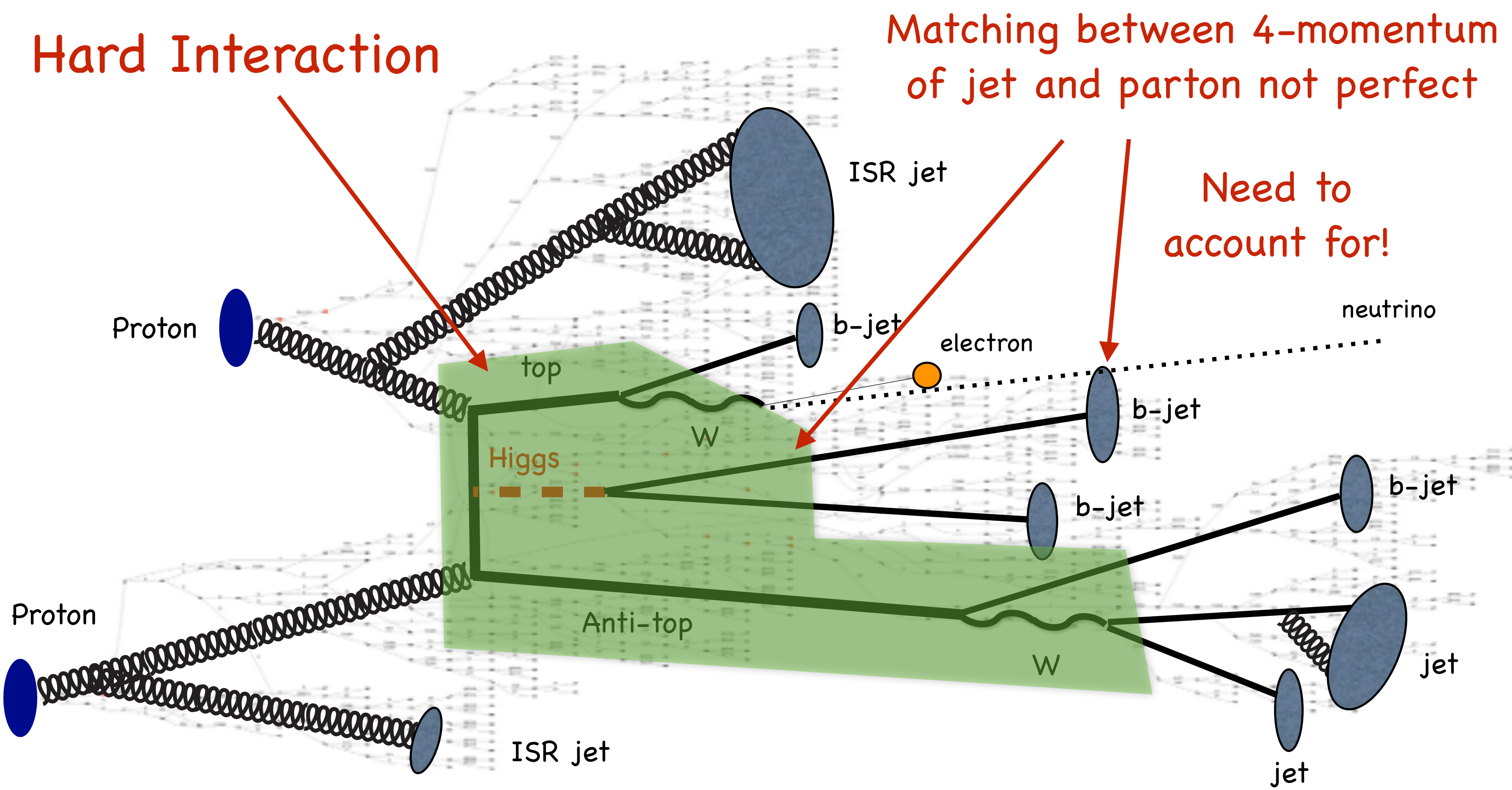
- Can be calculated at different order in pert. series (LO, NLO)
- Final state multiplicity fixed (exclusive process)
- Some kinematic configurations induce large logs (need resummation)

2) $W(y,x)$

- Number of final state objects limited to exclusive process
- Integration very time consuming -> limits final state multiplicity
- Transfer function fit dependent (input from experiment)

tth: di-lepton vs semileptonic channel

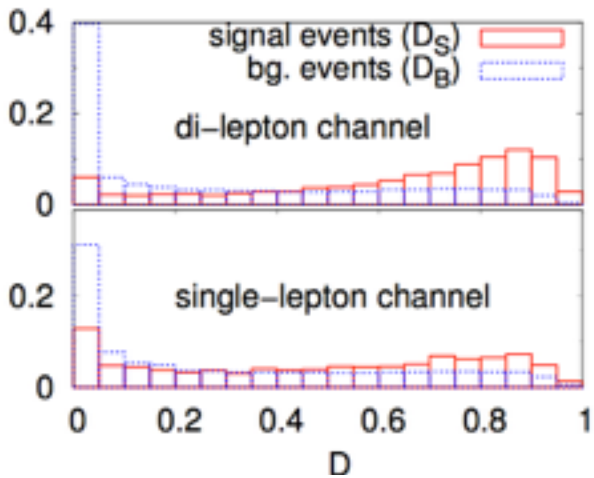
[Artoisenet et al. PRL 111 (2013)]



- Analysis with 4 b-jets and std reconstruction as input to MEM
- Full integration over invisible particles

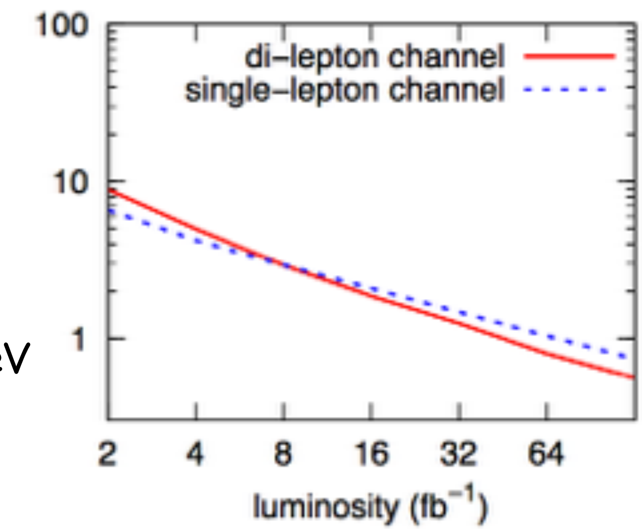
[Artoisenet et al. PRL 111 (2013)]

process	incl. σ	efficiency	$\sigma^{\rm rec}$
$t\bar{t}h$, single-lepton	111 fb	0.0485	5.37 fb
$t\bar{t}h$, di-lepton	17.7 fb	0.0359	0.634 fb
$t\bar{t}$+jets, single-lepton	256 pb	0.463×10^{-3}	119 fb
$t\bar{t}$+jets, di-lepton	40.9 pb	0.168×10^{-3}	6.89 fb



$$D_i = \frac{P(x_i|S)}{P(x_i|S) + P(x_i|B)}$$

Projection at 14 TeV



- Using Matrix Element Method di-lepton channel as sensitive than single-lepton channel

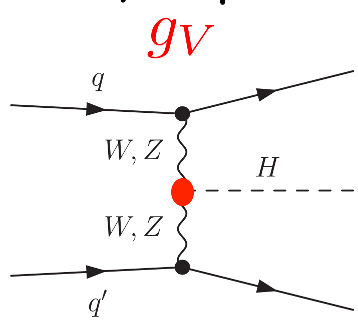
- However, single-lepton channel uses standard input, **boosted region not captured** [Plehn, Salam, MS PRL 104 (2009)]

We want to study more objects in final state ->
Transfer function limits us. Do we always need it?

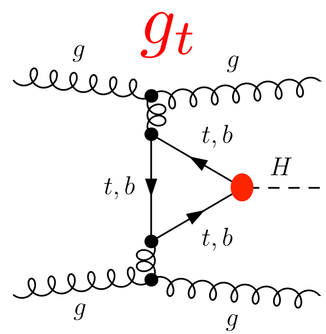
Transfer functions only important if matrix element varies quickly:

Example

[Andersen, Englert, MS PRD 84 (2013)]

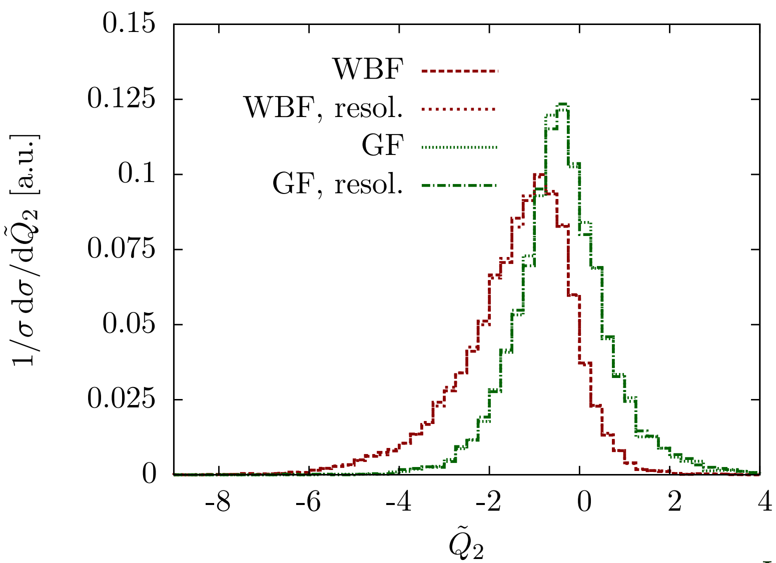


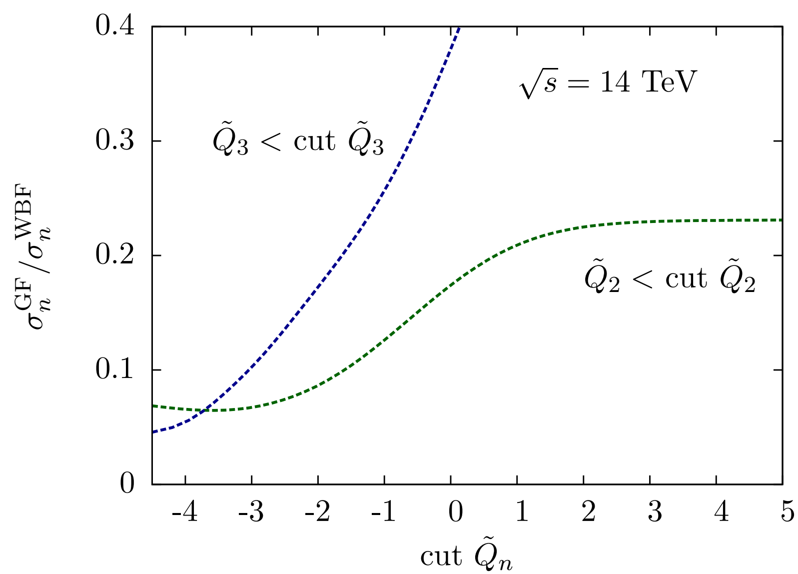
vs



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:





$$\tilde{Q}_n = -\log\left[\frac{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2}{|\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2}\right]$$

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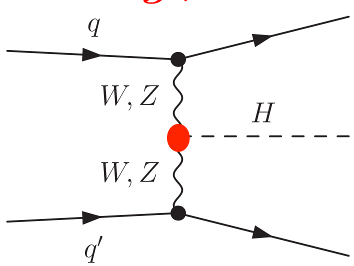
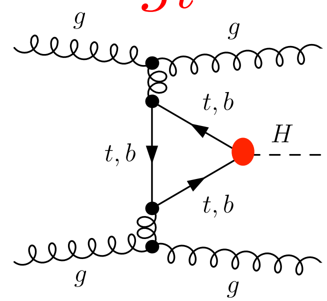
Example g_V



vs g_t



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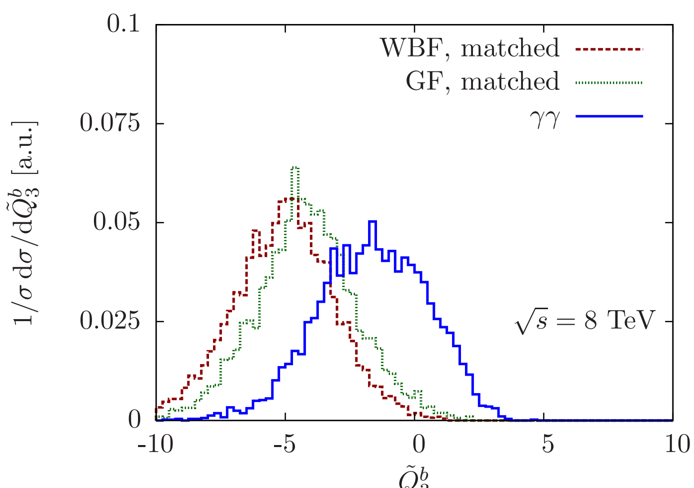


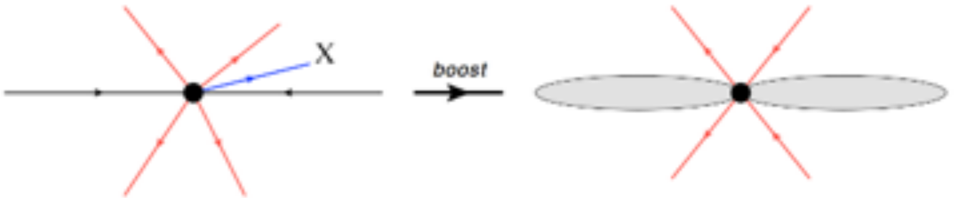
$S/B \nearrow 100\%$

$$\tilde{Q}^b_n(p^\gamma_1, p^\gamma_2, \{p^j_n\}) = -\log\left[\frac{\{|\mathcal{M}^{\mathrm{WBF}}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\mathrm{GF}}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$

After removing transfer function we can improve on precision of matrix element $|M(y)|^2$

Matrix element method at NLO: [Campbell, Giele, Williams JHEP 1211 (2012)]

Boost along transverse and longitudinal direction such that LO final state multiplicity momenta balance



Born phase space, but long. boost not unique, need longitud. integration

$$\mathcal{P}_{NLO}^{MEM}(\{Q_n\}) = \frac{1}{\sigma_{NLO}} \int_{x_{min}}^{x_{max}} dx_1 \mathcal{P}_{NLO}(\Phi_B)$$

Calculate virtual for born topology

real for jet function

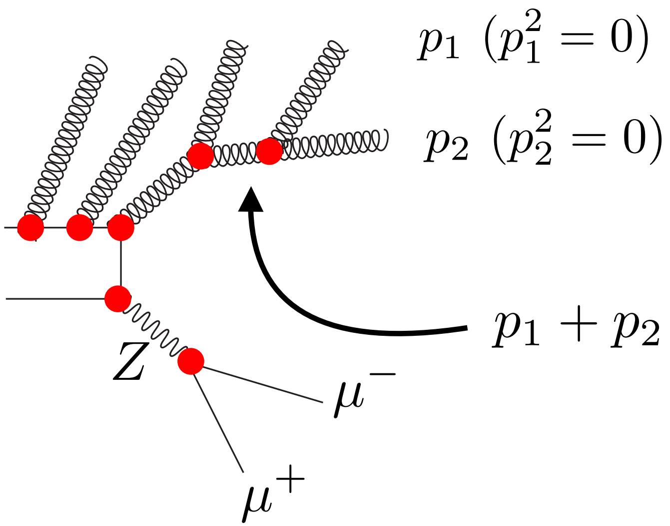
$$\eta^{lab,i} = \frac{1}{2} \log \left(\frac{x_a^2 s}{s_{ab}} \frac{s_{ib}}{s_{ai}} \right)$$

Application to H->4l (boost easier to identify)

sensitivity LO vs NLO improvement ~ 10%

Remove limitation of final state objects on $|M(y)|^2$

Shower approximation for matrix element, i.e. **shower deconstruction**:



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

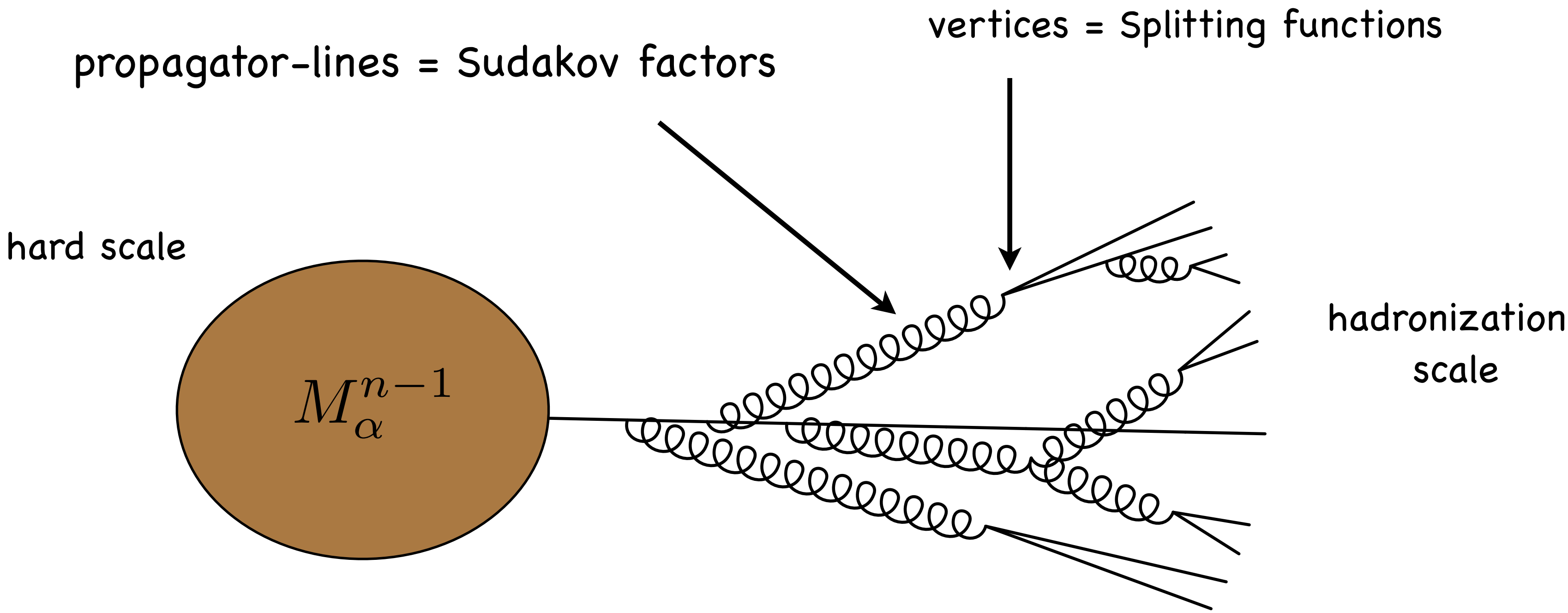
These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

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 $1/(p_1 + p_2)^2 \to \infty$

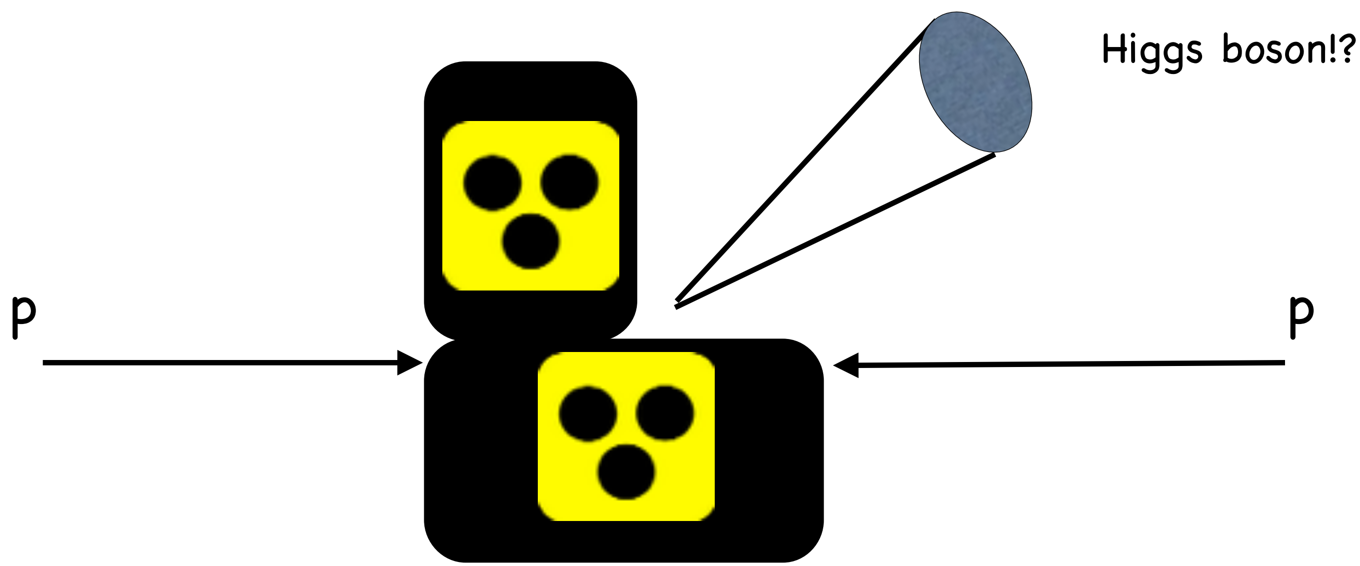
Factorization of emissions in soft/collinear limit

and Sudakov factors allow semiclassical approximation of quantum process:



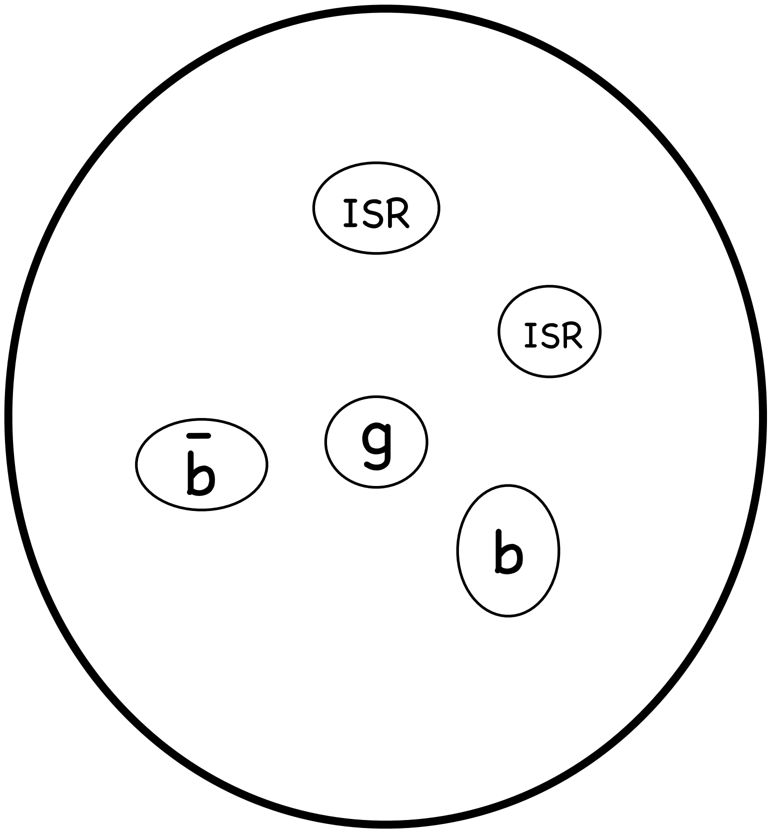
- Can calculate weight for shower history iteratively
- Can use smaller objects and more objects (more information)

This approach can be used as a tagger for Higgs bosons in H -> bb

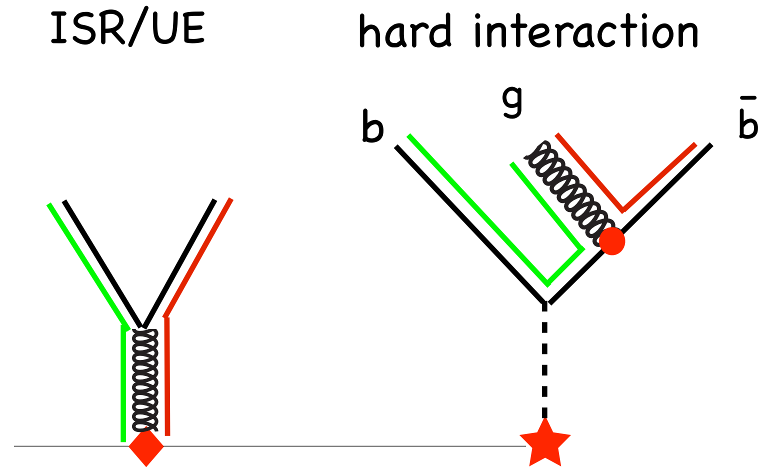


In boosted resonances radiation collimated, need Sudakov factors for valid description

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

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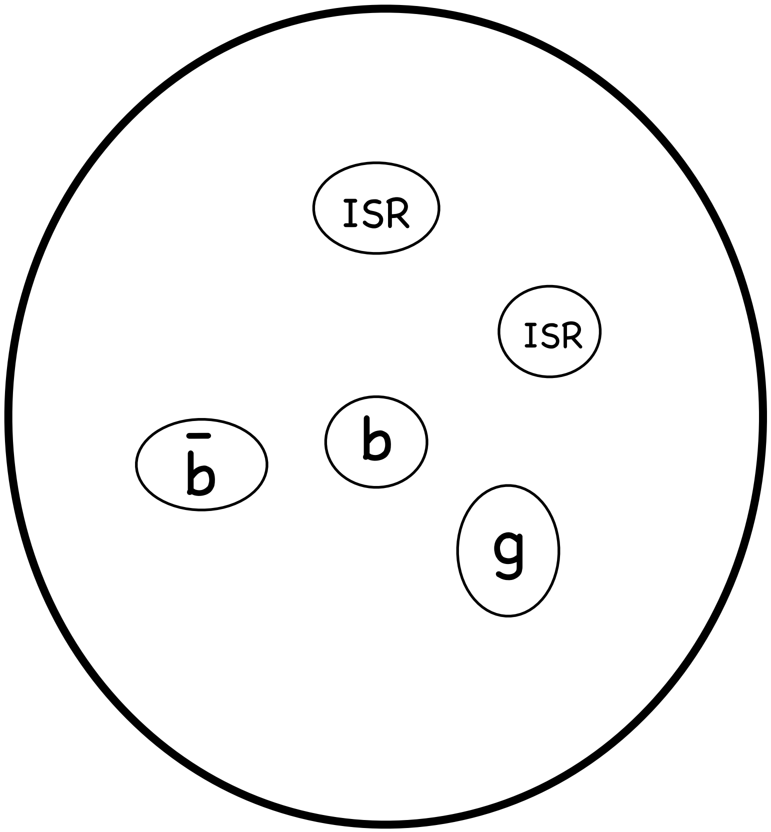

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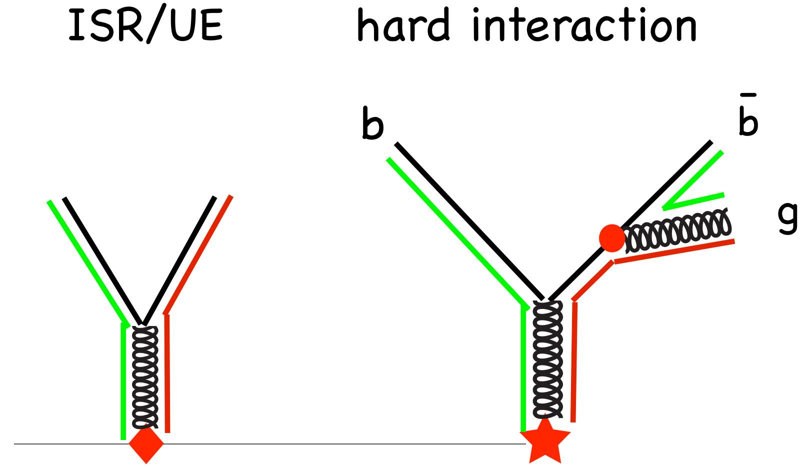

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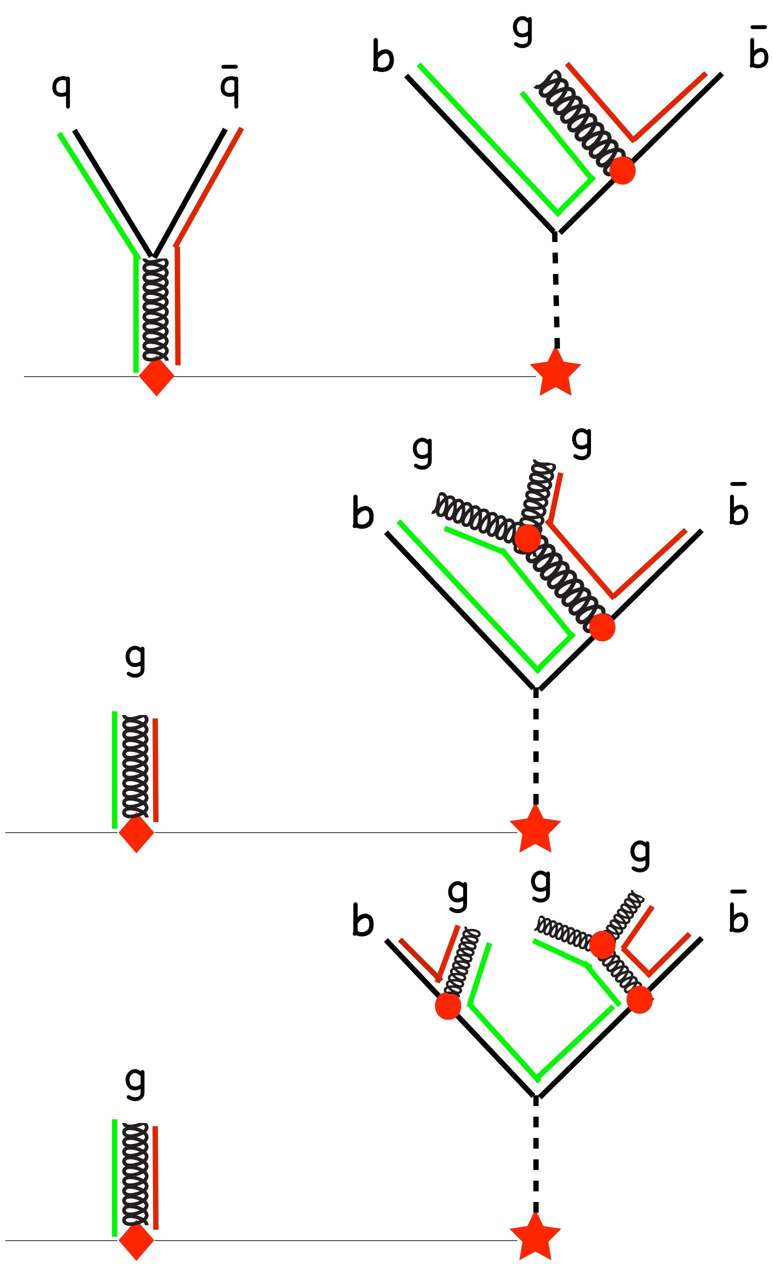
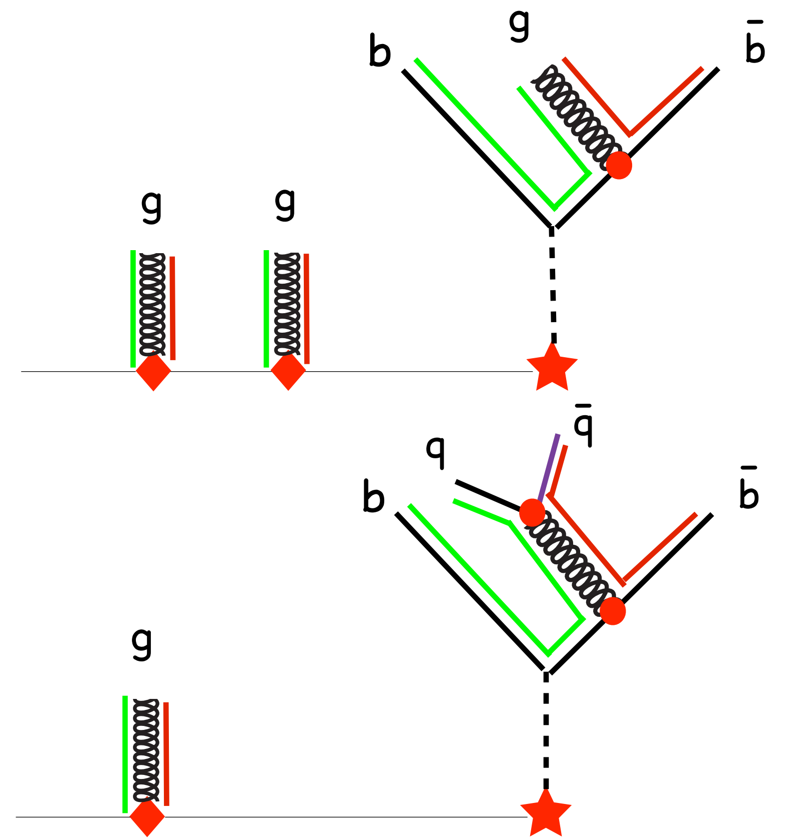


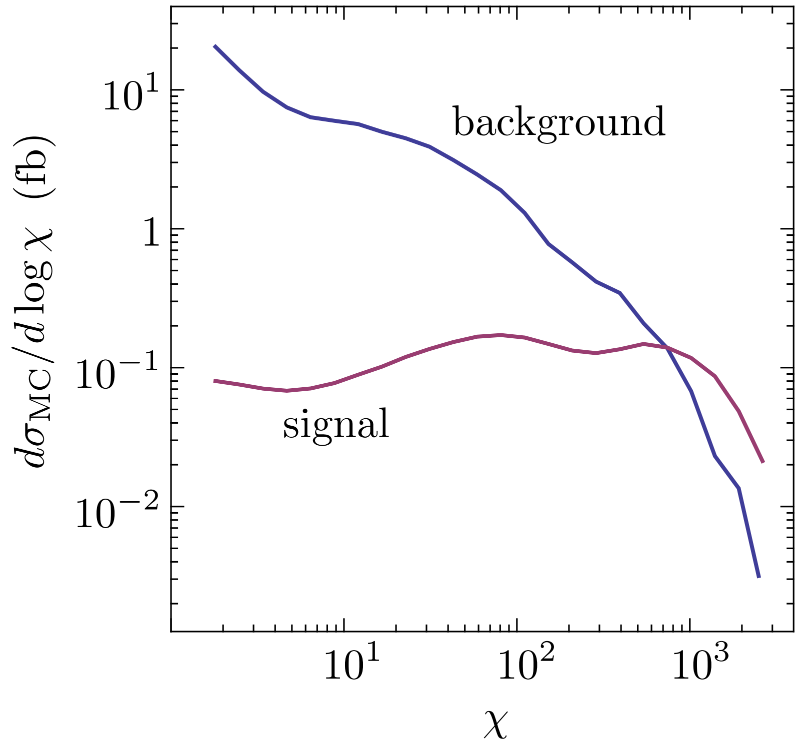


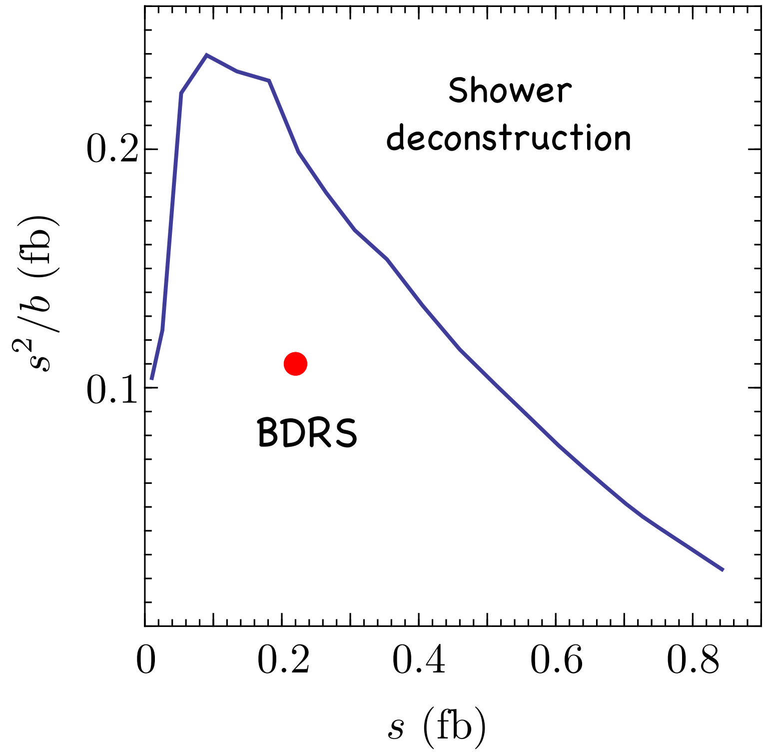
- And many more...
- And for all backgrounds...

Results for Higgs boson:

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

[Soper, MS PRD 84 (2011)]



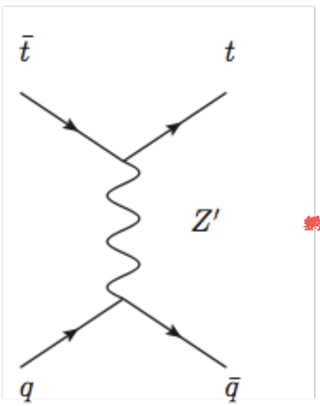


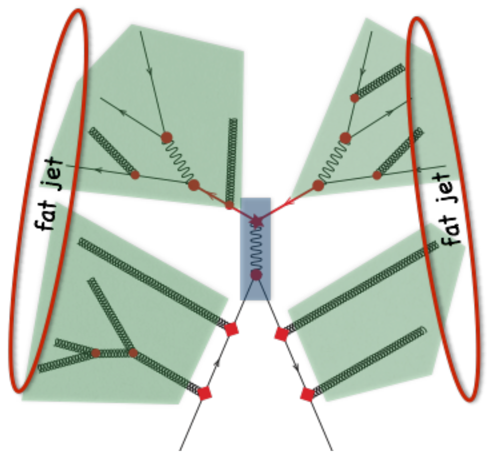
imperfect b-tagging (60%,2%) no b-tag required

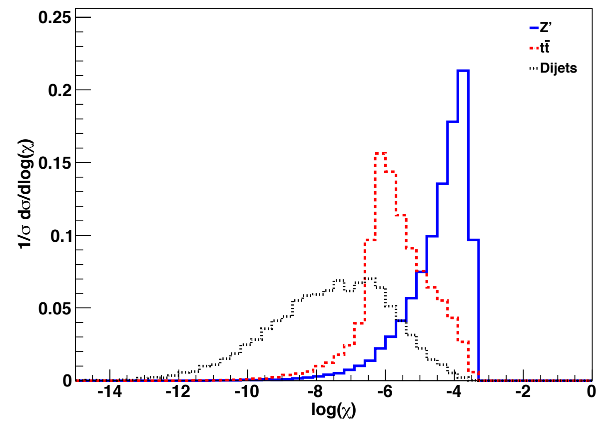
Next step, merge hard matrix element with shower approx.:

First attempt of Event Deconstruction in pp -> Z' -> tt

[Soper, MS PRD 89 (2014)]







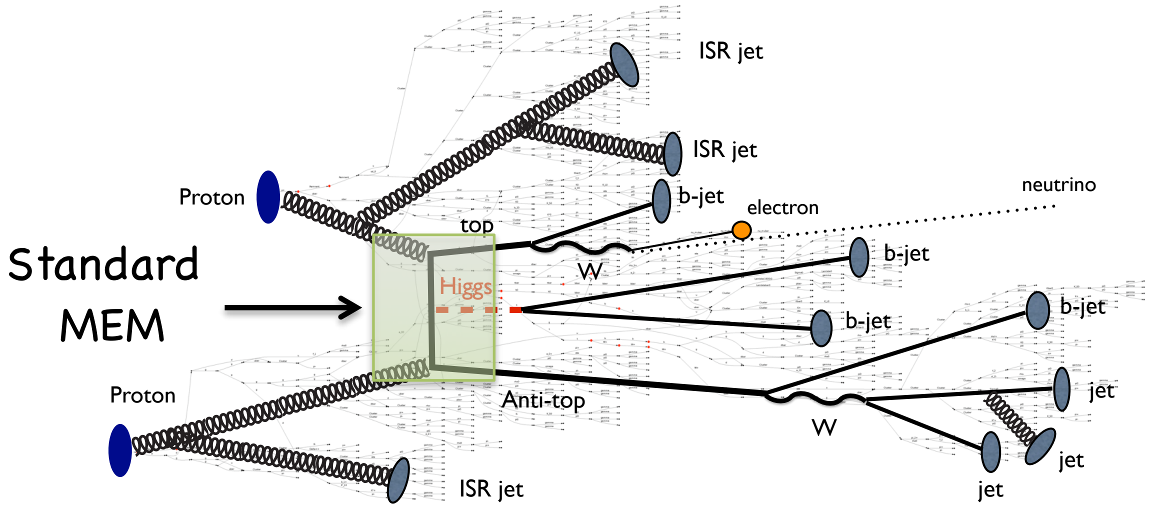
For full Event Deconstruction many steps missing:

- Include full model of Initial State Radiation
- Merge high-mult. matrix elements (CKKW)
- Add model for soft/non-pert radiation
- Improved sampling over histories

Summary

- Matrix Element Method is active field of research
  [see also MEM Workshops in Louvain (2013) and Zurich (2014)]
- Measurement of Higgs properties relies on reconstruction
  MEM can be important tool in many processes

- My personal view:



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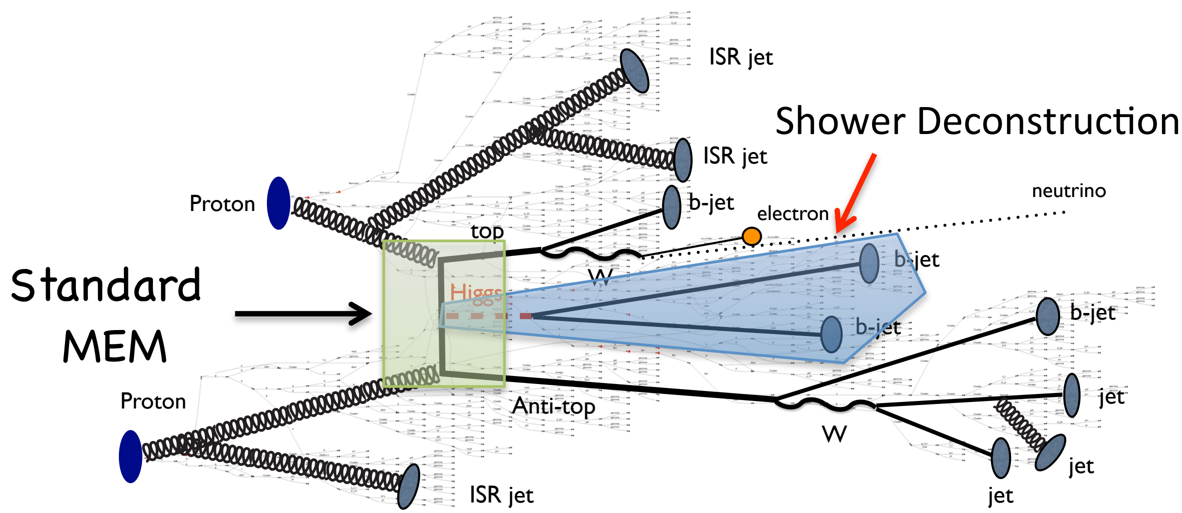

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  Event Deconstruction, i.e. Pattern Recognition for full event

Future MEM