

Matrix Element Methods for particle and event identification

Michael Spannowsky

University of Durham

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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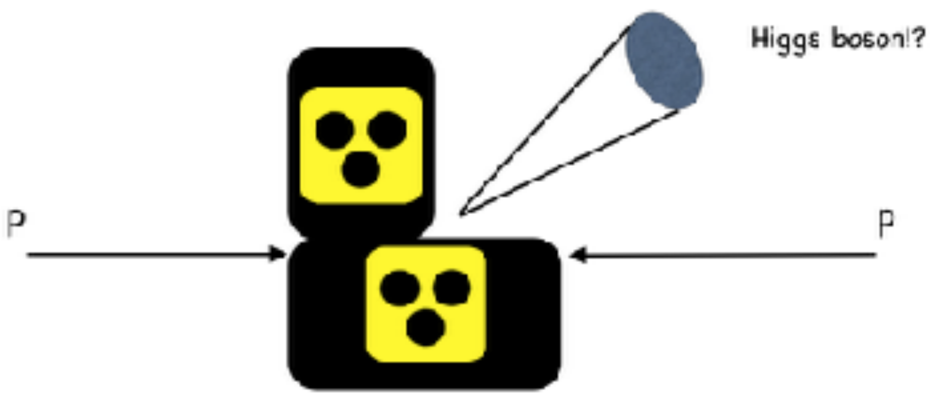
Phenomenology

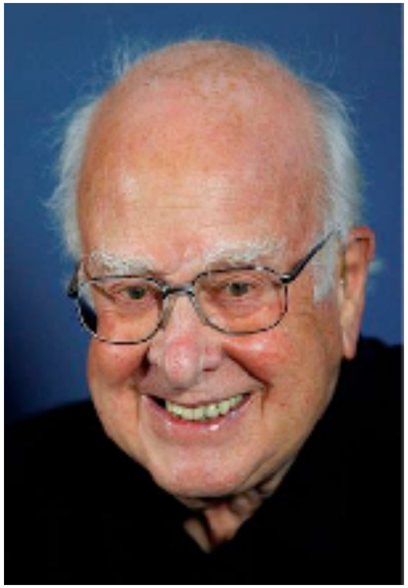
You can compare measurement vs theory prediction for full events or only for individual objects (= tagging)

Identification exploits fact that quantum numbers of signal resonance different than backgrounds

Quantum numbers are:
mass, colour, spin, couplings (width)

→ exploit relation between radiation and QM numbers





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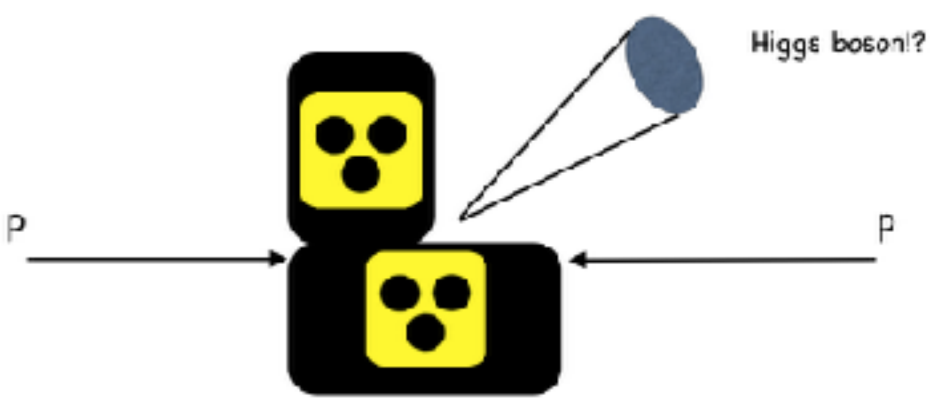

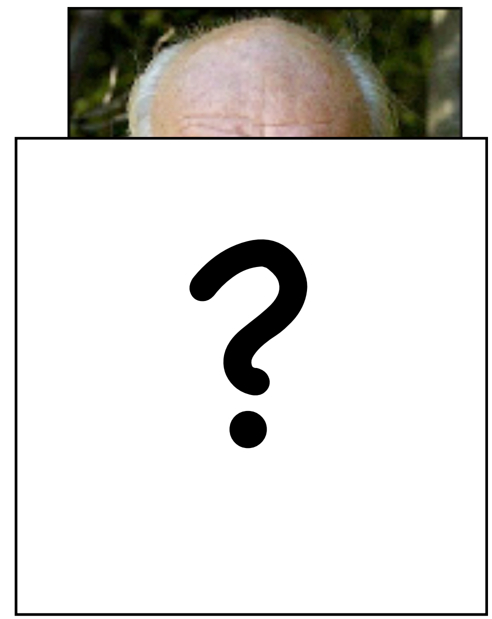

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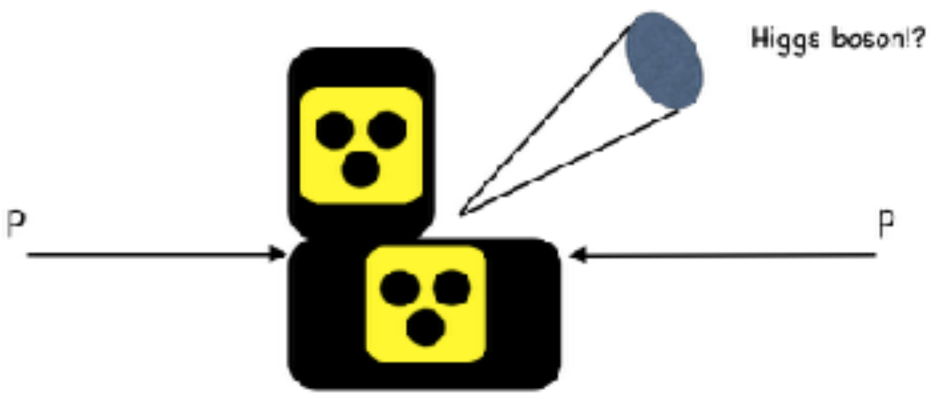

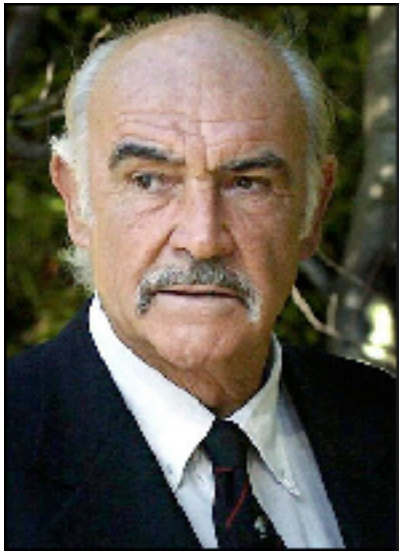

[Sean Connery]

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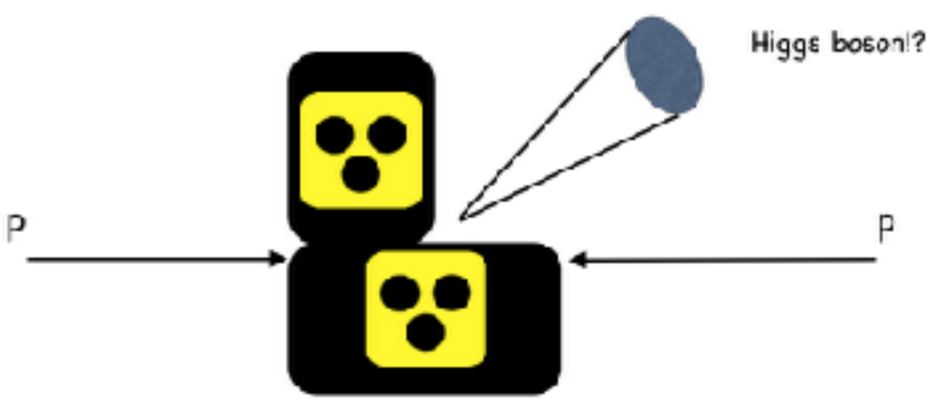

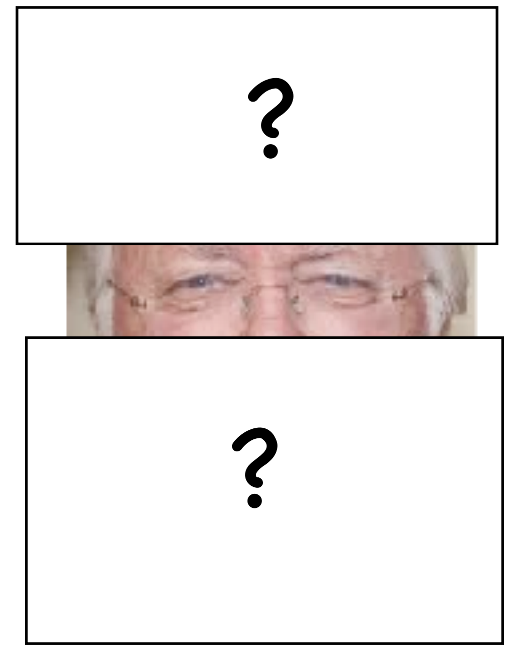

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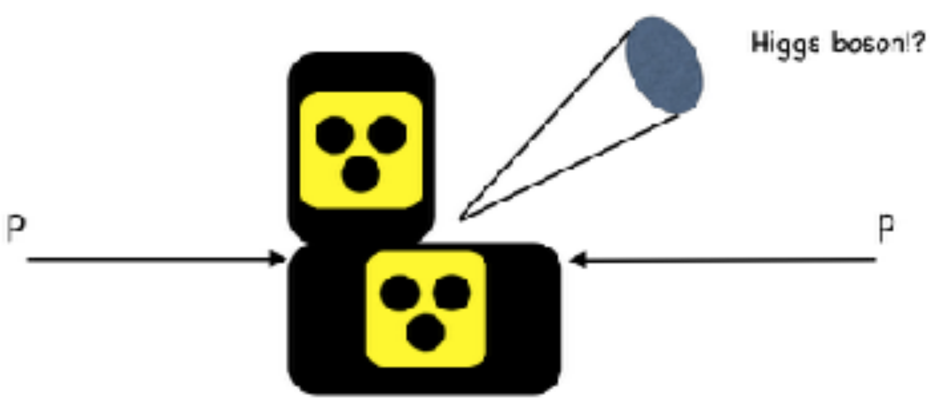
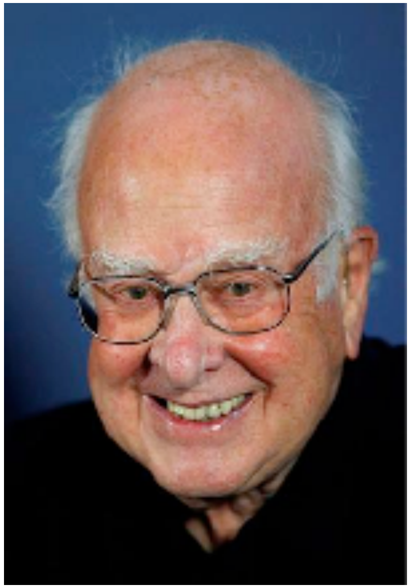


[Richard Attenborough]

You can compare measurement vs theory prediction for full events or only for individual objects (= tagging)

Taking the full information simultaneously into account will give you the best chance to discriminate competing hypotheses

→ face recognition for object/event



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Matrix Element Method

Machine Learning MVAs

Experiments measure radiation

Event Generators predict radiation

Comparison

“The strange death of theory”

Frankfurter Allgemeine Zeitung

23.01.2017

or is it?

Matrix Element Method vs Multi-variate Analysis

(= pQCD = QFT)

Tilman's proposal from yesterday:

Matrix Element Method vs Multi-variate Analysis

(= pQCD = QFT)

Tilman's proposal from yesterday:

Matrix Element Method vs Multi-variate Analysis

(= pQCD = QFT)

- MVA well motivated to extract correlations without existing theory, i.e. **stock trade**
- In particle physics we established gauge theories, thus, we have existing theory to predict connection of 'input with output'
- Current pheno approach:

We take first-principle QFT: $\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{Higgs}}$

Put it into an event generator to generate pseudo-data

Then a smart physicist or MVA comes up with way to access the Lagrangian we put in in the first place

$\longrightarrow$ Seems like an unnecessary detour...

Training MVAs on Monte Carlo

- MVAs will optimise for - according to MC - most sensitive exclusive phase space regions

  $\longrightarrow$ theory uncertainties difficult to control

- Full event generators are mashup of different parts that are partly tuned, i.e. hard interaction, UE, ISR,...

- Highly computationally intensive. If you want to template correlations of say 7 particles:
  - Time estimate:

    7 microjets, each 4-momentum components divided into only 10 bins

    -> $10^{28}/7! \sim 10^{24}$ configurations

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

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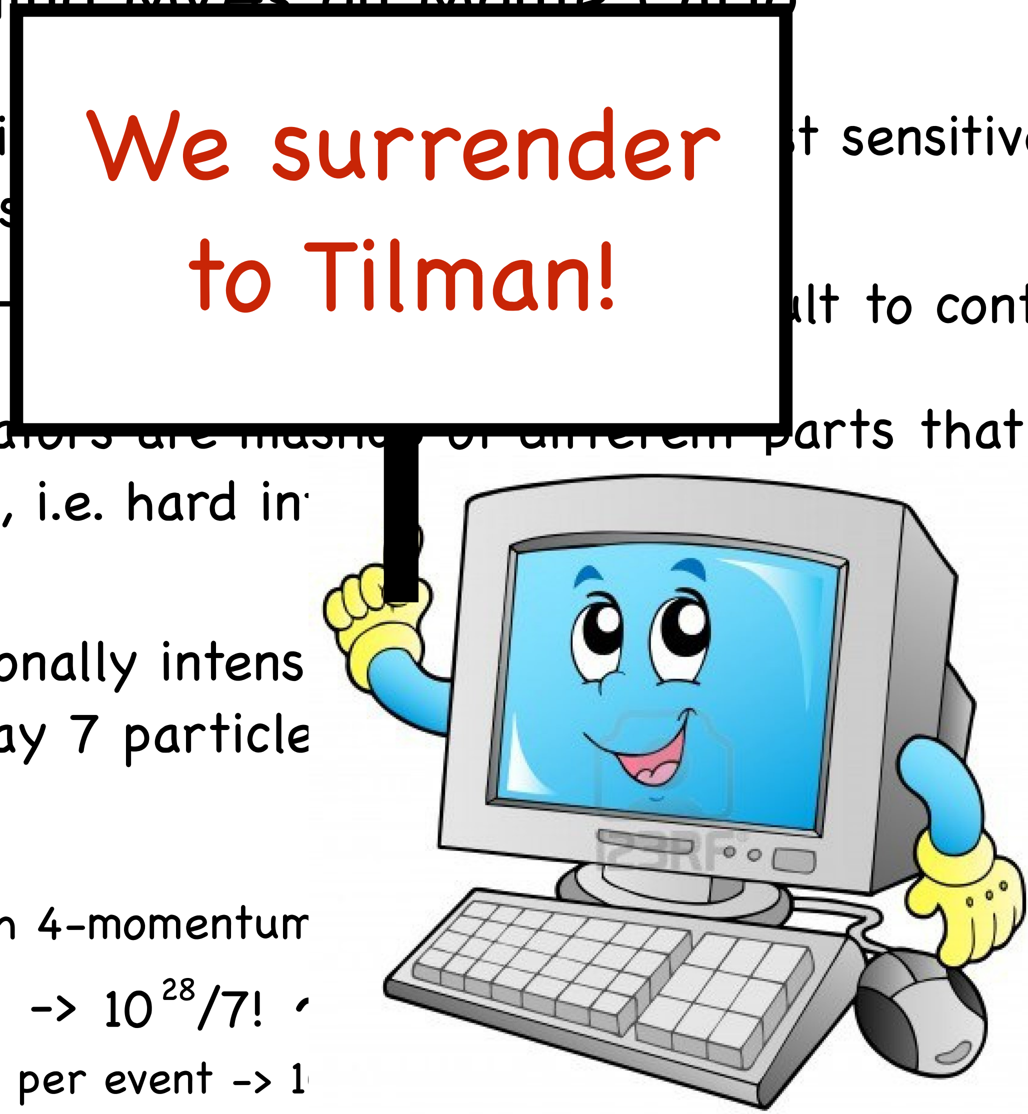


Training MVAs on data only

- Less plagued by systematics

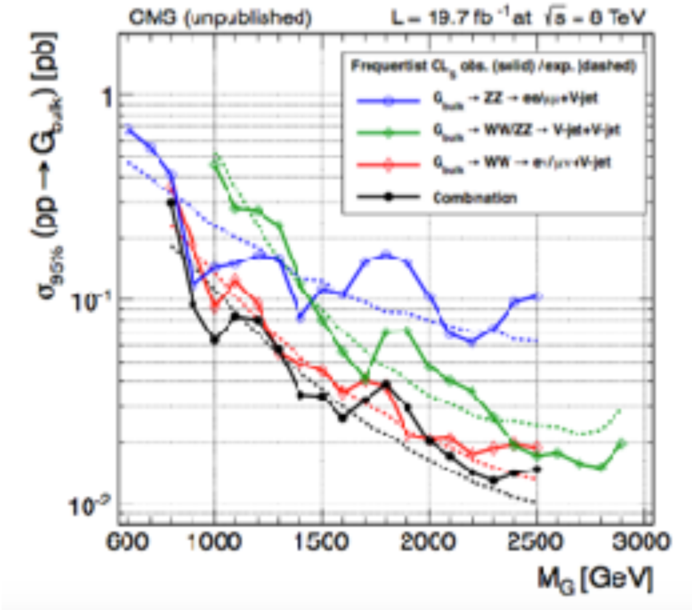
- But only possible if objects to reconstruct or events to measure already in data.
  -> oxymoron for discovery of anything new, e.g. gluino-tag, axion-tag, pp->HH->4b,...

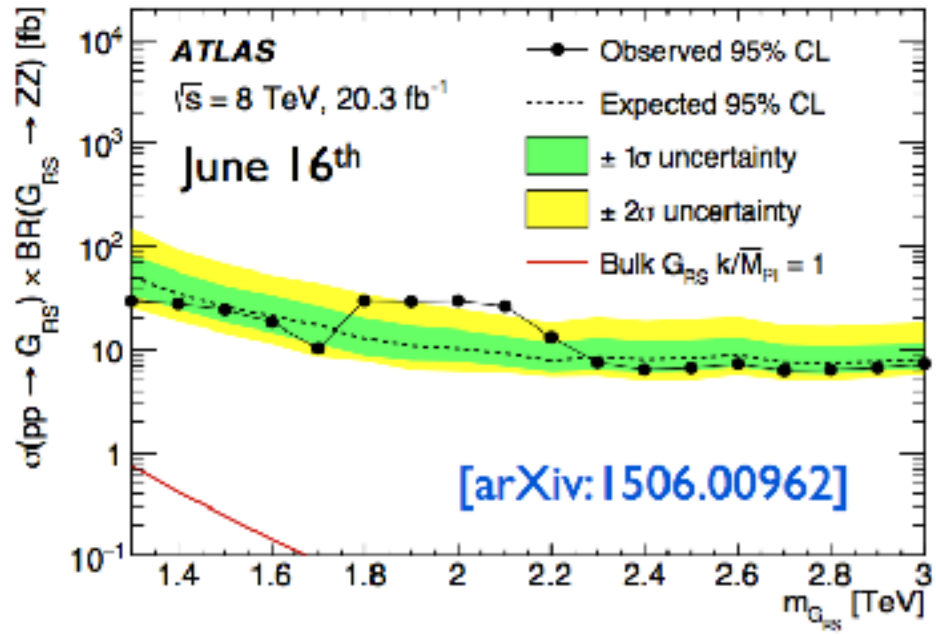
- Everything done purely on data without theory cross-check has 0 safety margins...

➡2 TeV excess in ATLAS and CMS might be an example (though I am not saying that anything was done wrongly)

Brief interlude for the 2 TeV di-boson excess

[CMS EXO-13-009]





- CMS sees small but consistently excesses in di-boson final states

- First excess in semileptonic final state using jet substructure from 2012

	CMS	ATLAS
$V_{jet}\ V_{jet}$	1.3σ	3.4σ (2.5σ global)
$\ell\ell\ V_{jet}$	2σ	-
$\ell\nu\ V_{jet}$	1.2σ	-

- While masses seem consistent cross sections dont across channels

ATLAS VV excess

Most significant. Lets focus on this analysis

[Talk by C. Delitzsch at BOOST 2015]

Event Selection

- Compared to semileptonic analysis only boosted regime is considered
- Reject events with electron or muon candidate or $E_T^{miss} > 350$ GeV (orthogonal to other diboson resonance searches)
- Overlap between WW, WZ, ZZ selection due to chosen mass window
- Rapidity difference: $|y_1 - y_2| < 1.2$
- p_T asymmetry: $|(p_{T_1} - p_{T_2})|/(p_{T_1} + p_{T_2}) < 0.15$
- $m_{JJ} > 1.05$ TeV: trigger plateau of large-R jet trigger

August 11, 2015 — Searches for diboson resonances using boson tagging in ATLAS — 15

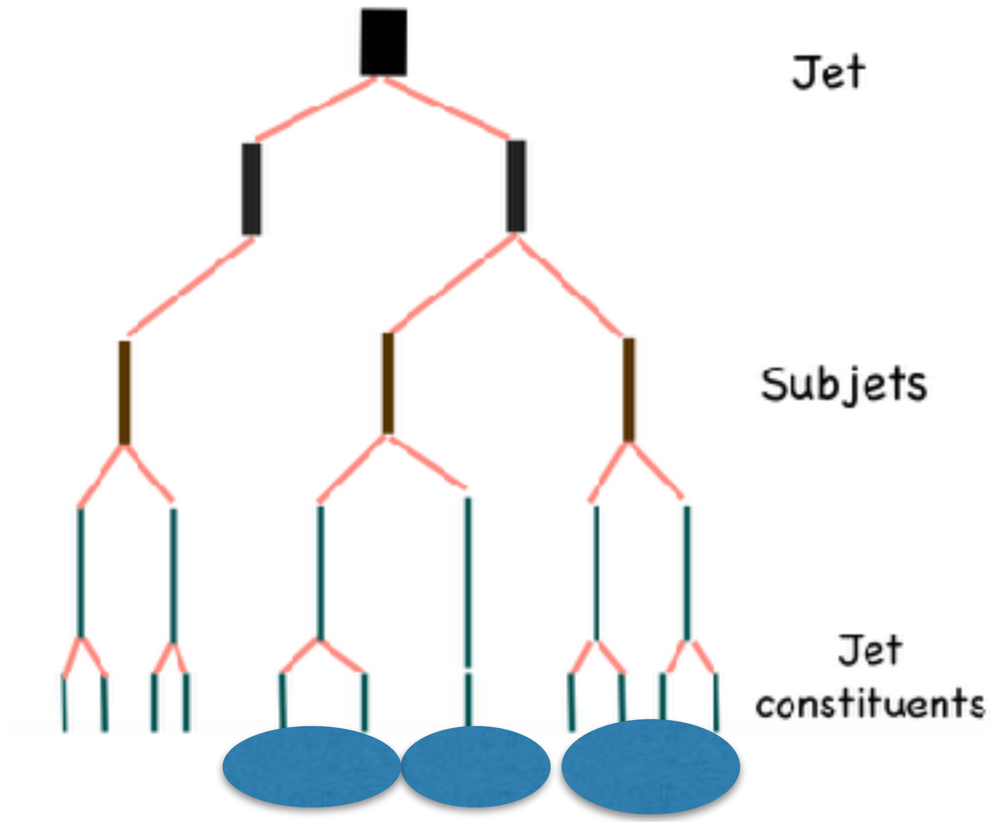
- For ungroomed fatjets pT,j > 540 GeV
- Reconstruction of VV final state follows same principles as discussed before

Resonance reconstruction

BDRS method

- Only y-cut applied when declustering
- y-cut fires, stop declustering and filter while keeping 1-3 subjets

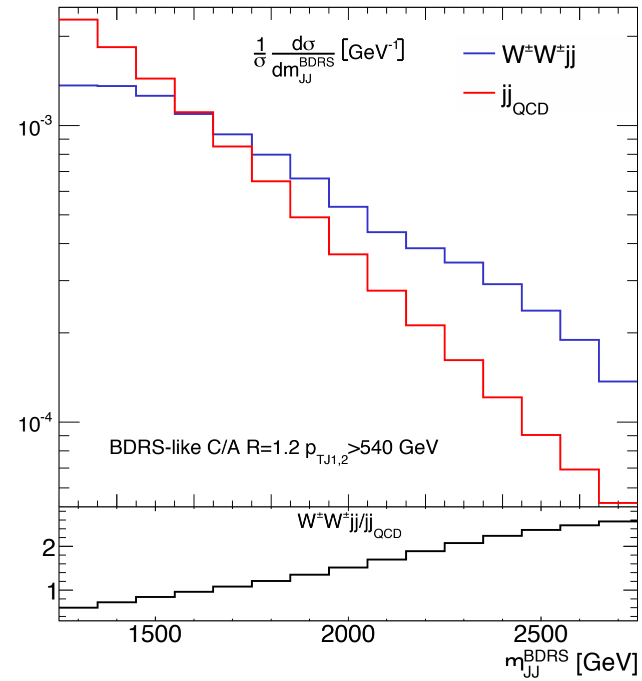
Filtering parameter	Value
$\sqrt{y_f}$	0.2
μ_f	1
R_f	0.3
n_f	3



[Goncalves, Krauss, MS '15]

Without theory background irrelevant in the control region can be significant in the signal region

there ELW backgrounds that have not been checked, but are in this case fortunately small!



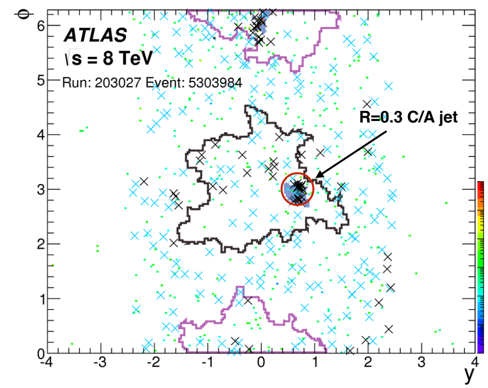
cuts	$W' \to WZ$	jj_{QCD}	$t\bar{t}$	VV	Vj	Vjj_{EW}	jj_{EW}	$W^\pm W^\pm jj$
	cross sections in fb							
BDRS 2J-tag, $p_\perp^J > 540$ GeV	1.17	28302	45.6	5.34	370	50.8	119	0.50
$\sqrt{y} > 0.45$	0.59	4290	9.7	0.67	44	5.4	10	0.1
$\lvert y_1 - y_2 \rvert < 1.2$	0.45	2791	8.0	0.52	24	3.2	5.8	0.06
$\lvert p_{T1} - p_{T2} \rvert / (p_{T1} + p_{T2}) < 0.15$	0.44	2776	7.8	0.51	24	3.2	5.74	0.054
WZ selection	0.21	26.7	0.18	0.25	0.83	0.01	0.22	0.0005
WZ selection, $1.9 < m_{JJ} < 2.1$ TeV	0.14	0.33	0.002	0.04	0.01	0.0002	0.002	0.00001

TABLE I: Cut-flow analysis for signal and SM background components. The selections follow the ATLAS publication and the cross-sections are given in fb.

But reconstruction algorithm can also seize to work in signal region

- Why start with R=1.2 jets when searching for W/Z with 1-2 TeV pT?

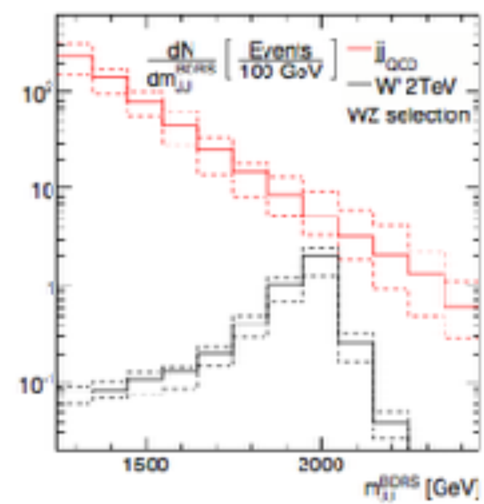
$$\Delta R_{q\bar{q}} \simeq \frac{2m_W}{p_T} \simeq 0.12 \cdots 0.4$$



W/Z decay products in small area of detector

Jet absorbs lots of radiation from diff. sources

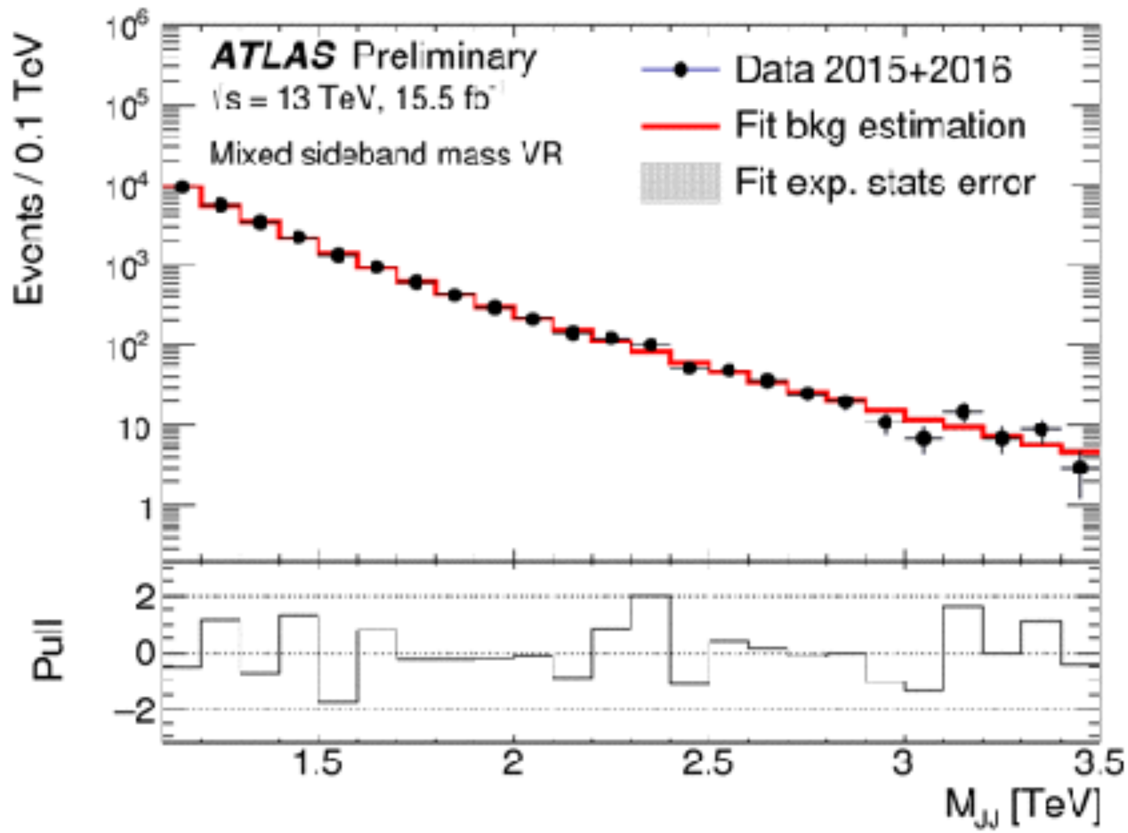
- Filtering step entirely ineffective for R=0.3 and nf = 1-3



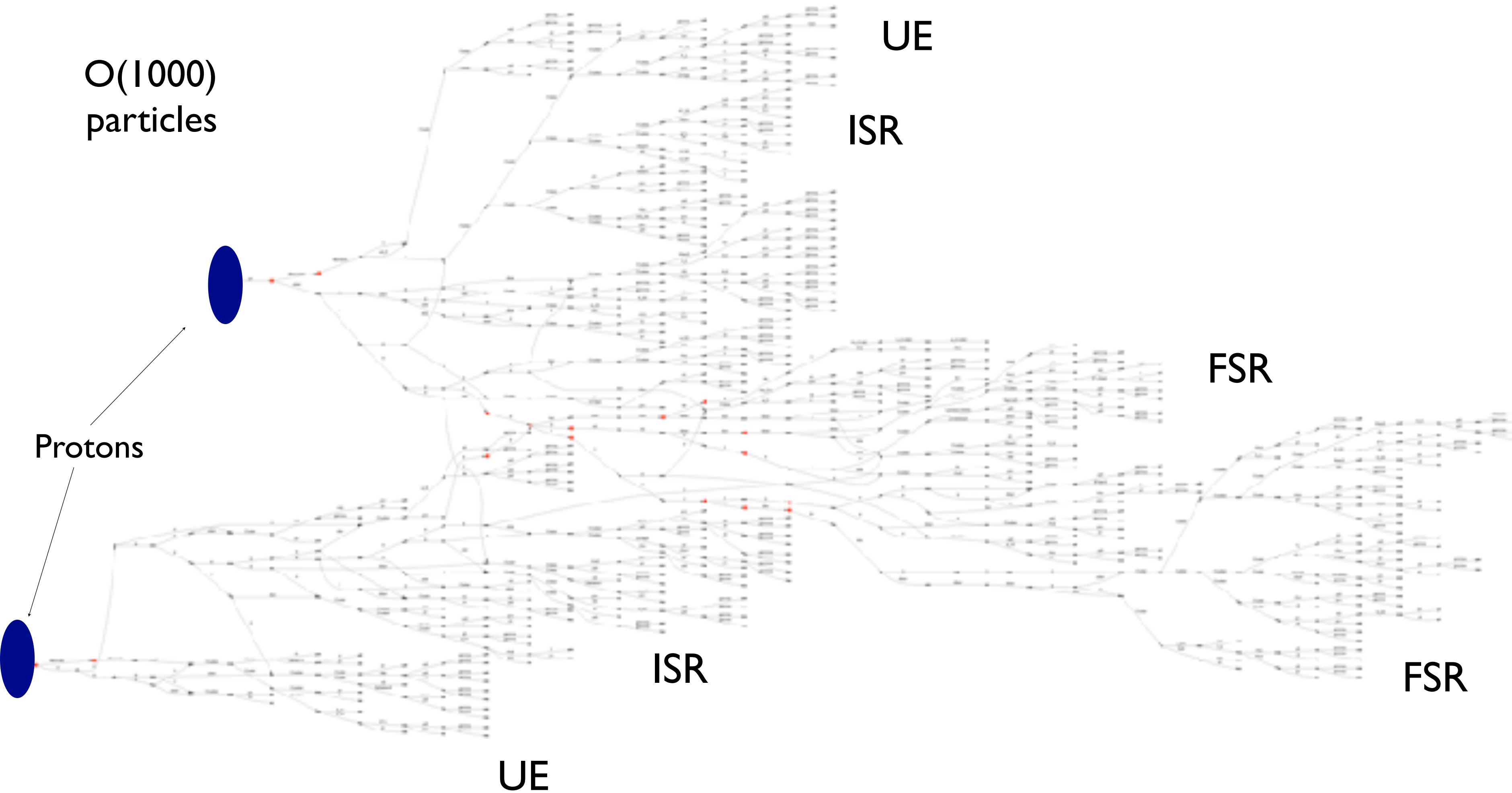
- Mass-drop procedure compares varying number of topoclusers (energy uncertainties unknown)

End of the story:

- Tagging algorithm changed to D2 and resonance was not seen in 13 TeV runs…



Is it possible to use matrix element methods approach given complexity of LHC events?



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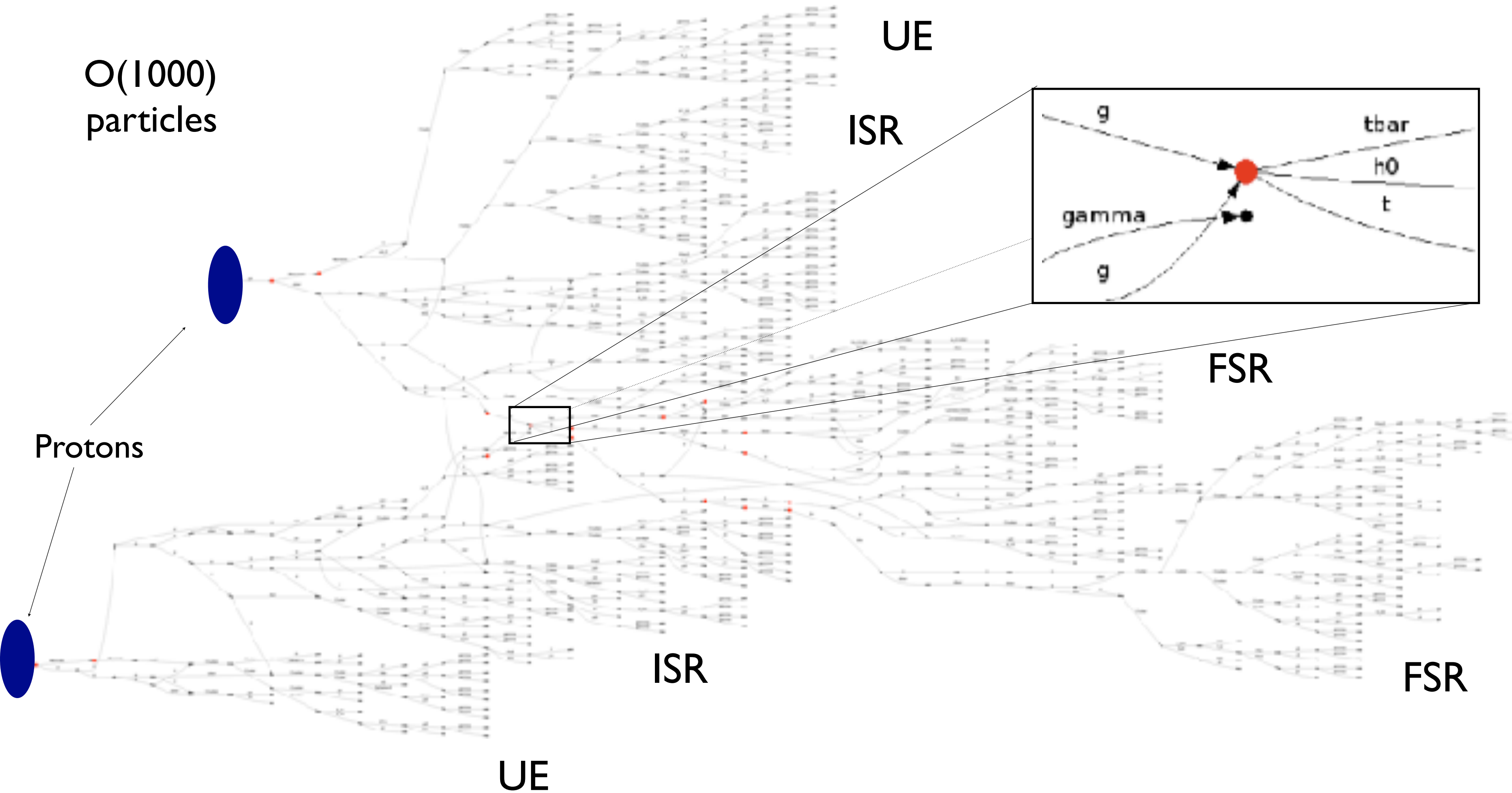

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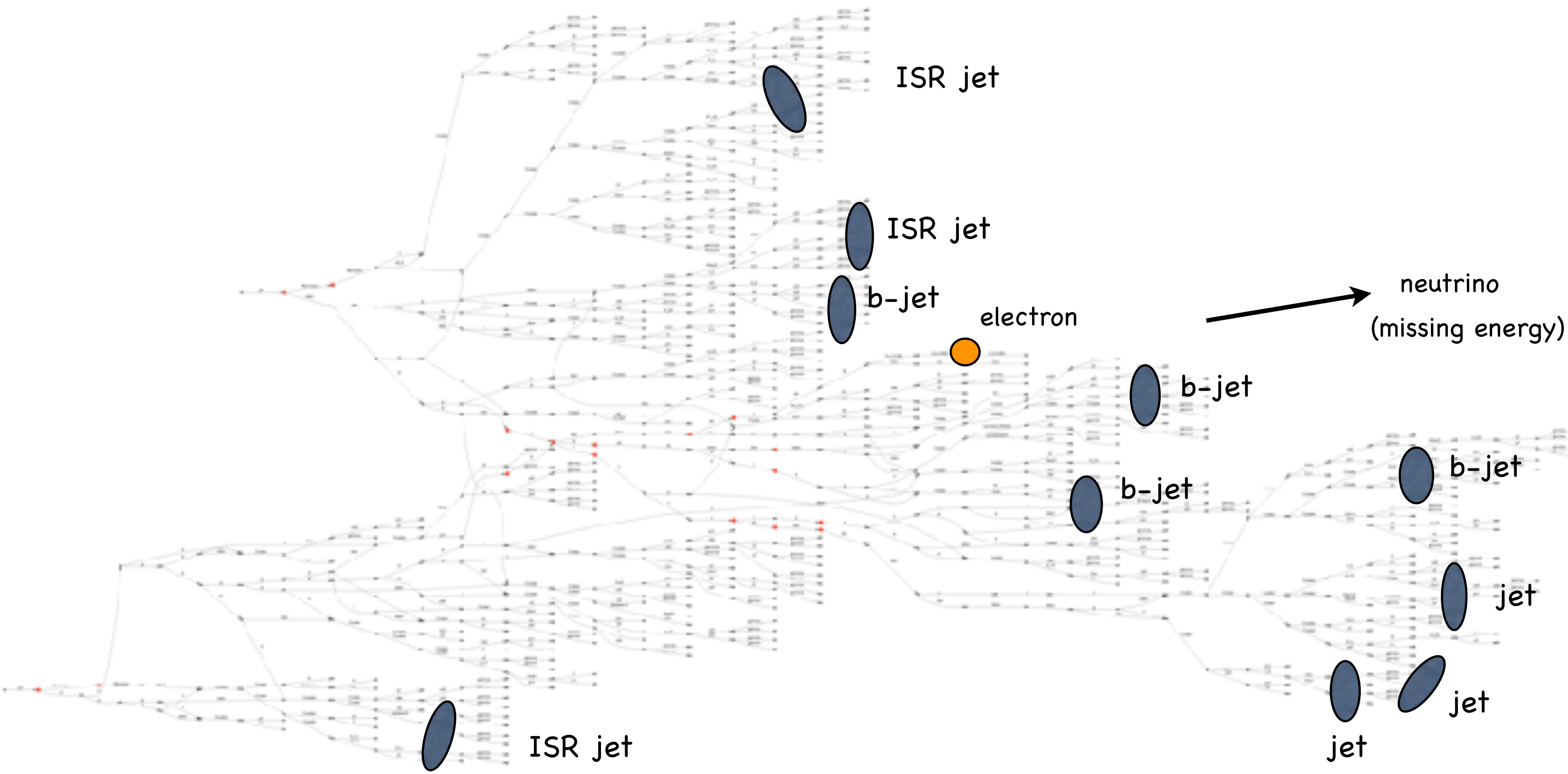
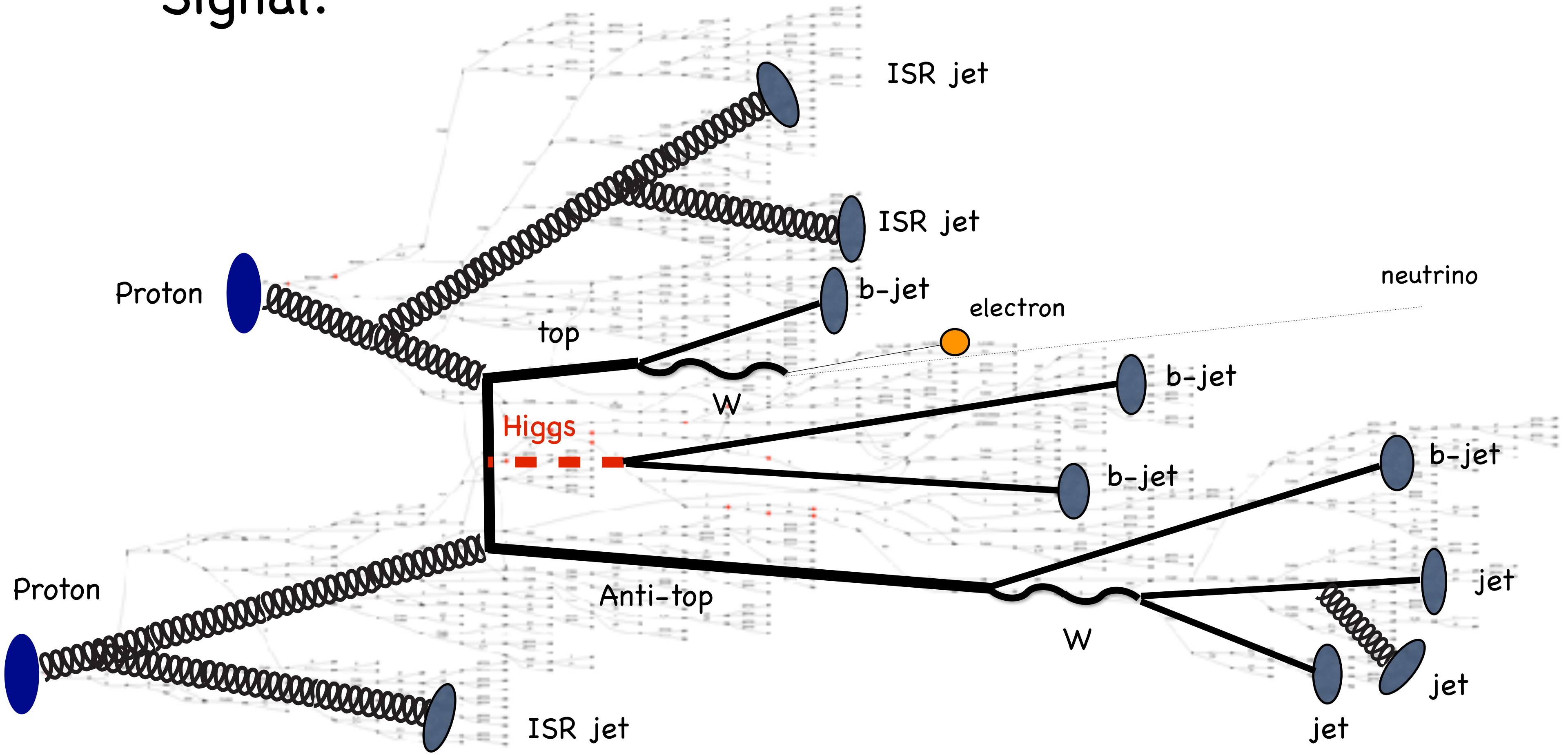
Inverse Problem: Final state measured
(‘phase space point chosen’)



Give final state radiation distinctive meaning in terms of hypothesis

Signal:



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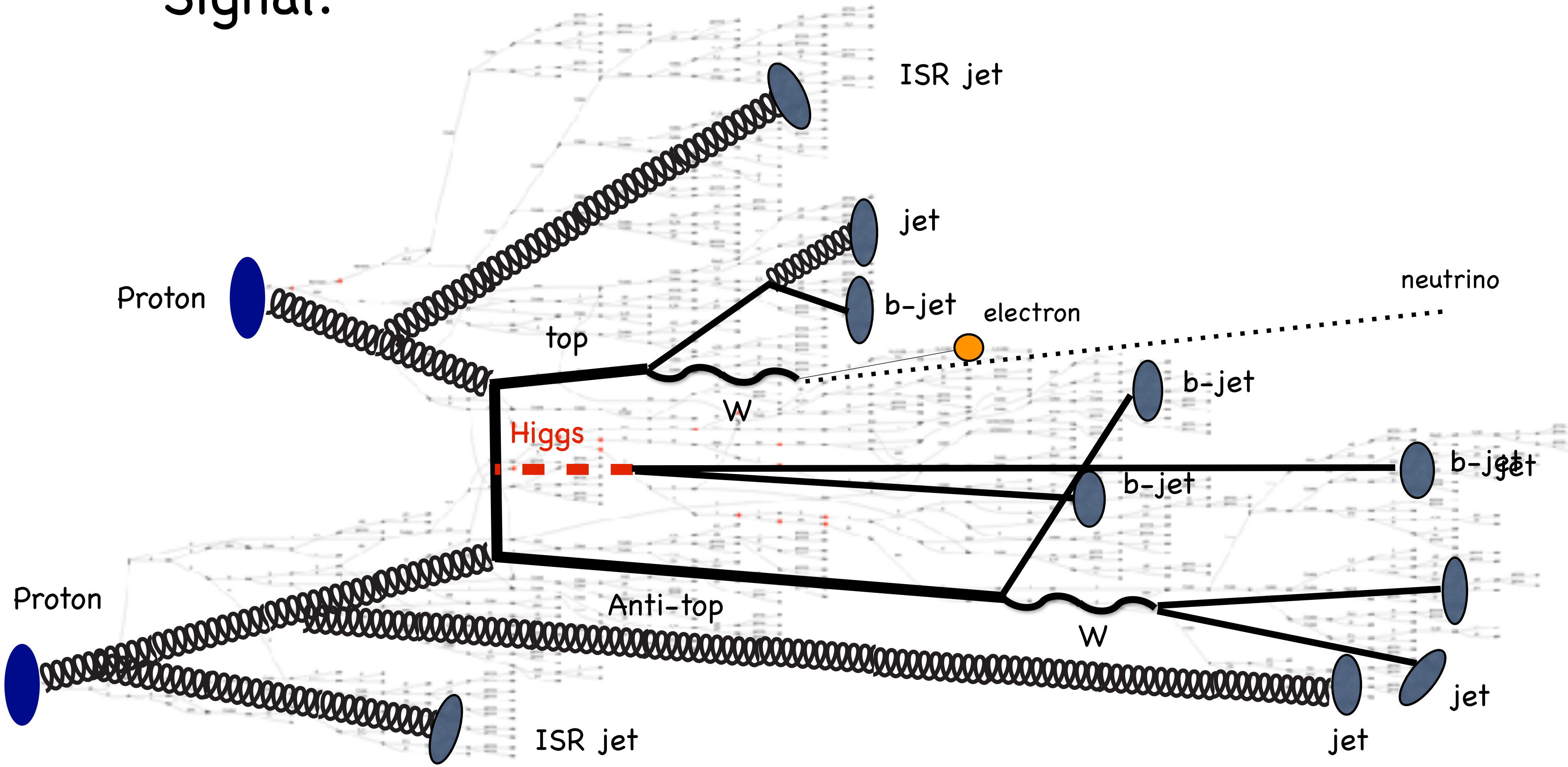

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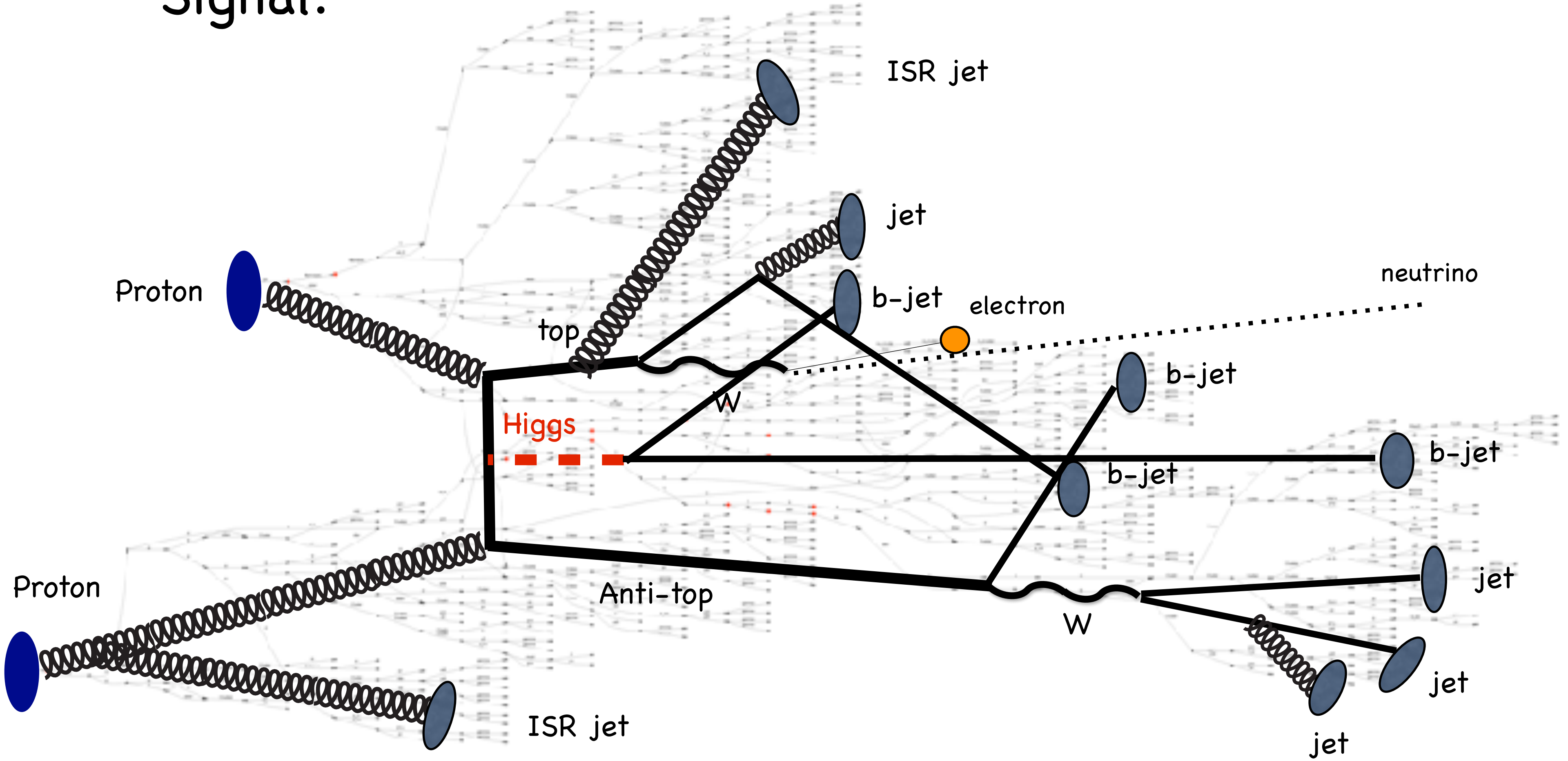
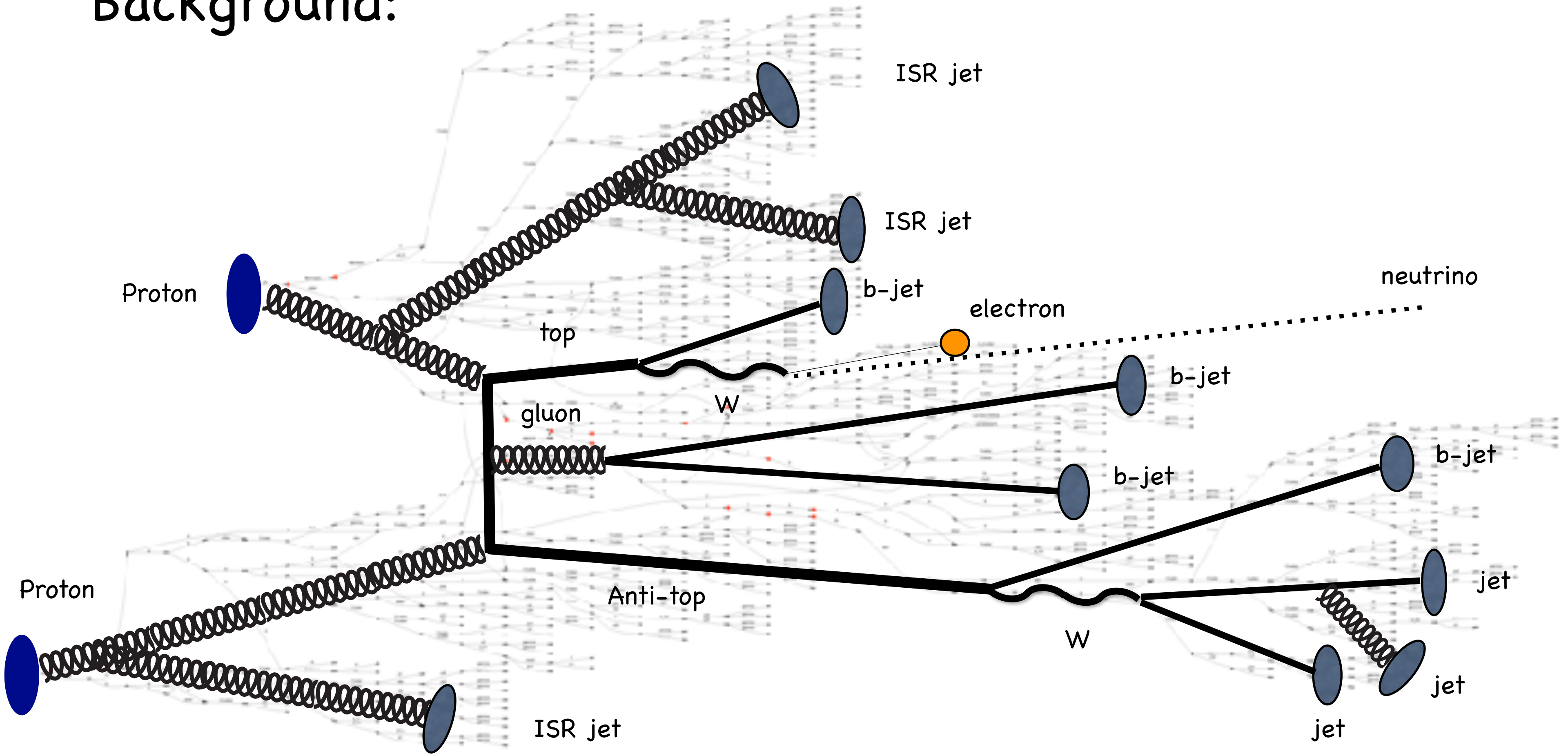
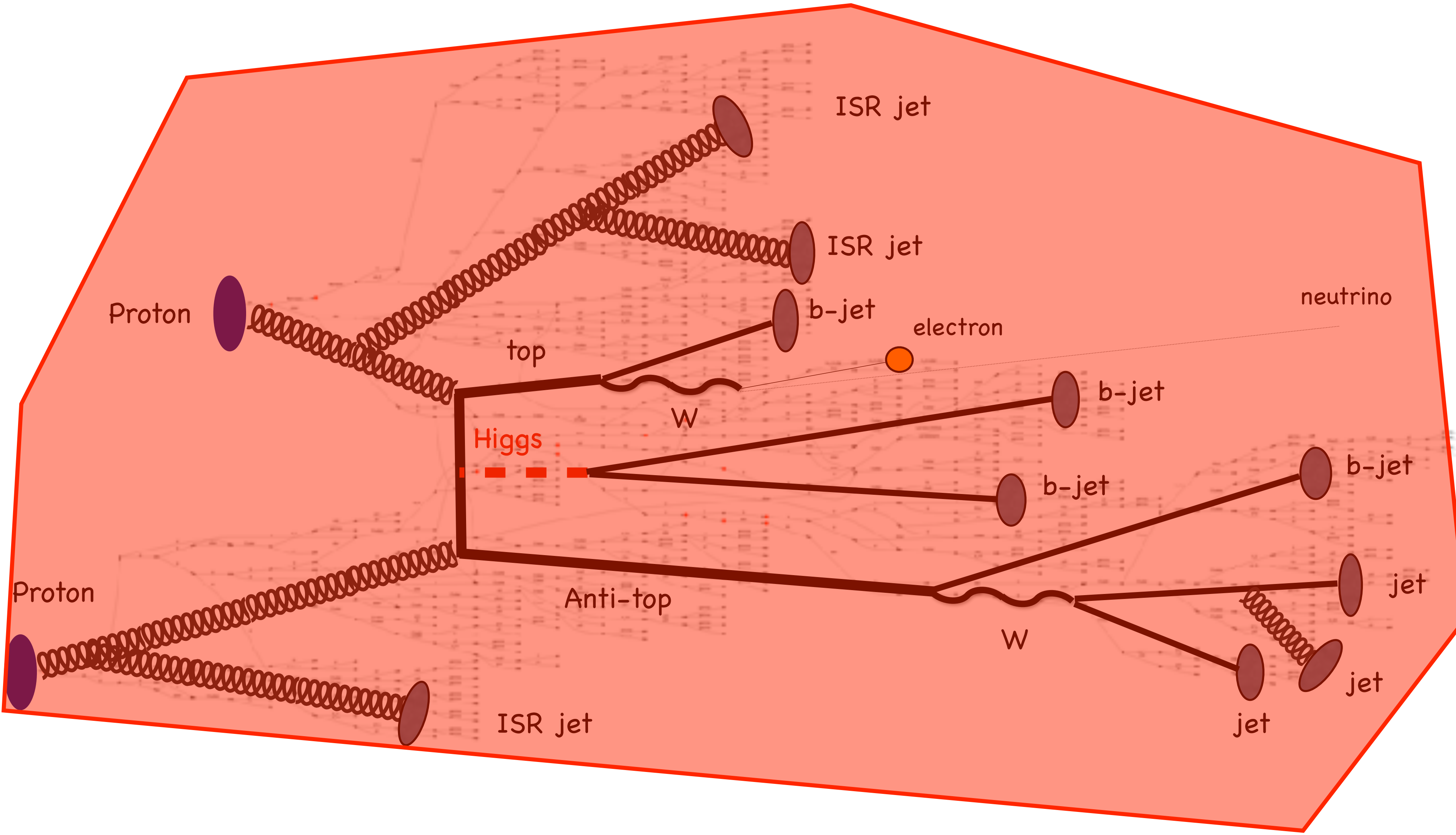


Give final state radiation distinctive meaning in terms of hypothesis

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.

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

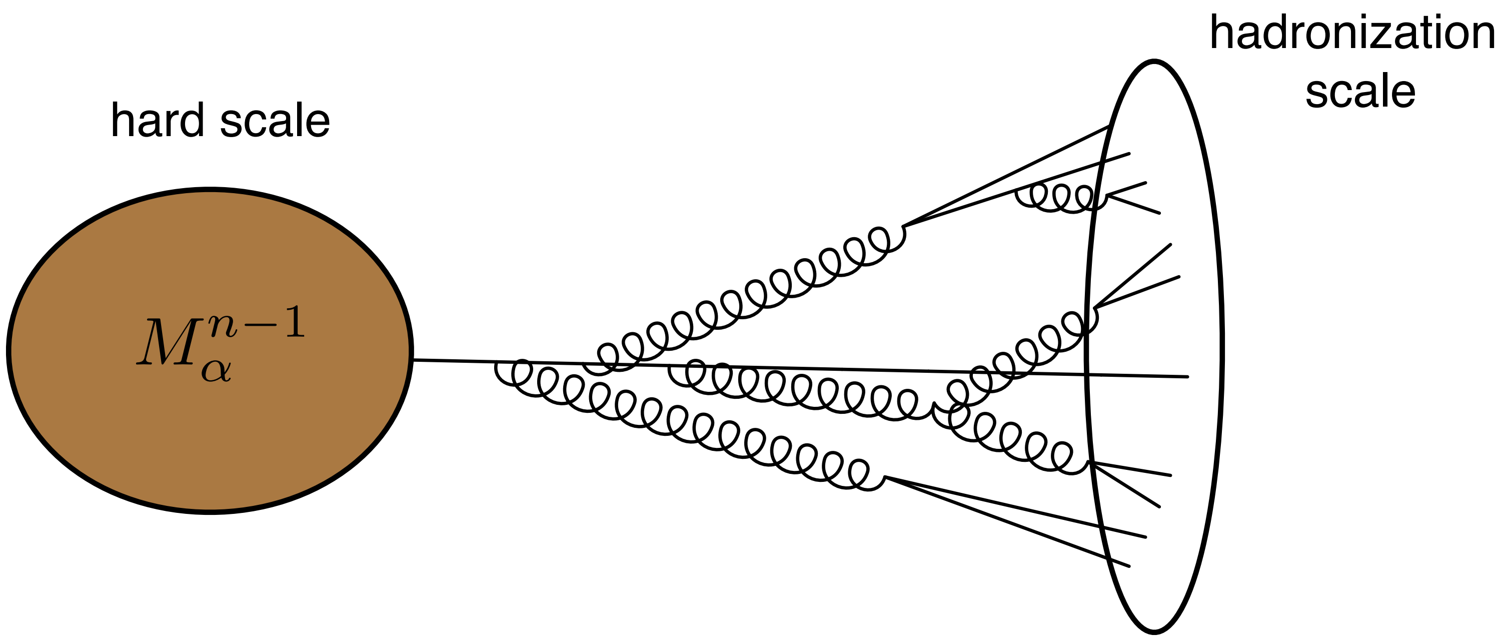
$|M_\alpha|^2$ is squared matrix element

$W(\mathbf{x},\mathbf{y})$ 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) $|M(y)|^2$

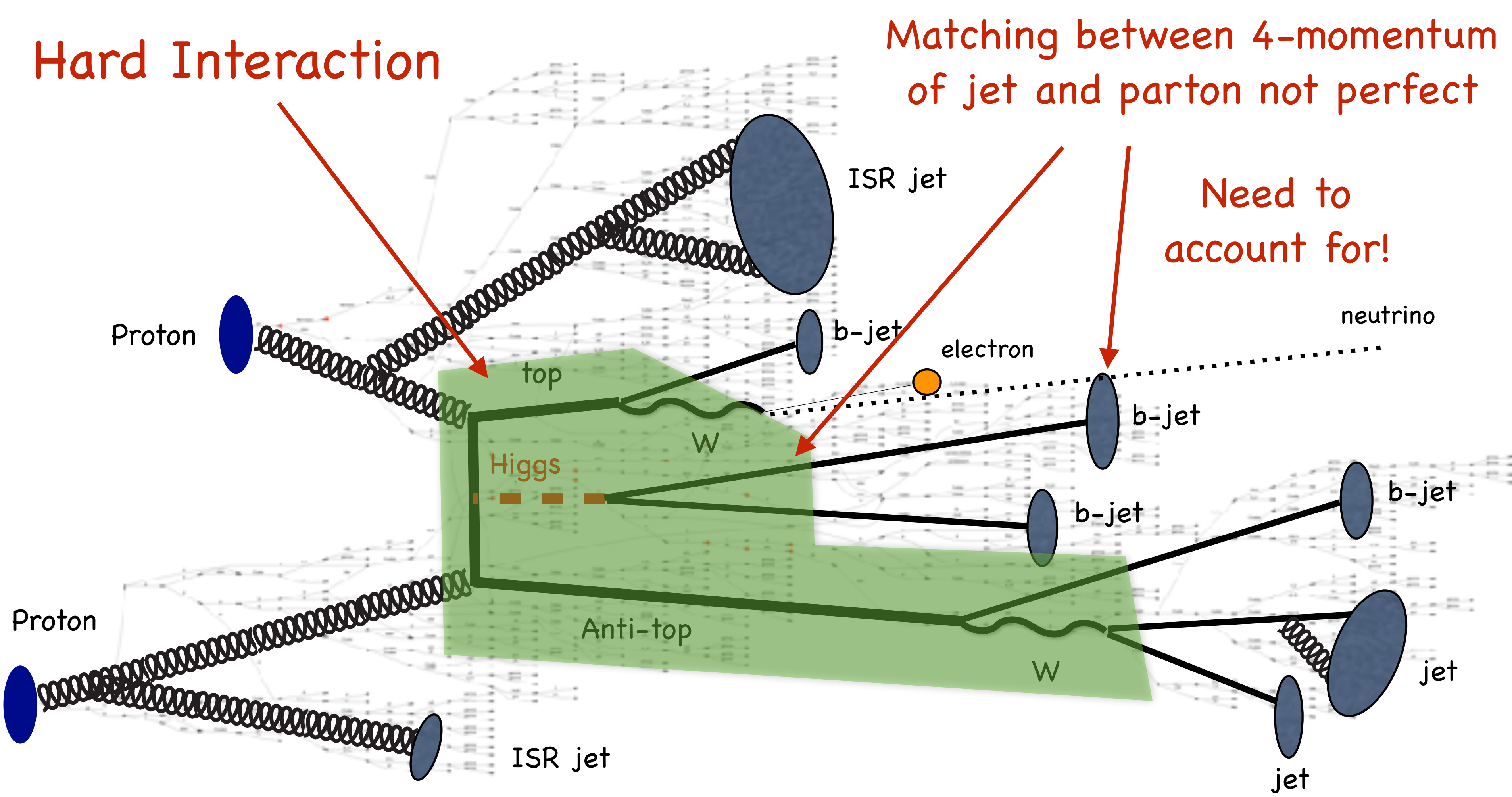
- Can be calculated at different order in pert. series (LO, NLO)
- Final state multiplicity fixed (exclusive process)
- Some kinematic configurations induce large logs (need resummation)

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

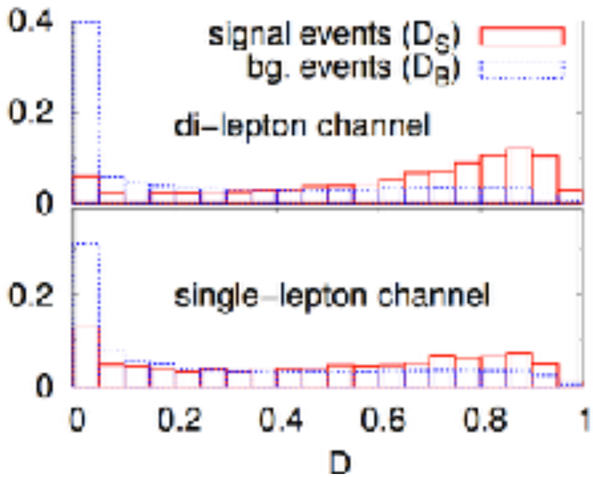
[Artoisenet et al. PRL 111 (2013)]



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

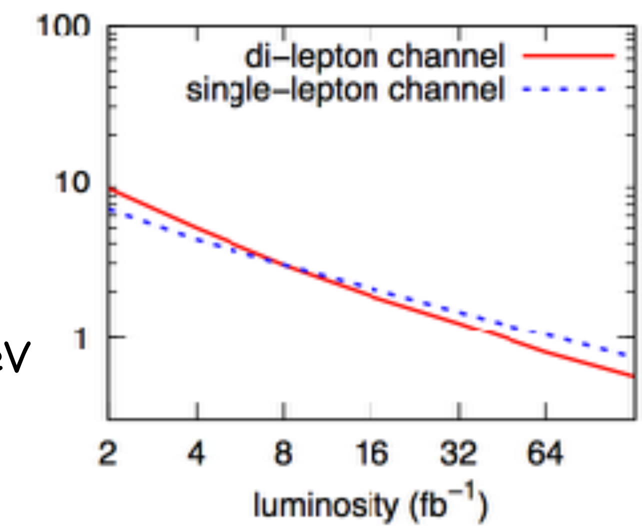
[Artoisenet et al. PRL 111 (2013)]

process	incl. σ	efficiency	σ^{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)]

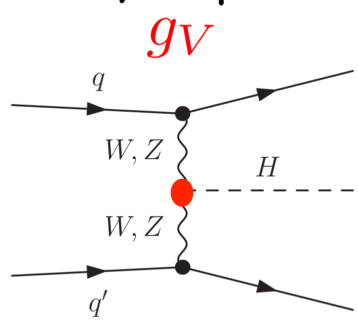
We want to study more objects in final state ->

Transfer function limits us. Do we always need it?

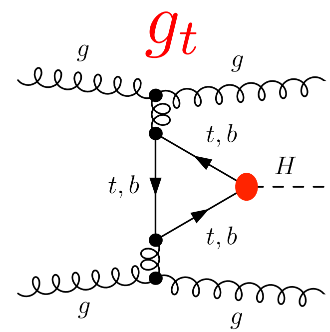
Transfer functions only important if matrix element varies quickly:

Example

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

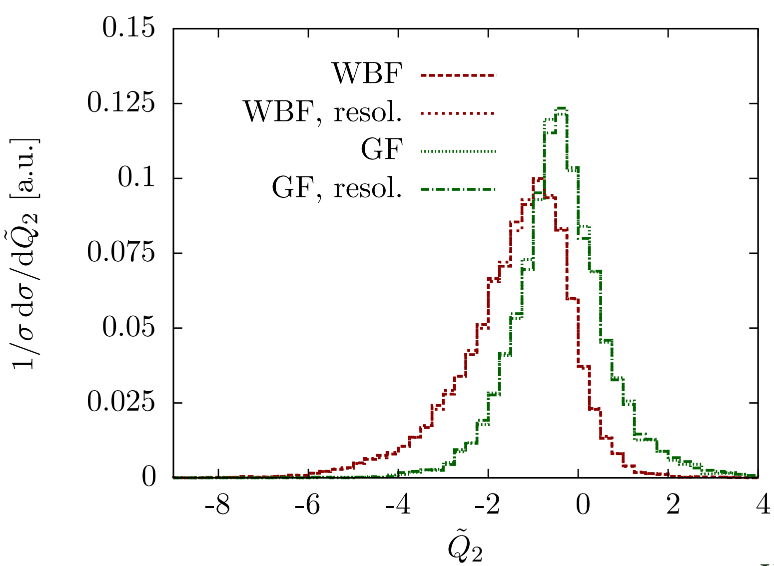


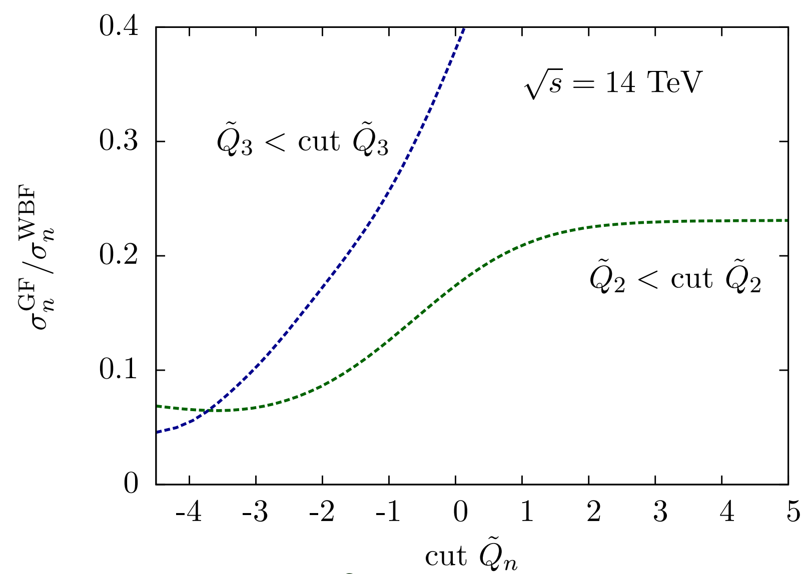
vs



in $H \to \gamma\gamma$

Higgs reconstructed, but no transfer function for jets:





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

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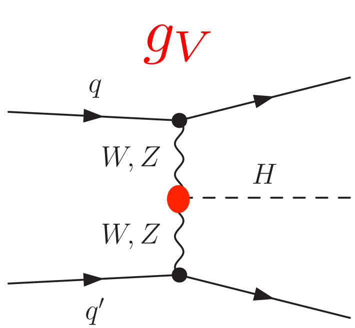

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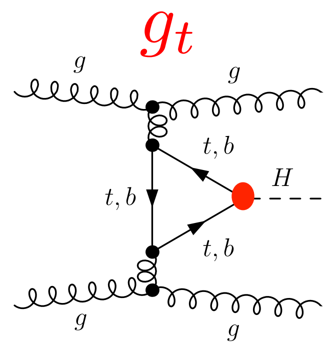

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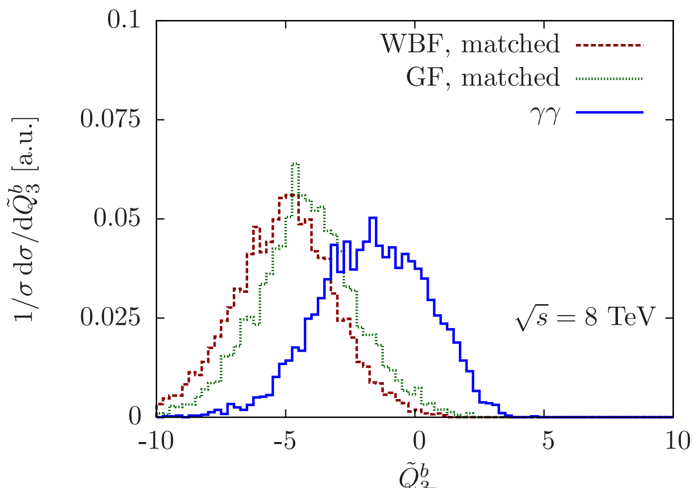


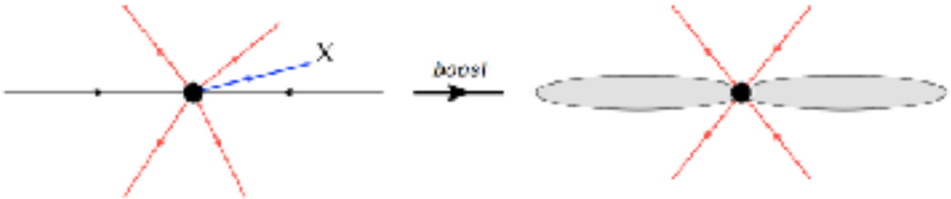
$S/B \nearrow 100\%$

$$\tilde{Q}_n^b(p_1^\gamma, p_2^\gamma, \{p_n^j\}) = -\log\left[\frac{\{|\mathcal{M}^{\rm WBF}(pp \to (h \to \gamma\gamma)j^n)|^2 + |\mathcal{M}^{\rm GF}(pp \to (h \to \gamma\gamma)j^n)|^2\}}{|\mathcal{M}^{2\gamma}(pp \to \gamma\gamma j^n)|^2}\right]$$

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

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

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

Calculate virtual for born topology

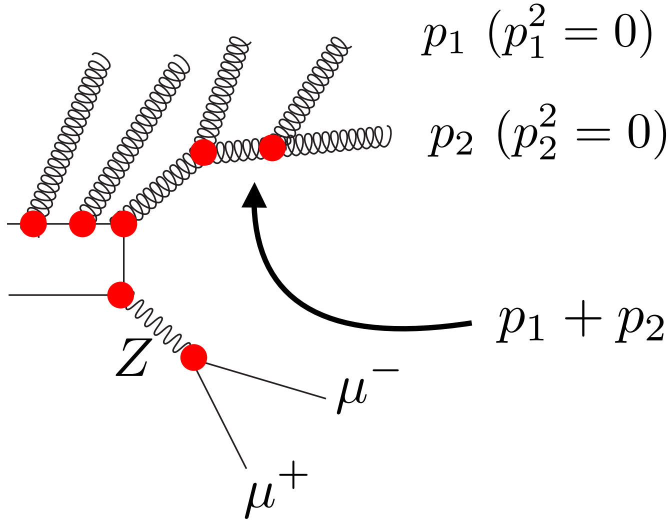
real for jet function

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

sensitivity LO vs NLO improvement ~ 10%

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)

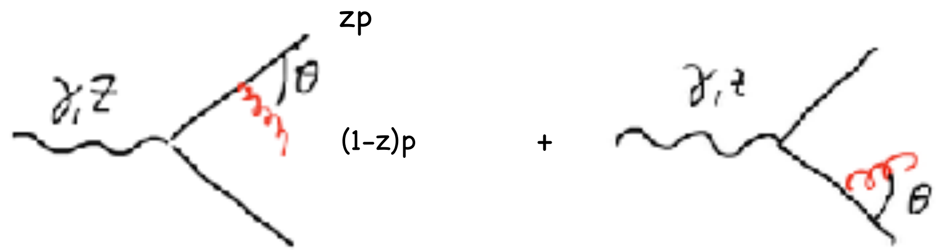
These emissions are enhanced if they are collinear and/or soft with respect to the emitting parton

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

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

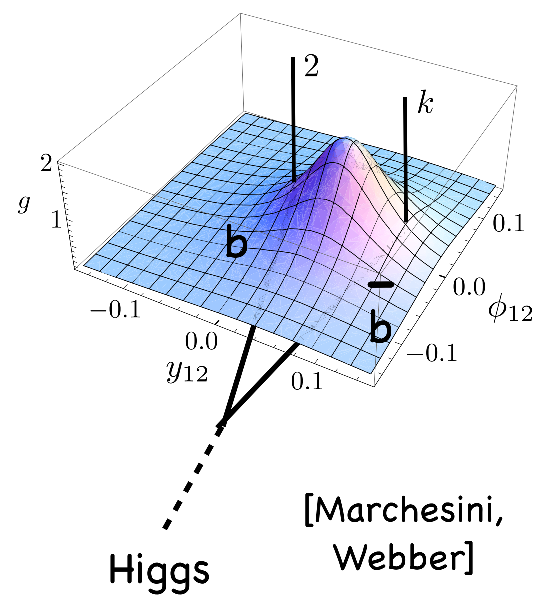
Soft limit: $E_g \to 0$ $\quad k^\mu \ll p_i^\mu$ the matrix element for

$e^+e^- \to \bar{q}qg$ 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:

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

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

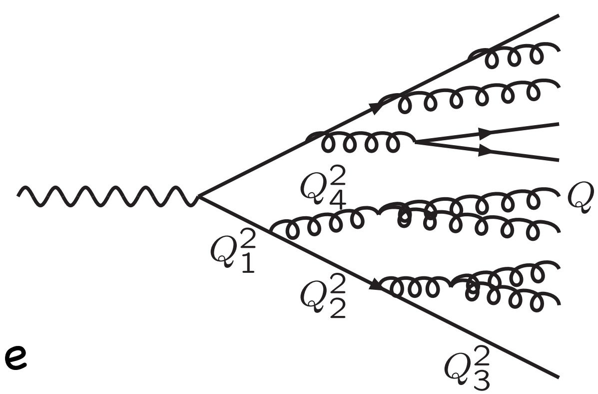
$$= \exp\left(-\int_0^T \frac{d\mathcal{P}_{\text{something}}(t)}{dt} dt\right)$$

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

Sudakov form factor provides "time" ordering of shower:

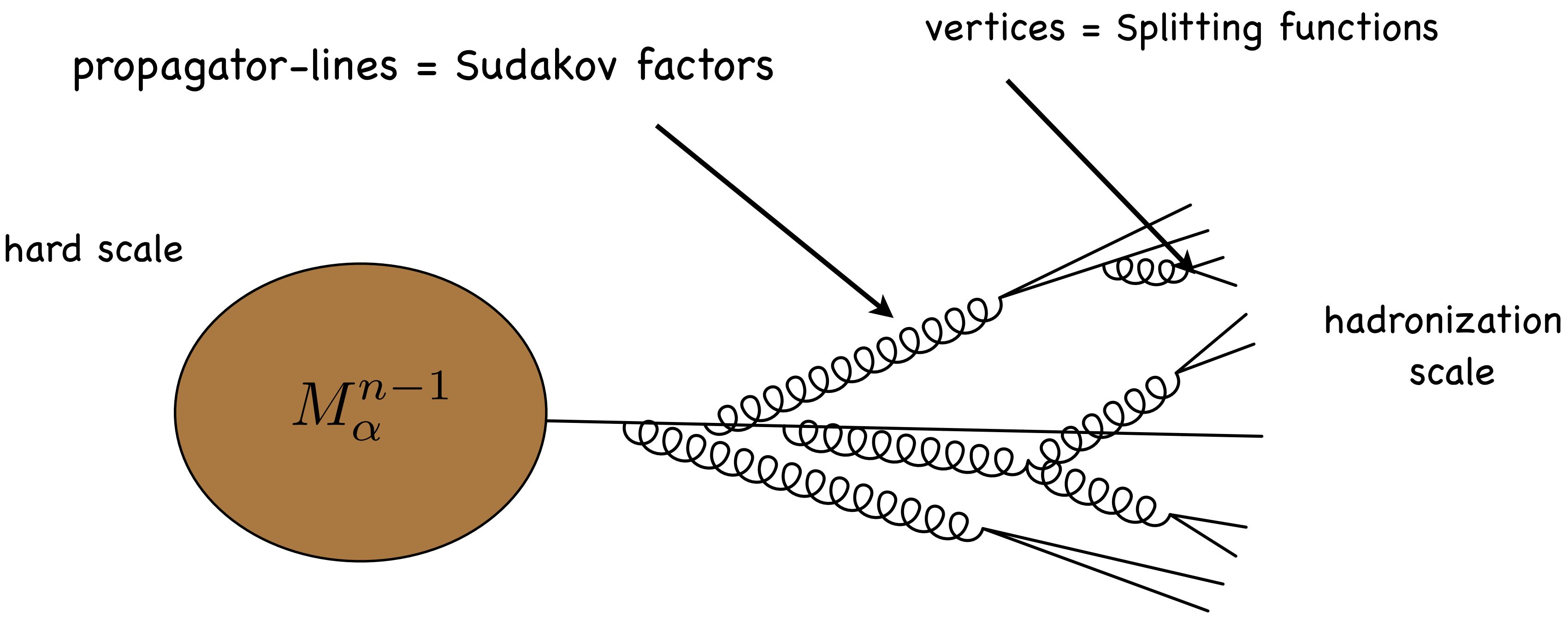
$Q_1^2 > Q_2^2 > Q_3^2$

low Q^2 ⟷ longer time



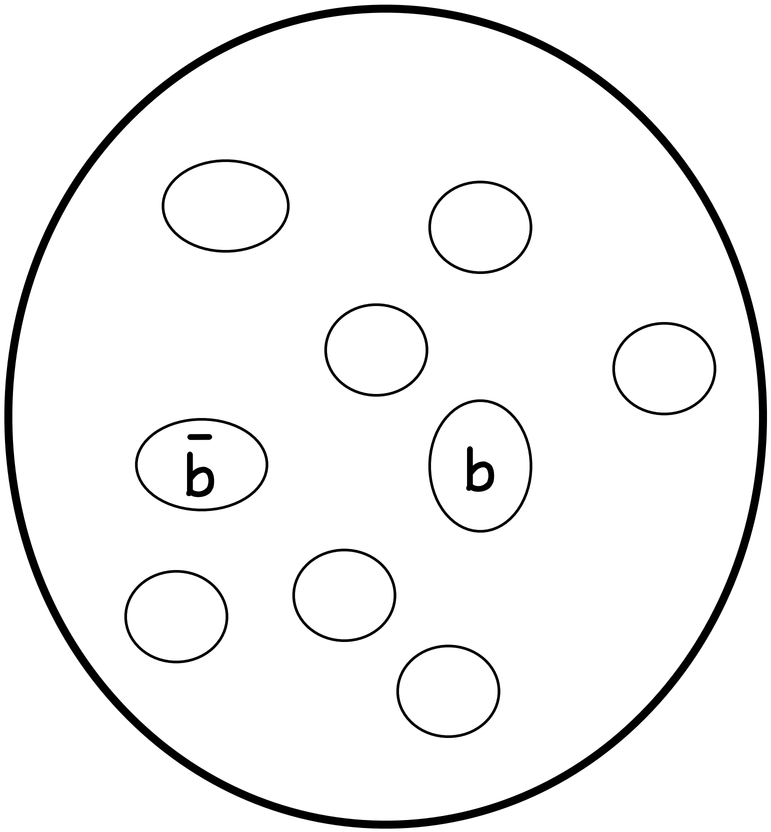
In summary:

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

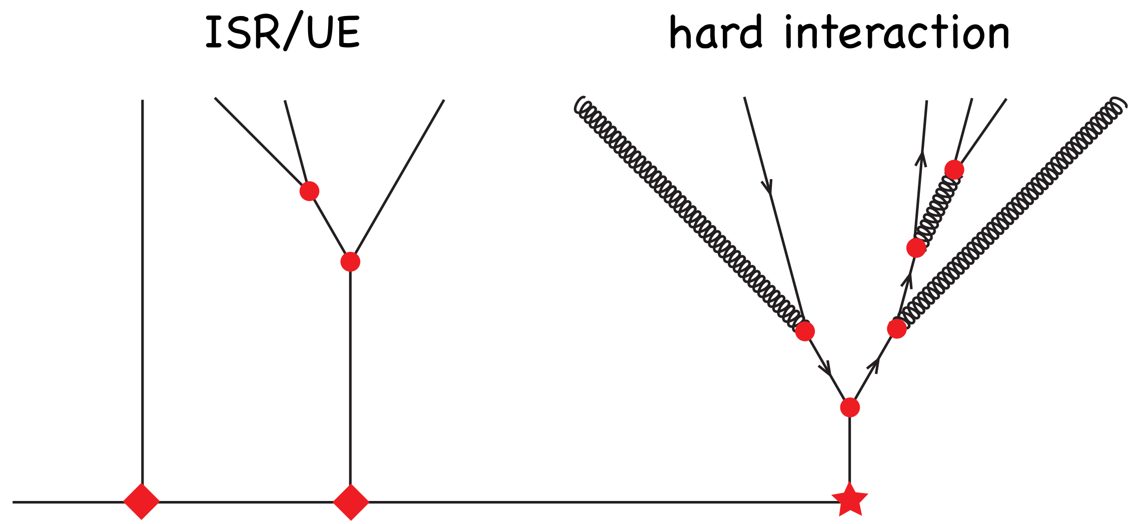


Shower deconstruction = first-principal calculation for resummed MEM

Fat jet: R=1.2, anti-kT



microjets

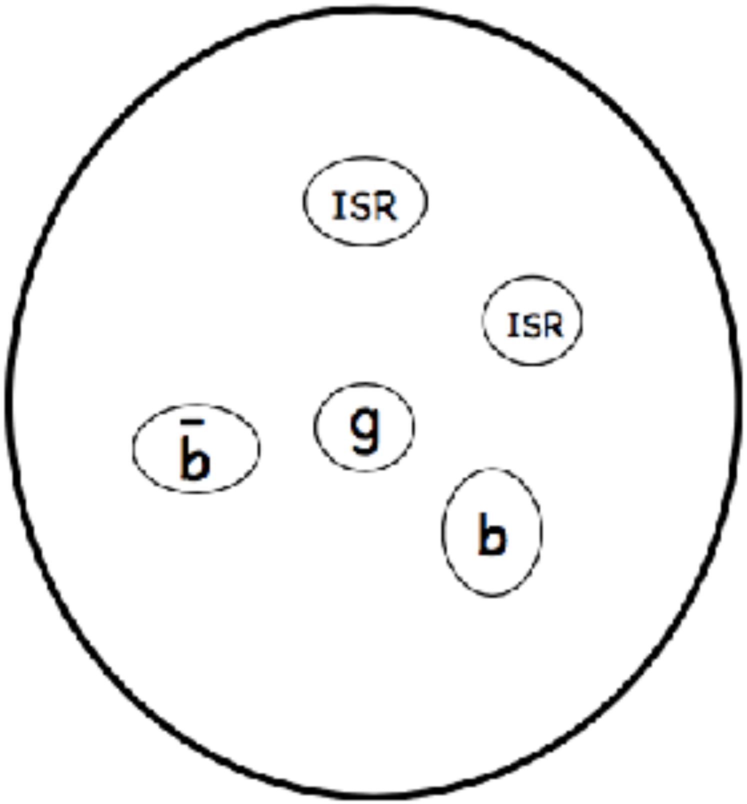


Build all possible shower histories

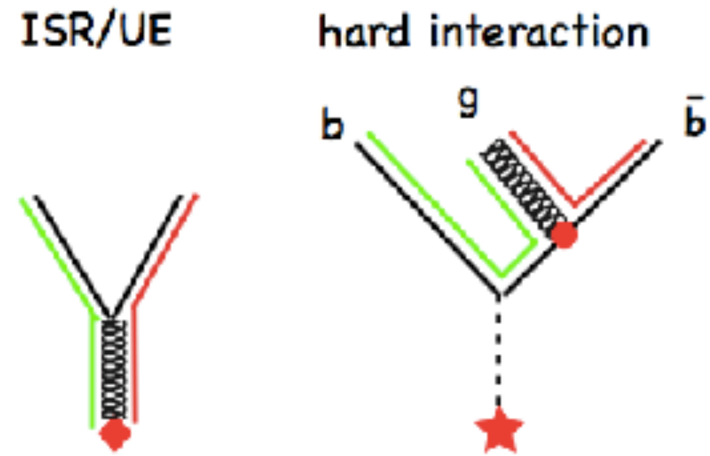
signal vs background hypothesis based on:

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

Fat jet: R=1.2, anti-kT



microjets



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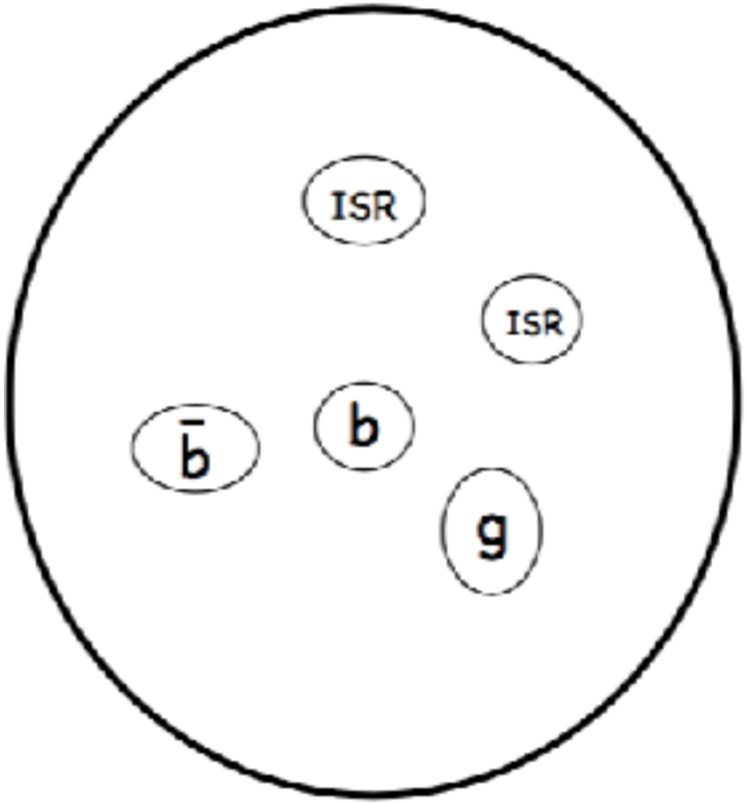
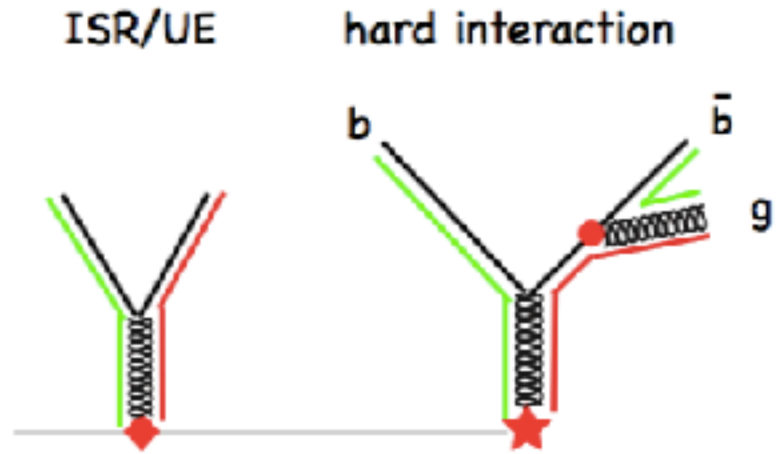


microjets



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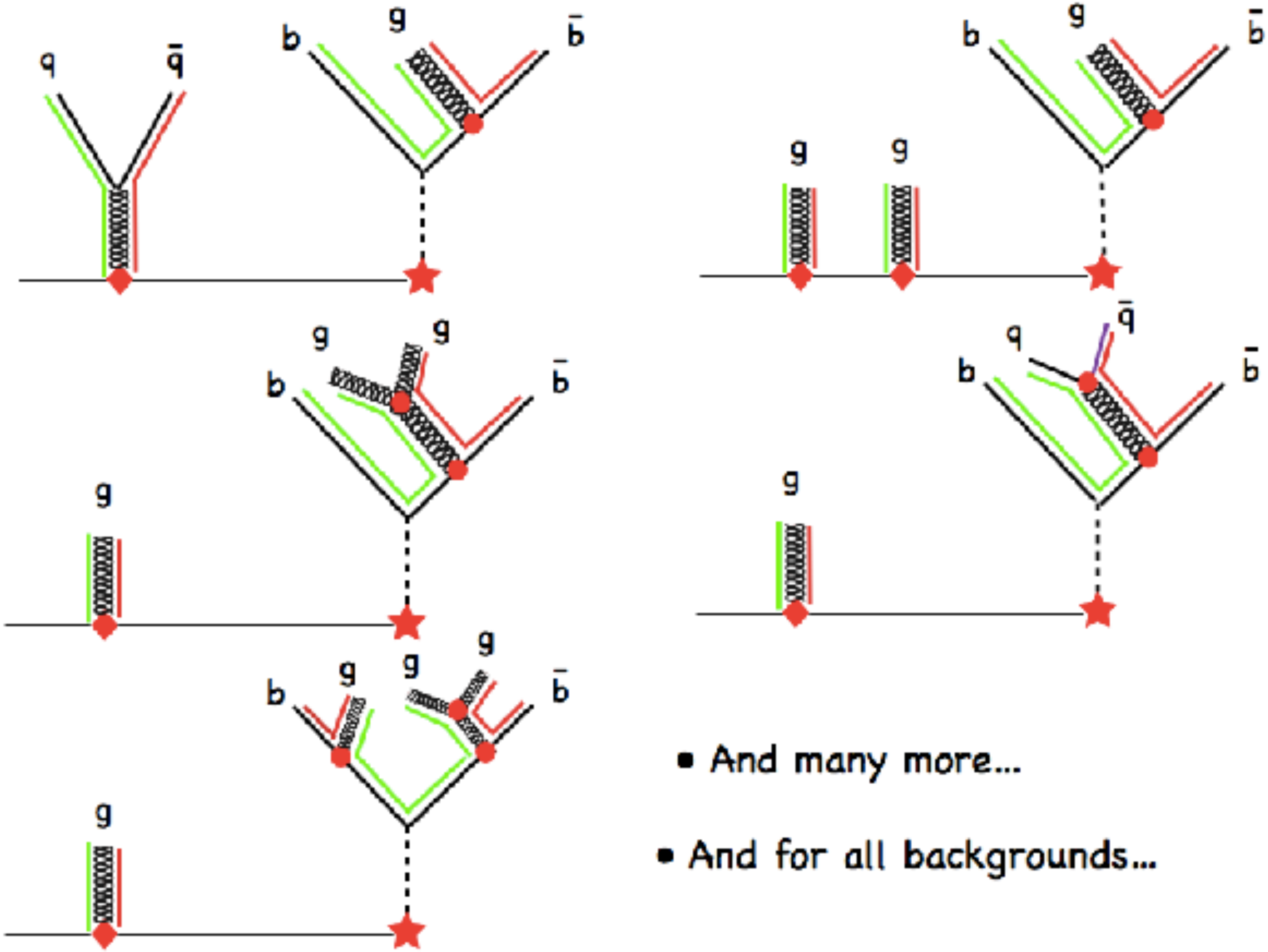
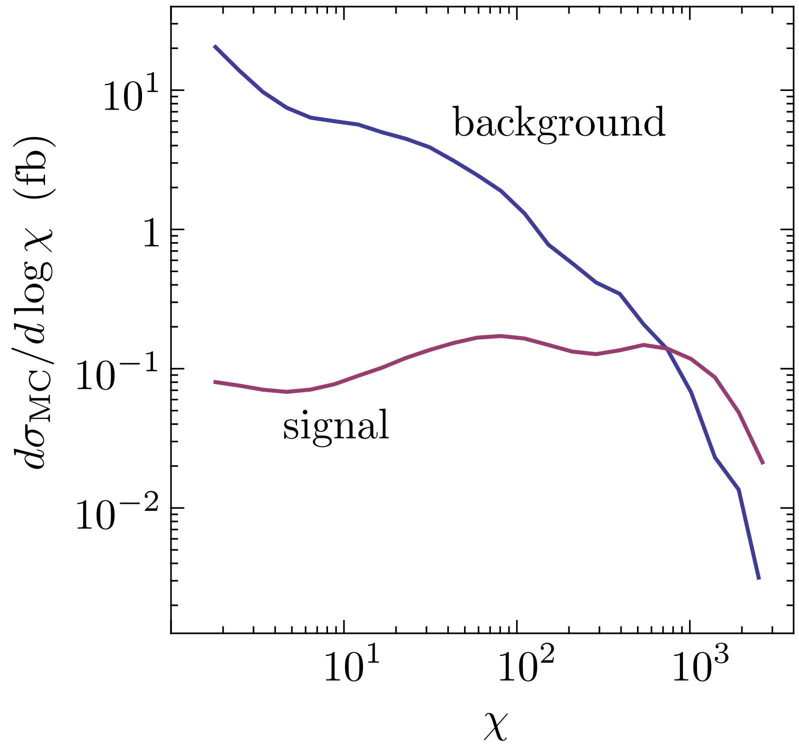
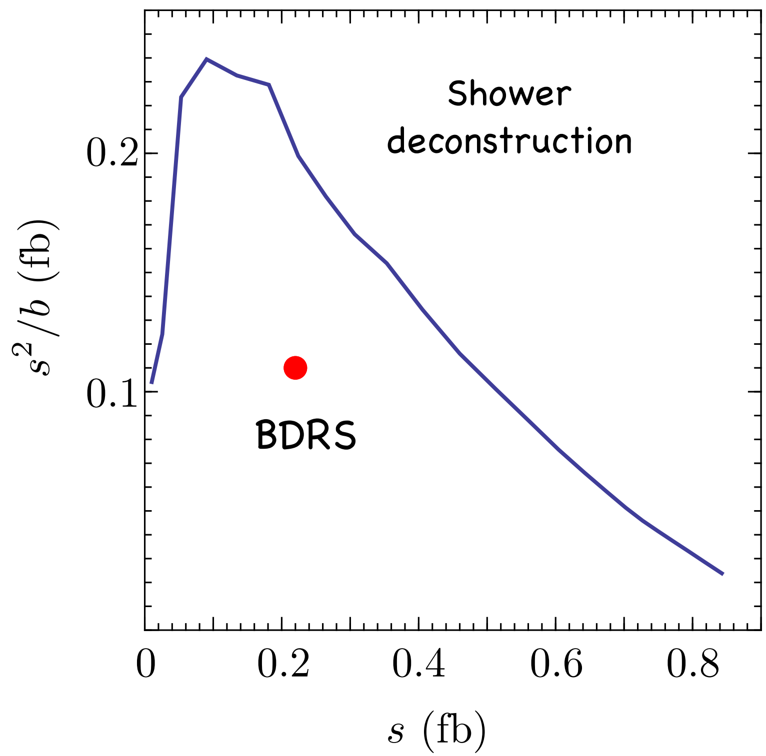


- And many more...
- And for all backgrounds...

Results for Higgs boson:

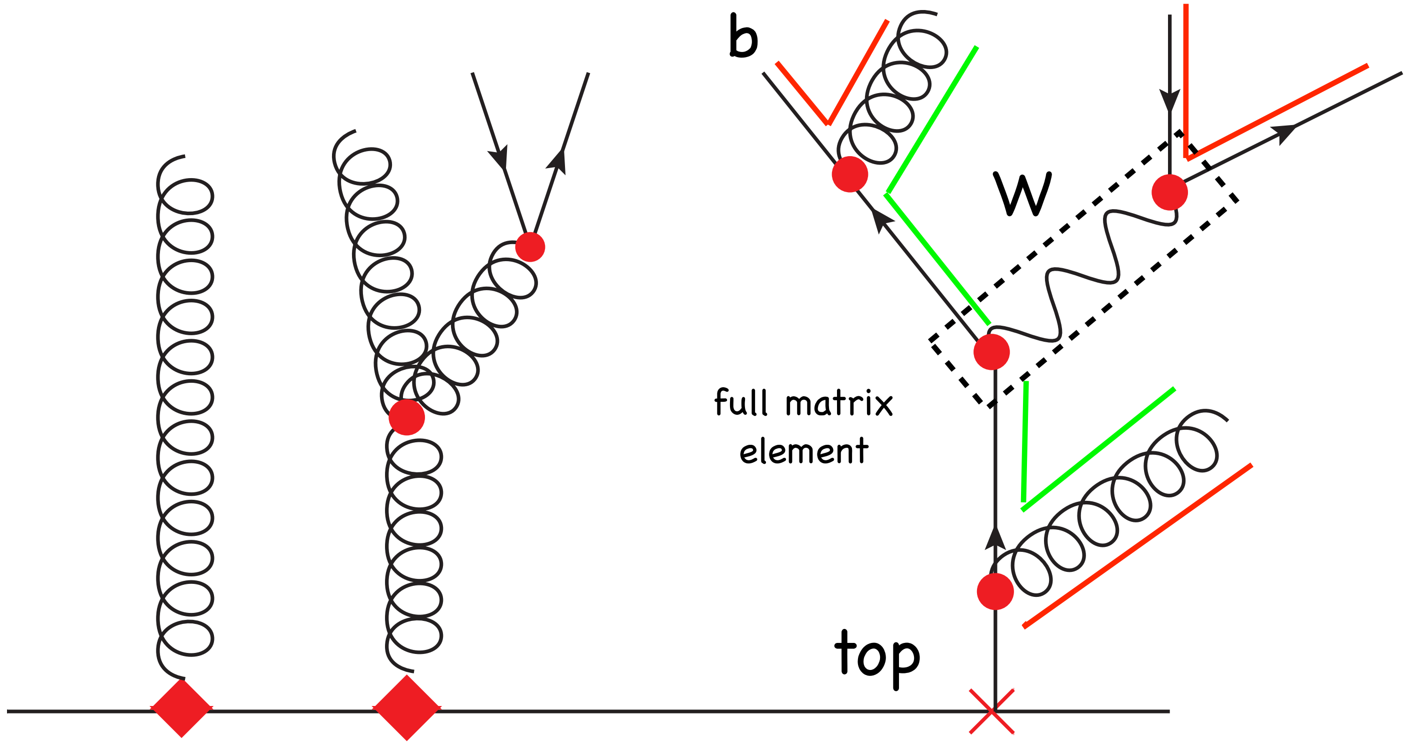
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$$





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

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



Conceptional difference compared to Higgs from last year:

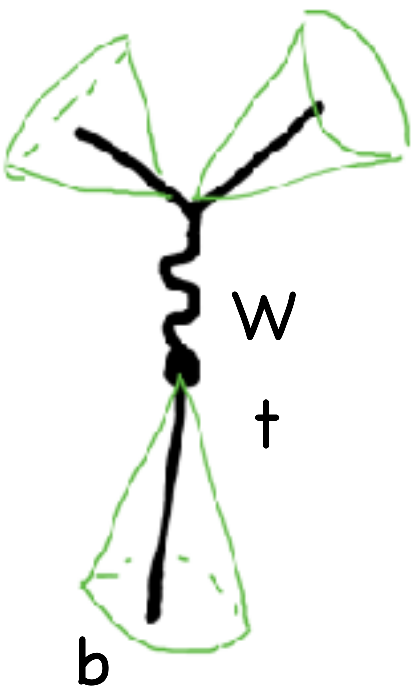
- Splitting functions for massive emitter and spectator
- Full matrix element for top decay

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

Different scenarios based on pT vs mass

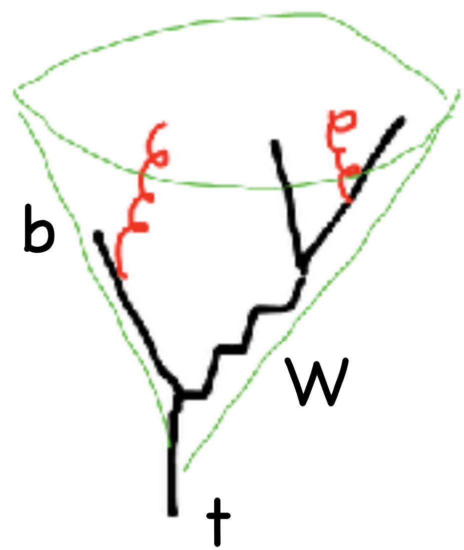
Scenario 1

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



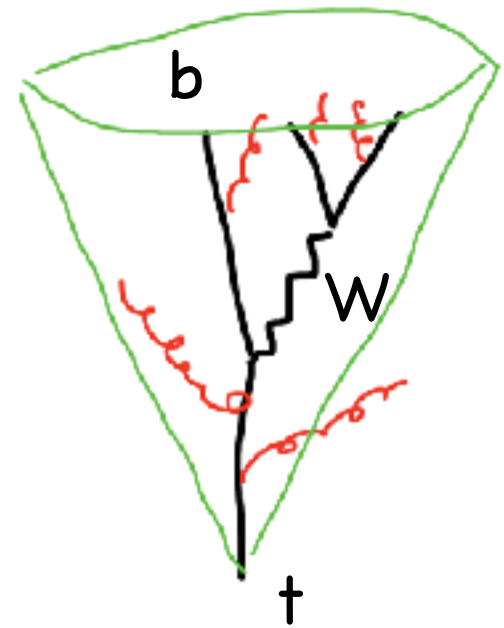
Scenario 2

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



Scenario 3

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

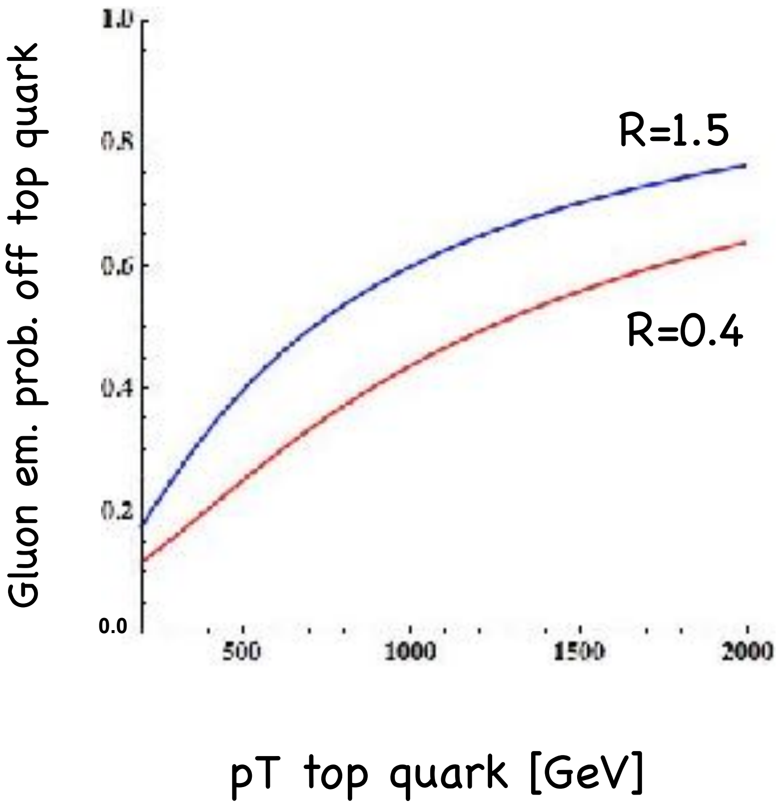


Standard (resolved) reconstruction focuses on Scenario 1

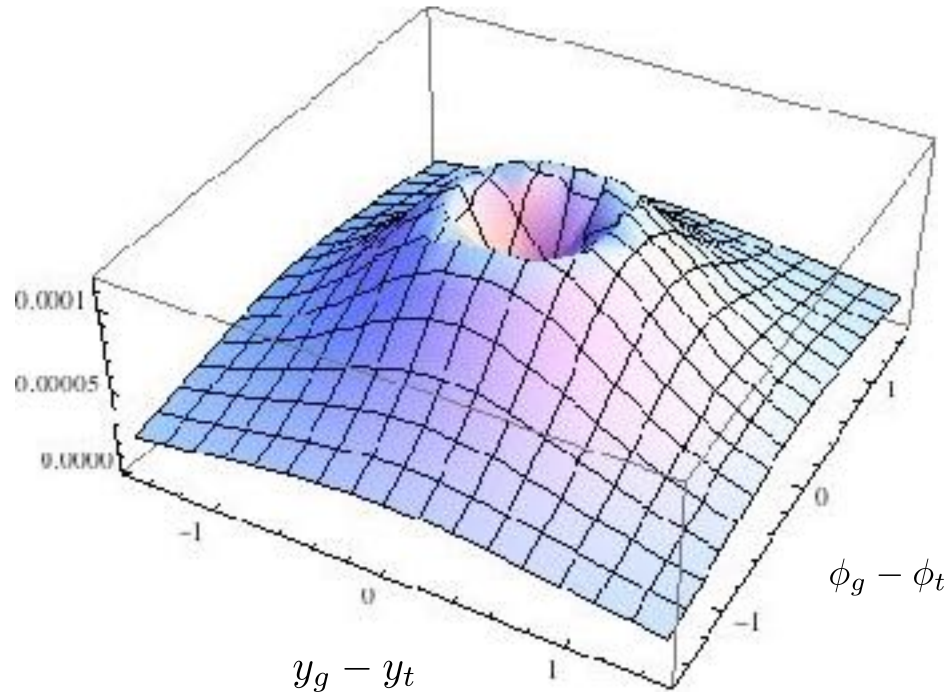
Physics cases require Scenarios 2 and 3 -> tagging for accelerated charges

Characteristic radiation profiles for gluon emissions from tops

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



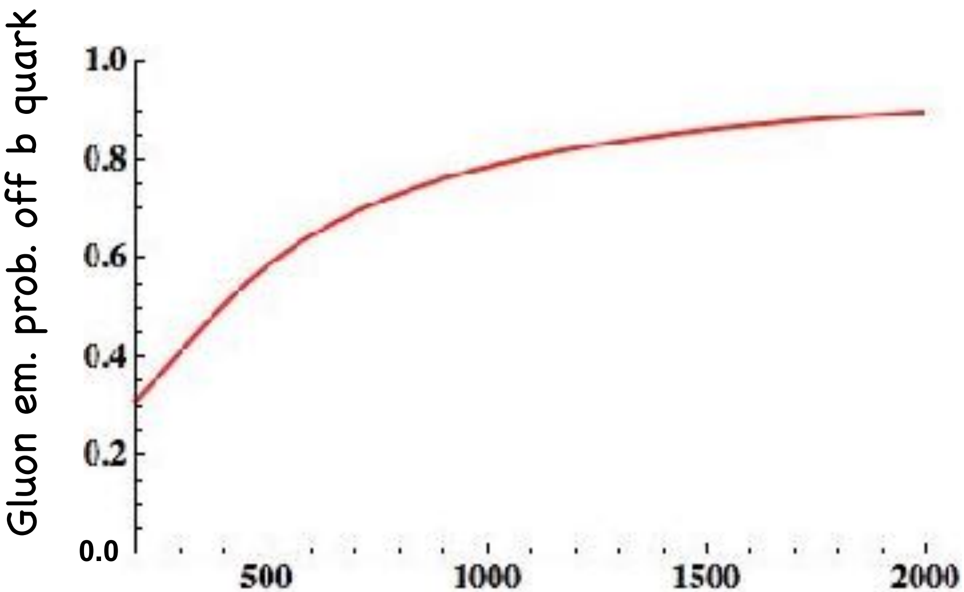
Dead region around top



pT top 500 GeV, pT gluon 20 GeV

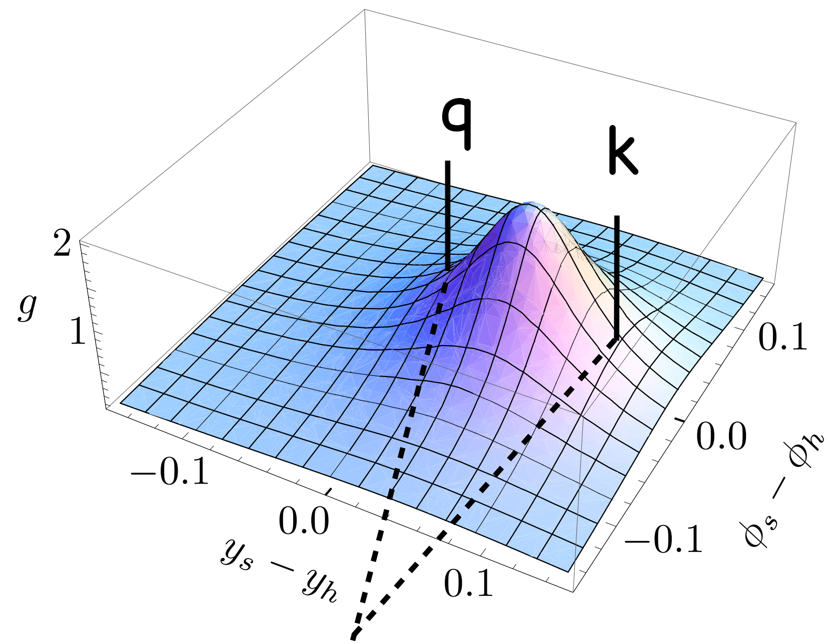
Radiation off bottom quark down to hadronization scale

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



pT top quark [GeV]
pT bottom = pT top / 3

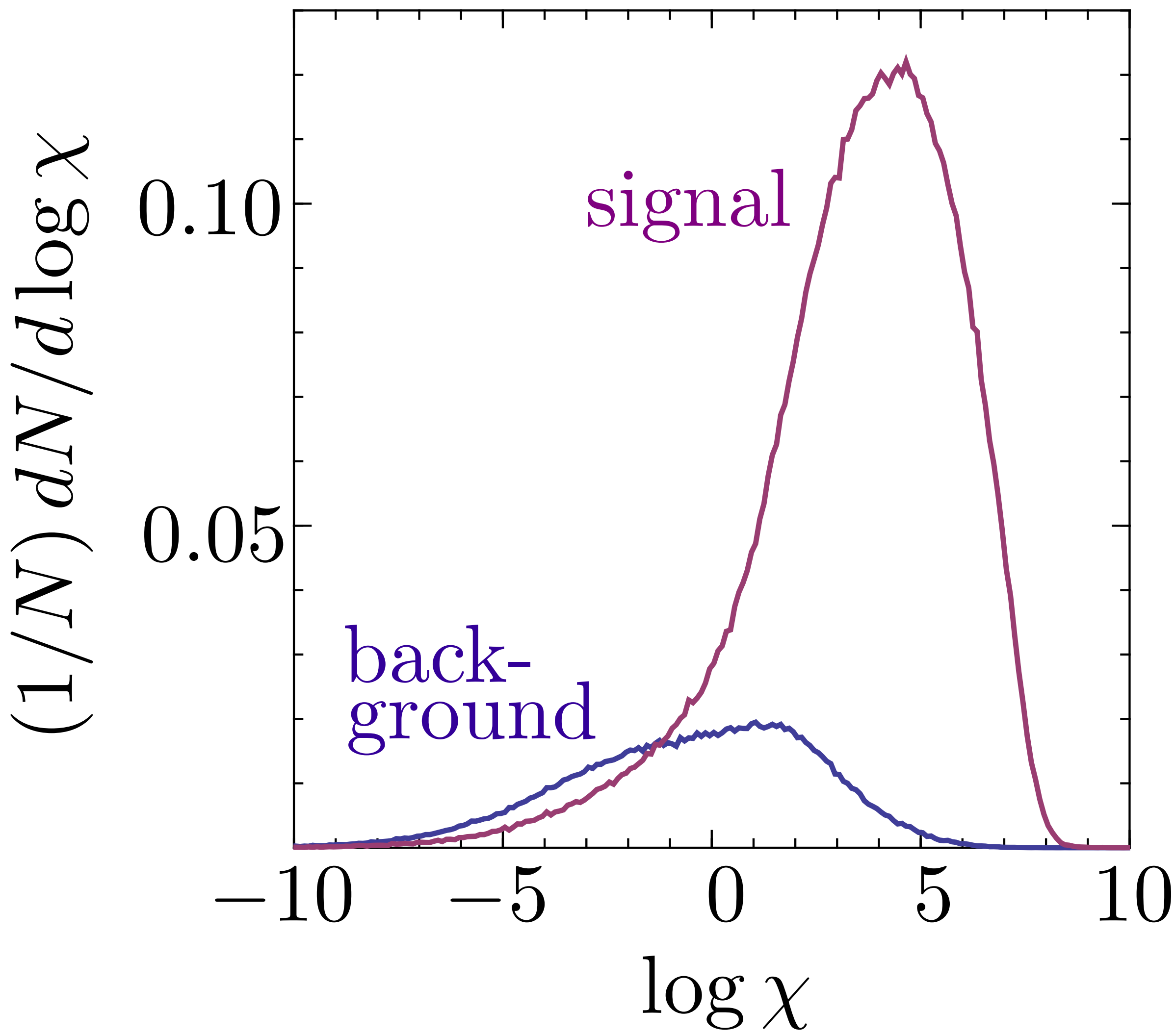
angular distribution for radiation off W decay products



W decay products

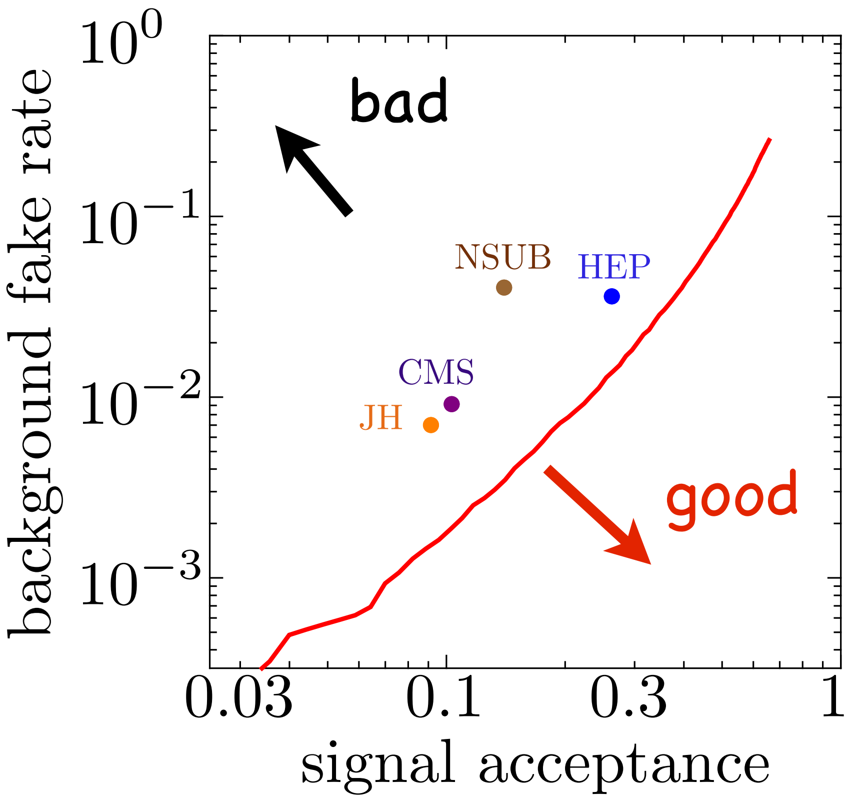
All calculated and build-in into shower/event deconstruction

chi distribution for top vs QCD

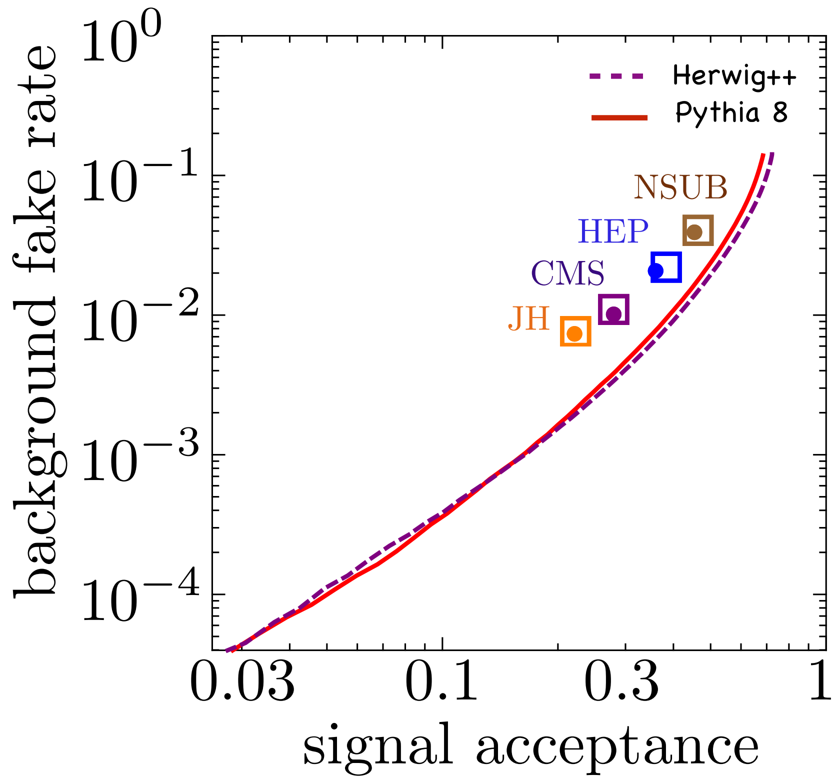


Results for top quark tagging:

pTj > 200 GeV, R=1.5 CA

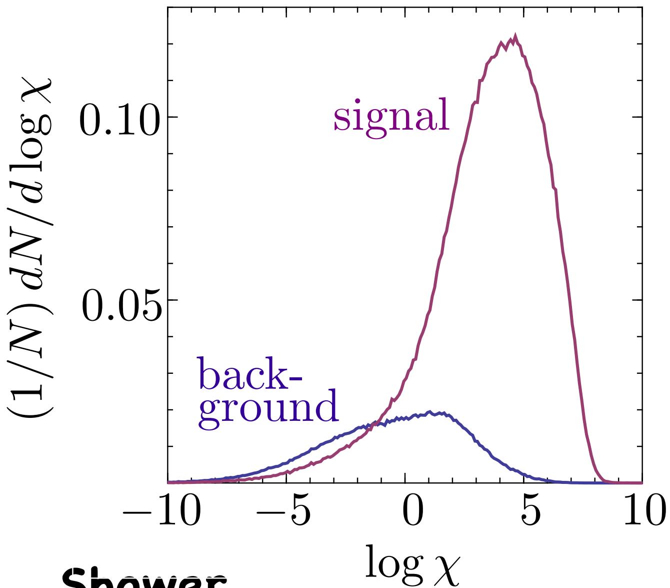


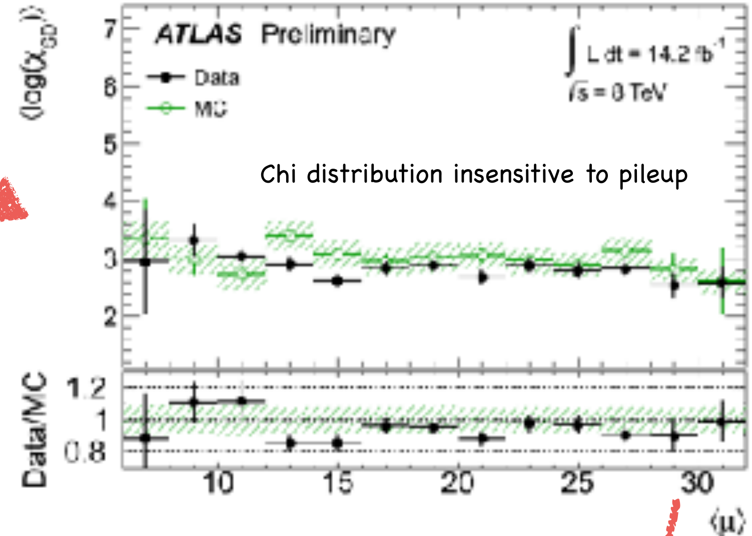
pTj > 500 GeV, R=1.2 CA



microjets: kT, R=0.2, pT>5 GeV

ATLAS results

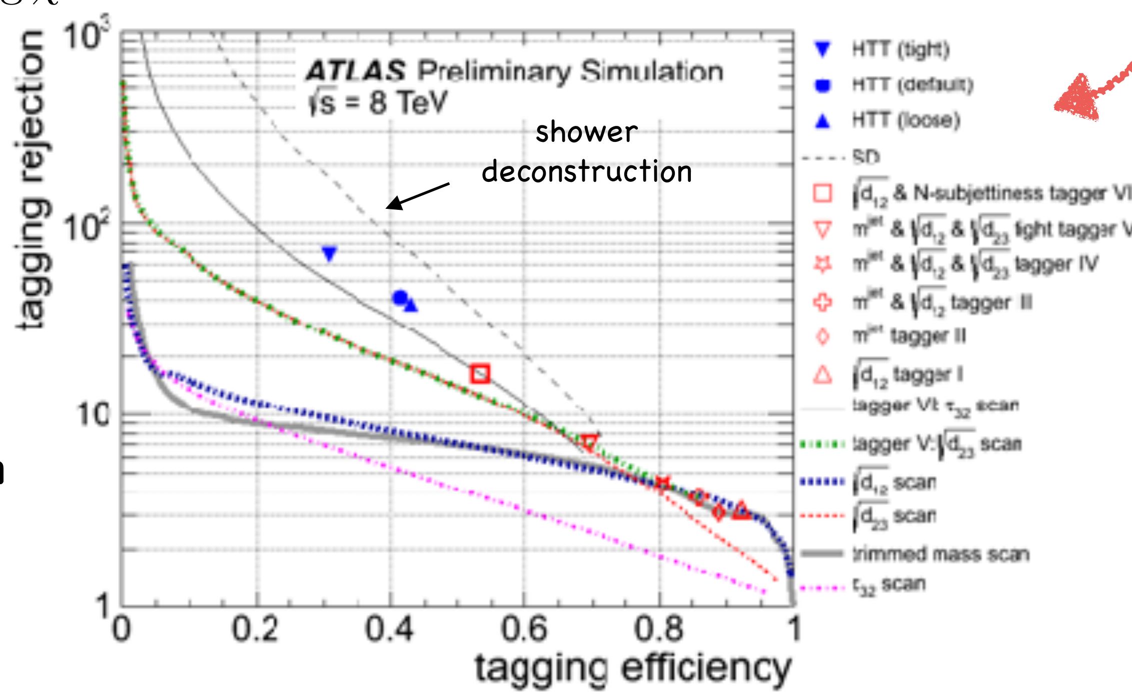




Shower deconstruction improves on best taggers by factor 2-4 in S/B

[1603.03127 ATLAS & MS]

See talk by Deepak Kar



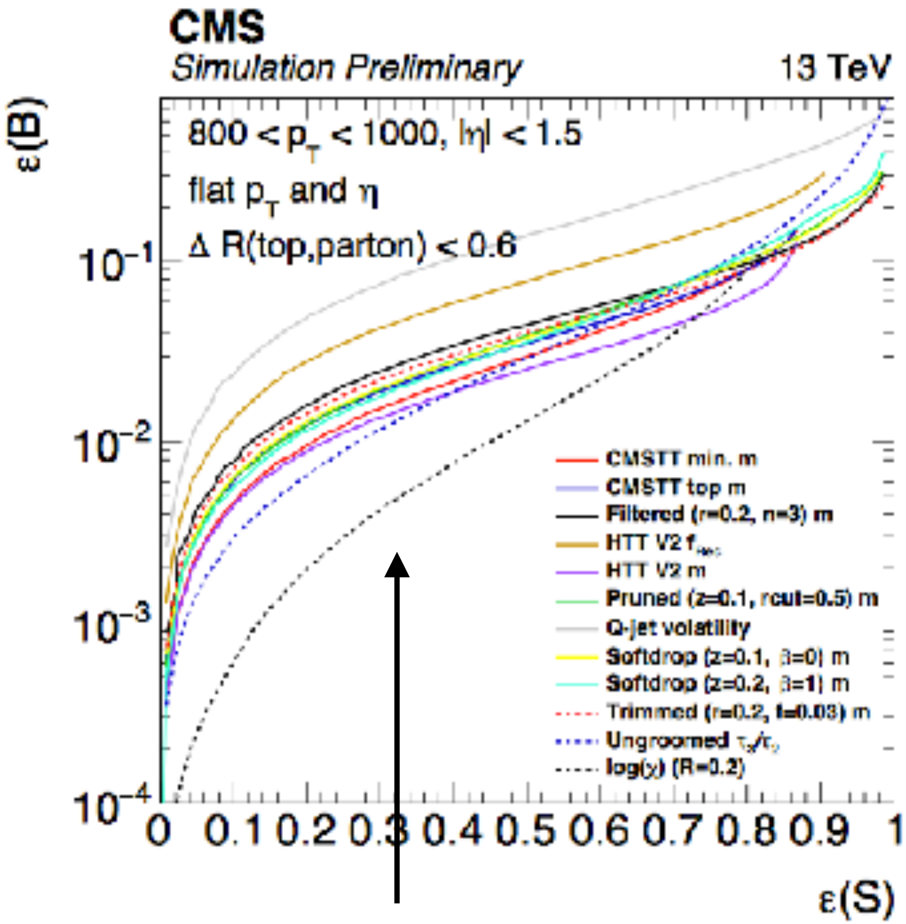
Shower Deconstruction

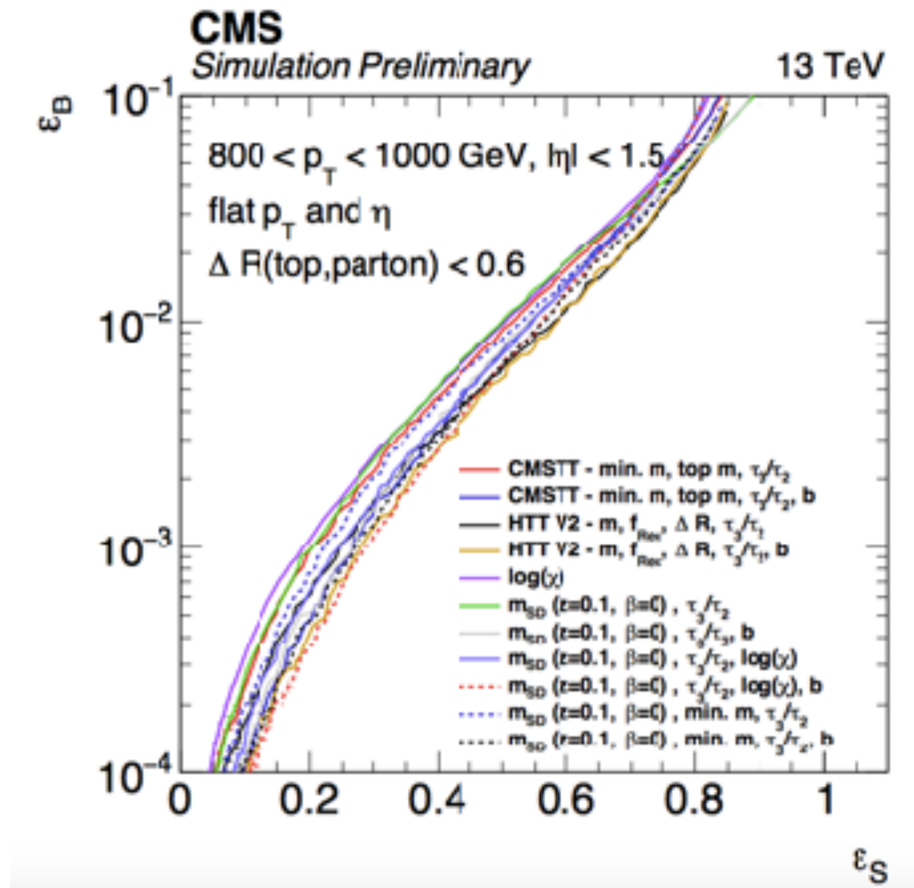
and

HEPTopTagger

from same author

Results by CMS





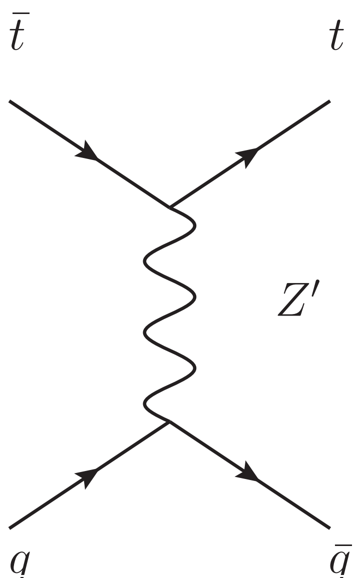
- Shower deconstruction best single variable
- Efficiencies matched if taggers combined

First application of Event Deconstruction
= full event MEM + parton shower resummation

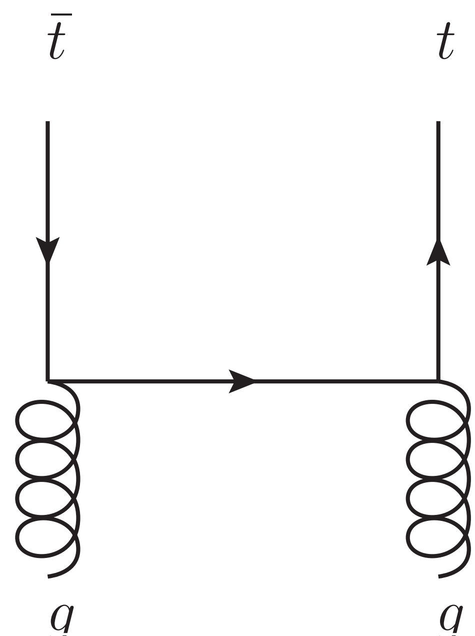
fully hadronic Z' -> tt

[Soper, MS '14]

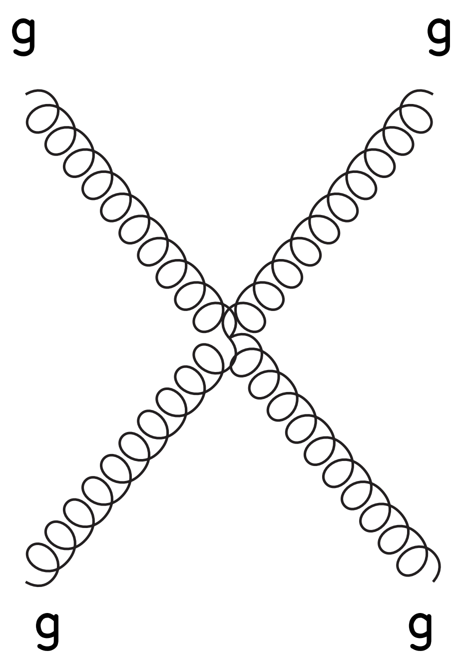
Signal



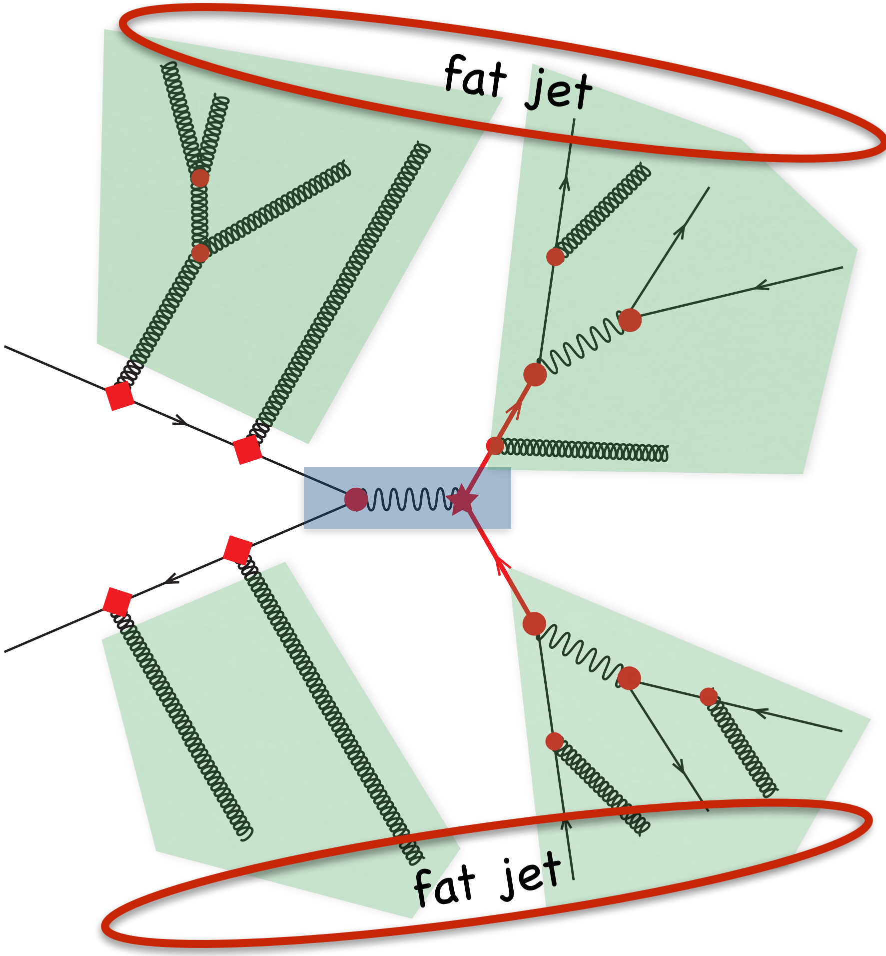
$t\bar{t}$



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:

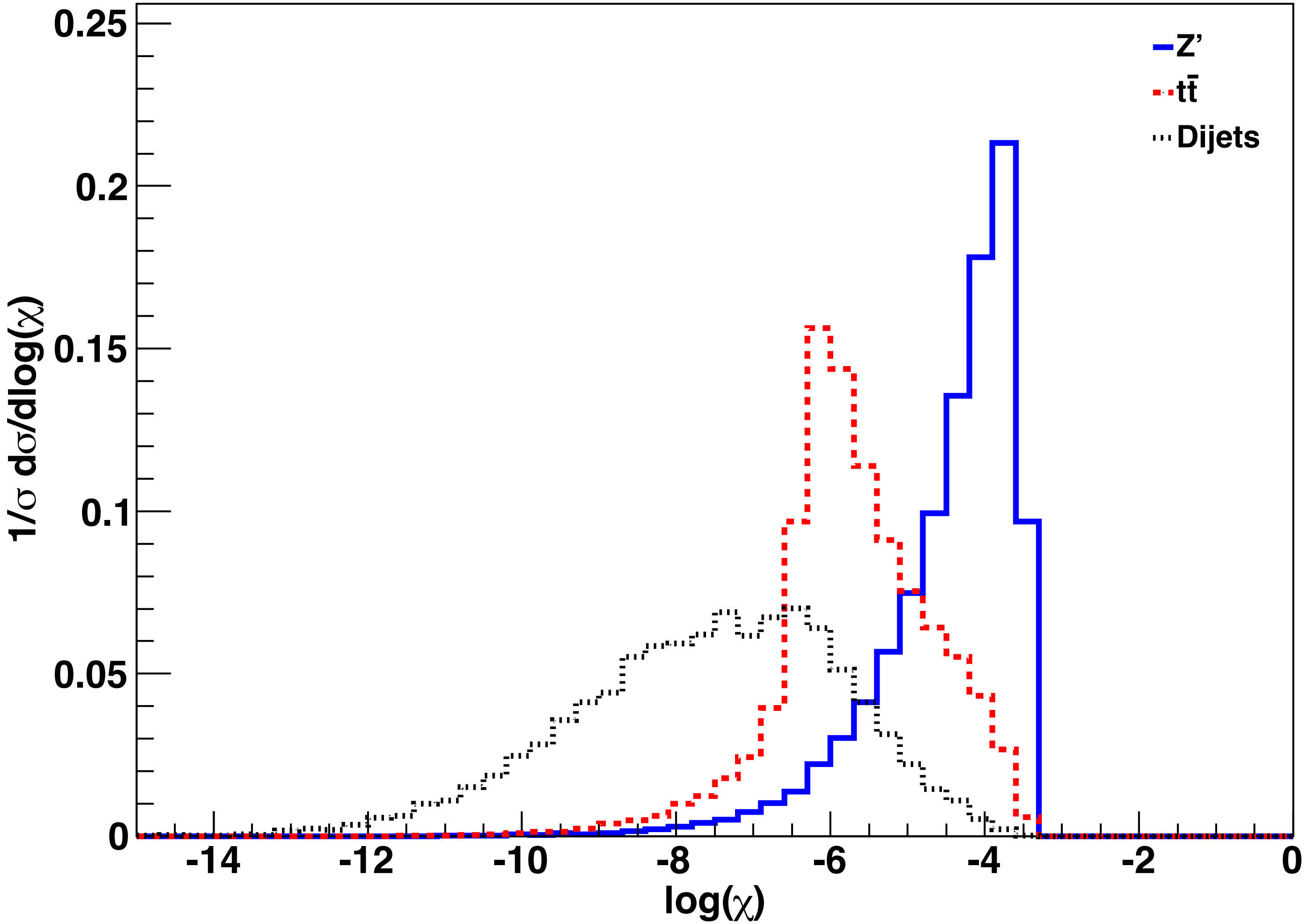
dijets	1.73 nb
ttbar	2.27 pb

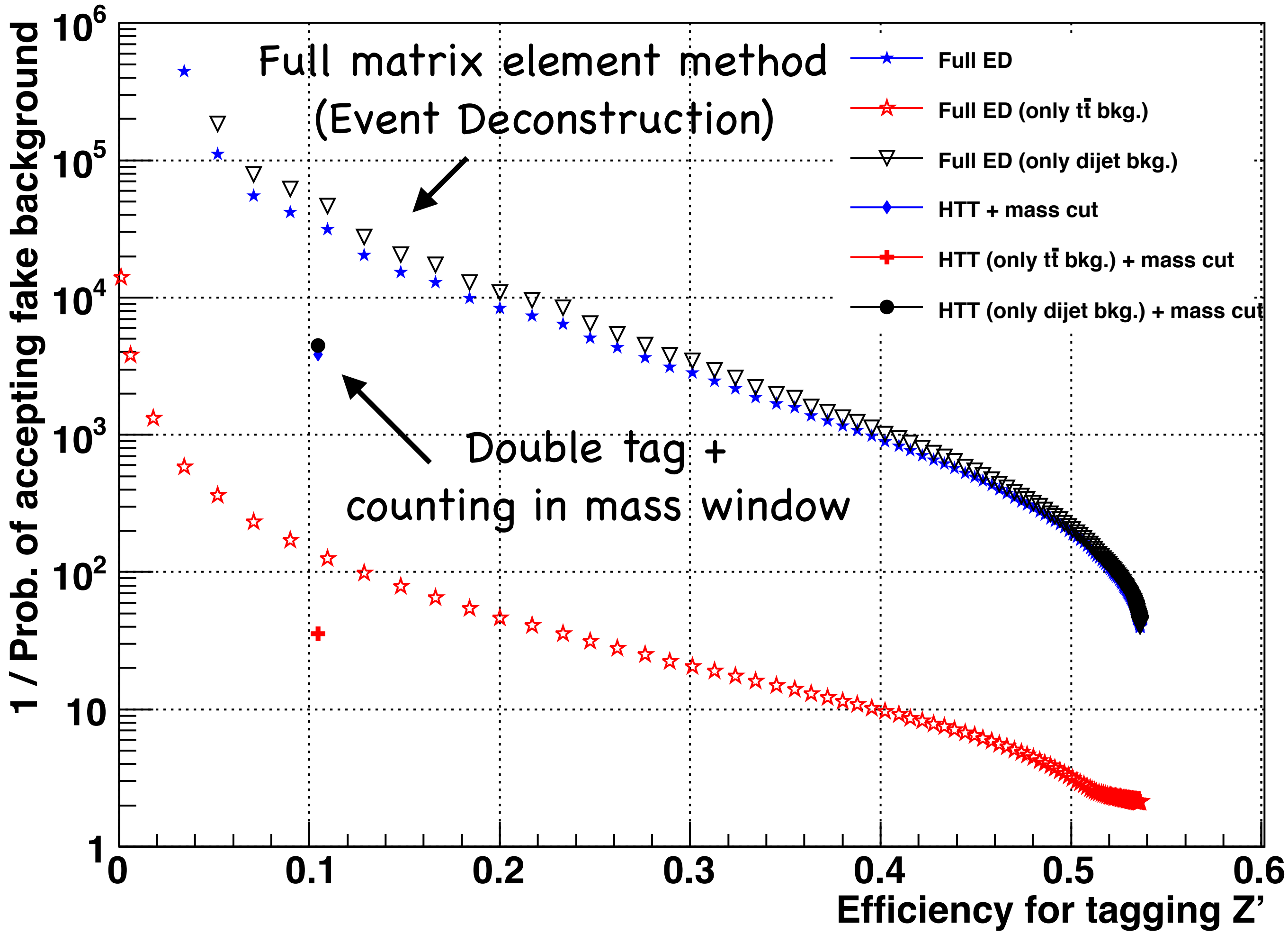
Recluster fatjet constituents using microjets kT R=0.2 pT>10 GeV

Z′ width in Event Dec. 130 GeV

Hard matrix element generated with MadGraph5

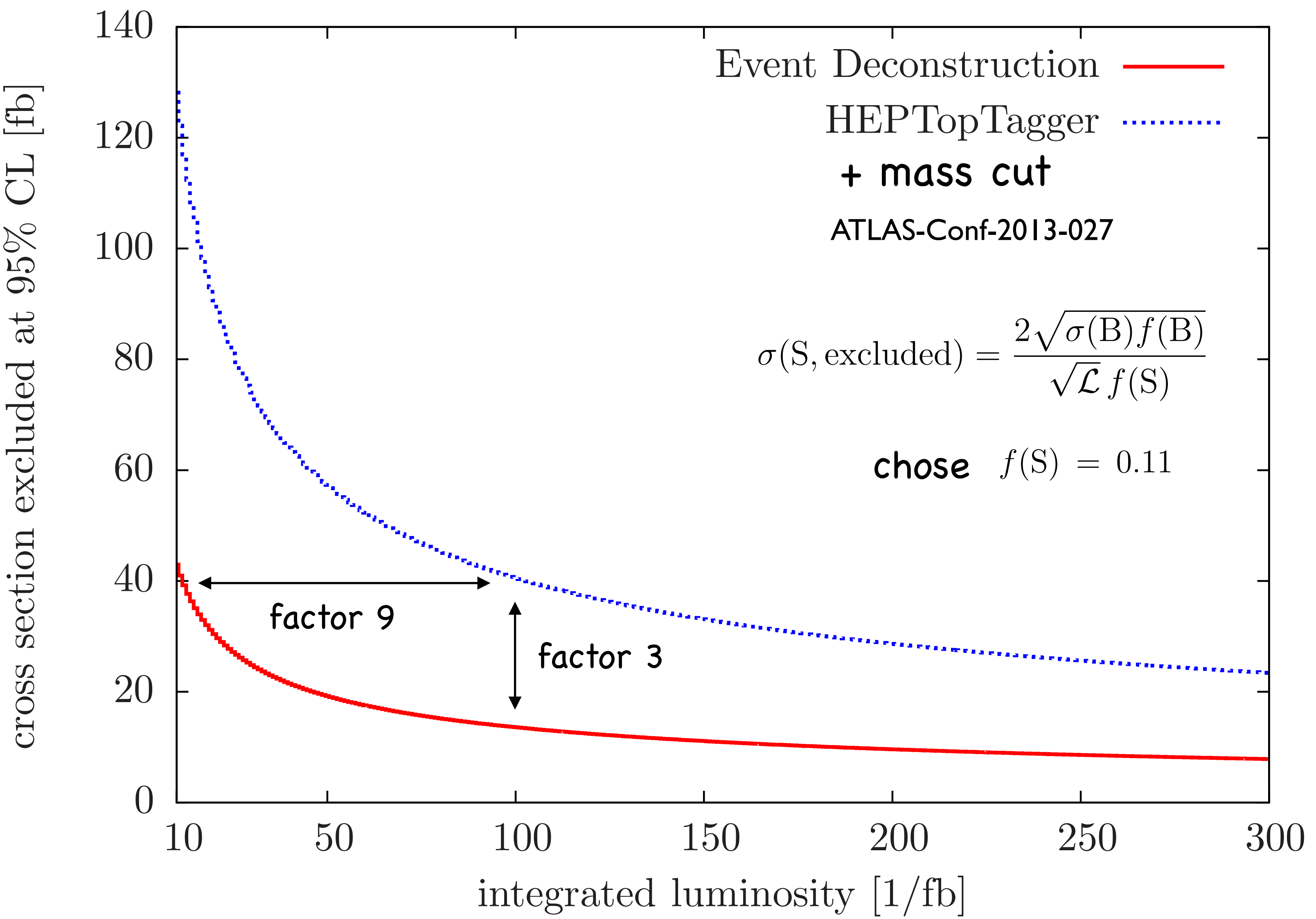
$$\chi = \frac{P(X|Z')}{P(X|t\bar{t} + \text{dijets})}$$





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

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


cross section excluded at 95% CL [fb]
140
120
100
80
60
40
20
0
10
50
100
150
200
250
300
integrated luminosity [1/fb]
Event Deconstruction
HEPTopTagger
+ mass cut
ATLAS-Conf-2013-027
$\sigma(\mathrm{S}, \mathrm{excluded}) = \frac{2\sqrt{\sigma(\mathrm{B}) f(\mathrm{B})}}{\sqrt{\mathcal{L}}\, f(\mathrm{S})}$
chose $f(\mathrm{S}) = 0.11$
factor 9
factor 3

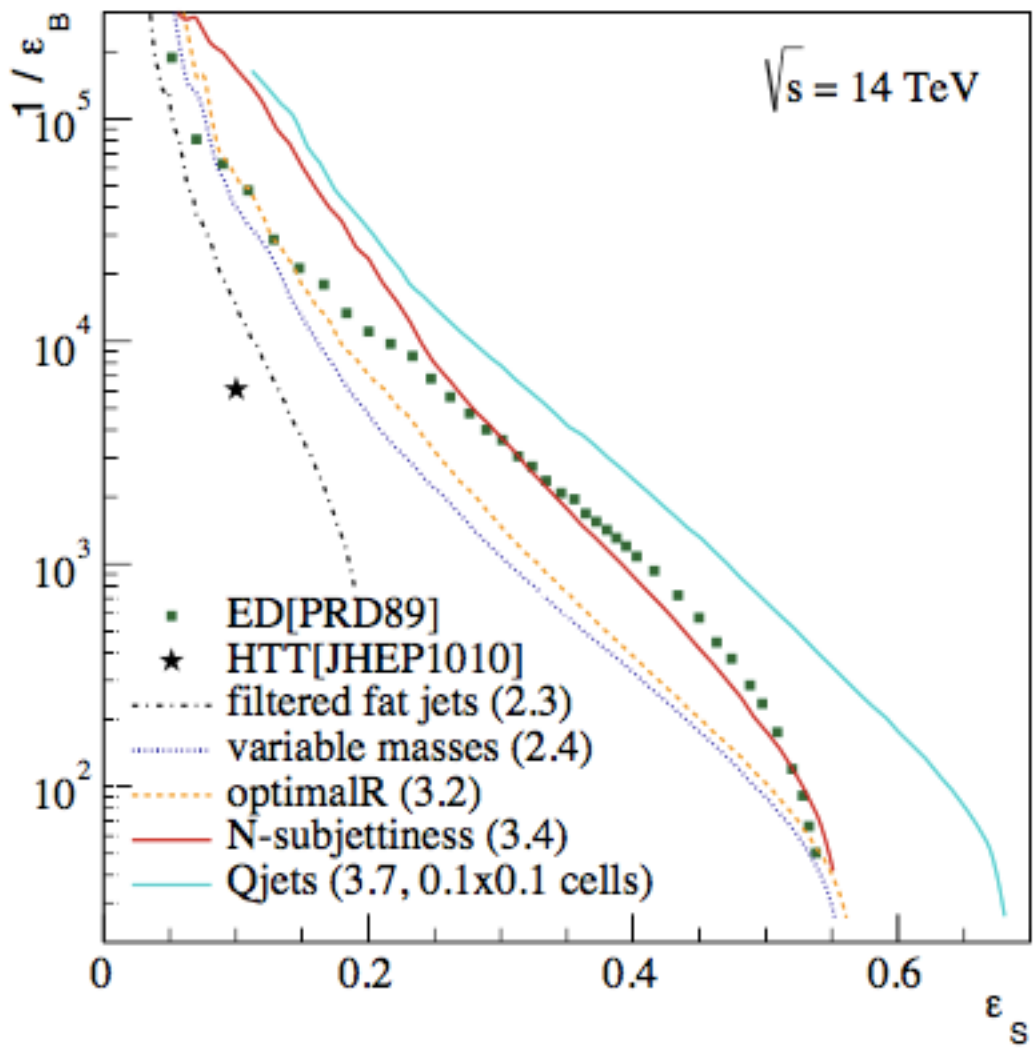
Brief comment on Tilman's 'challenge'

3 theorists and 2 CMS postdocs worked for 1 year
vs
1 week unoptimised implementation of Event Deconstruction by 1 person

ED includes mimic of detector response using imperfect width measurement in matrix element

huge improvement due to QJets rather peculiar...

[Kasieczka, Plehn, Schell, Strebler, Salam '15]



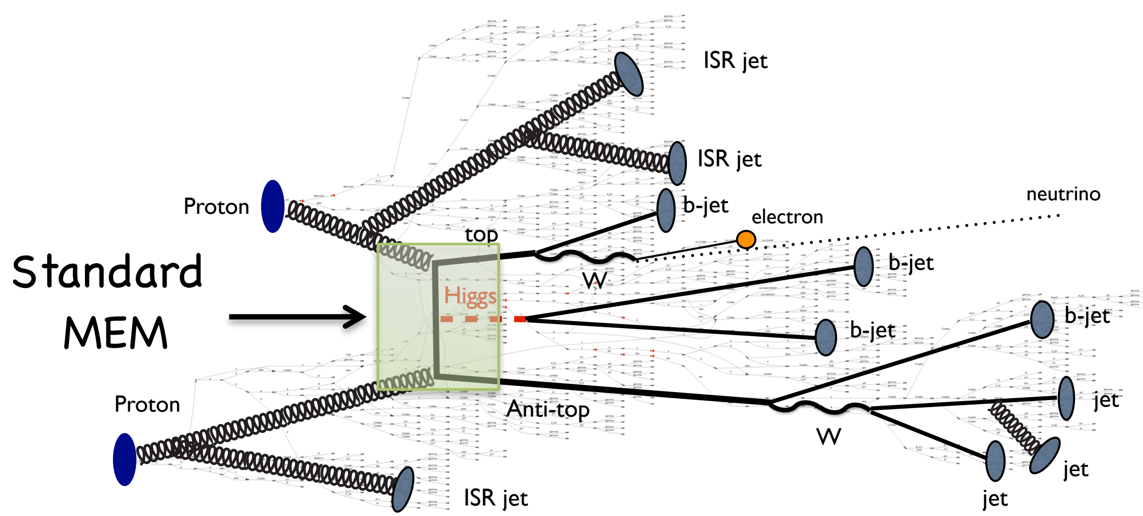
Summary

- Matrix Element Method is active field of research
  [see also MEM Workshops in Louvain (2013) and Zurich (2014)]

- Current interest in machine-learning is not taking matrix element methods out of the picture! MEM can help to check MVAs

- My personal view:

MEM is much more than object identification!



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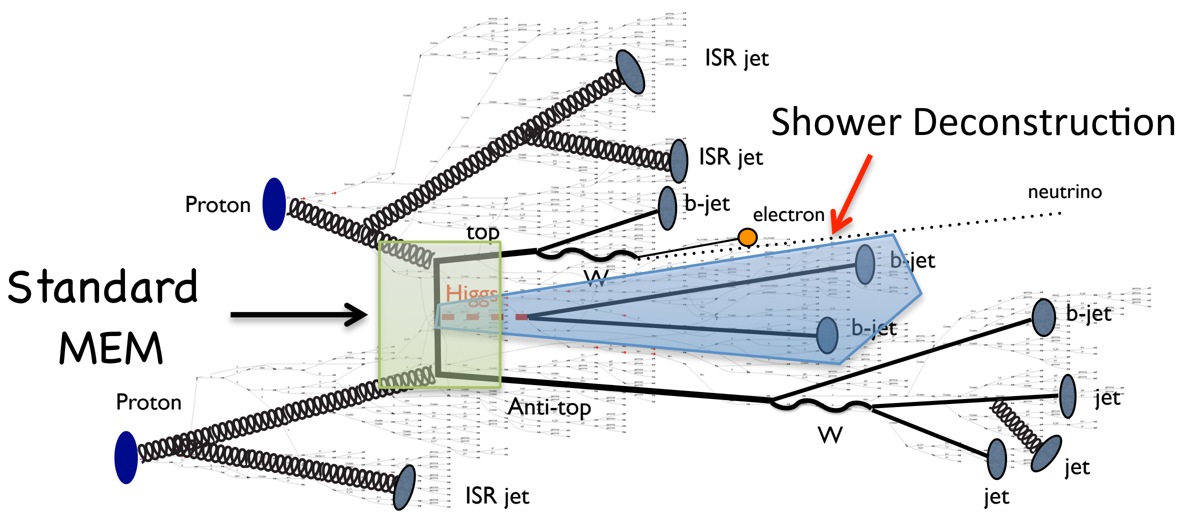

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  Event Deconstruction, i.e. Pattern Recognition for full event

Future MEM