Jet observables for Higgs measurements

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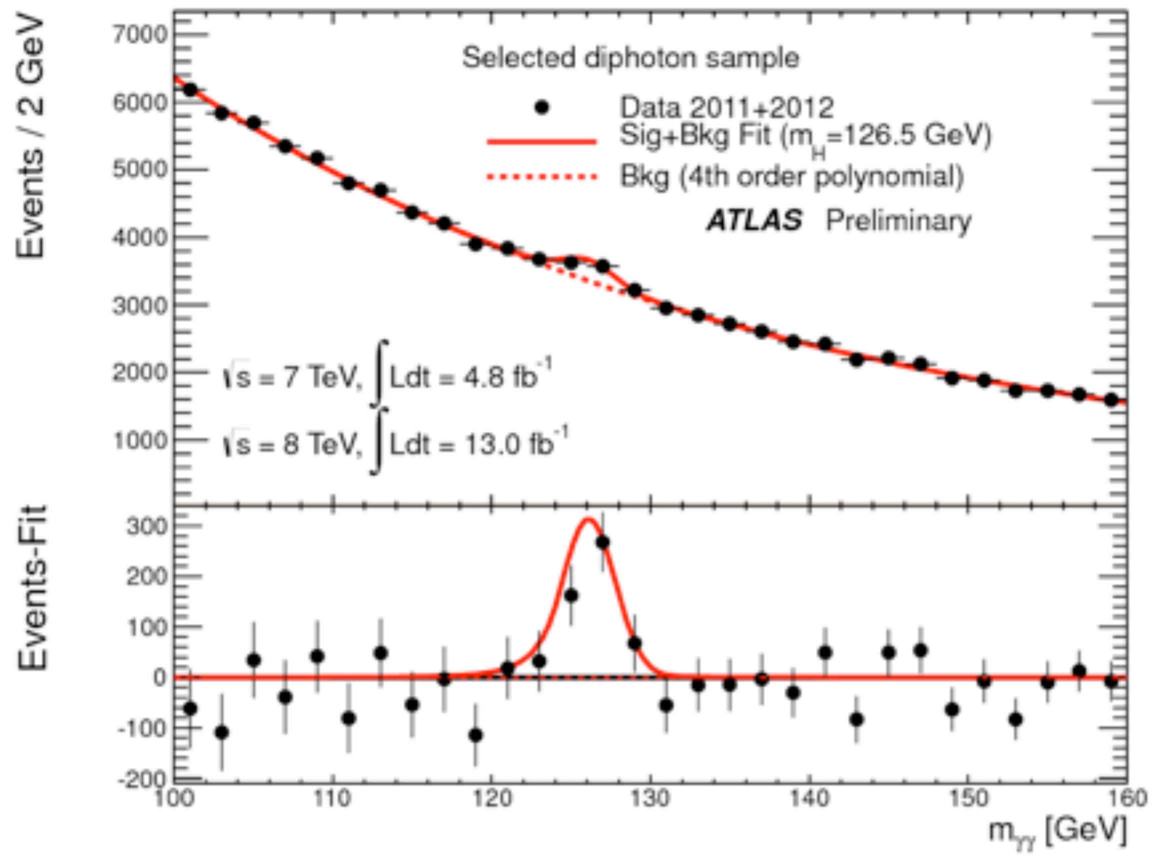
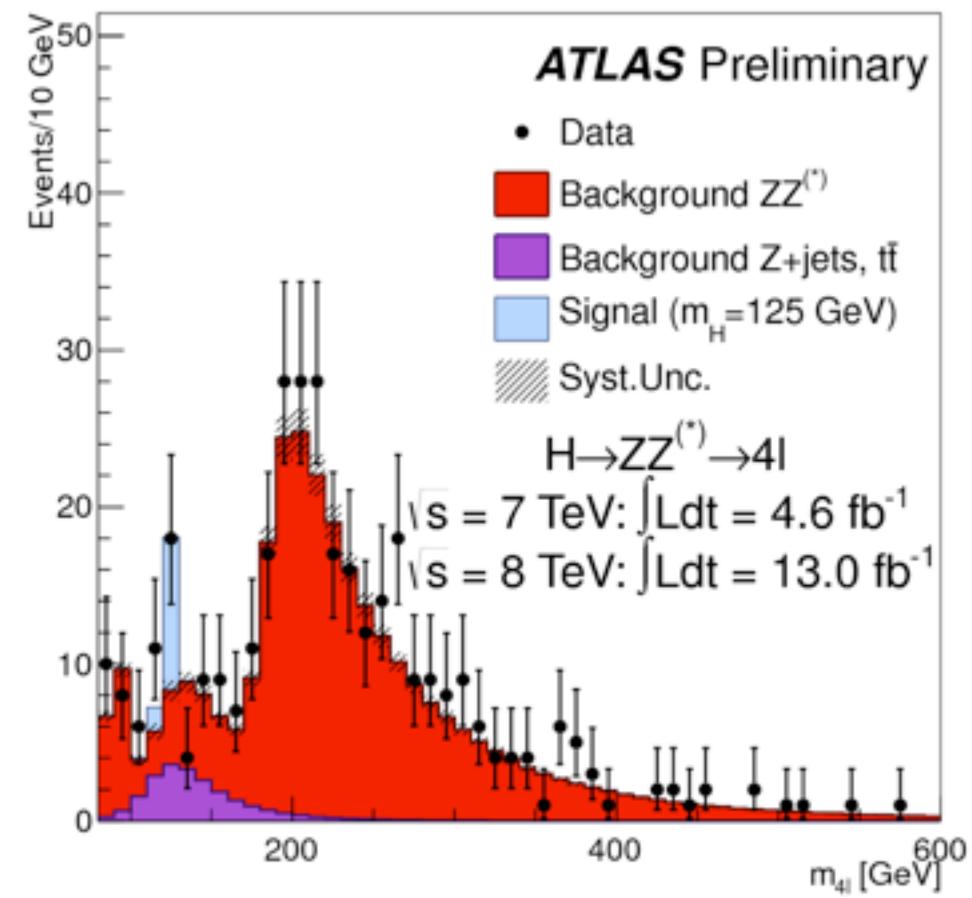
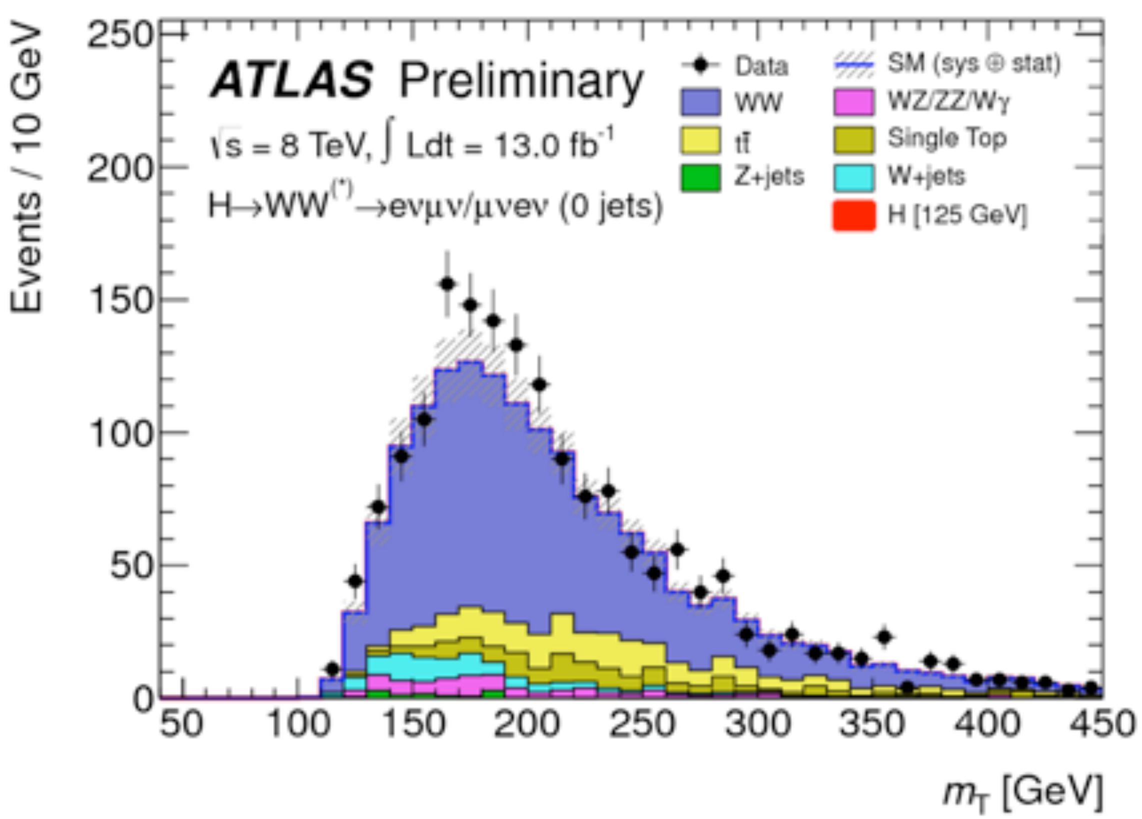
University of Durham

7 + 8 TeV data:



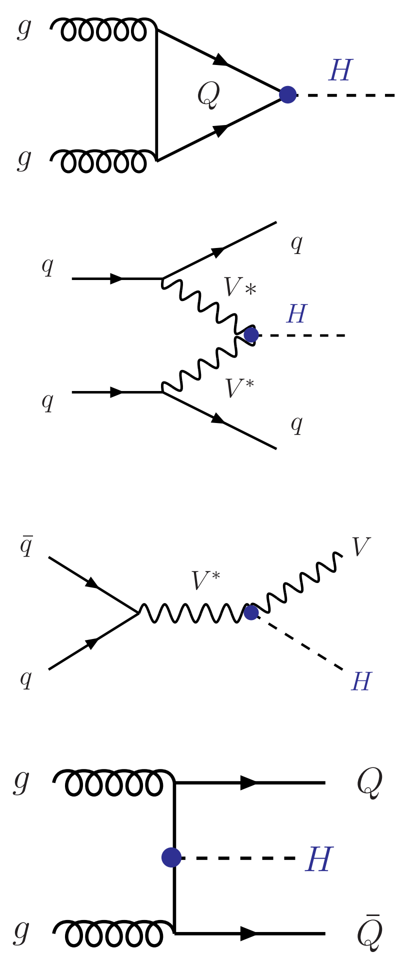




Recently observed clear excesses in 3 independent channels:

- 2 Photons
- 4 Leptons (electrons/muons)
- 2 Leptons (electrons/muons) + MET

Need cross correlation between many channels:



production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
WH/ZH	$b\bar{b}$ (subjet)

assumed: $\Gamma_H = \Sigma_{SM}\Gamma_i \quad \Gamma_i \sim g_d^2$

[Lafaye, Plehn, Rauch, Zerwas, Duehrssen (2009)]

Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

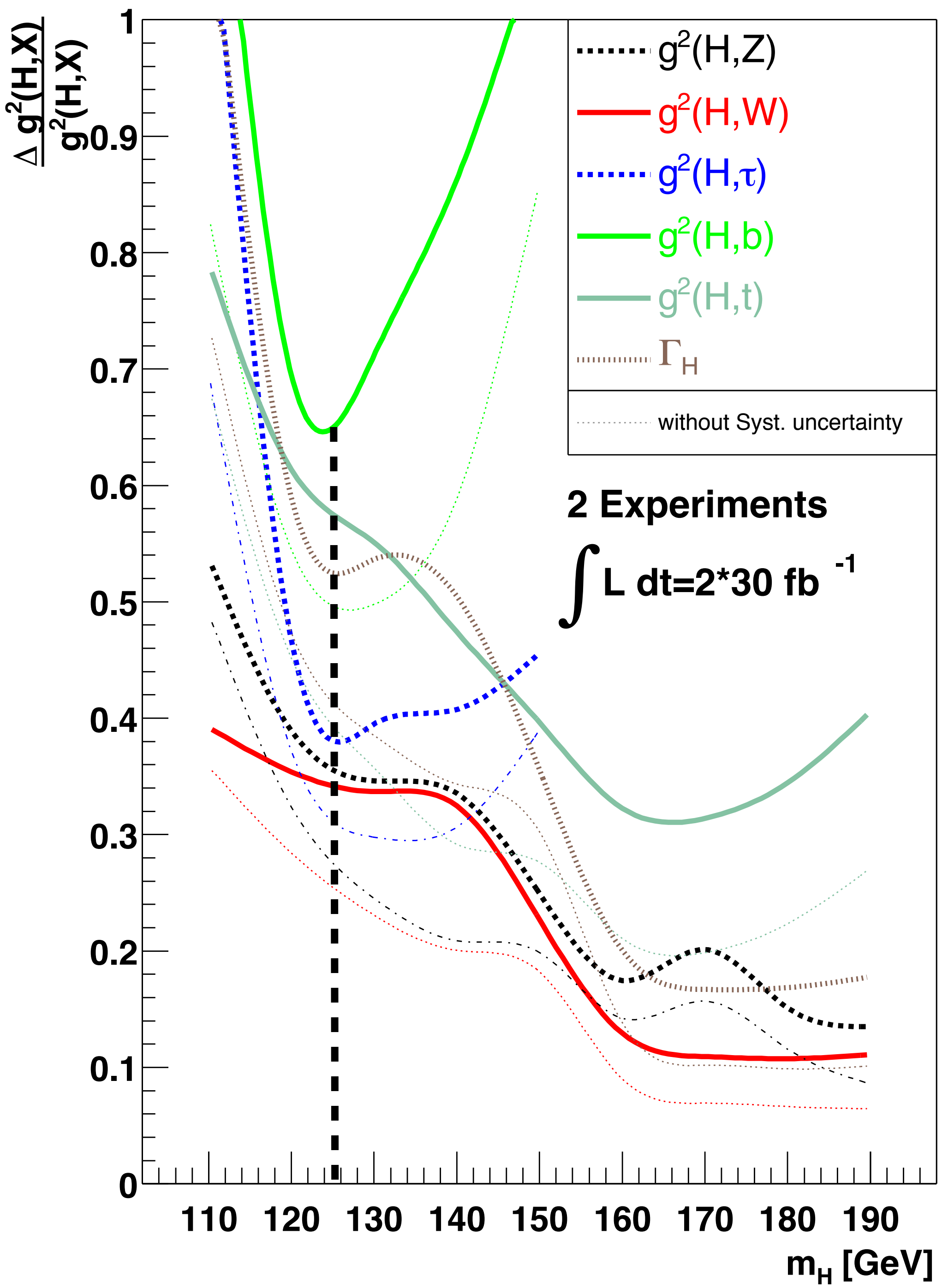
Sum of all possible decays

- Every measurement affected by production and decay

Uncertainty of all coupling measurements driven by total width, i.e. channel with largest BR: H-> bb

Hbb difficult but can use new techniques, i.e. Jet substructure!

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was PRD 62 (2000); Duehrssen (2005)]



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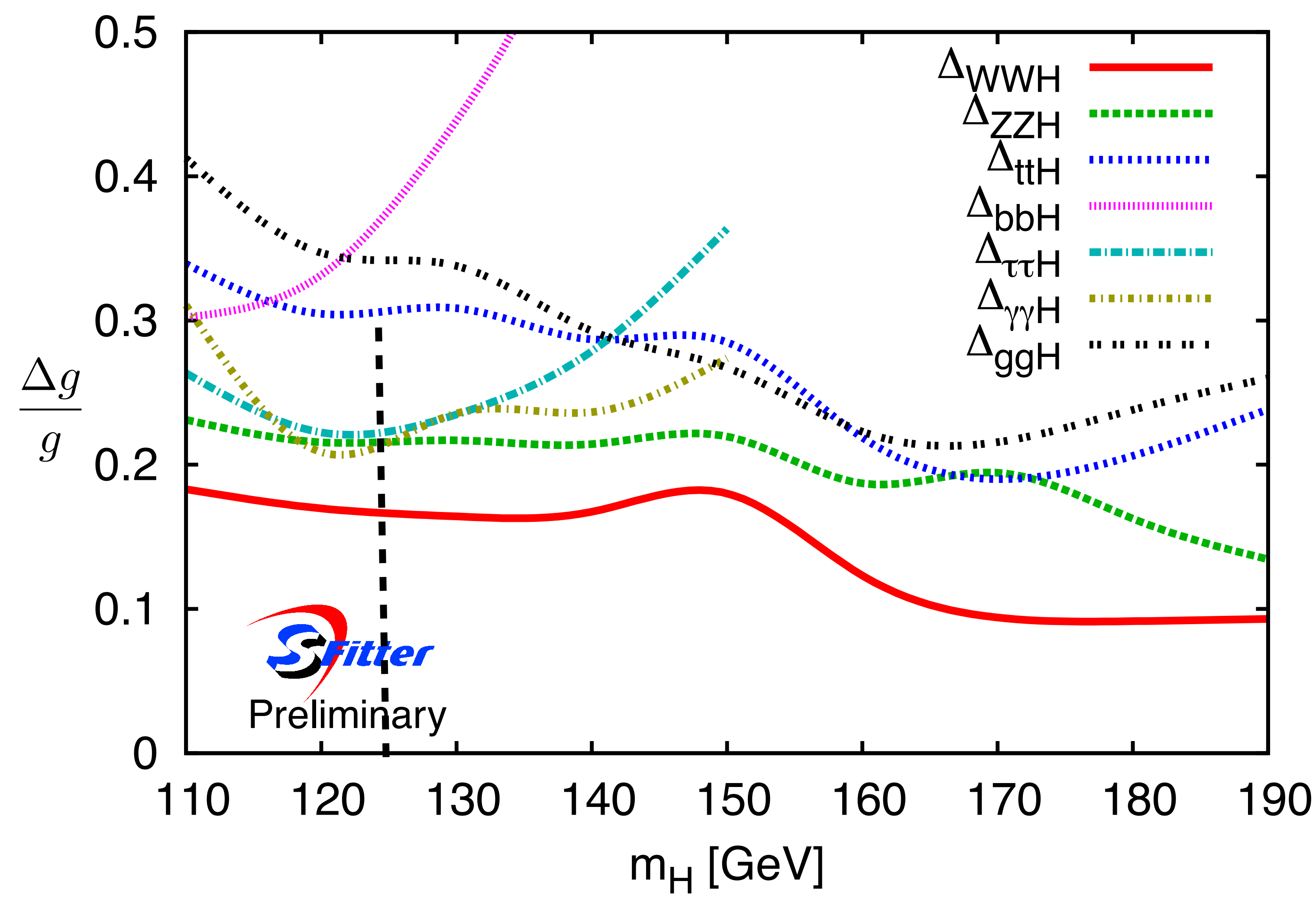
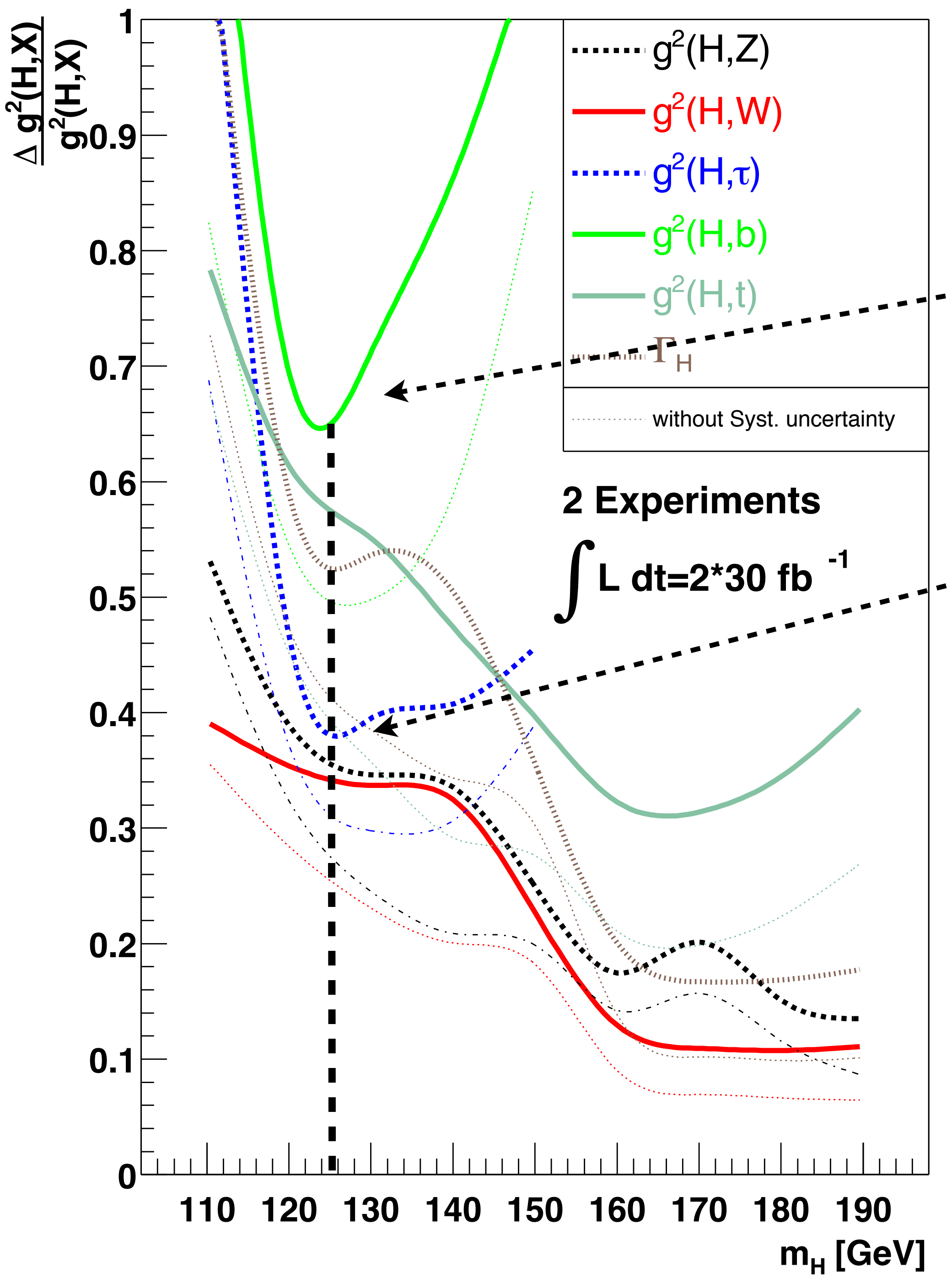


- Huge improvement from boosted Higgs analysis
- also for non-b decay modes due to better knowledge of total width

→ To reduce uncertainty for all coupling, need to measure b and t coupling

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was PRD 62 (2000); Duehrssen (2005)]



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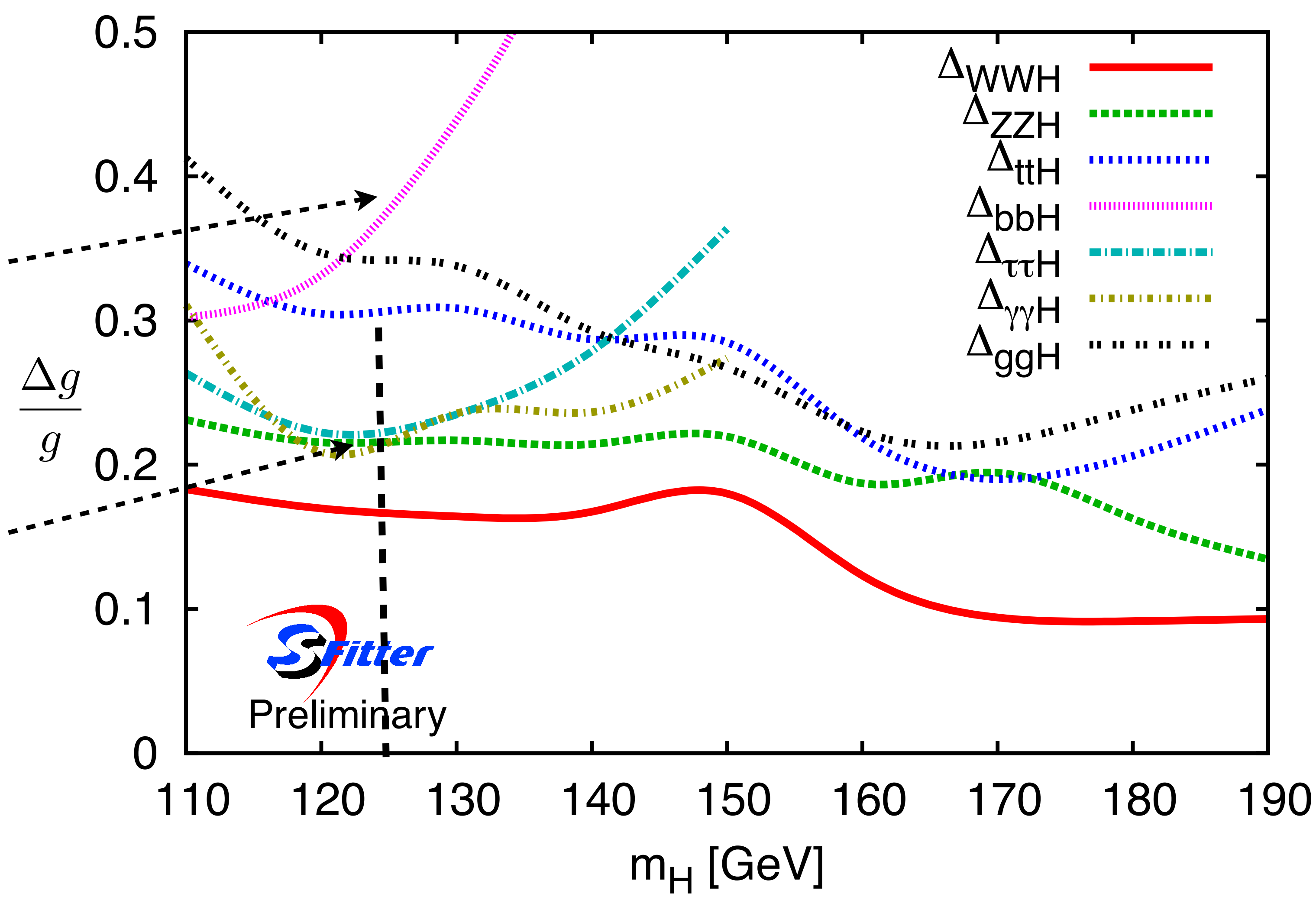

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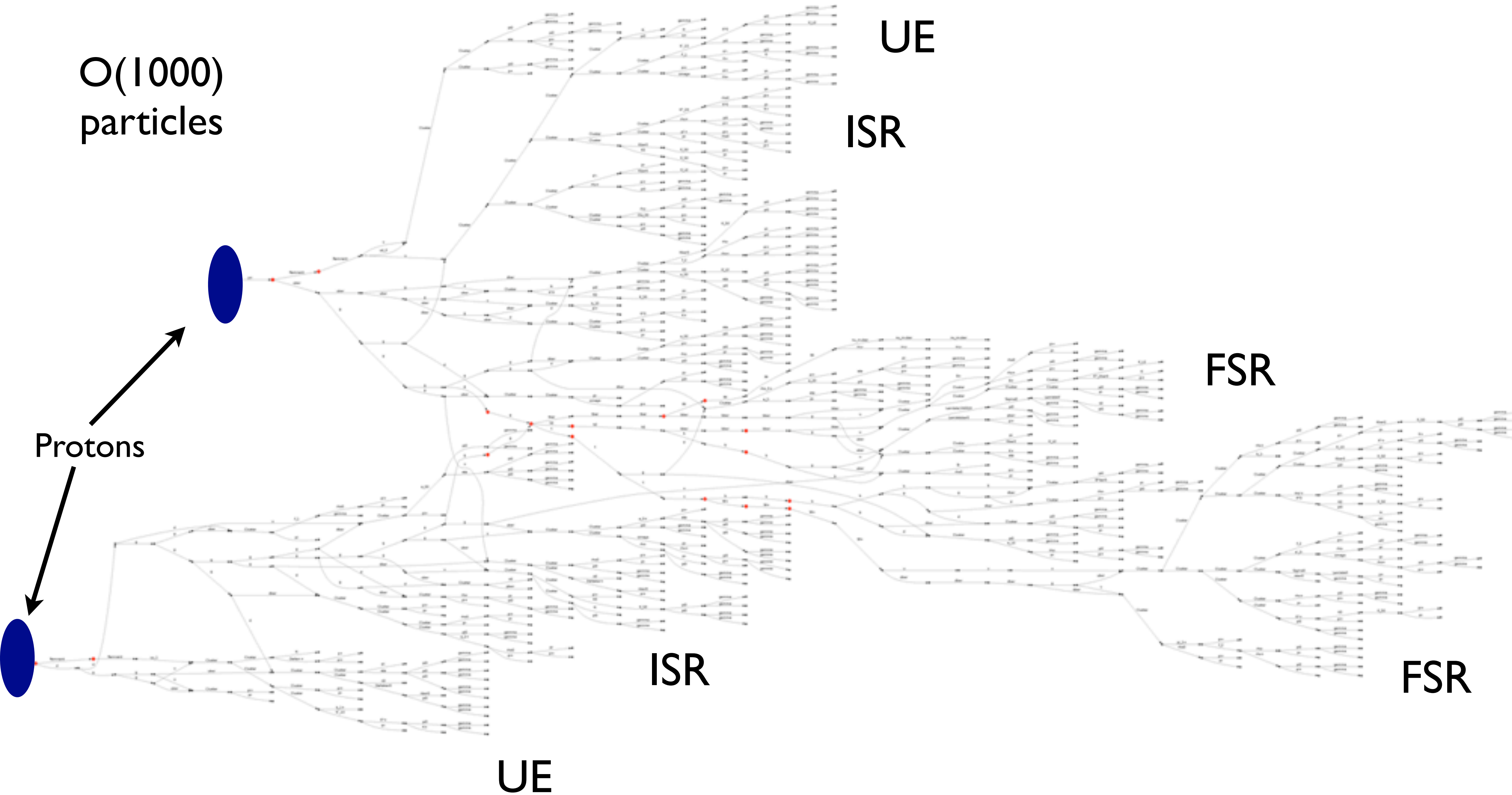

Tedious for theorists and experimentalists

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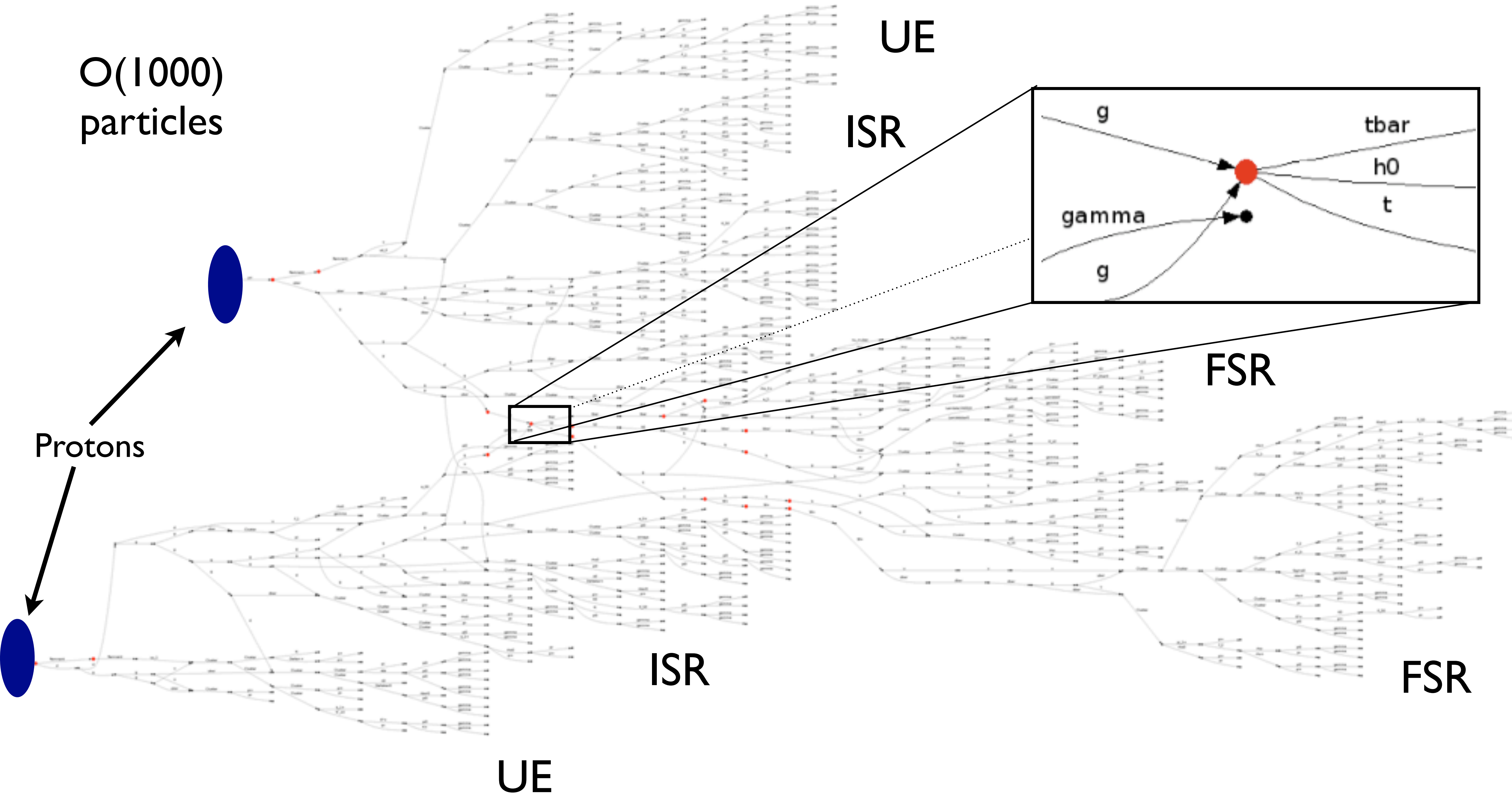


Tedious for theorists and experimentalists

Observables for measuring the CP of the Higgs boson in Hjj

- For light Higgs with 125 GeV CP can be measured using angular correlations of tagging jets in Gluon Fusion with 2 additional jets

[Plehn, Rainwater, Zeppenfeld PRL 88 (2002)]

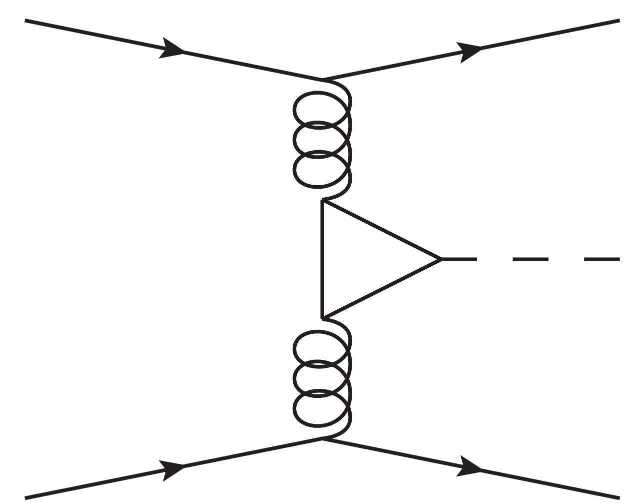
- Event shape observables can be used to measure CP of Higgs

[Englert, MS, Takeuchi 1203.5788]

Interaction:

$$\mathcal{L} = \frac{\alpha_s}{12\pi v} H G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\alpha_s}{16\pi v} A G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

Gluon-Fusion



For tagging jets with $|p_z^J| \gg |p_{x,y}^J|$

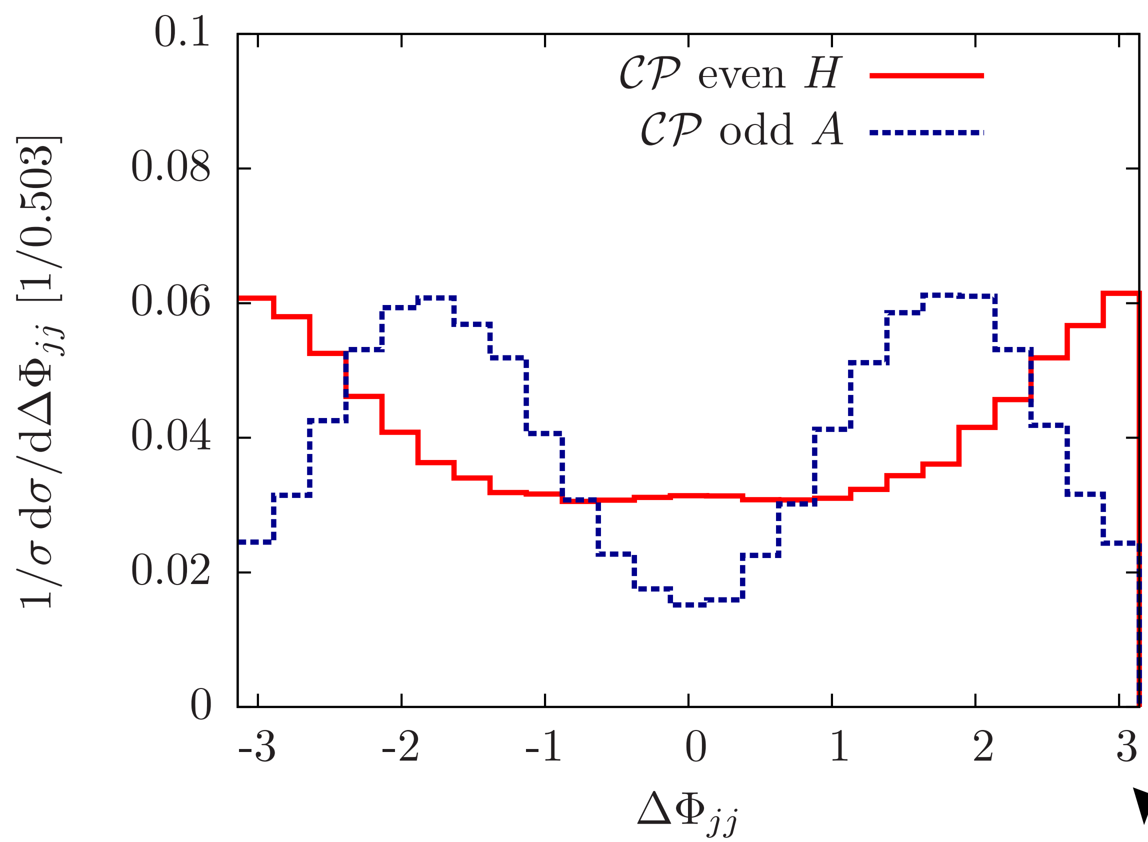
$$\mathcal{M}_{\rm even} \sim J_1^\mu J_2^\nu \left[g_{\mu\nu}(q_1 \cdot q_2) - q_{1\nu} q_{2\mu} \right]$$

$$\sim \left[J_1^0 J_2^0 - J_1^3 J_2^3 \right] \mathbf{p}_T^{J_1} \cdot \mathbf{p}_T^{J_2}$$ ~ 0 for $\Delta\phi_{jj} = \pi/2$

$\mathcal{M}_{\rm odd}$ contains Levi-Civita tensor which is 0 if two of momenta linearly dependent, i.e. if $\Delta\phi_{jj} = 0$ or $\Delta\phi_{jj} = \pi$

Tagging jets approach:

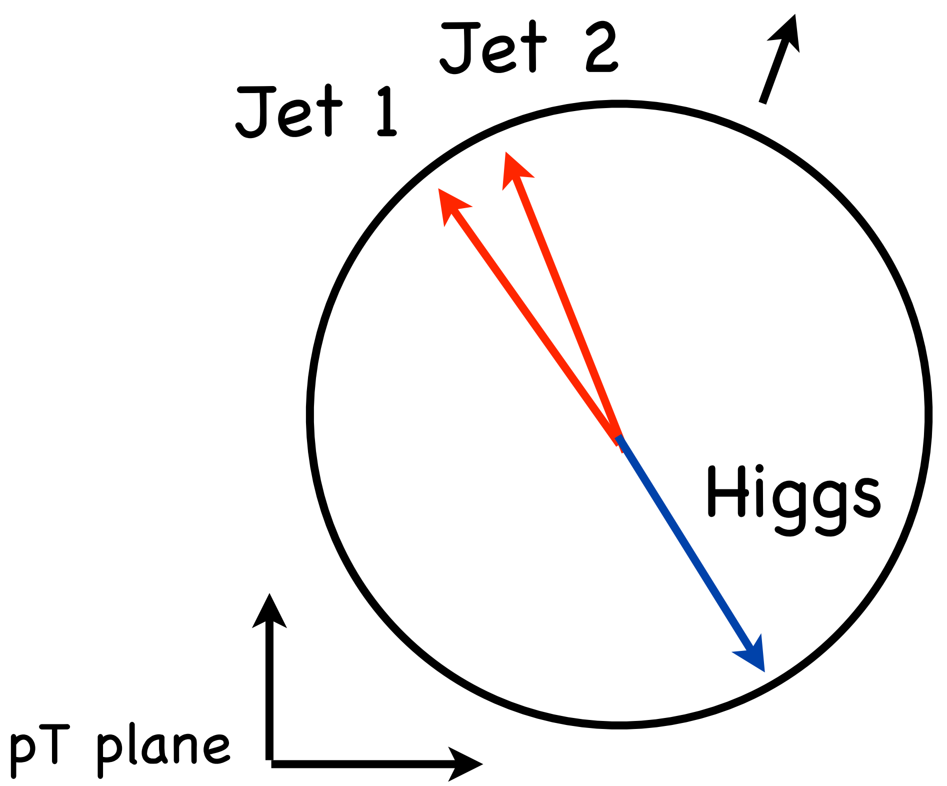
azimuthal angle between all jets with larger or smaller rapidity wrt Higgs

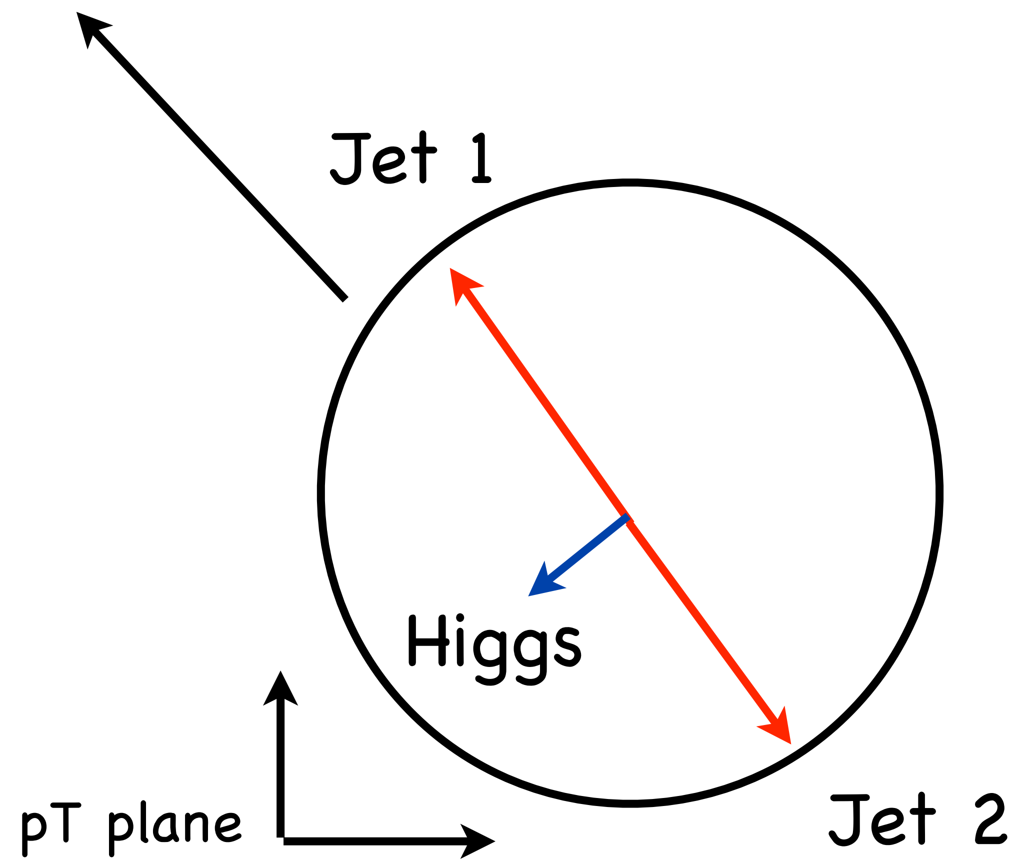


$$p^\mu_< = \sum_{j\in\{\text{jets: } y_j<y_h\}} p^\mu_j$$

$$p^\mu_> = \sum_{j\in\{\text{jets: } y_j>y_h\}} p^\mu_j$$

$$\Delta\Phi_{jj} = \phi(p_>) - \phi(p_<)$$





Event shapes

- Event shapes well studied experimentally and theoretically

  [Bethke, Nucl.Phys.Proc.Suppl. 121 (2003)] [Kluth. et al, EPJC 21 (2011)]

  [Banfi et al., JHEP 0408] [Gehrmann-De Ridder et al., JHEP 0712]

- Avoids vetoing of jets which can induce large theo. uncertainties

  [Stewart, Tackmann PRD 85 (2012)]

- Event shape measurements established in experimental collaborations already now [CMS, PLB 699 (2011)]

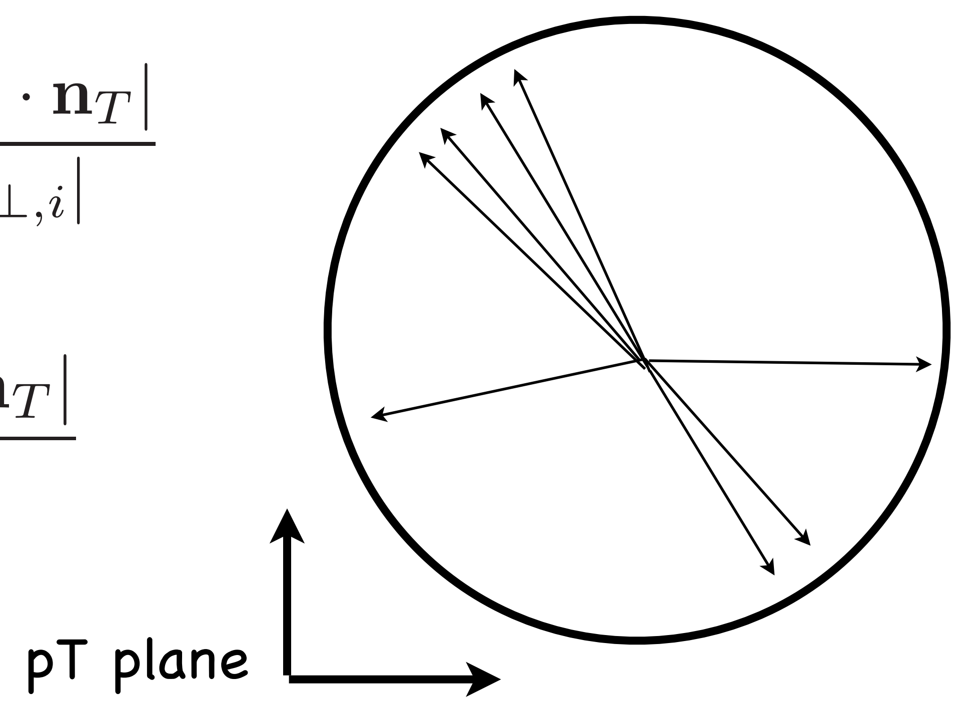
  e.g.

transverse thrust

$$T_{\perp,g} = \max_{\mathbf{n}_T} \frac{\sum_i |\mathbf{p}_{\perp,i} \cdot \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$

transverse thrust minor

$$T_{m,g} = \frac{\sum_i |\mathbf{p}_{\perp,i} \times \mathbf{n}_T|}{\sum_i |\mathbf{p}_{\perp,i}|}$$



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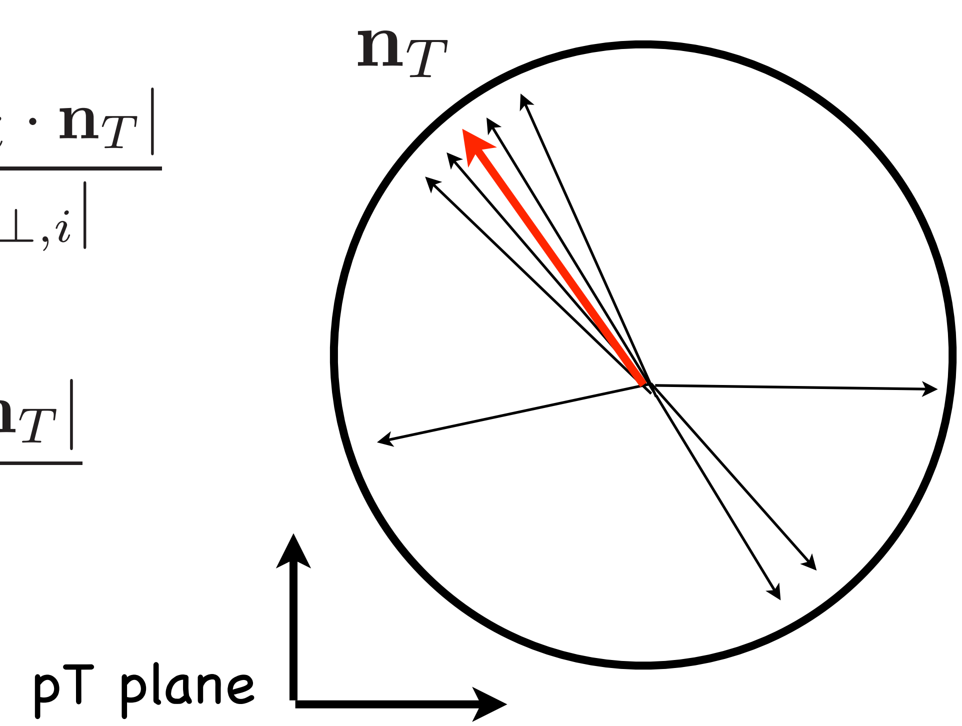
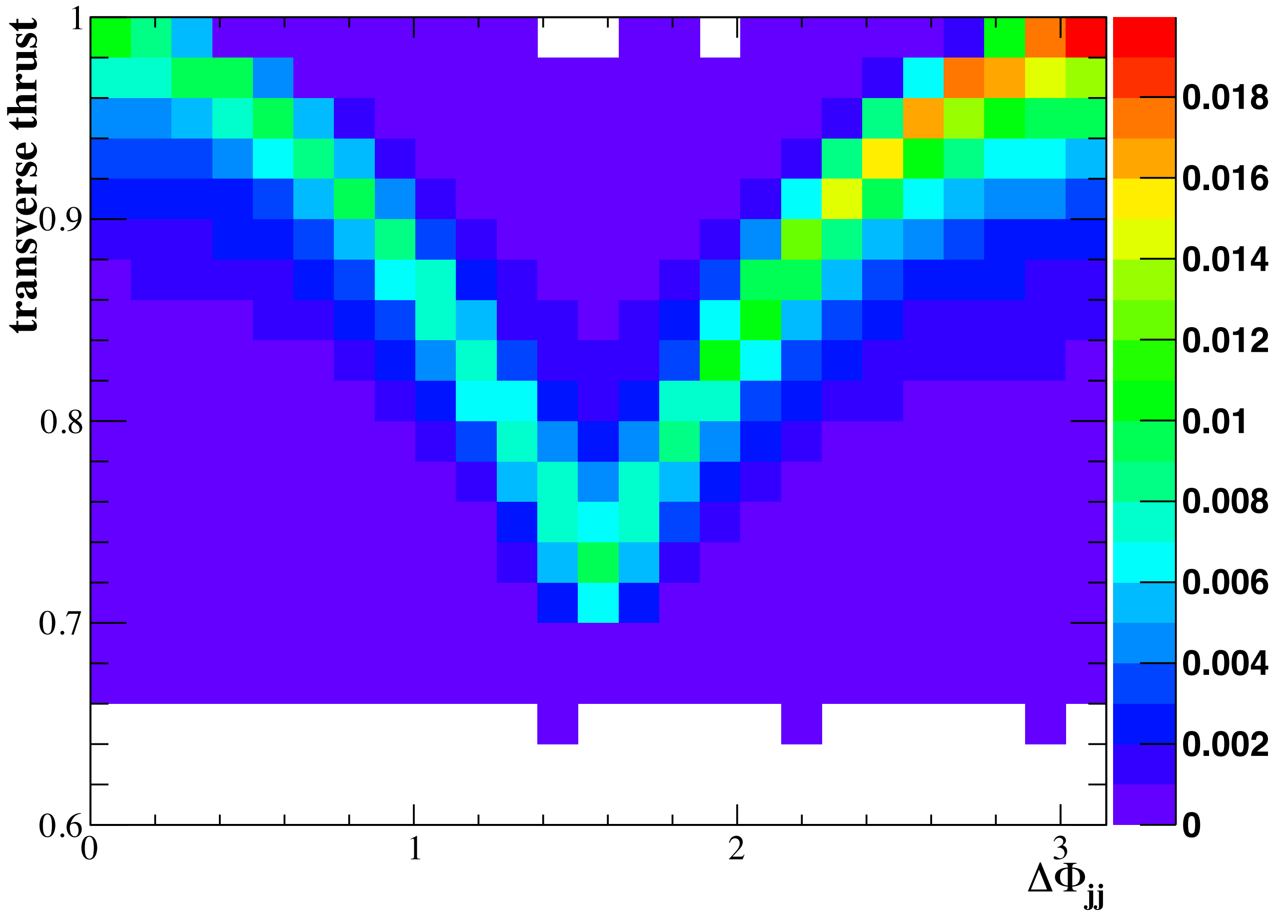
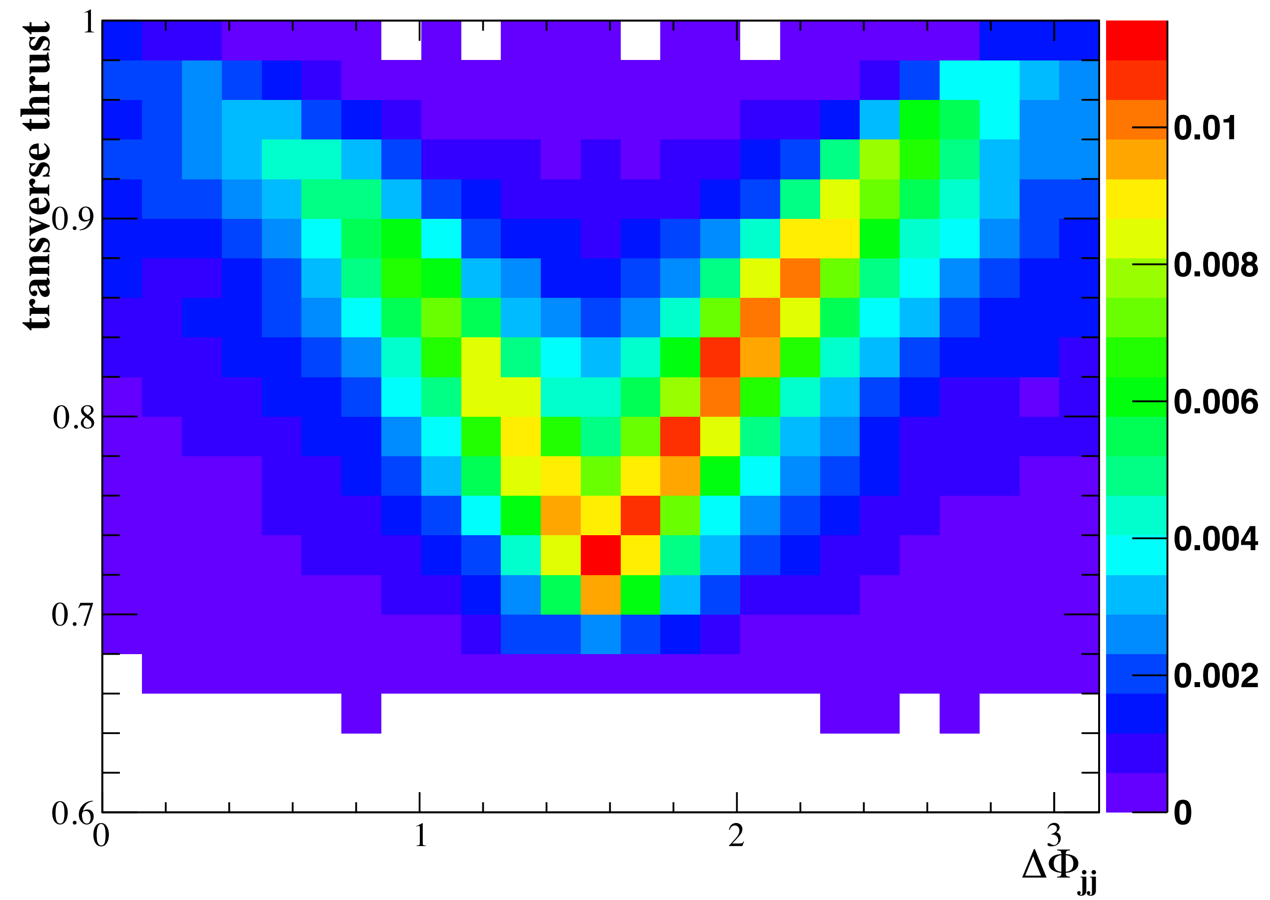


Obvious correlation between thrust and $\Delta\Phi_{jj}$



(a) $\mathcal{CP}$ even Higgs



(b) $\mathcal{CP}$ odd Higgs

Event selection cuts

two tagging jets: $p_{T,j} \geq 40 \text{ GeV}, \text{ and } |y_j| \leq 4.5$

$$m_{jj} = \sqrt{(p_{j,1} + p_{j,2})^2} \geq 600 \text{ GeV}$$

two taus, hard and central: $p_{T,\tau} \geq 20 \text{ GeV}, \text{ and } |y_\tau| \leq 2.5$

$$|m_{\tau\tau} - m_H| < 20 \text{ GeV}$$

I. Use event shapes with constituents: (theorist's approach)

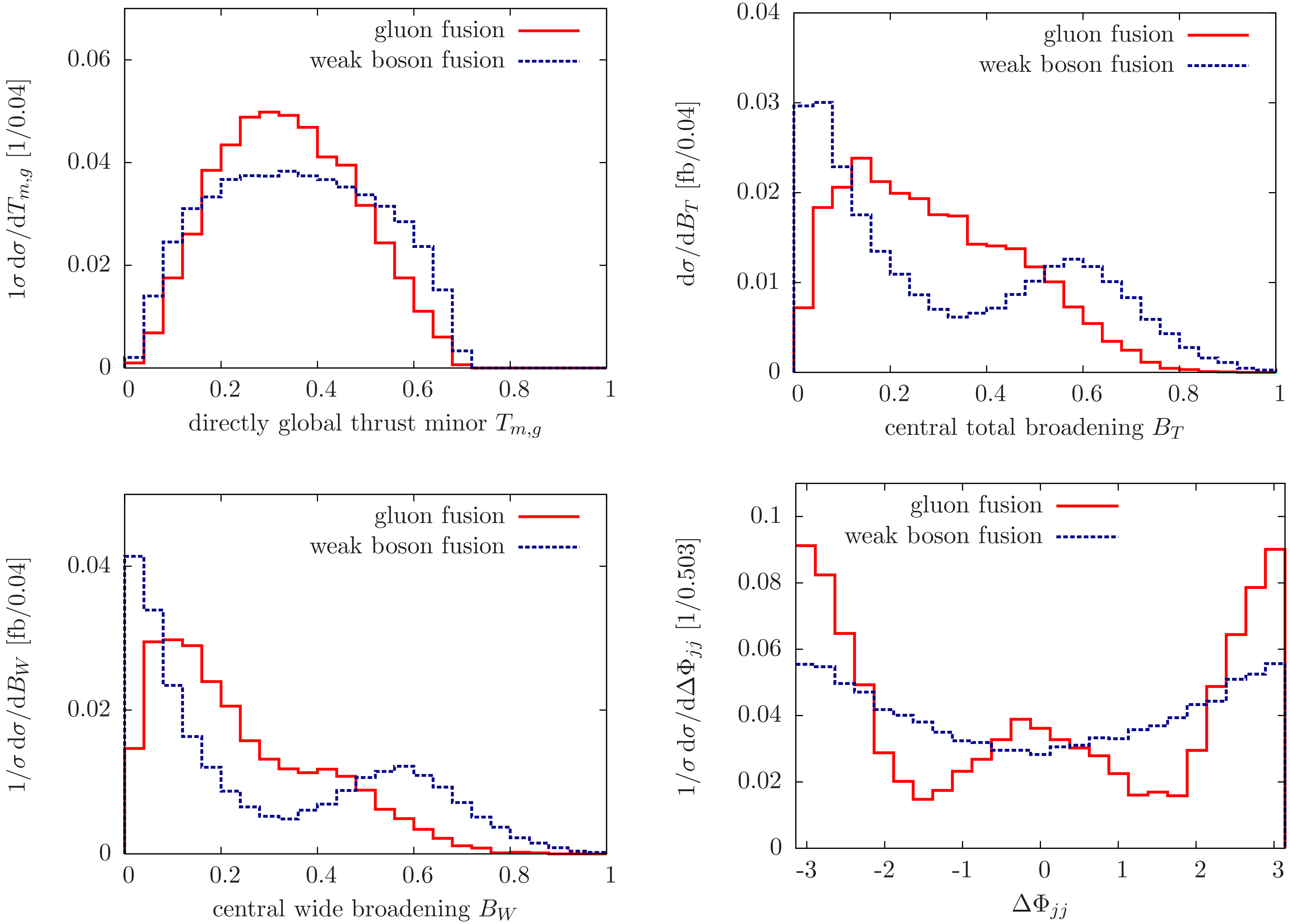
$$p_{T,i} \geq 1 \text{ GeV} \qquad |\eta_i| \leq 4.5$$

II. reduce pileup sensitivity, use

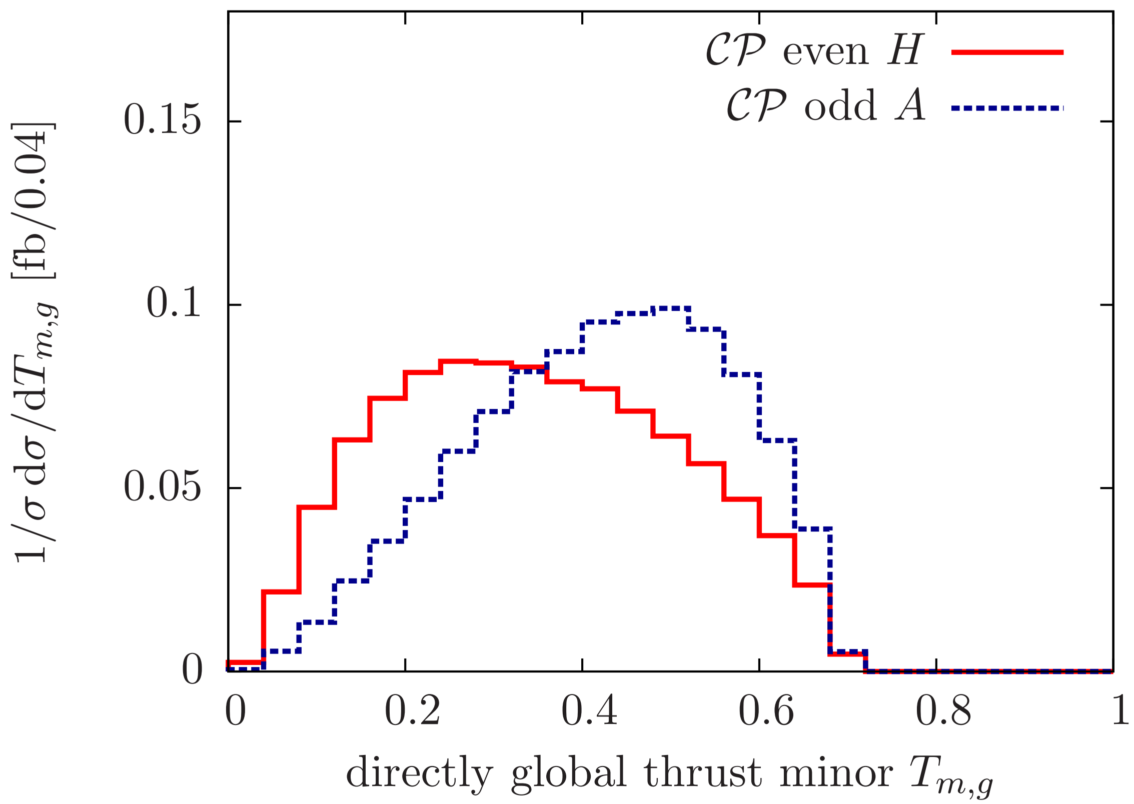
$$p_{T,j} \geq 40 \text{ GeV}, \quad \text{if } 2.5 \leq |y_j| \leq 4.5, \text{ and}$$
$$p_{T,j} \geq 10 \text{ GeV}, \quad \text{if } |y_j| \leq 2.5.$$

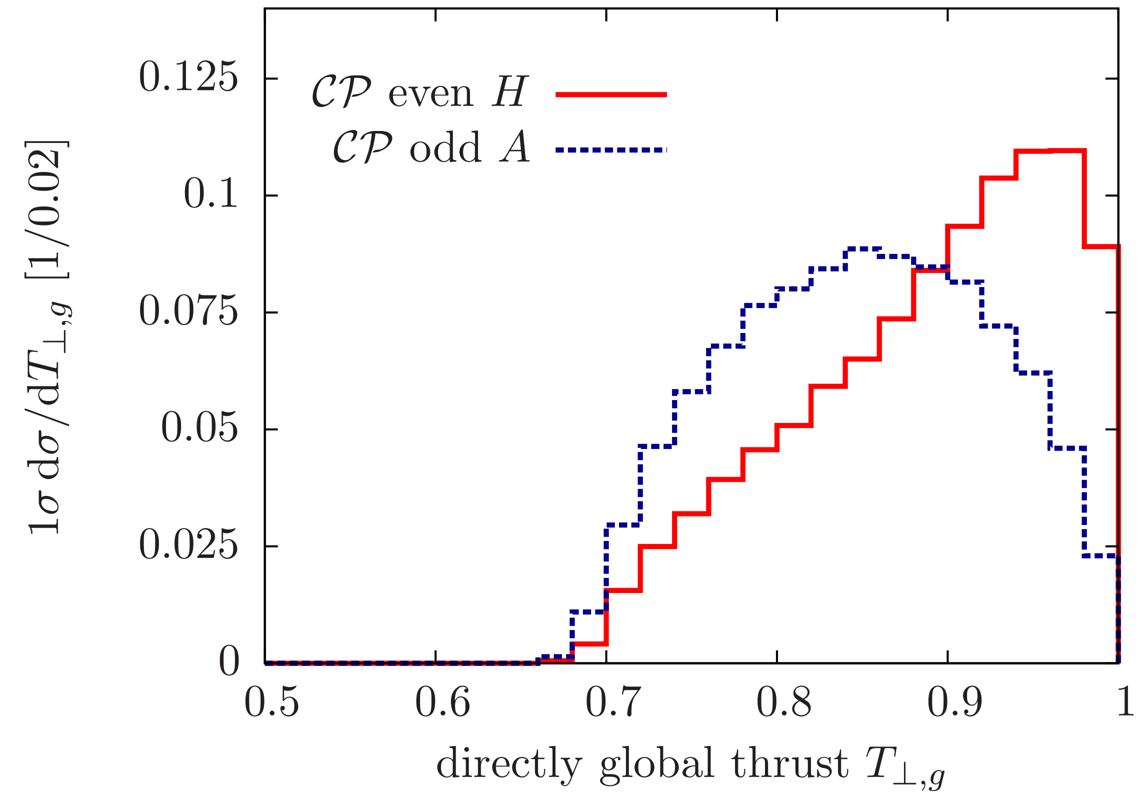
(compromise between theory and experiment)

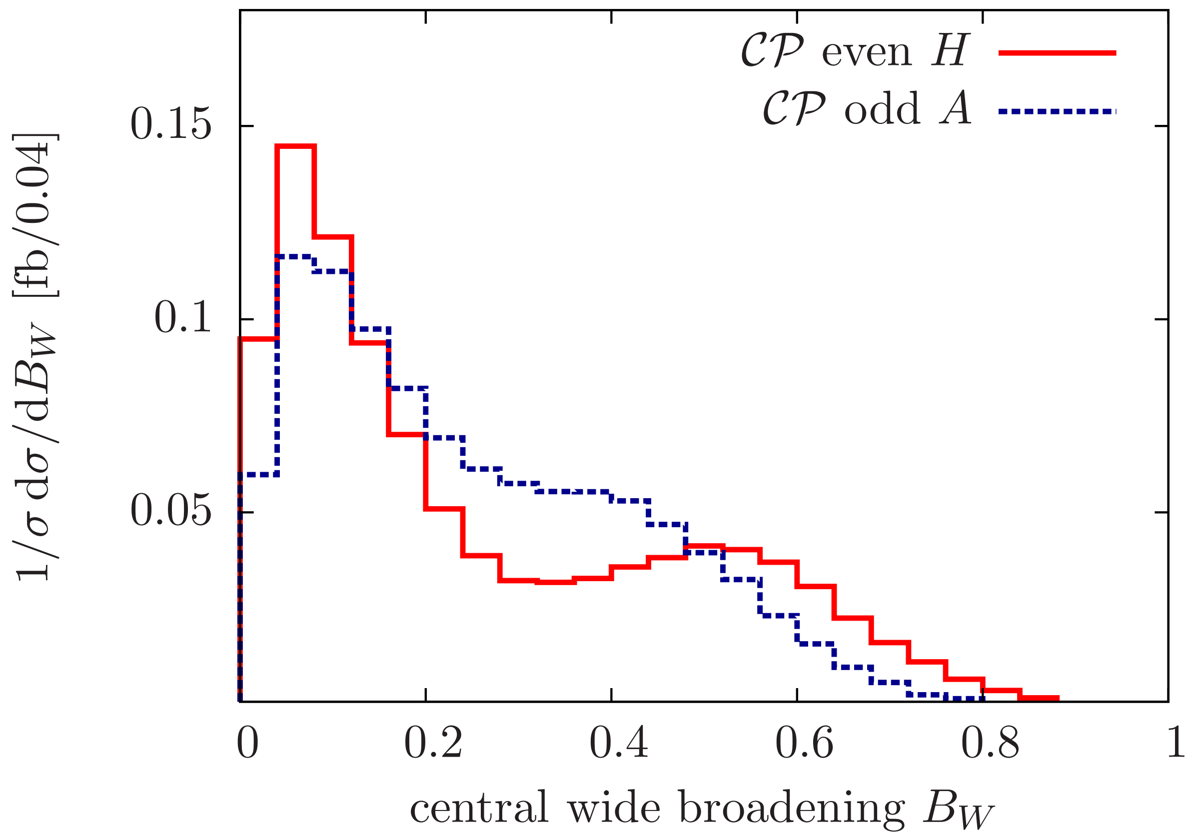
GF vs WBF

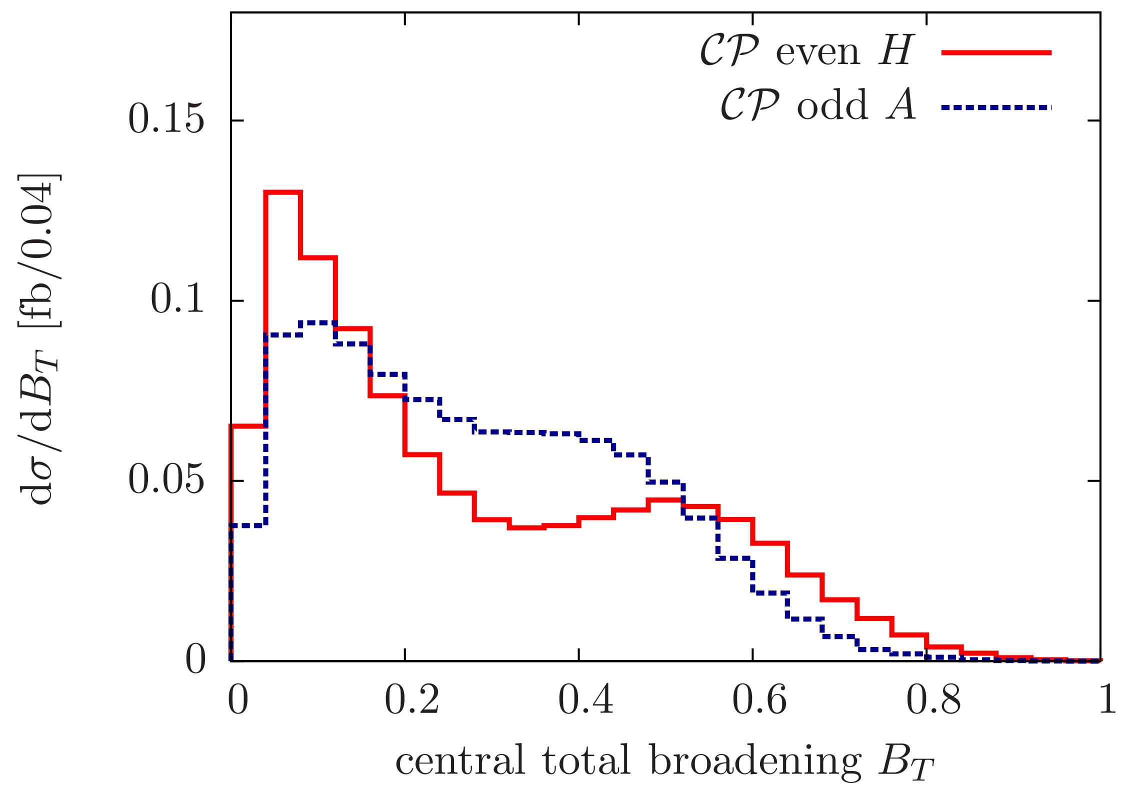

gluon fusion
weak boson fusion
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
$1\sigma\,\mathrm{d}\sigma/\mathrm{d}T_{m,g}$ [1/0.04]
directly global thrust minor $T_{m,g}$
gluon fusion
weak boson fusion
0.04
0.03
0.02
0.01
0
0
0.2
0.4
0.6
0.8
1
$\mathrm{d}\sigma/\mathrm{d}B_T$ [fb/0.04]
central total broadening B_T
gluon fusion
weak boson fusion
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
$1/\sigma\,\mathrm{d}\sigma/\mathrm{d}B_W$ [fb/0.04]
central wide broadening B_W
gluon fusion
weak boson fusion
0.1
0.08
0.06
0.04
0.02
0
-3
-2
-1
0
1
2
3
$1/\sigma\,\mathrm{d}\sigma/\mathrm{d}\Delta\Phi_{jj}$ [1/0.503]
$\Delta\Phi_{jj}$

Distributions CP-odd vs CP-even

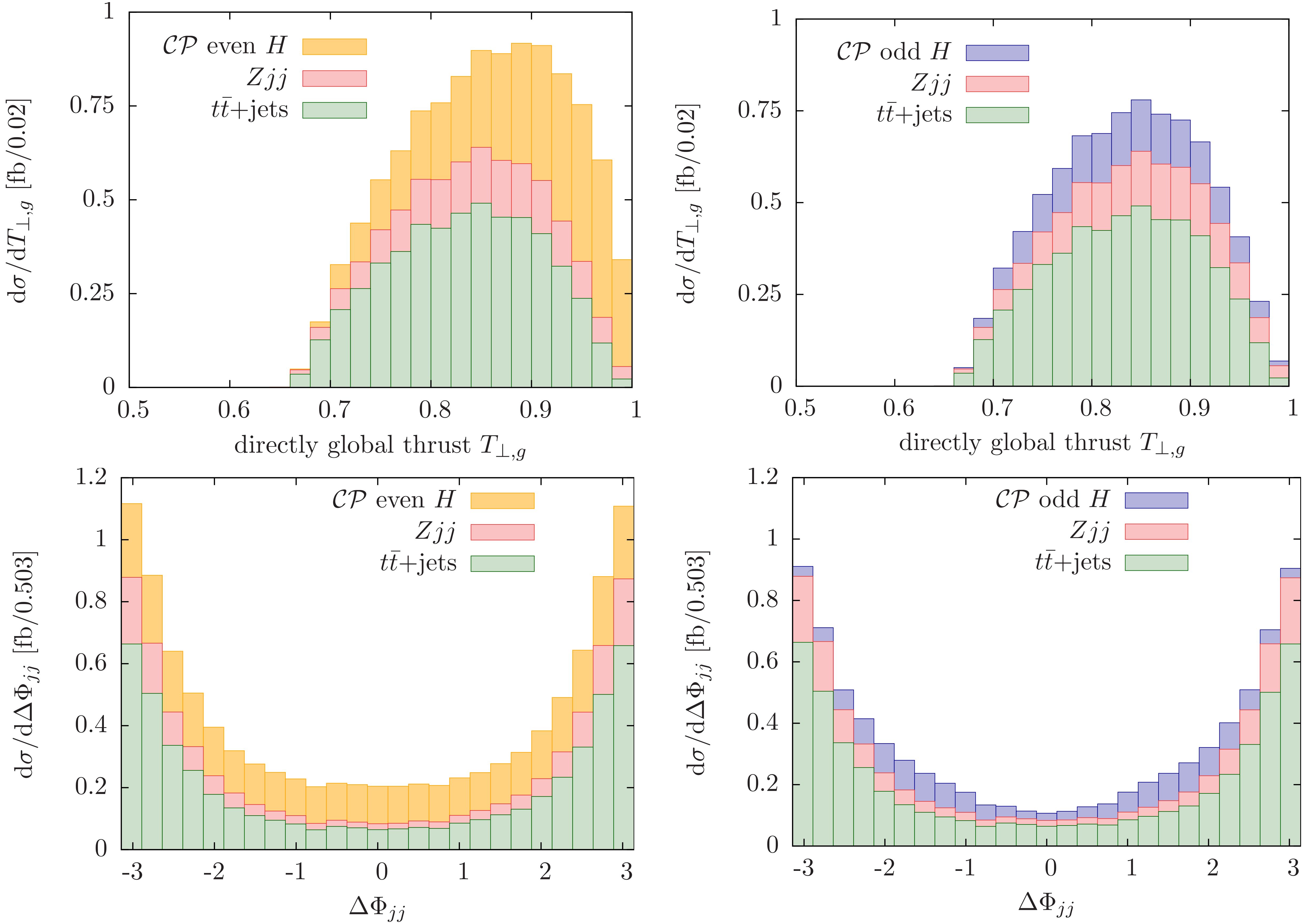




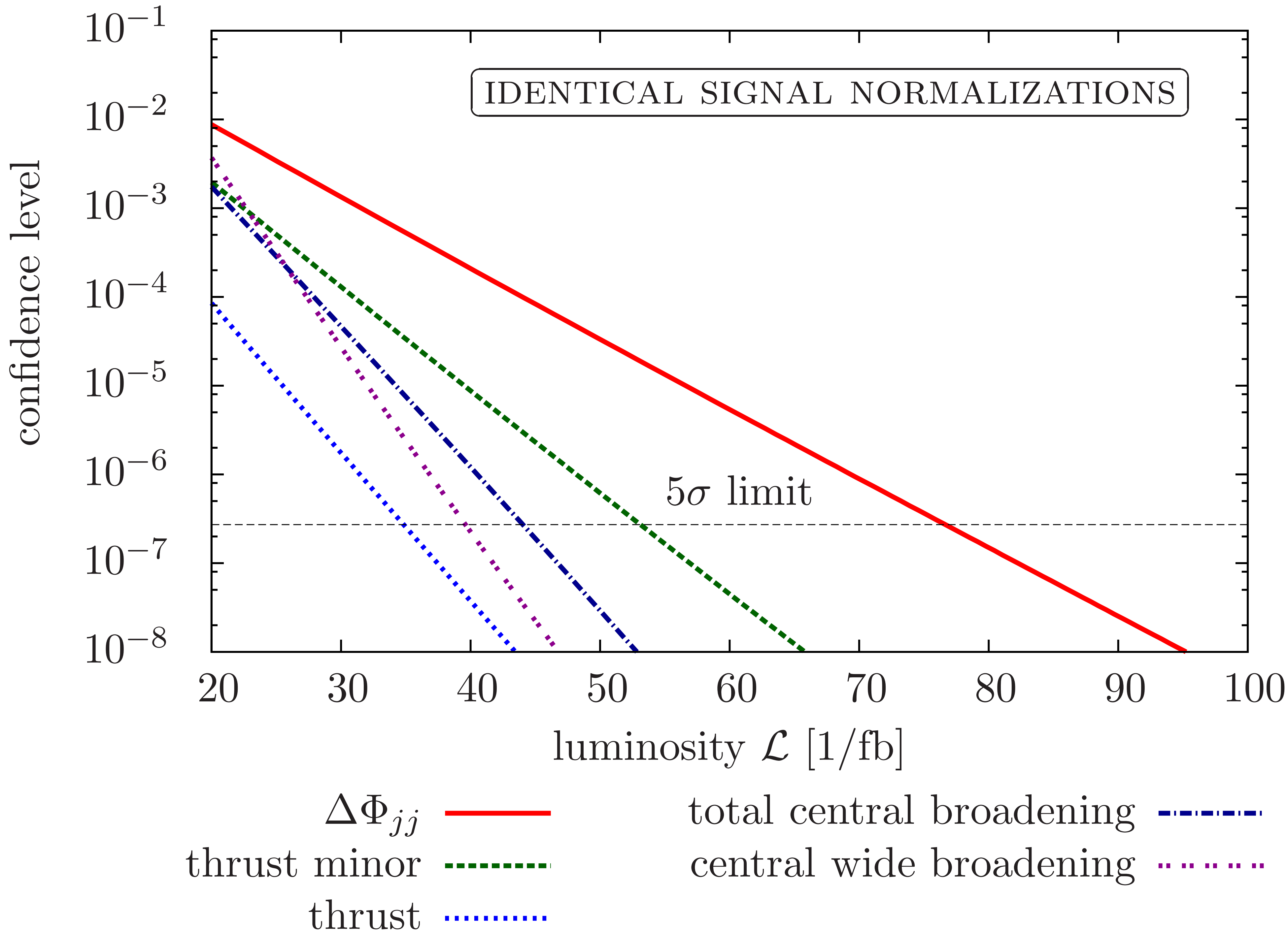




Distributions CP-odd vs CP-even



Sensitivity for discrimination between CP and CP-odd (normalized signal rates)



Matrix element method:
automized approach to perform hypothesis discrimination

- Often used for leptonic (clean) final state (incl. Tevatron)

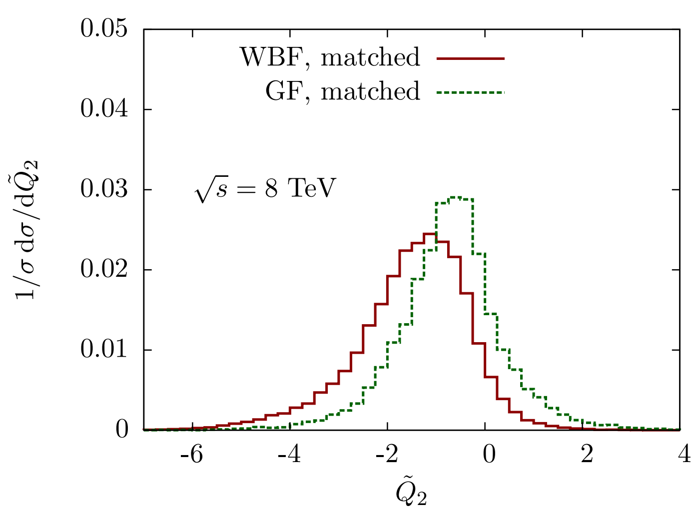
  [Kondo (1988); Campbell, Giele, Williams (2012); Gainer, Freytas (2012); Madweight; ...]

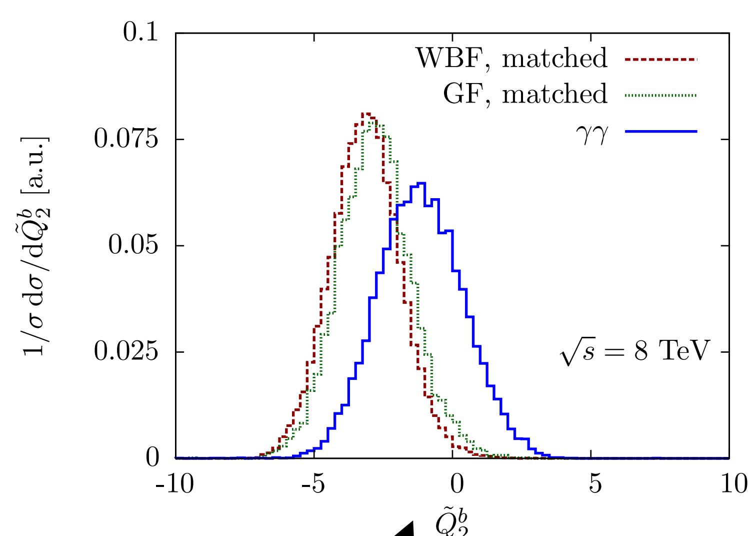
Example: Hjj with Higgs decay to photons

[Andersen, Englert, MS 1211.3011]

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

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





- Method separates GF vs WBF and reduces backgrounds
- Possible to loosen WBF-cuts in 8 TeV analysis to increase statistics and significance for CP measurements

Features of observables can be combined and improved

Our approach:

Shower/Event deconstruction

- Maximal information approach to discriminate signal from backgrounds -> UE, ISR, FSR, hard process
- Pattern matching algorithm with one discriminating analytic function
- Have to respect experimental limitations

[Soper, MS PRD 84 (2011); Soper MS 1211.3140]

Playground: Boosted HZ final state

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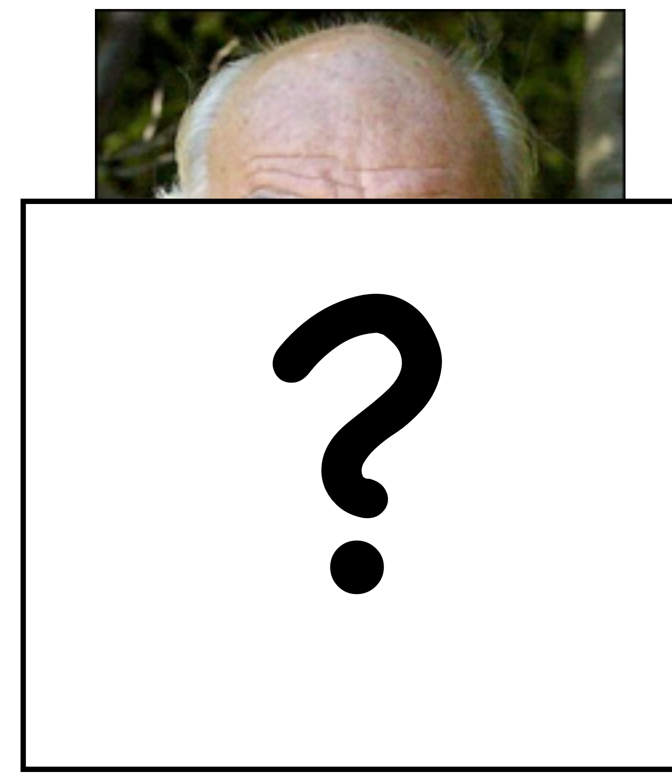

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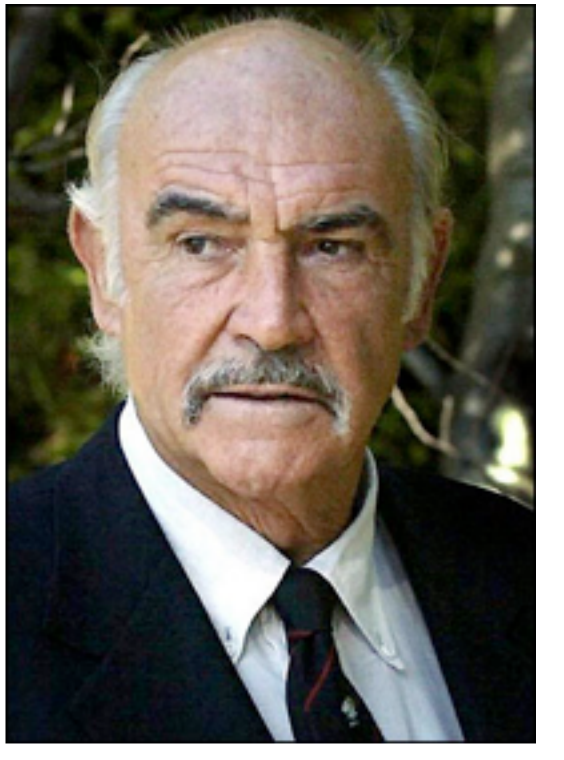

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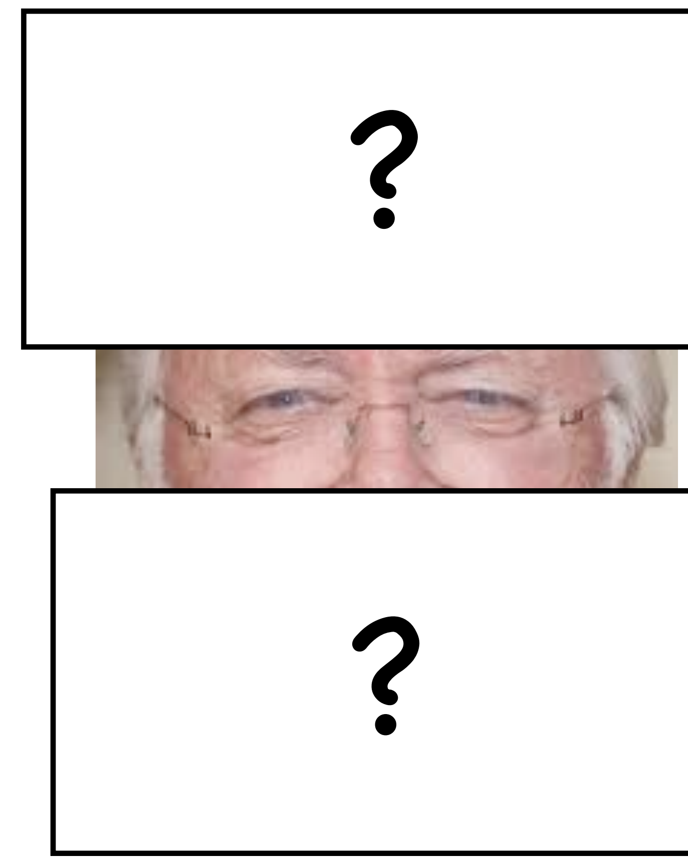

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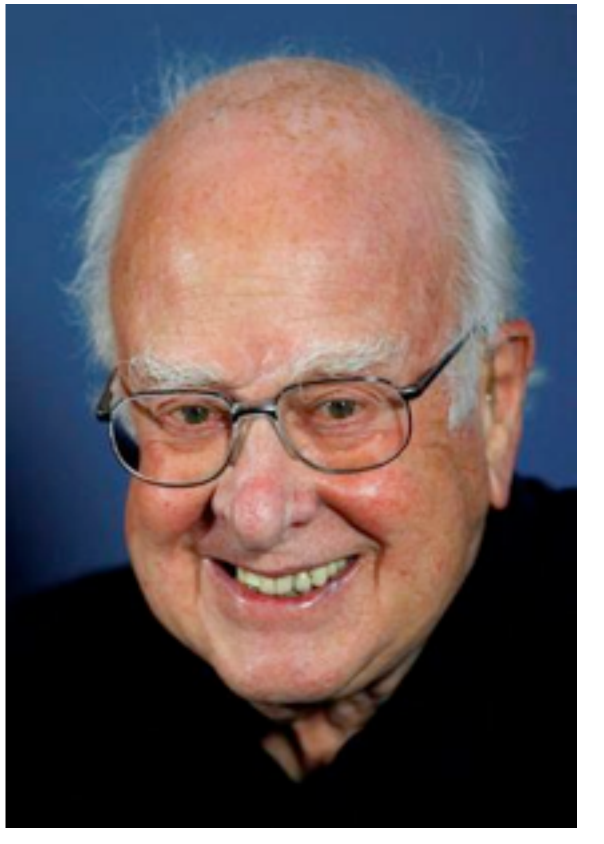

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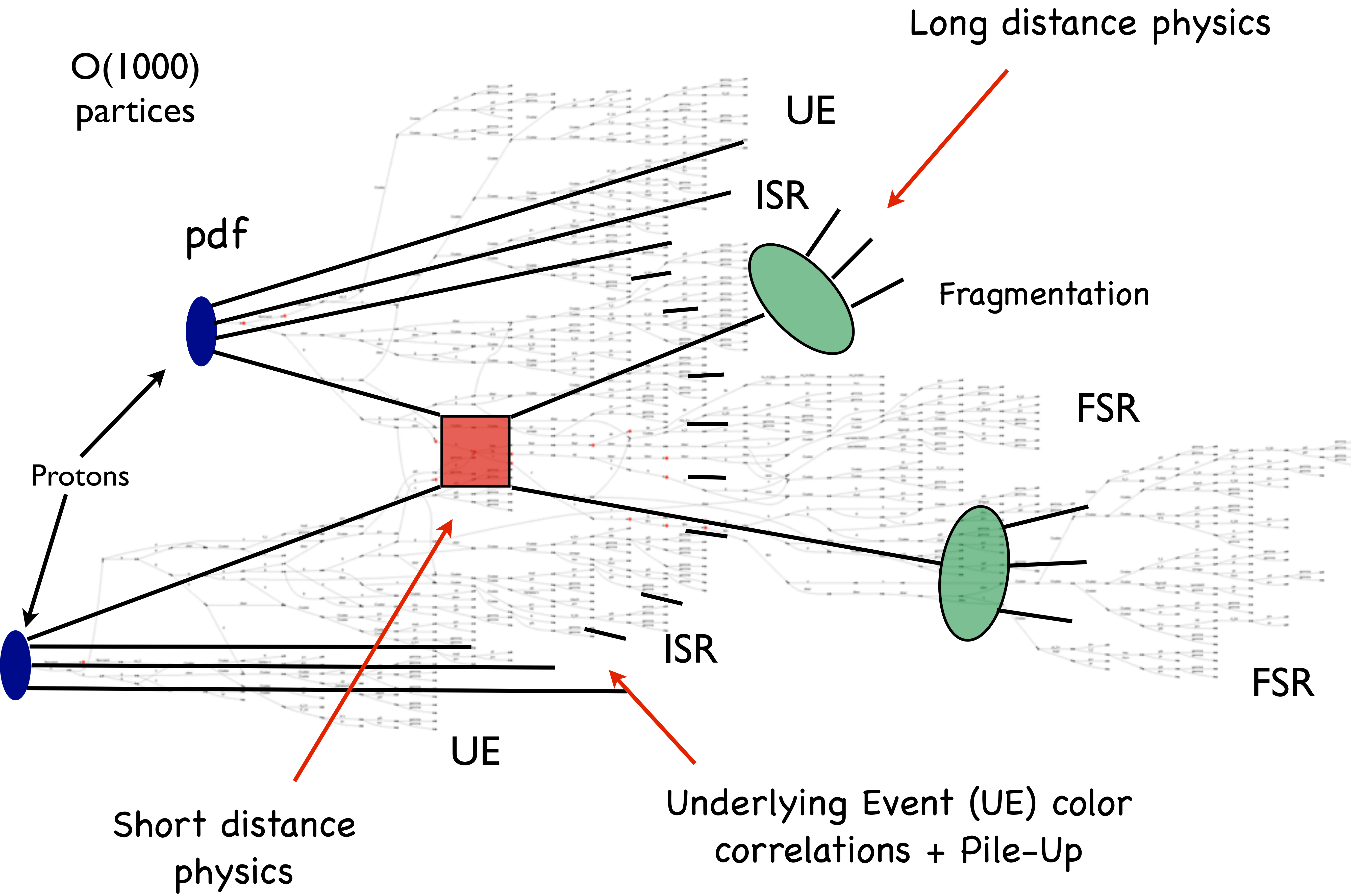
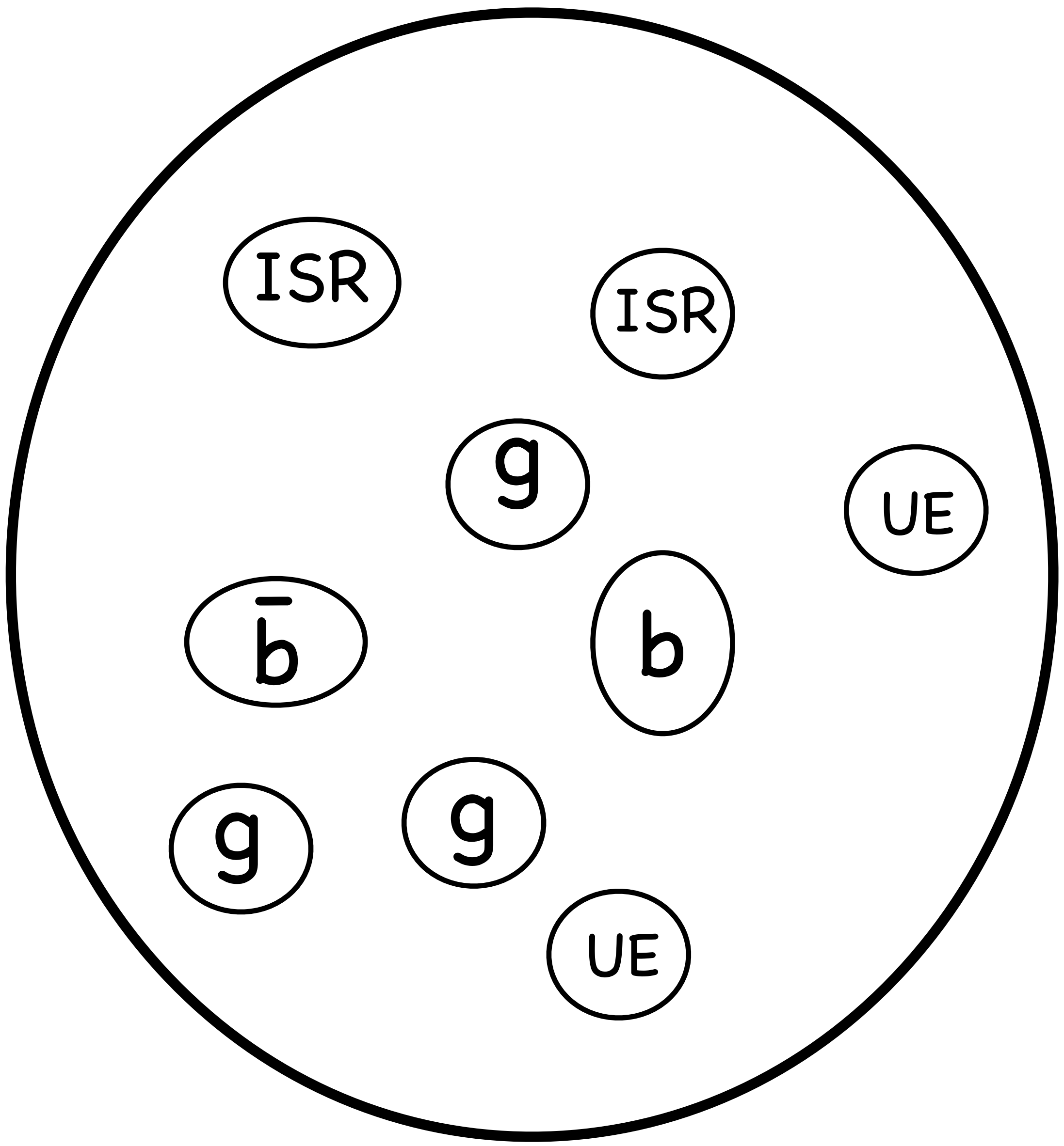
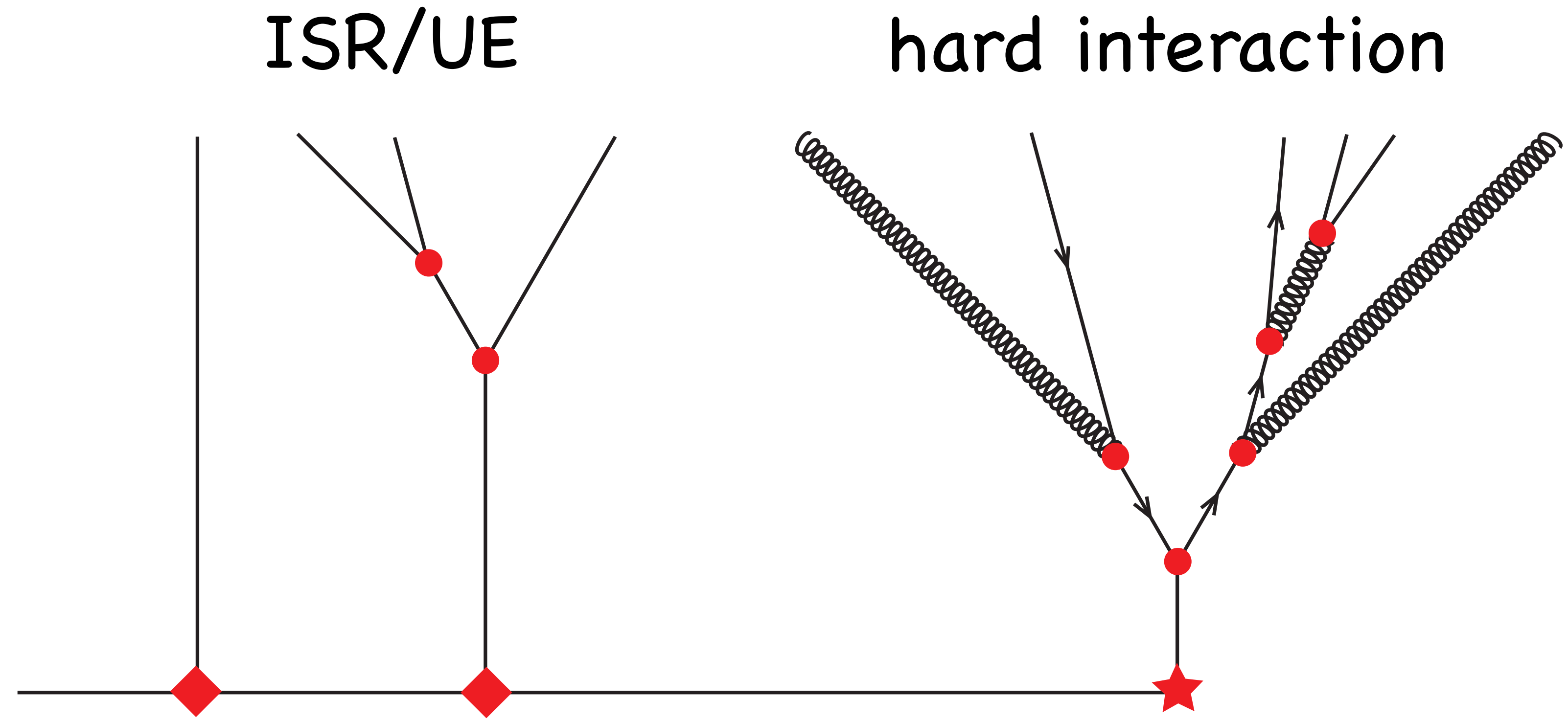

Long distance physics
O(1000)
partices
UE
ISR
pdf
Fragmentation
FSR
Protons
ISR
FSR
UE
Short distance
physics
Underlying Event (UE) color
correlations + Pile-Up

Fat jet: R=1.2, anti-kT



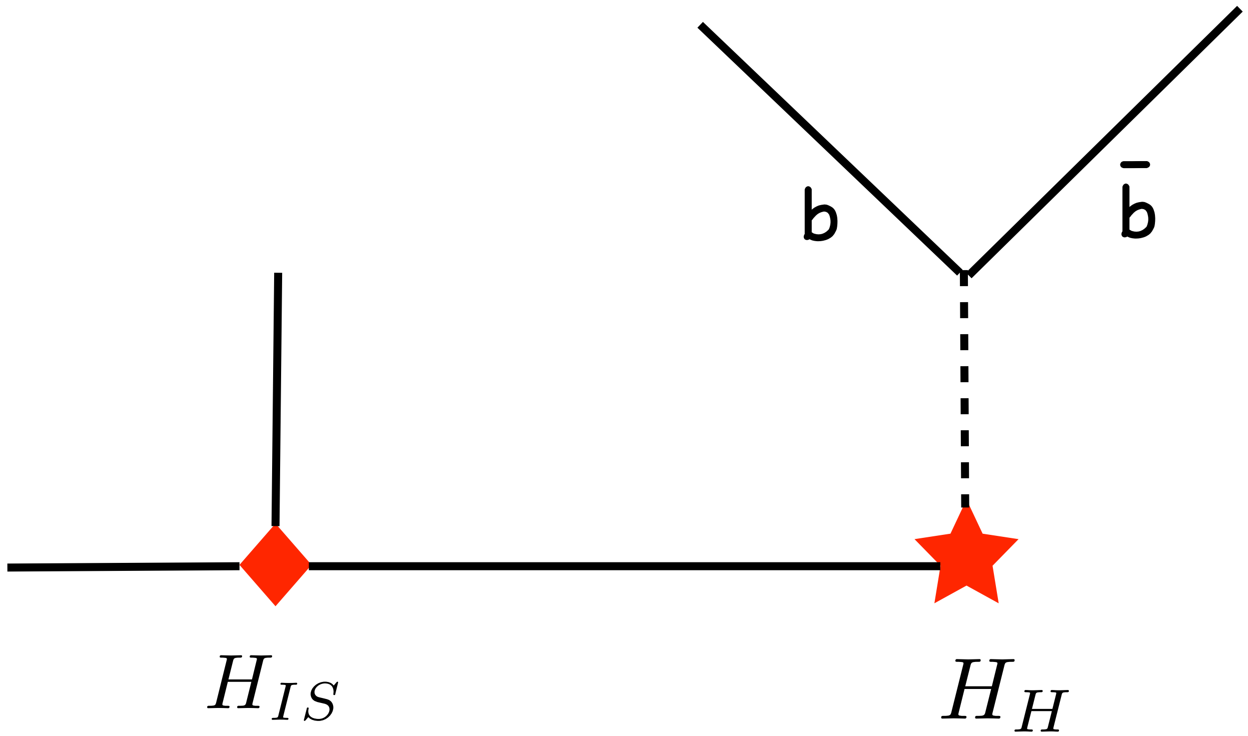
microjets
R=small, kT

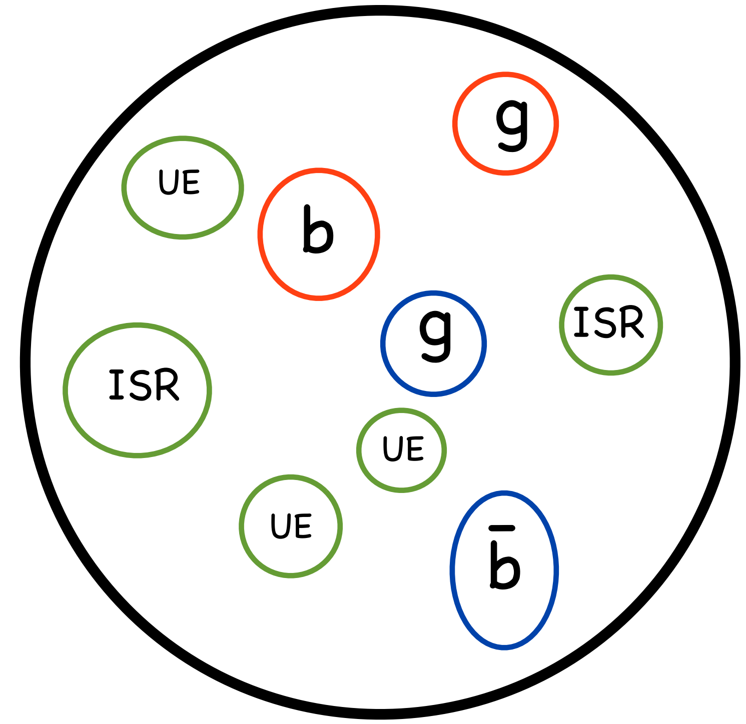


Build all possible shower histories

signal vs background hypothesis based on:

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





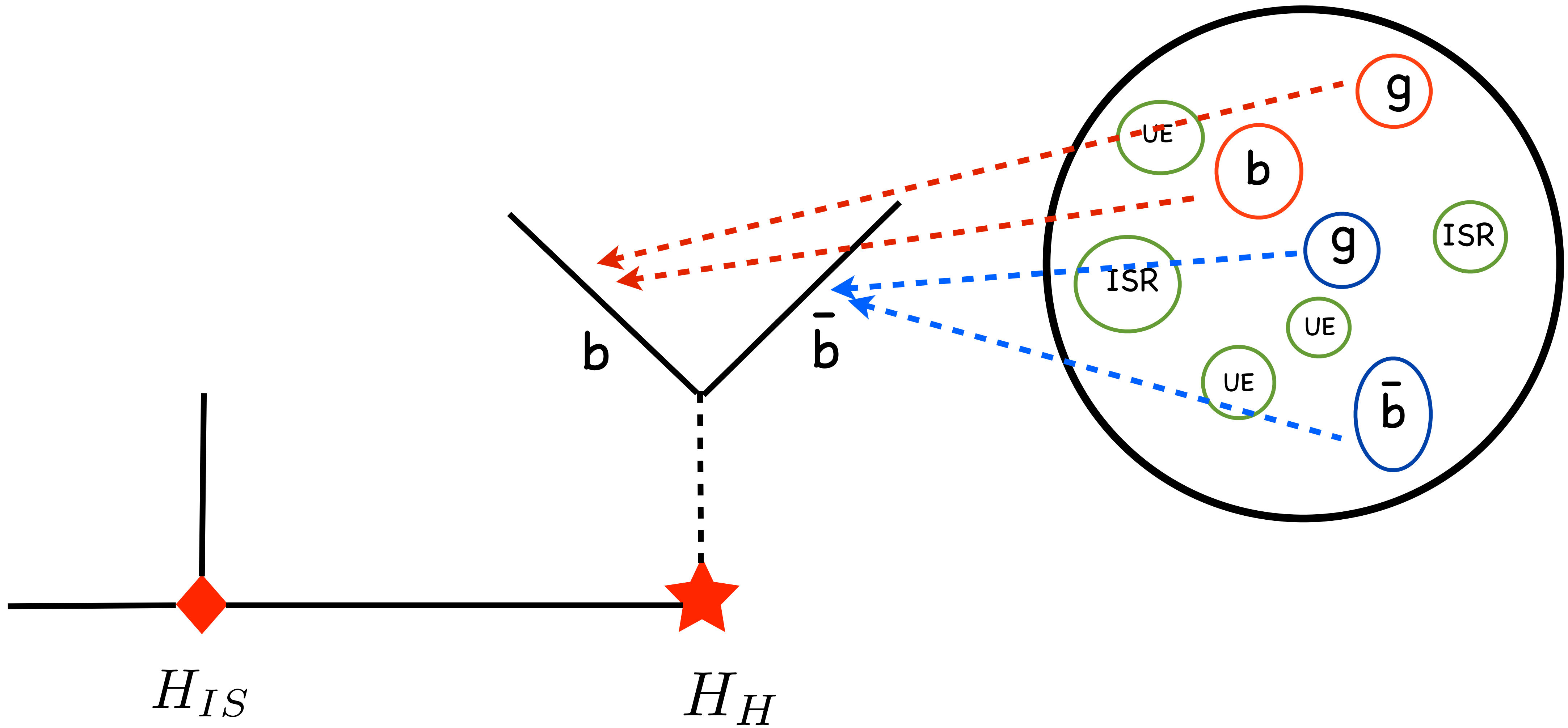
Higgs has to decay:

$$He^{-S} = 16\pi^2 \frac{\Theta(|m_{b\bar{b}} - m_H| < \Delta m_H)}{4 m_H \, \Delta m_H}$$

$$\frac{1}{4(2\pi)^3} \int dm^2_{b\bar{b}} \int dz \int d\varphi \; He^{-S} = 1$$

Mass window

$$\Delta m_H = 10 \text{ GeV}$$



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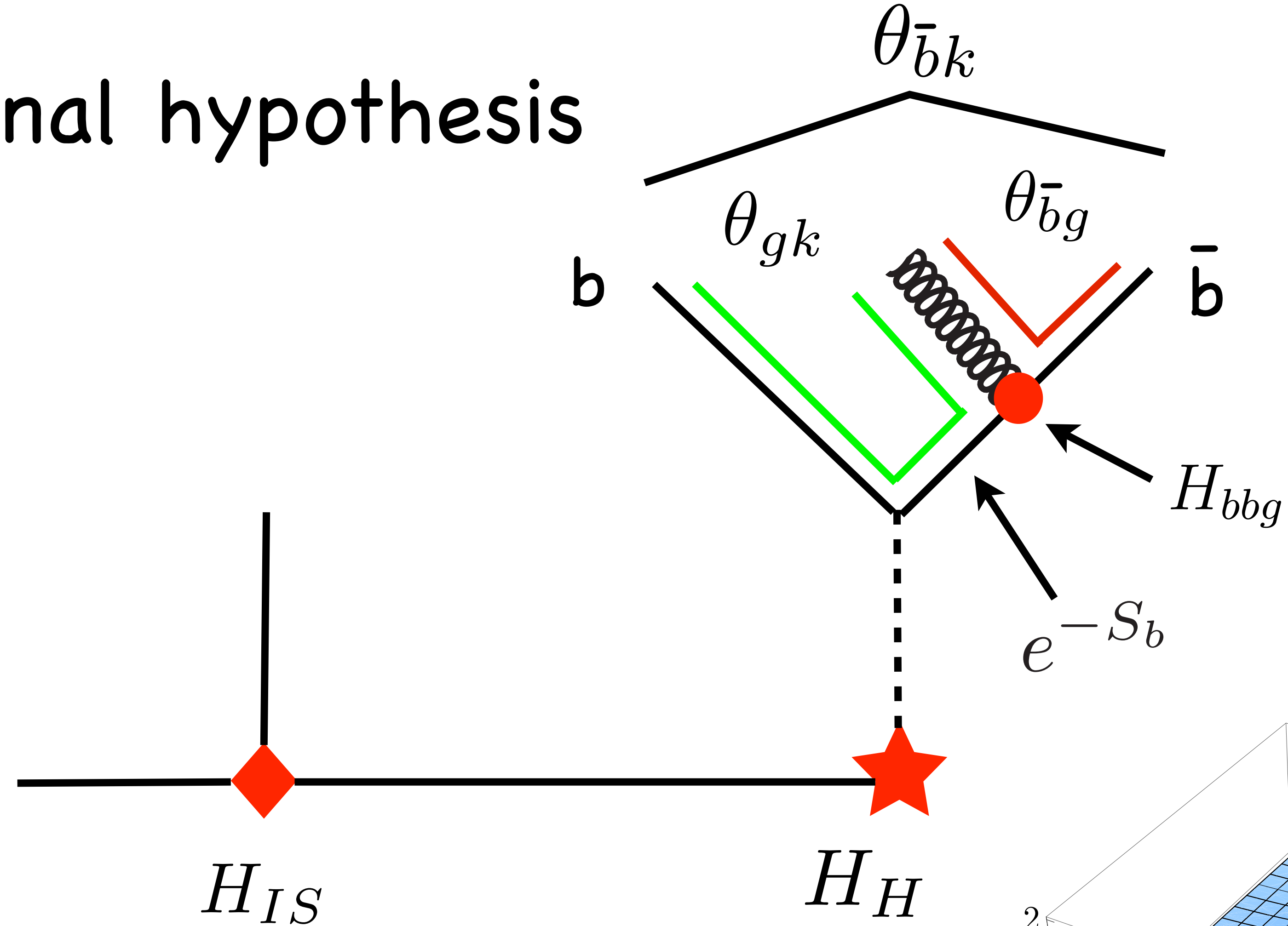
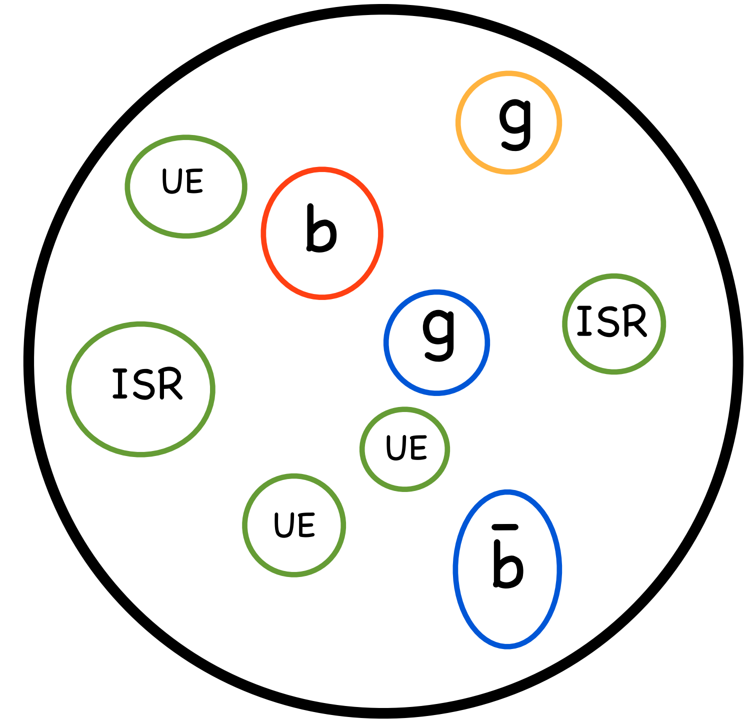
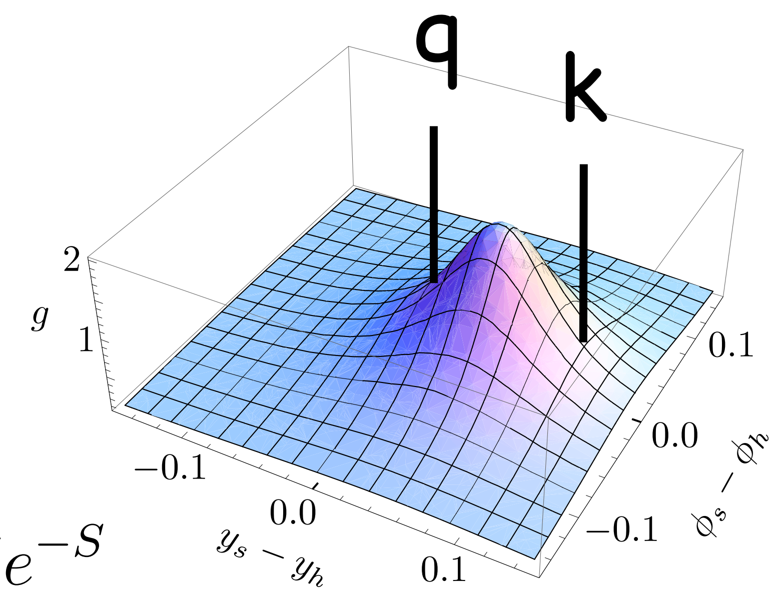
Signal hypothesis







[Marchesini, Webber, (1984)]

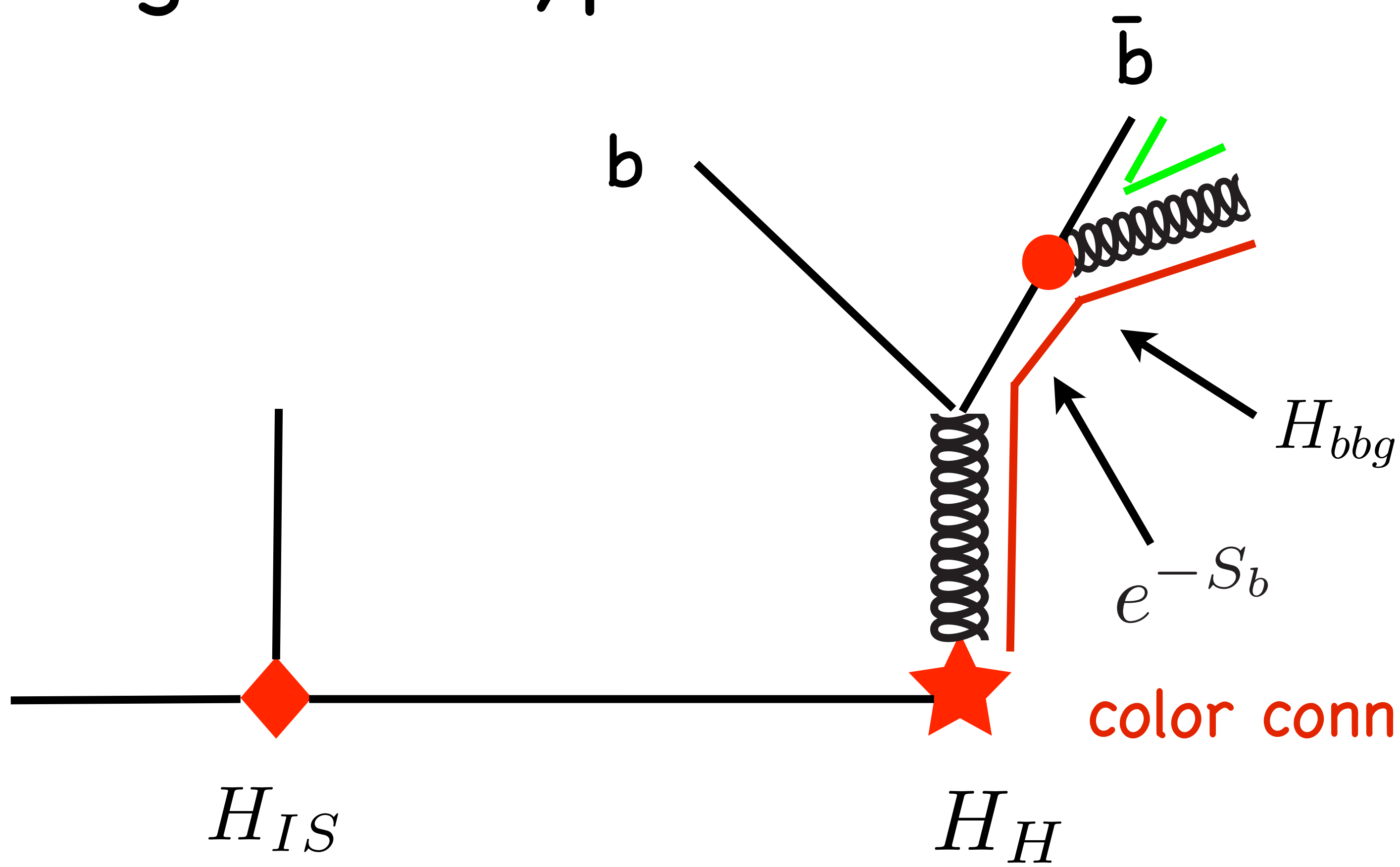
b-quarks radiate gluons

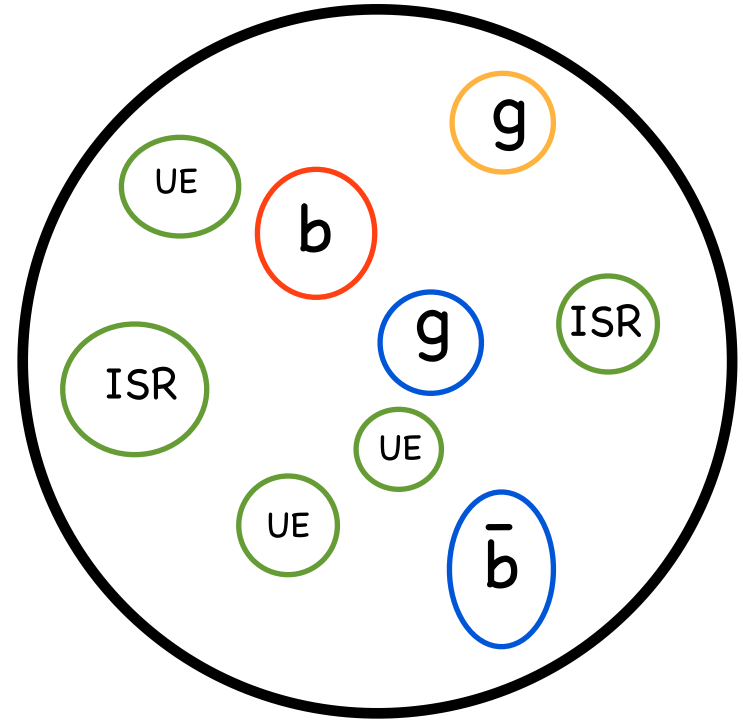
$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

$$S \approx \int d\bar{\mu}_J^2\, \Theta(\mu_J^2 < \bar{\mu}_J^2) \int d\Delta\bar{y} \int d\Delta\bar{\phi} \sum_{\bar{s}} J(\bar{p}_A, \bar{p}_B)\, H(\bar{p}_A, \bar{p}_B)\, \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})$$

$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_\mathrm{F} \frac{\alpha_\mathrm{s}(\mu_J^2)}{\mu_J^2} \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2} \Theta\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

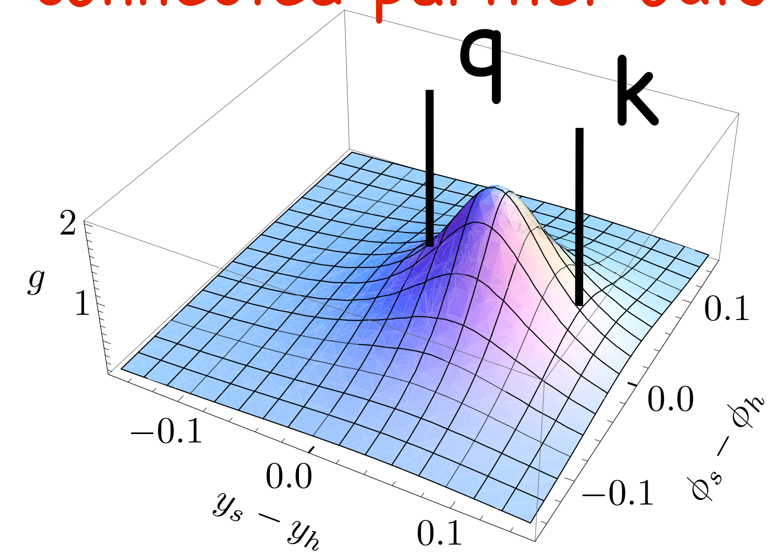
Background hypothesis





color connected partner outside fat jet

b-quarks radiate gluons

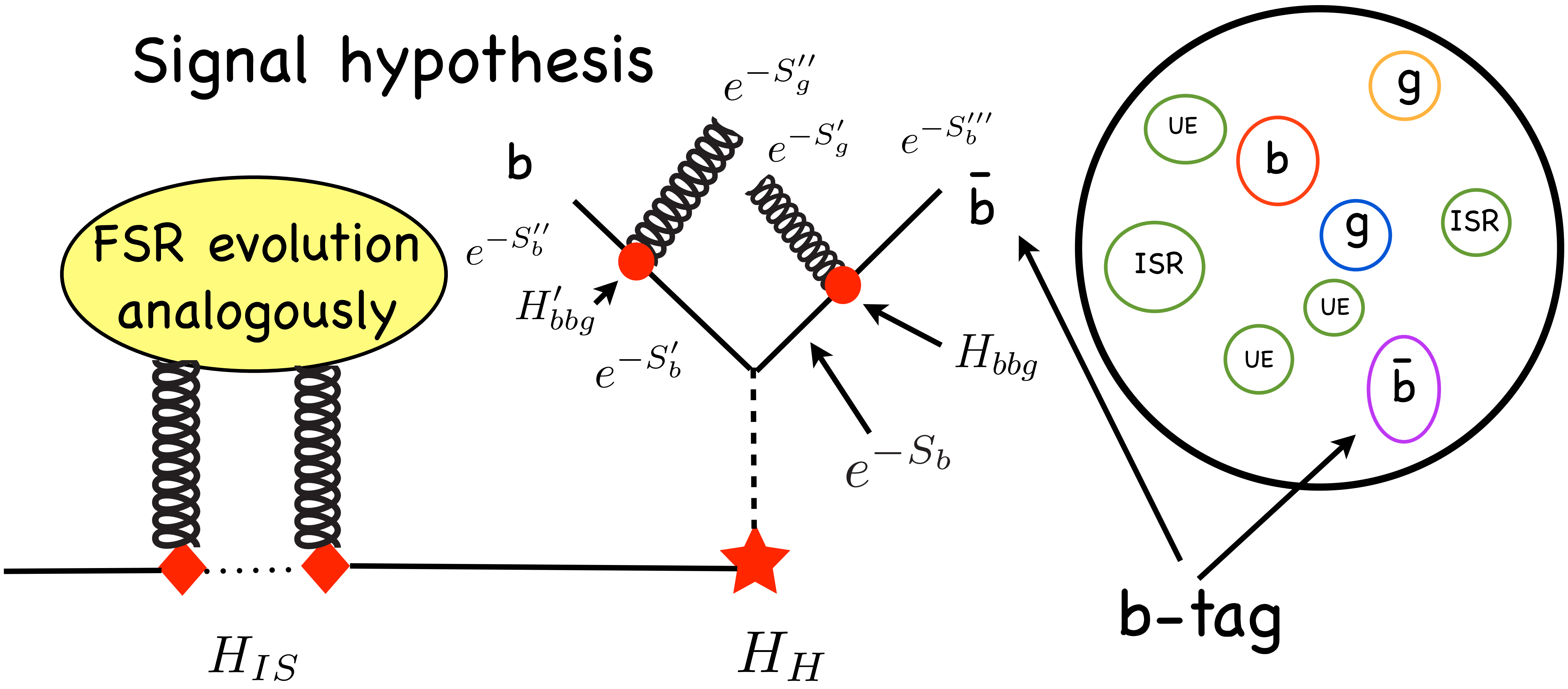


$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

$$S \approx \int d\bar{\mu}_J^2\, \Theta(\mu_J^2 < \bar{\mu}_J^2) \int d\Delta\bar{y} \int d\Delta\bar{\phi} \sum_{\bar{s}} \; J(\bar{p}_A, \bar{p}_B)\, H(\bar{p}_A, \bar{p}_B)\, \Theta(\{\bar{p}_A, \bar{p}_B\} \in \text{fat jet})$$

$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_F \frac{\alpha_s(\mu_J^2)}{\mu_J^2} \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2} \Theta\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

Signal hypothesis

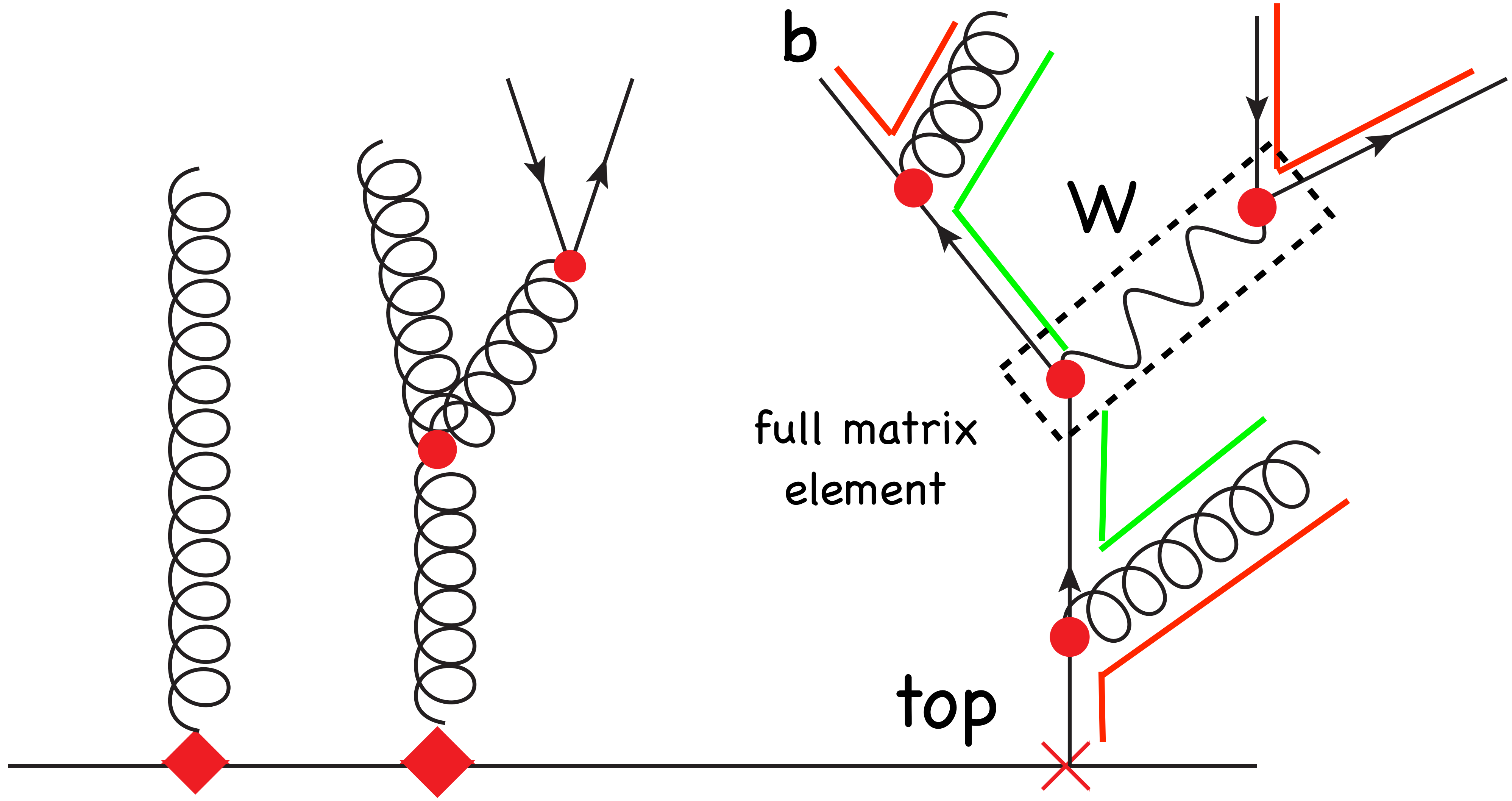


Wrapping up all factors gives weight for shower history

$$\chi = \frac{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Signal_j}\right)}{\sum_{ISR/Hard}\left(\sum_i \mathrm{ISR_i} \times \sum_j \mathrm{Backg_j}\right)}$$

Here $\mathrm{Signal_1} = \mathrm{H_H H_{split} e^{-S_{split}} H_{bbg} e^{-S'_b} e^{-S'''_b} e^{-S'_g} H'_{bbg} e^{-S''_b} e^{-S_b} e^{-S''_g}}$

Need to convert the shower history into analytic expression



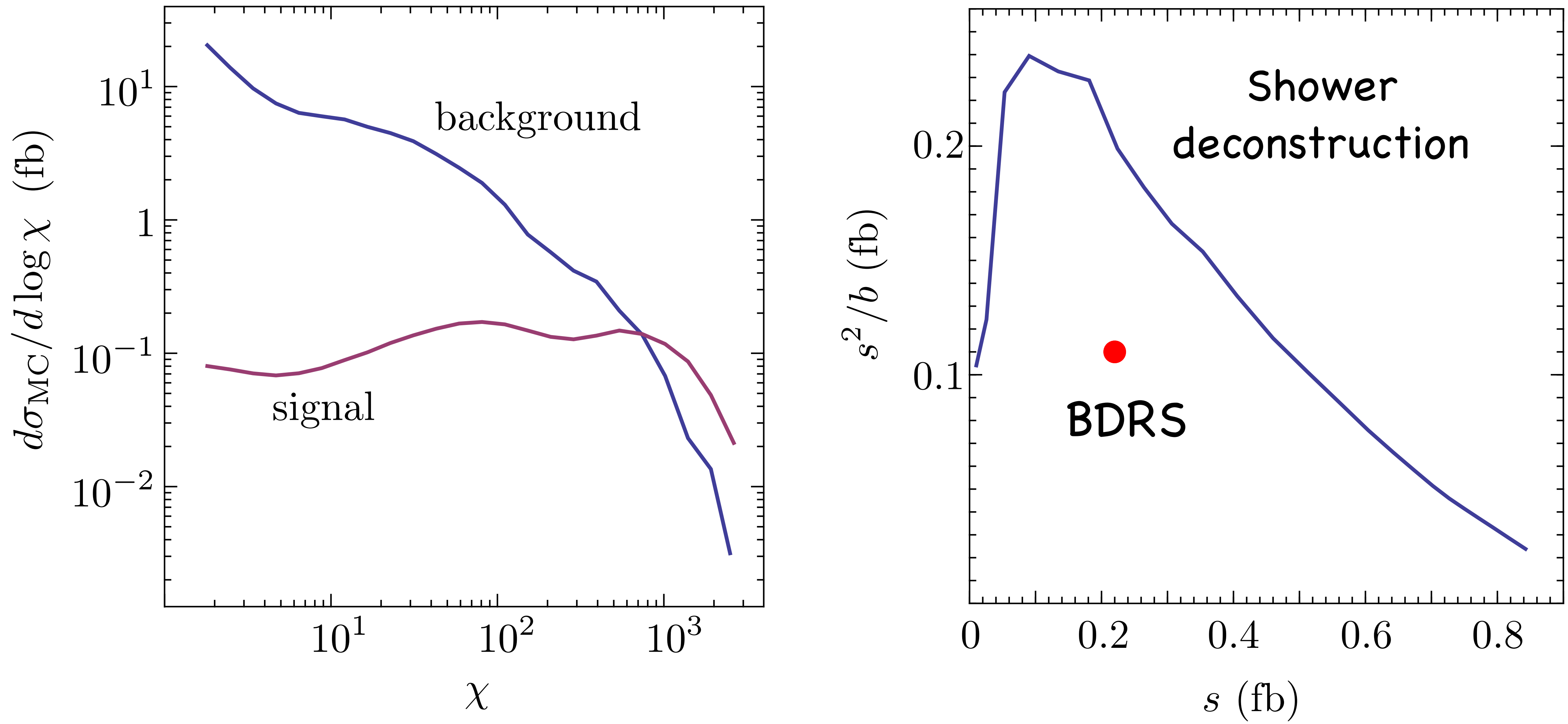
Conceptional difference compared to Higgs:

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

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

Results for Higgs boson:

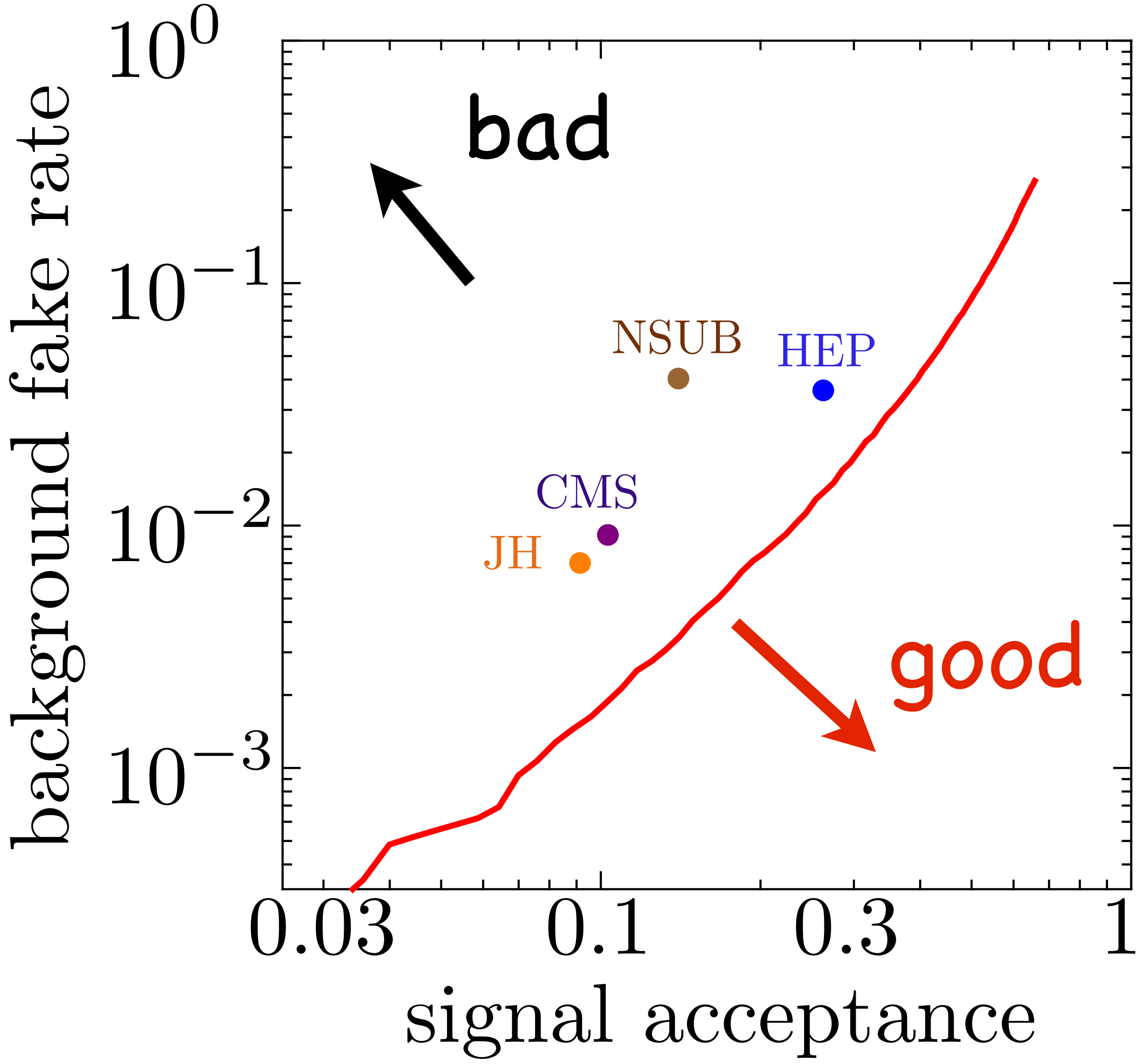
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$$



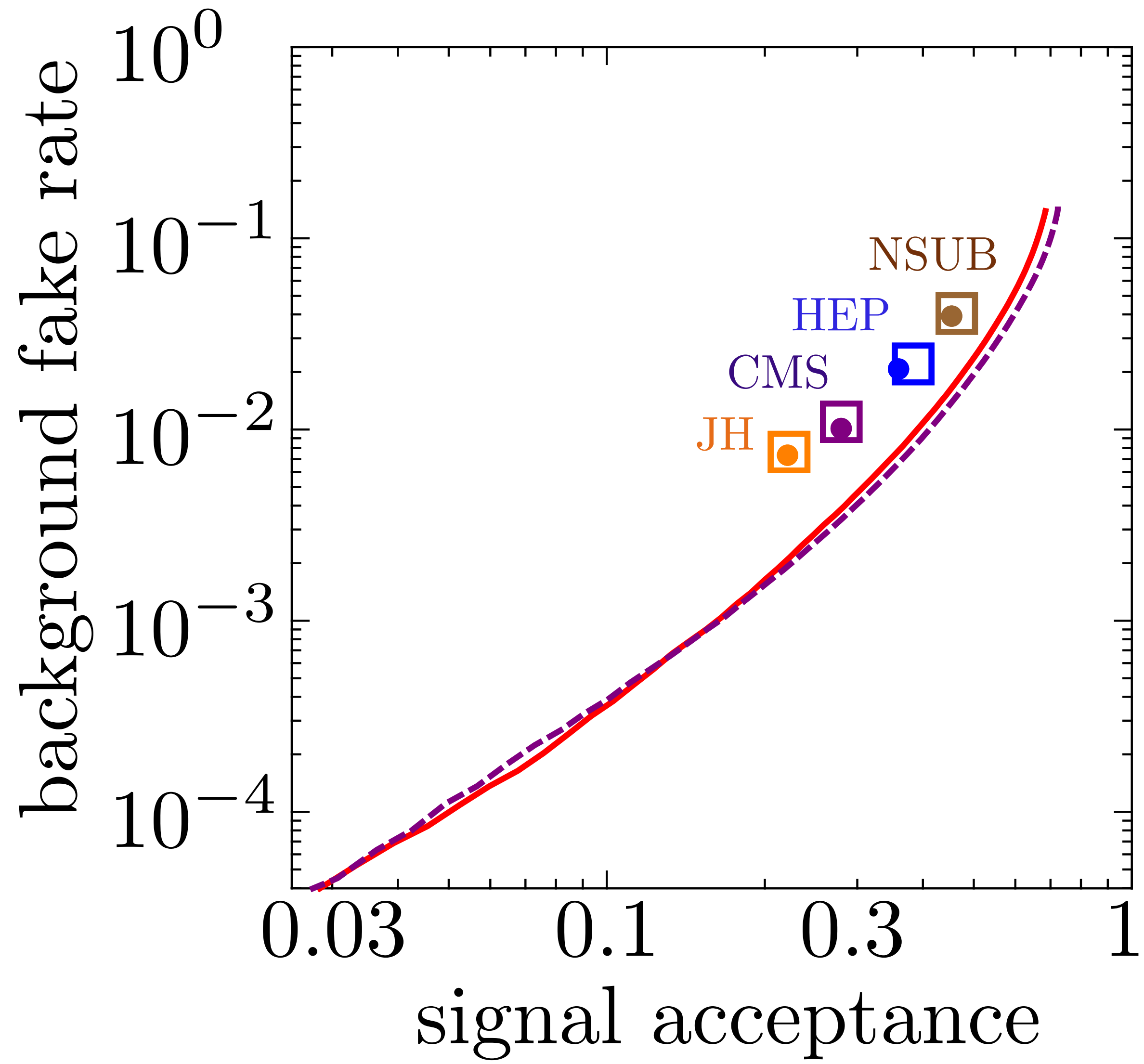
imperfect b-tagging (60%,2%) no b-tag required

Results for top quarks:

pTj > 200 GeV, R=1.5 CA



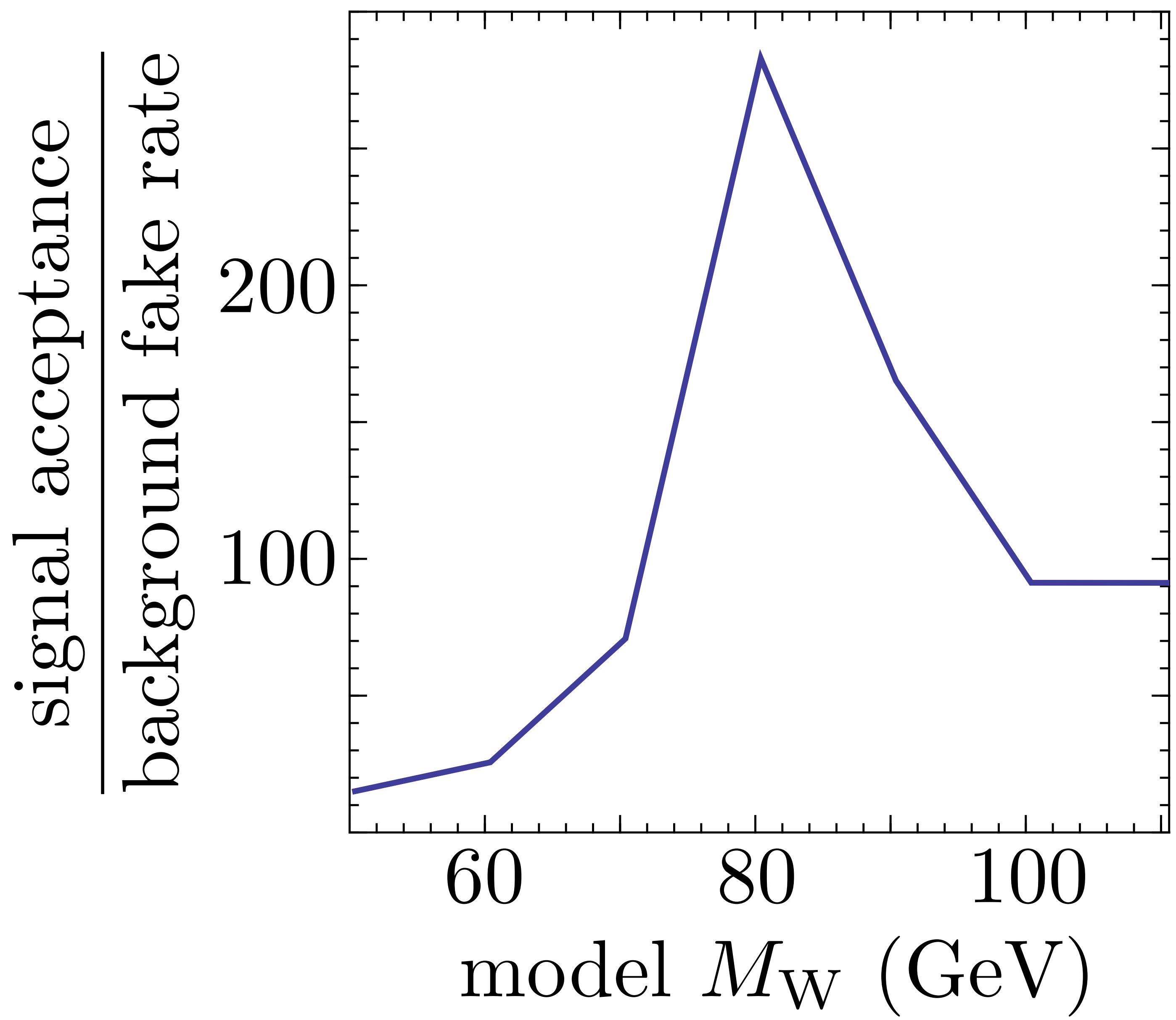
pTj > 500 GeV, R=1.2 CA



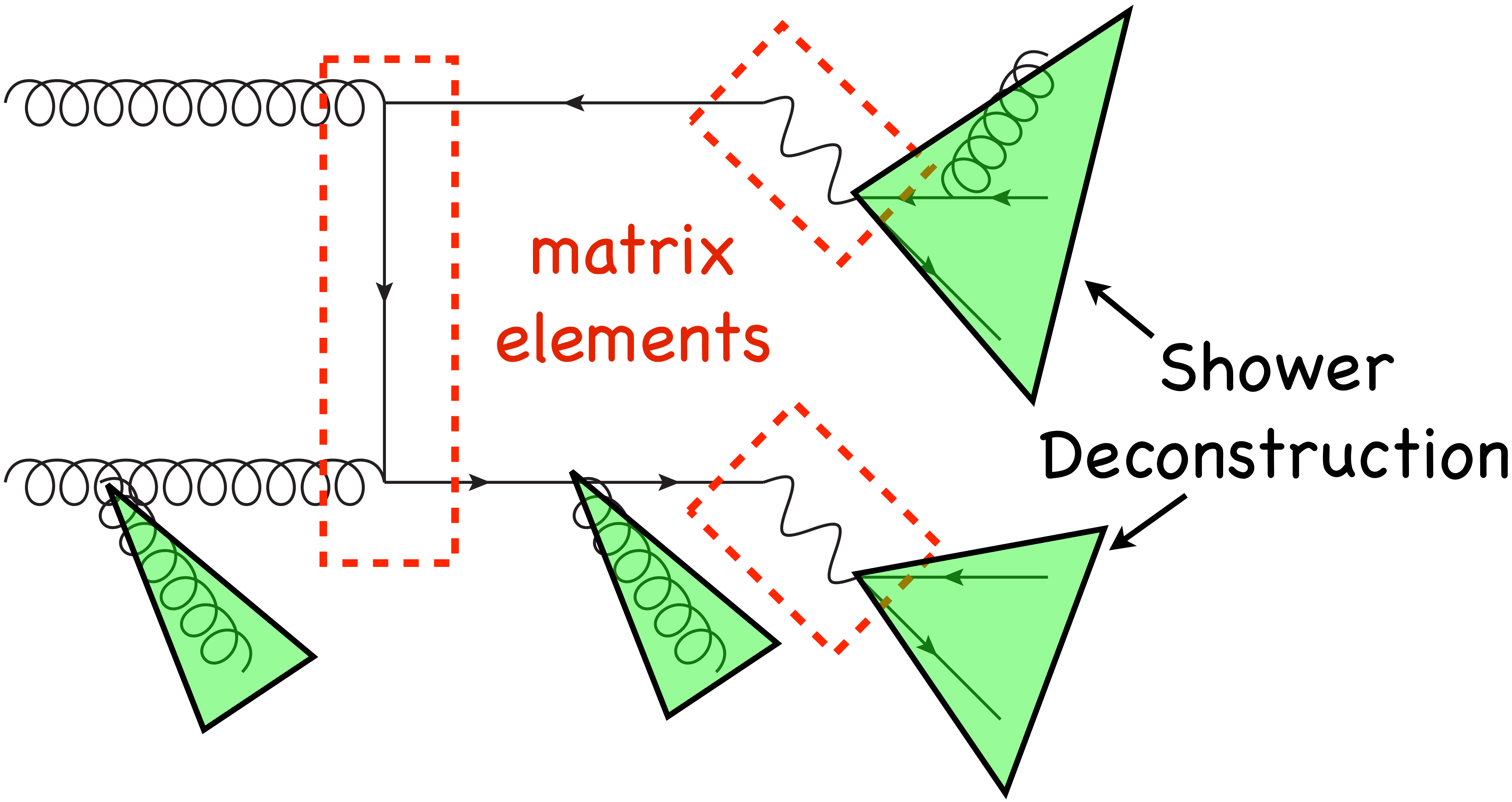
microjets: kT, R=0.2, pT>5 GeV

Shower deconstruction can be used to measure parameter of the theory, e.g. W mass.

Significance for different hypotheses for Mw:



shower deconstruction -> event deconstruction in 2013



Close collaboration with ATLAS Glasgow:

shower deconstruction is being tested in data

Conclusions

- To confirm it is Higgs boson its couplings and quantum numbers have to be measured

- Measuring hadronic decays and Higgs production in (partly) hadronic final states is paramount for this program

- New methods and observables can help

- Sensitive observables can be constructed in automized way

  $\longrightarrow$ Event Deconstruction

- Jets in Higgs physics will be active field for long time to come