QCD & BSM physics at the LHC

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Large c.o.m. energy makes LHC a BSM AND QCD machine

Recent technical developments

- High precision calculations for many legs
- Matching procedures (CKKW, MLM)
- IR safe and fast jet-algorithms
- Improved UE tunes

New Physics goals at LHC

- Explain ELWS breaking
- Find DM candidate
- Explain Hierarchy problems
- What are fundamental parameters

Plethora of Models!

Large c.o.m. energy makes LHC a BSM AND QCD machine

Recent technical developments

- High precision calculations for many legs   See talk by Kunszt
- Matching procedures (CKKW, MLM)   See talk by Hoeche
- IR safe and fast jet-algorithms   See talk by Dasgupta
- Improved UE tunes

  See talk by Field

New Physics goals at LHC

- Explain ELWS breaking
- Find DM candidate
- Explain Hierarchy problems
- What are fundamental parameters

Plethora of Models!

Hitoshi Murayama:

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- SUSY → Superpartners

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- SUSY ➜ Superpartners
- GUTs ➜ Z′, W′

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- Ex-Dim ➔ KK-tower

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- SUSY → Superpartners
- GUTs → Z', W'
- Ex-Dim → KK-tower
- TC → comp. resonance

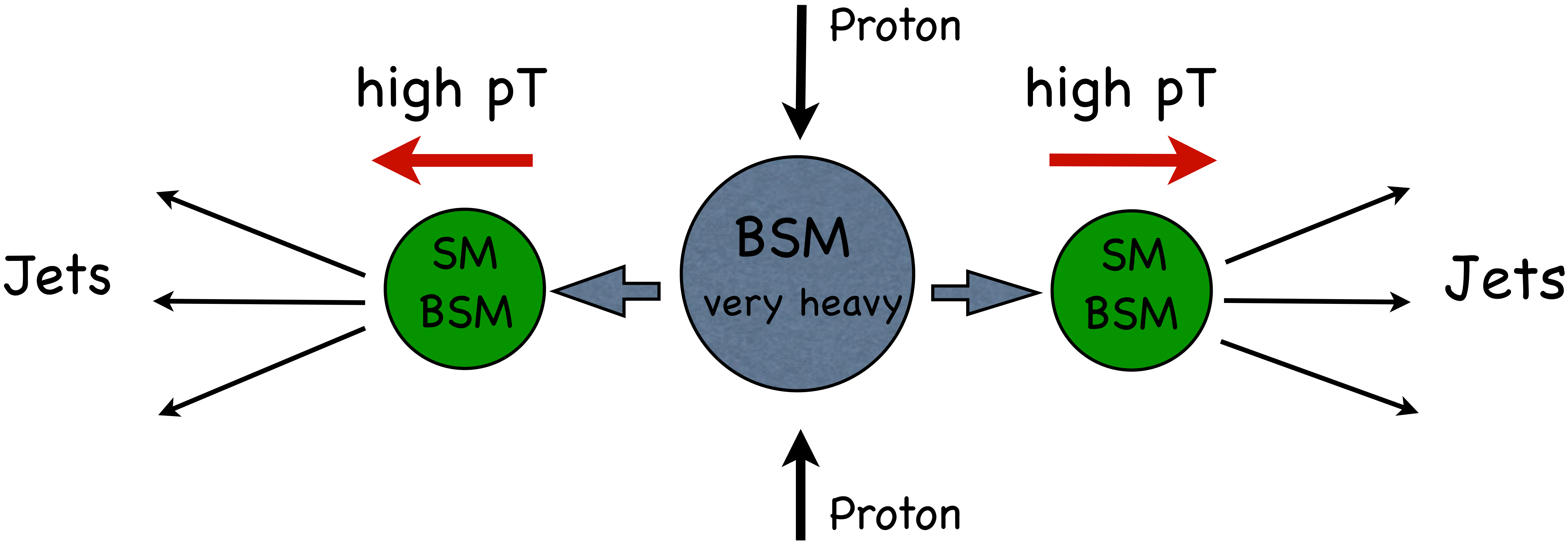
Hitoshi Murayama:

- SUSY ➔ Superpartners
- GUTs ➔ Z′, W′
- Ex-Dim ➔ KK-tower
- TC ➔ comp. resonance
- Not thought of ➔ ??

Most models predict TEV scale resonances

Decay often to jets

Boosted signal in New Physics search



- overlapping radiation
- jet-parton matching breaks down
- need big jet cone

The relevant kinematic pattern

smaller pT →

Business ↓

large pT, non-busy final state eg. Z'->ttbar	low pT, non-busy final state eg. pp->HW
large pT busy final state eg. SUSY cascades	low pT, busy final state eg. ttH

The relevant kinematic pattern

smaller pT

Business

large pT,
non-busy final state
eg. Z'->ttbar

- Elw. scale resonance highly boosted
- Decay prods highly collimated -> R < 1.0
- Less sensitive to UE/ISR
- Subjet approach necessary
- Original motivation and many techniques

large pT
busy final state
eg. SUSY cascades

The relevant kinematic pattern

smaller pT

Business

- Usually small signal CS
- But can be superior to standard analysis:
  - ➡ Event reconstruction impr.
  - ➡ b-tagging improved
  - ➡ combinatorial problem red.
- Big cone, sensitive to UE/ISR
- BDRS

low pT,
non-busy final state
eg. pp->HV

low pT,
busy final state
eg. ttH

The relevant kinematic pattern

smaller pT

Business

large pT,
non-busy final state
eg. Z'->ttbar

low pT,

large pT
busy final state
eg. SUSY cascades

- Hard radiation uncorrel. to hard interaction
- Increased comb. problem
- Additional criteria to select decay products

The relevant kinematic pattern

smaller pT

Business

- Most complicated
- Large cone, R > 1.2
- Sensitive to UE/ISR, hard uncorrelated radiation
- Only few approaches: HEPTopTagger, Shower deconstruction

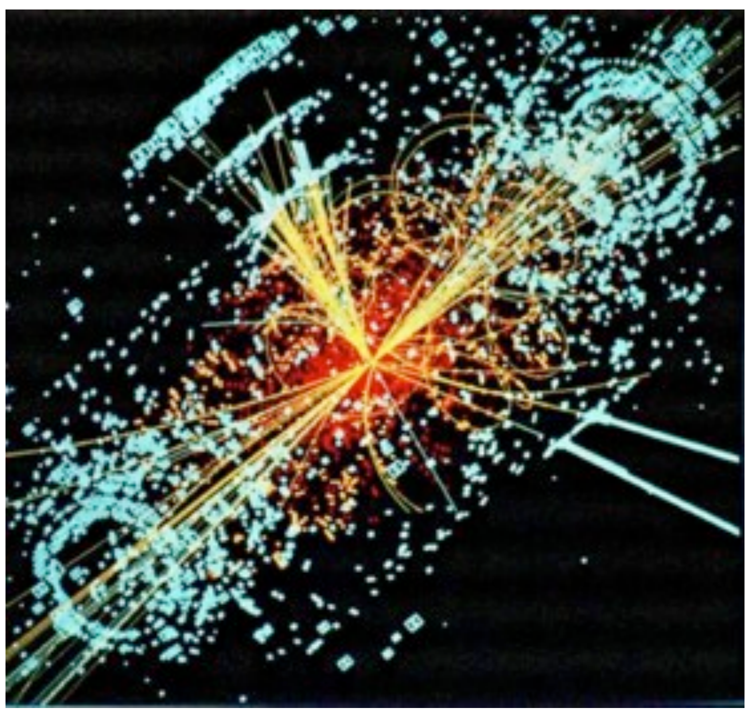
low pT,
non-busy final state
eg. pp->HW

low pT,
busy final state
eg. ttH

Jet definition not unambiguous: Which particles? How combined?

See talk by Dasgupta

Sequential recombination algorithms

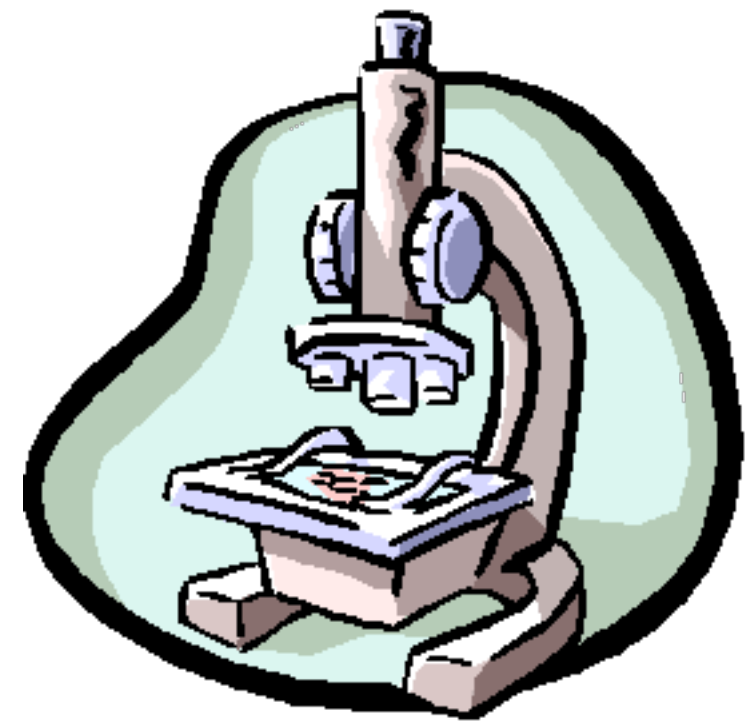


Recombination history

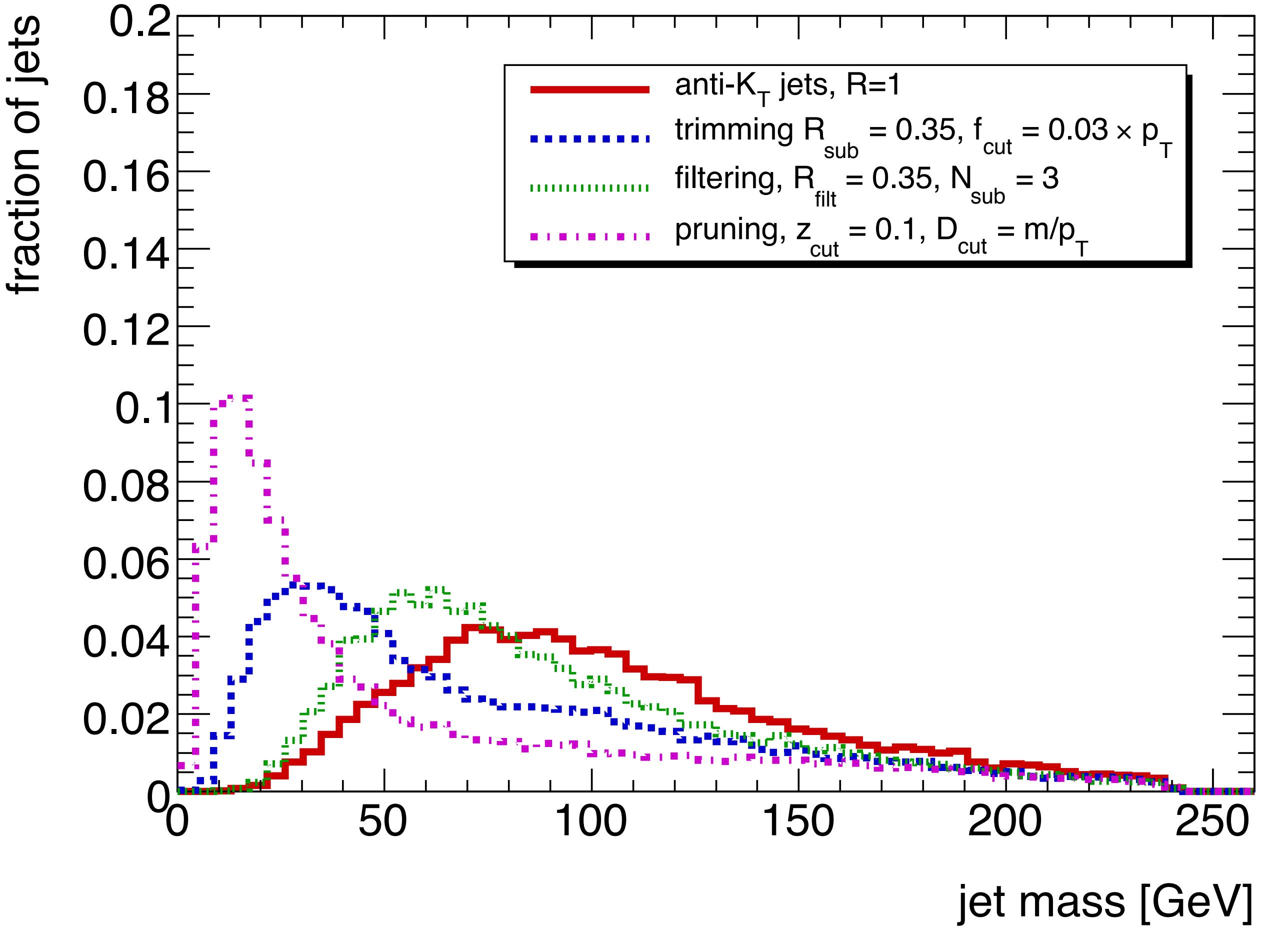
Jet substructure

=

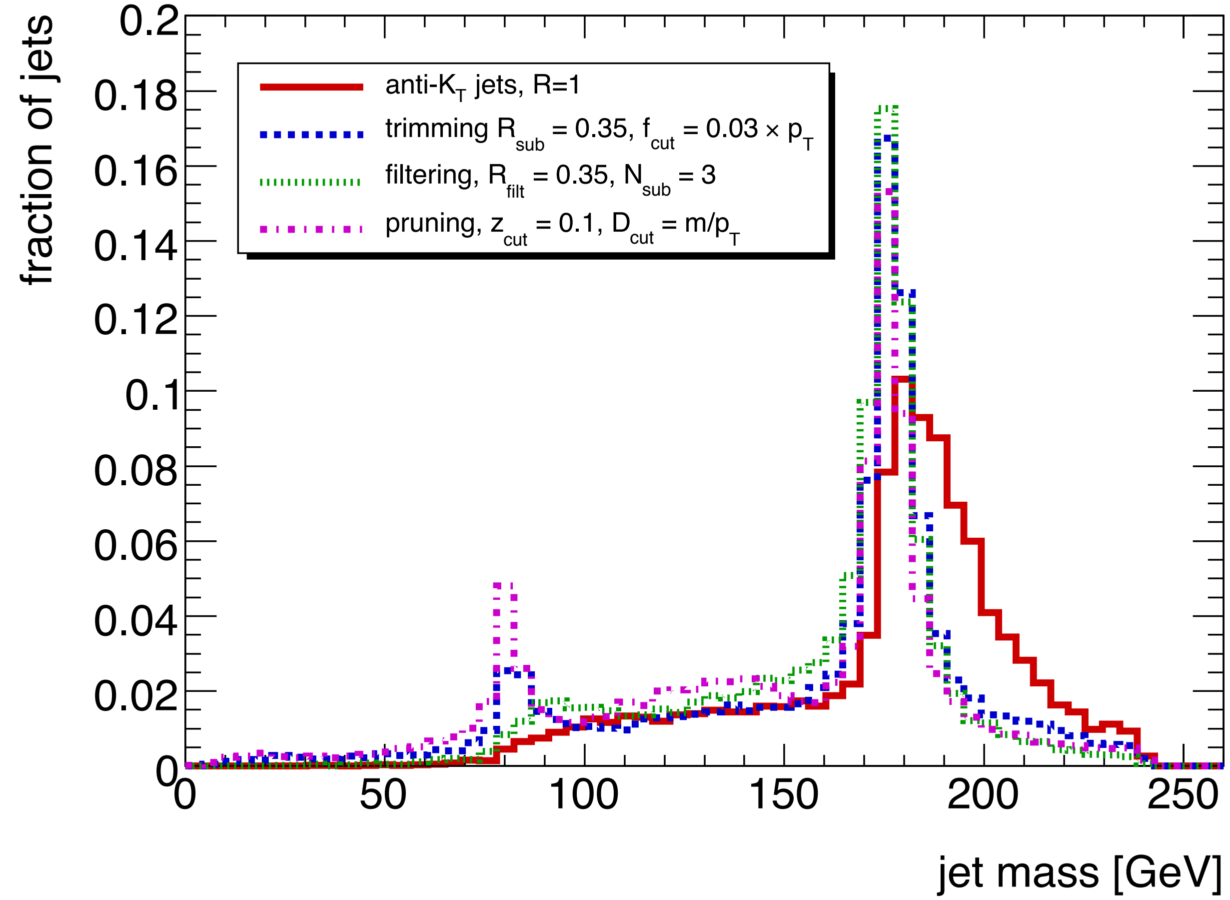
microscope for boosted resonance's properties



How much does UE/ISR affect fat-jet mass



(a) dijets, 500–600 GeV



(b) $t\bar{t}$, 500–600 GeV

see Boost 2010 proceedings [Karagoz, Salam, MS, Vos EPJ C71 (2011)]

Boosted Higgs search as an example

"Mirror, mirror on the wall ..."

Do I look like a Higgs jet or
do I look like a gluon jet?

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Don't answer:

To me you just look like a fat jet

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Idea: [M. H. Seymour, Z. Phys. C 62 (1994)]

Trailblazing analysis: [Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

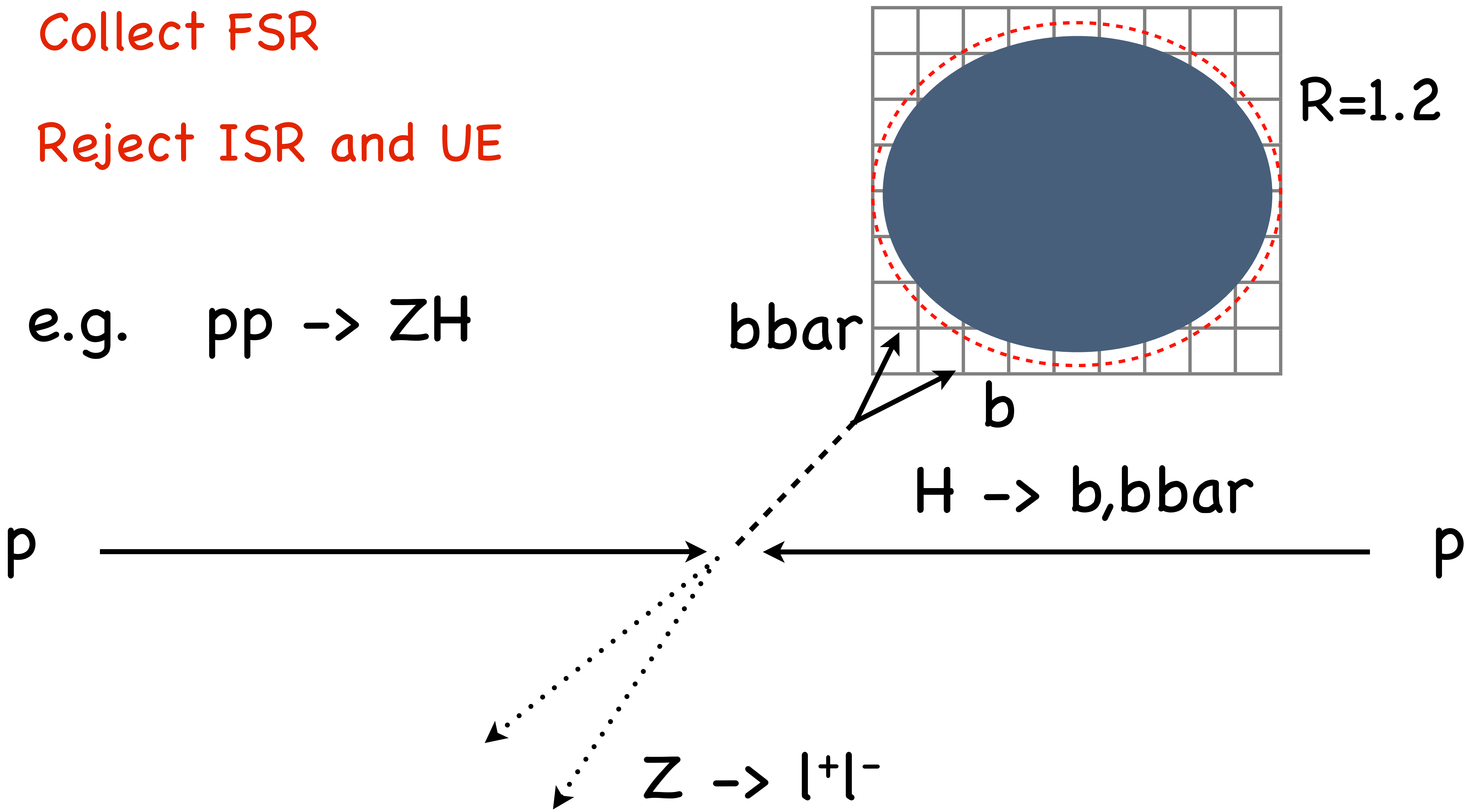
HV - Higgs discovery channel

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Collect FSR

Reject ISR and UE

e.g. pp -> ZH



HV - Higgs discovery channel

[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

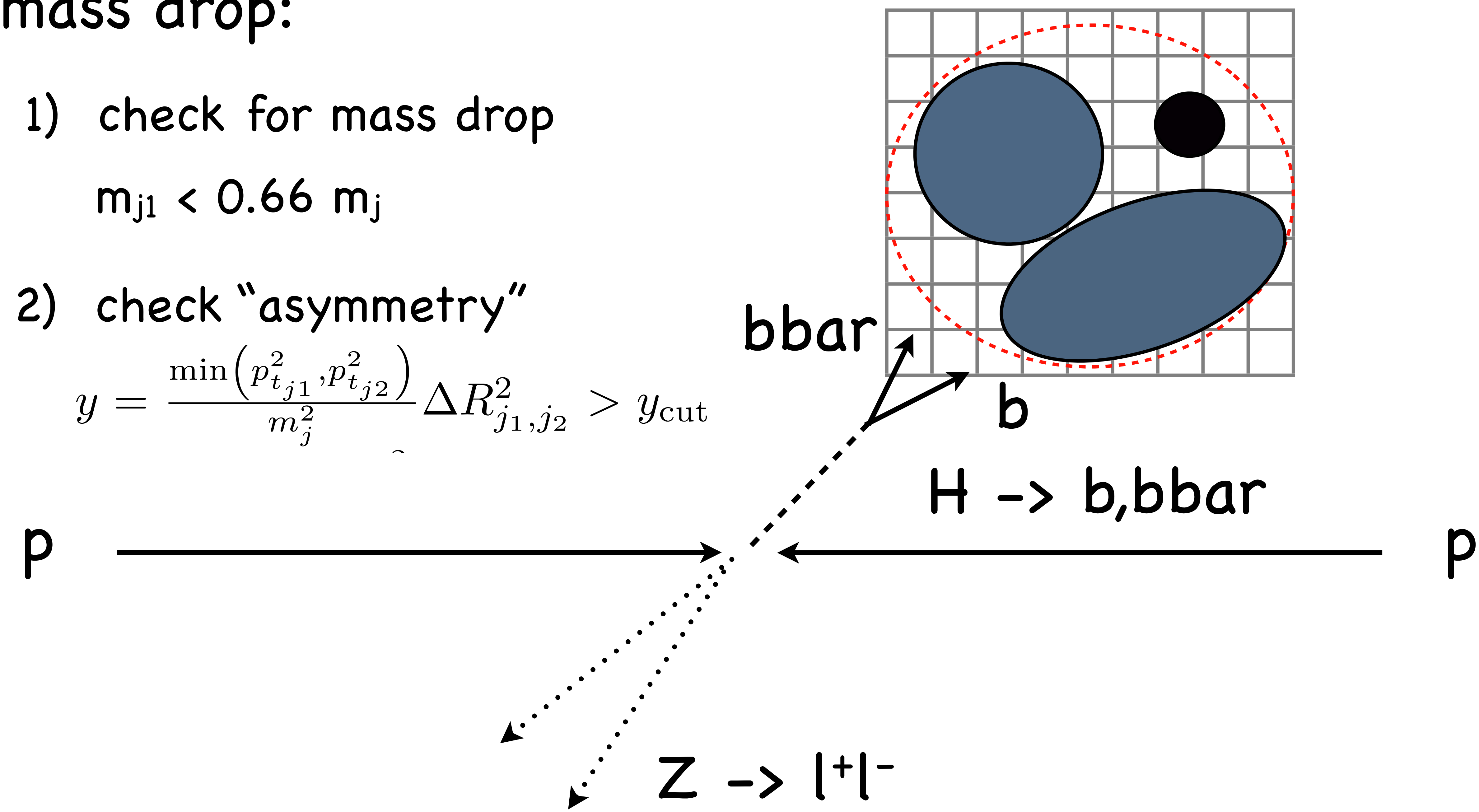
mass drop:

1) check for mass drop

$m_{j1} < 0.66\ m_j$

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\mathrm{cut}}$$

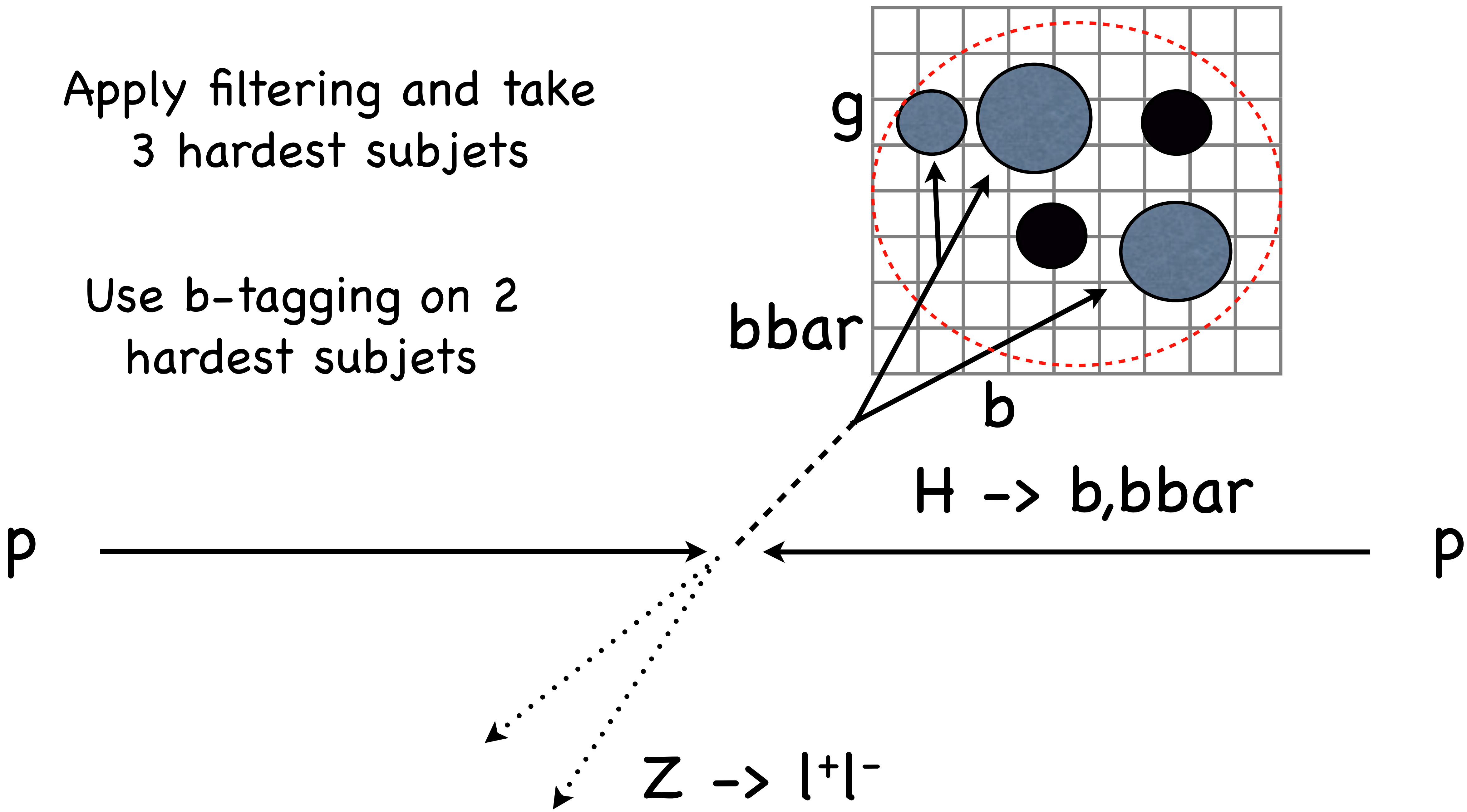


HV - Higgs discovery channel

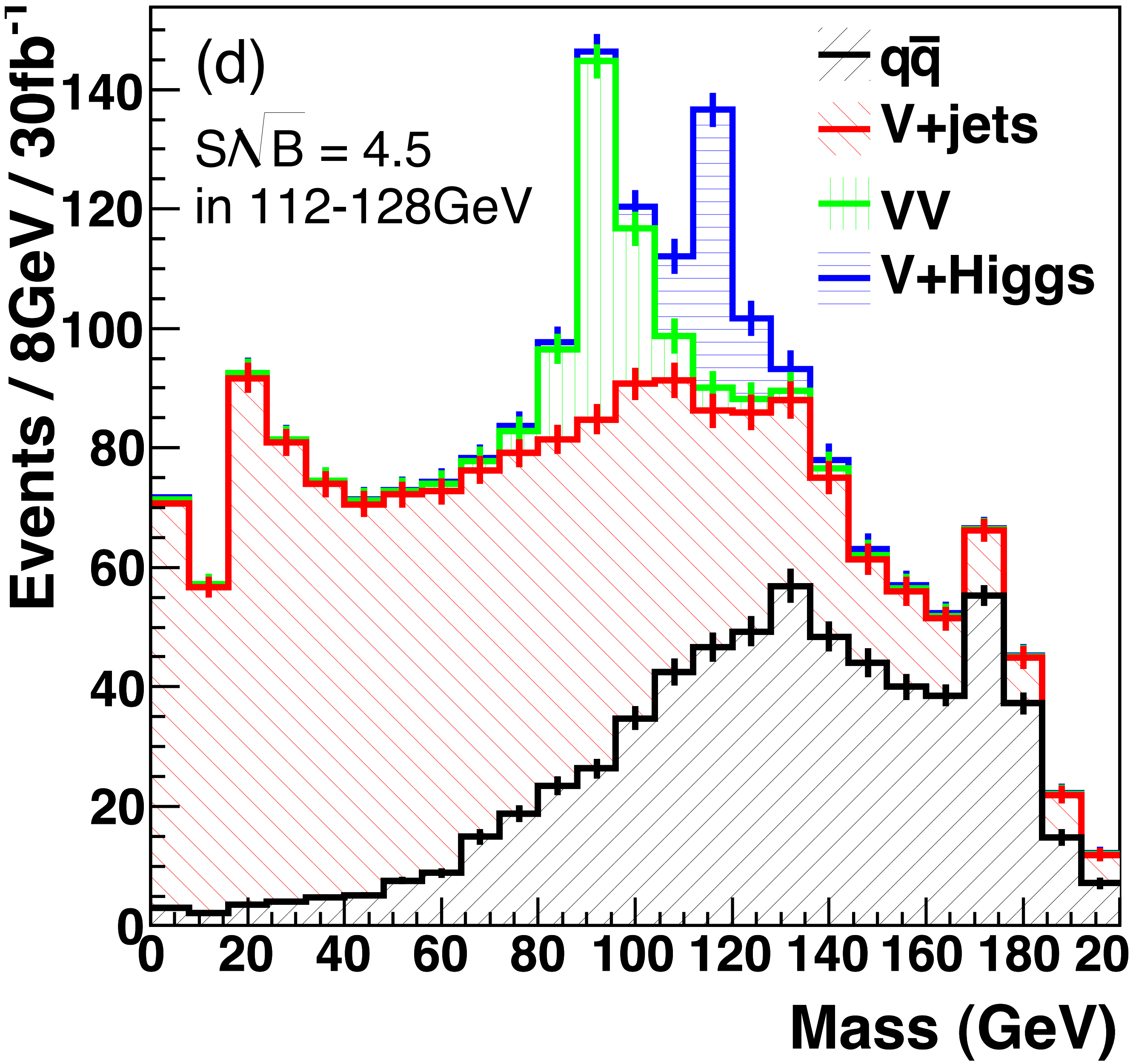
[Butterworth, Davison, Rubin, Salam PRL 100 (2008)]

Apply filtering and take 3 hardest subjets

Use b-tagging on 2 hardest subjets



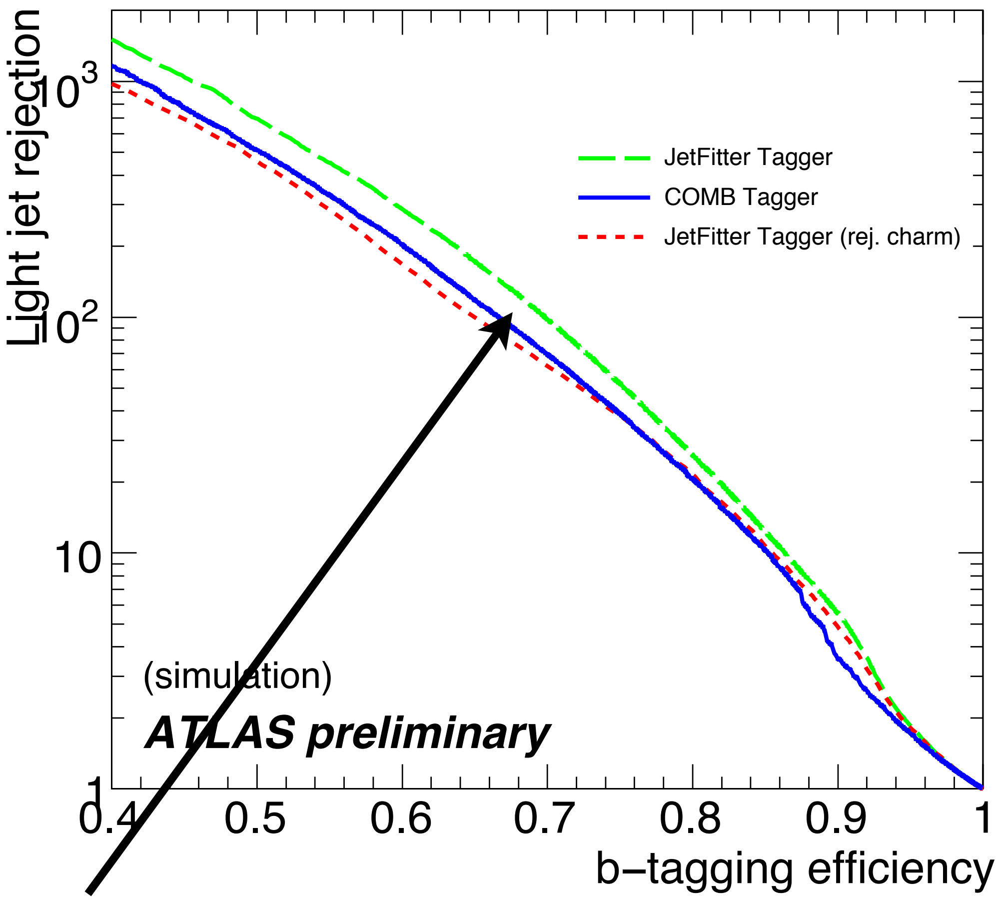
BDRS Result

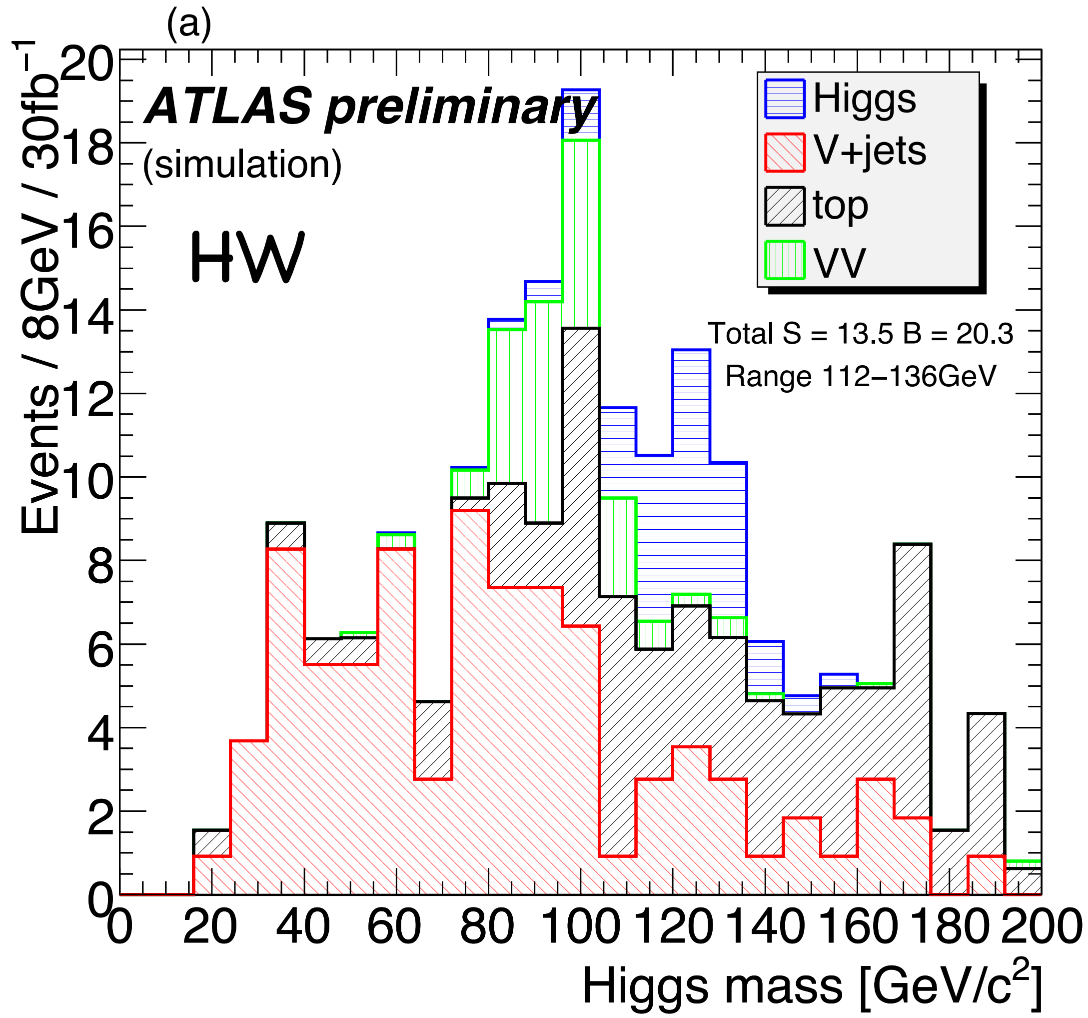


- LHC 14 TeV; 30 fb^{-1}
- HERWIG/JIMMY/Fastjet cross-checked with PYTHIA with "ATLAS tune"
- 60% b-tag; 2% mistag
- Combination of HZ and HW channels

ATLAS study

[ATL-PHYS-PUB-2009-088]





great b-tagging efficiency (0.7/0.01)

Channel	signal	$S/\sqrt{B}$
$llb\bar{b}$	5.34	1.5
$l\nu b\bar{b}$	13.5	3.0
$\nu\nu b\bar{b}$	16.3	1.6
Combined		3.7

$S_{BDRS} \approx 4.2$

versus

$S_{ATLAS} \approx 3.7$

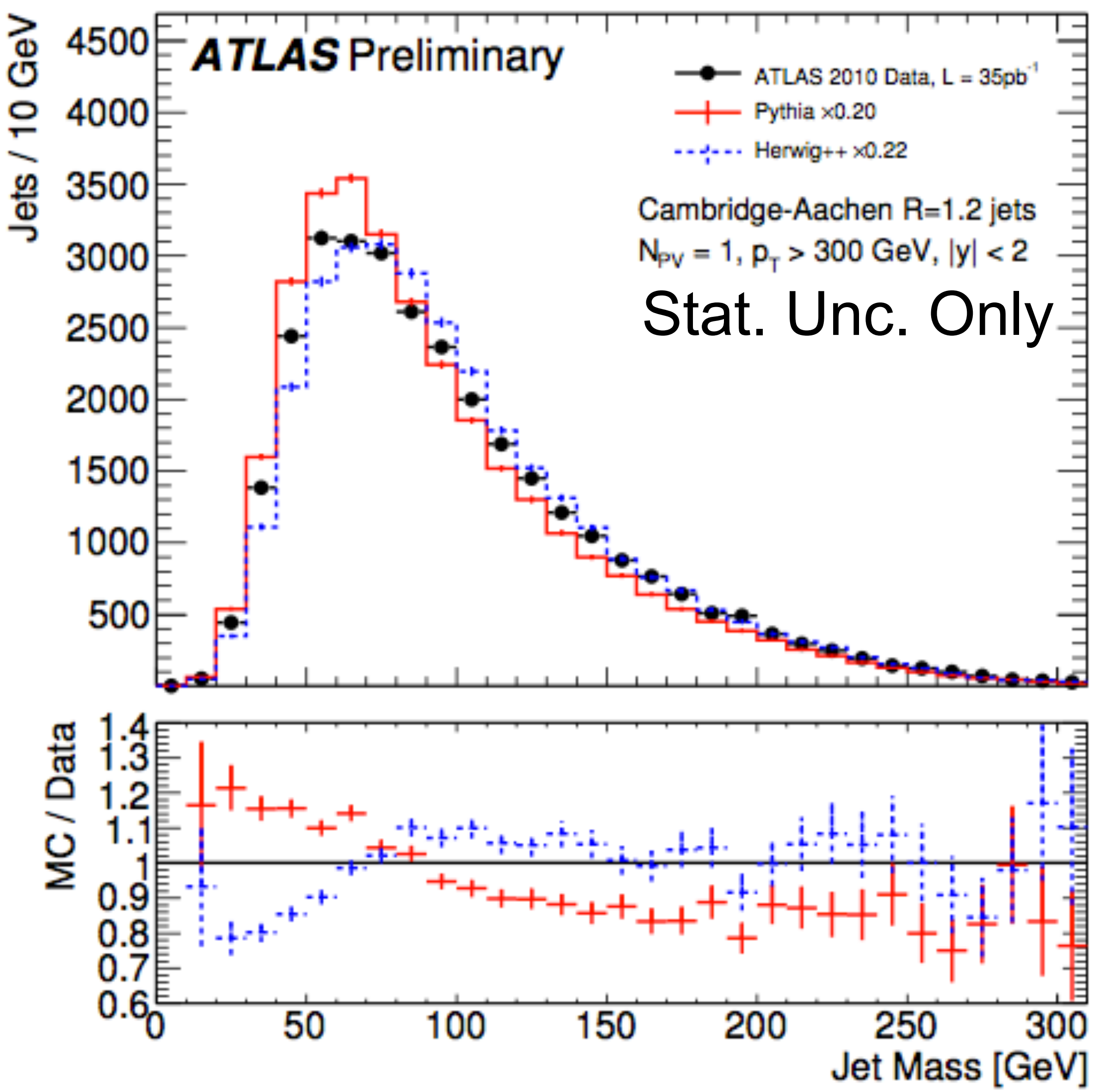
See talk by
Spreitzer and Loch

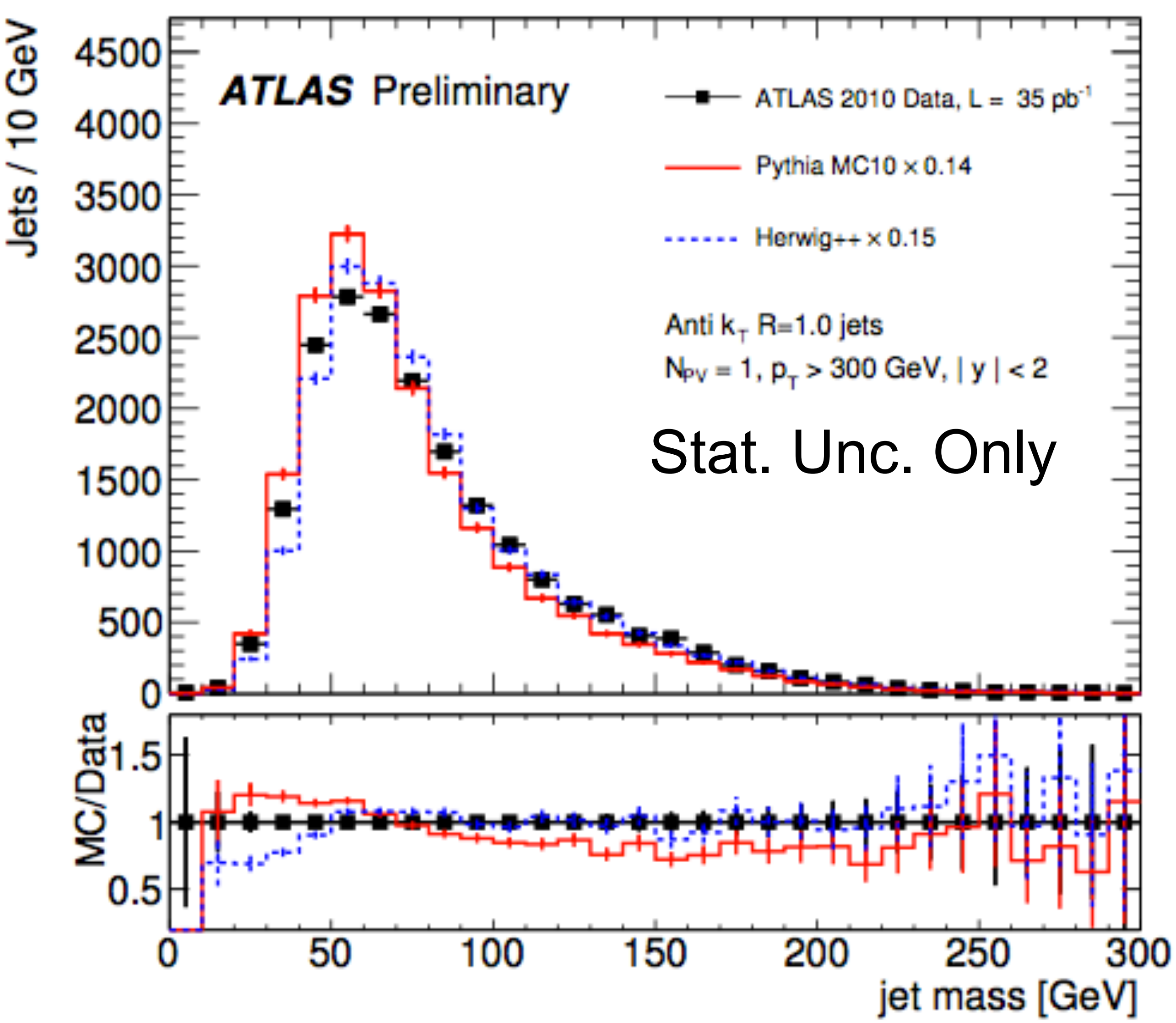
How about Data?

Recent measurements of dij and jet mass with 35 ipb

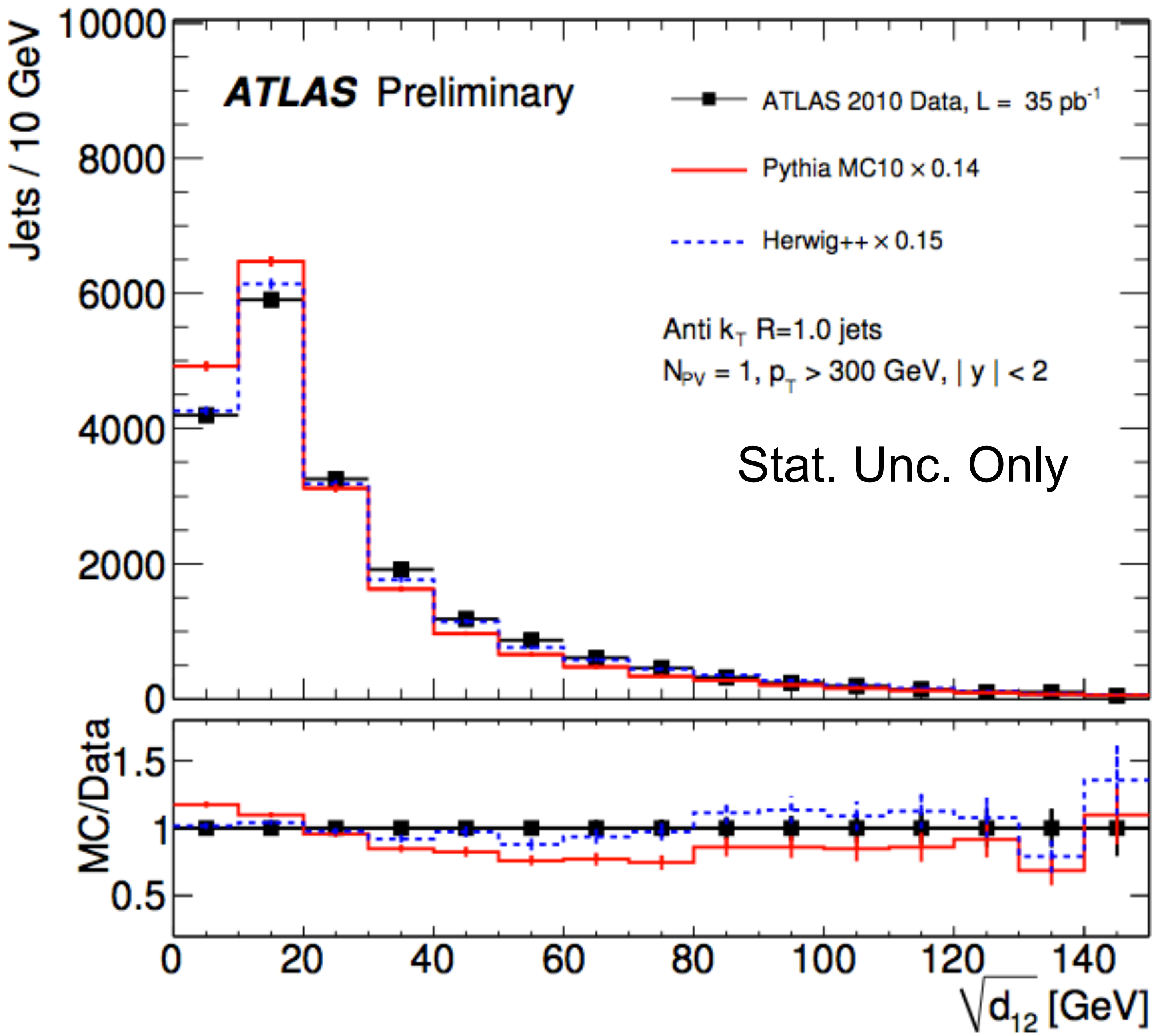
[ATLAS-CONF-2011-073, Talk A. Davison Boost 2011]

Jet mass:





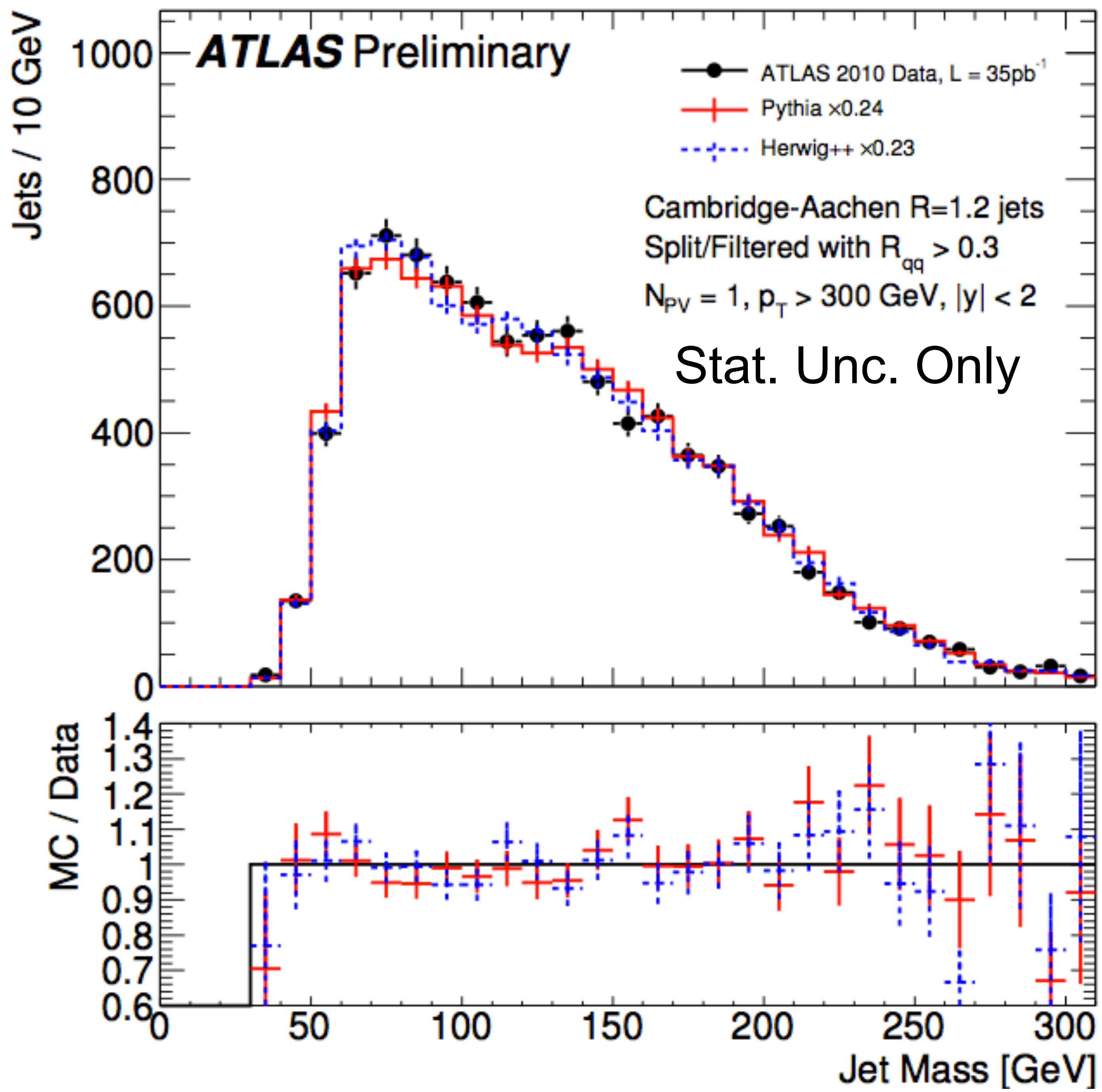
Measurement of kT-splitting scale



$$\sqrt{d_{12}} = \min(p_{Ta}, p_{Tb}) \times \delta R_{a,b}$$

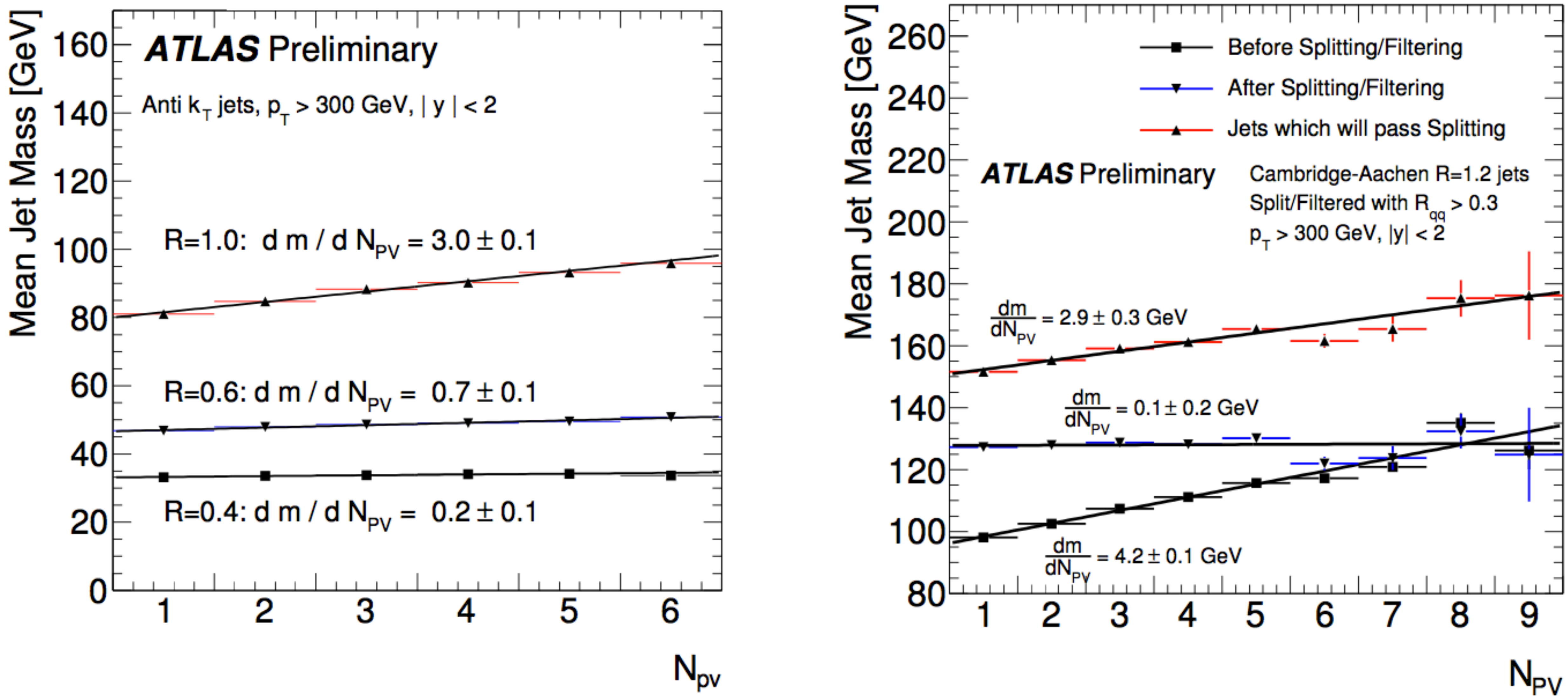
Good agreement with LO parton shower Monte Carlos

Filtered Mass Spectrum



Basic description appears to be very good

Pile-up

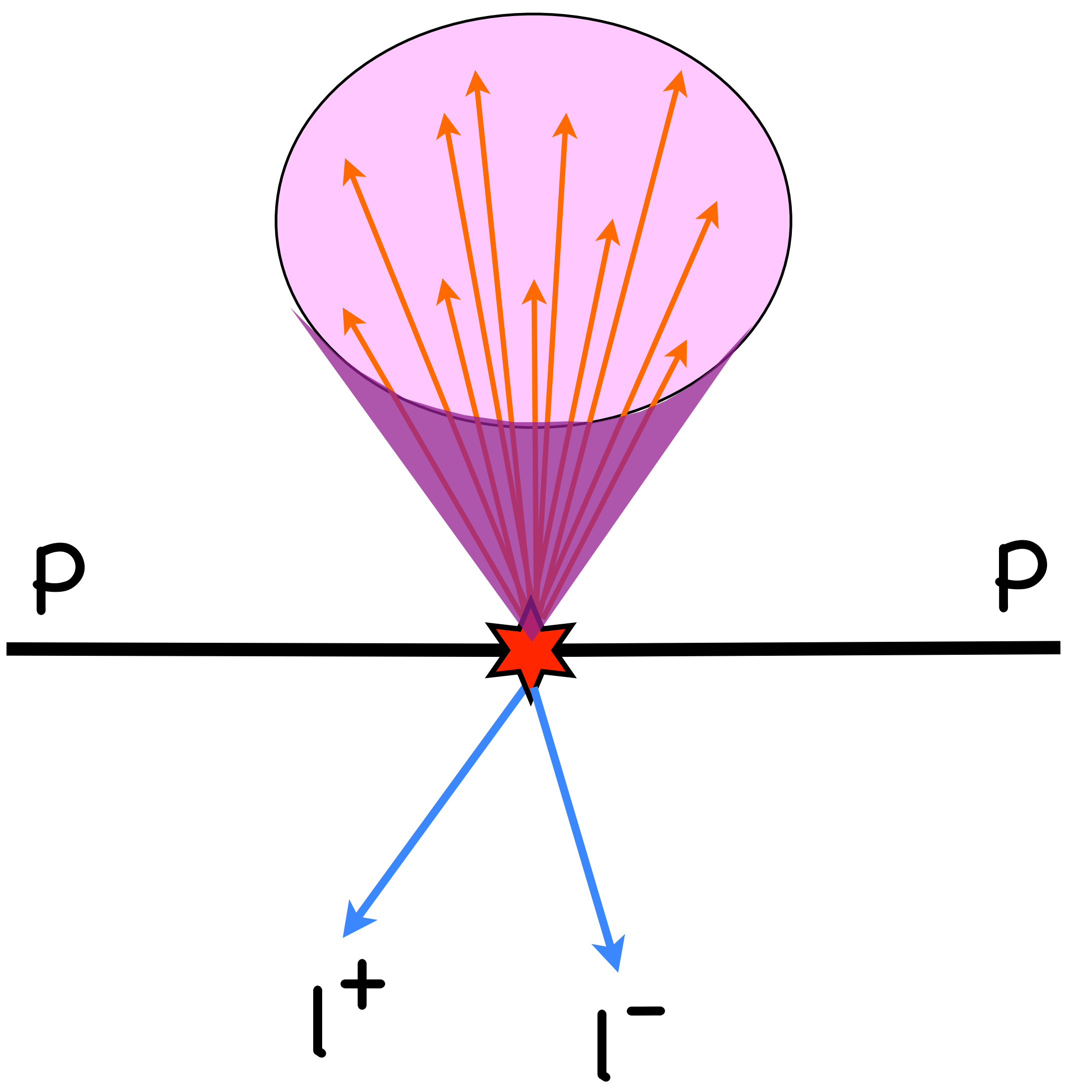


All measurements indicate large potential for jet substructure techniques and good agreement with MC

Jet grooming procedures	Filtering	[Butterworth et al. PRL 100 (2008)]
See talk by Loch	Pruning	[Ellis et al. PRD 80 (2009)]
	Trimming	[Krohn et al. JHEP 1002 (2010)]
2-pronged resonances	Mass-drop/Filtering and variations	[Butterworth et al. PRL 100 (2008)] [Plehn et al. PRL 104 (2010), Kribs et al. PRD 81 (2010)]
3-pronged resonances	y-splitter Top Tagger	[Butterworth et al. PRD 55 (2002)] [Broijmans ATL-COM-PHYS-2008-001]
	Johns Hopkins Tagger	[Kaplan et al. PRL 101 (2008)]
	HEP Top Tagger	[Plehn et al. JHEP 1010]
See talk by Loch	tree-less approach	[Jankowiak et al. JHEP 1106]
General methods	Template method	[Almeida et al. PRD 82 (2010)]
	N-subjettiness	[Kim PRD 83 (2011)] [Thaler et al. JHEP 1103]
	Multi-variate	[Gallicchio et al. JHEP 1104]
	Shower deconstruction	[Soper et al. 1102.3480]

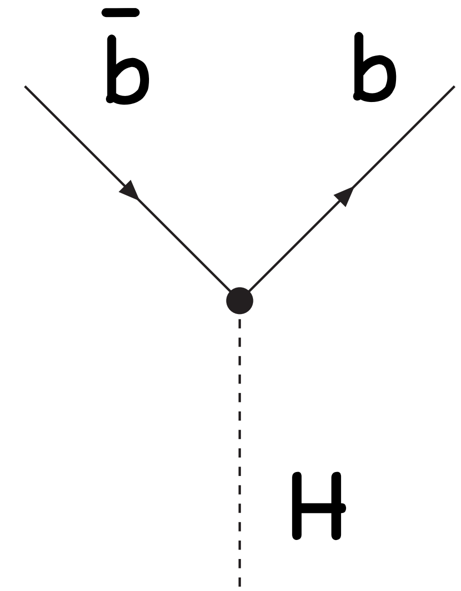
Shower deconstruction

a maximum information approach
applicable for all kinematic patterns

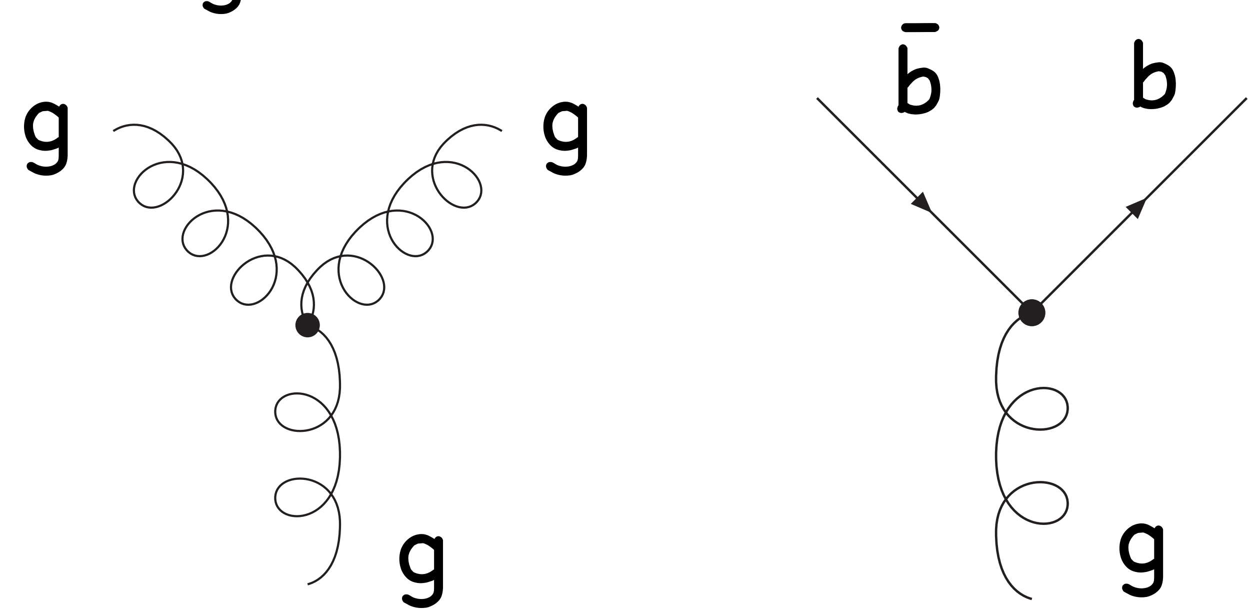


pT>200 GeV

signal



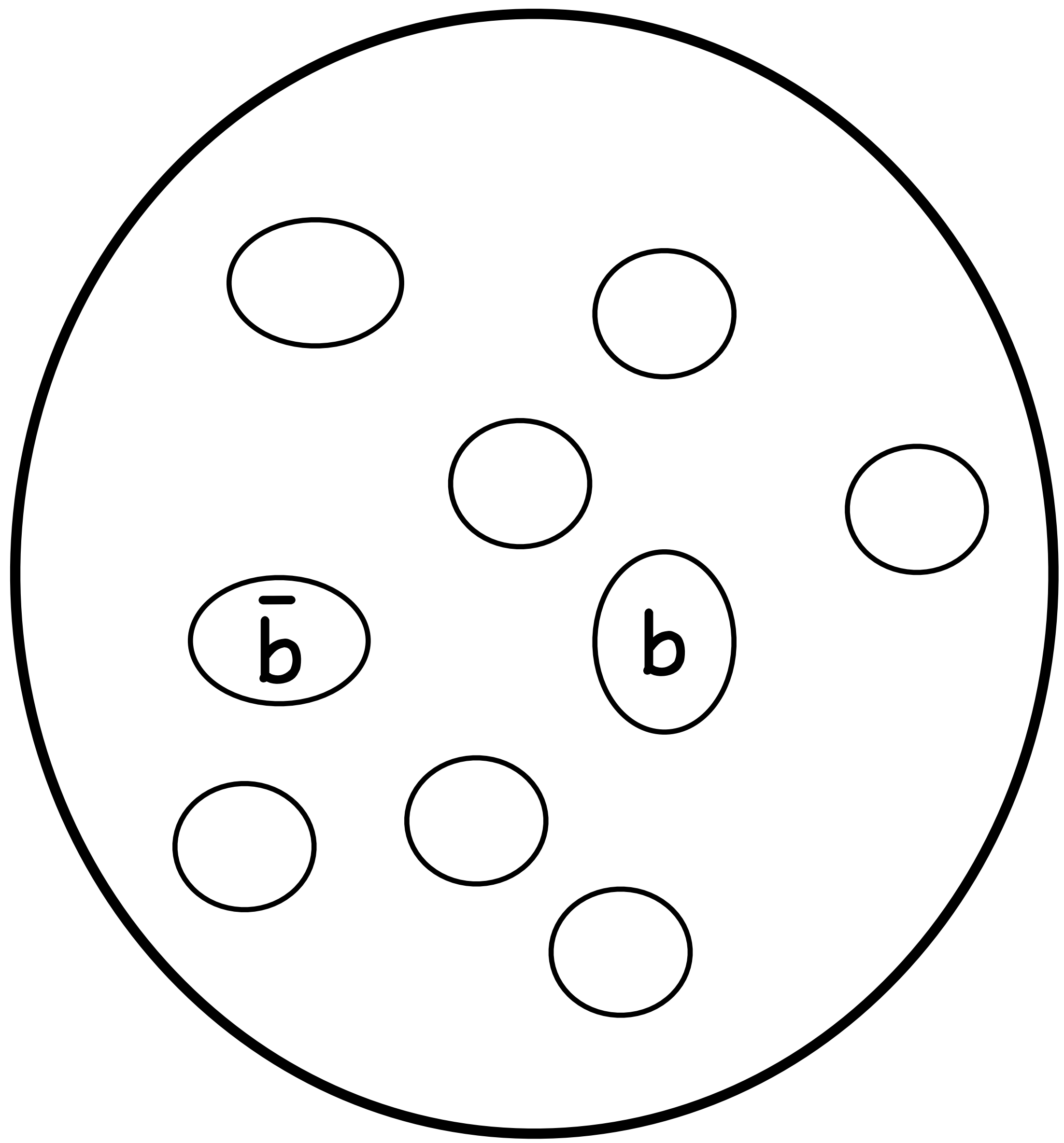
background



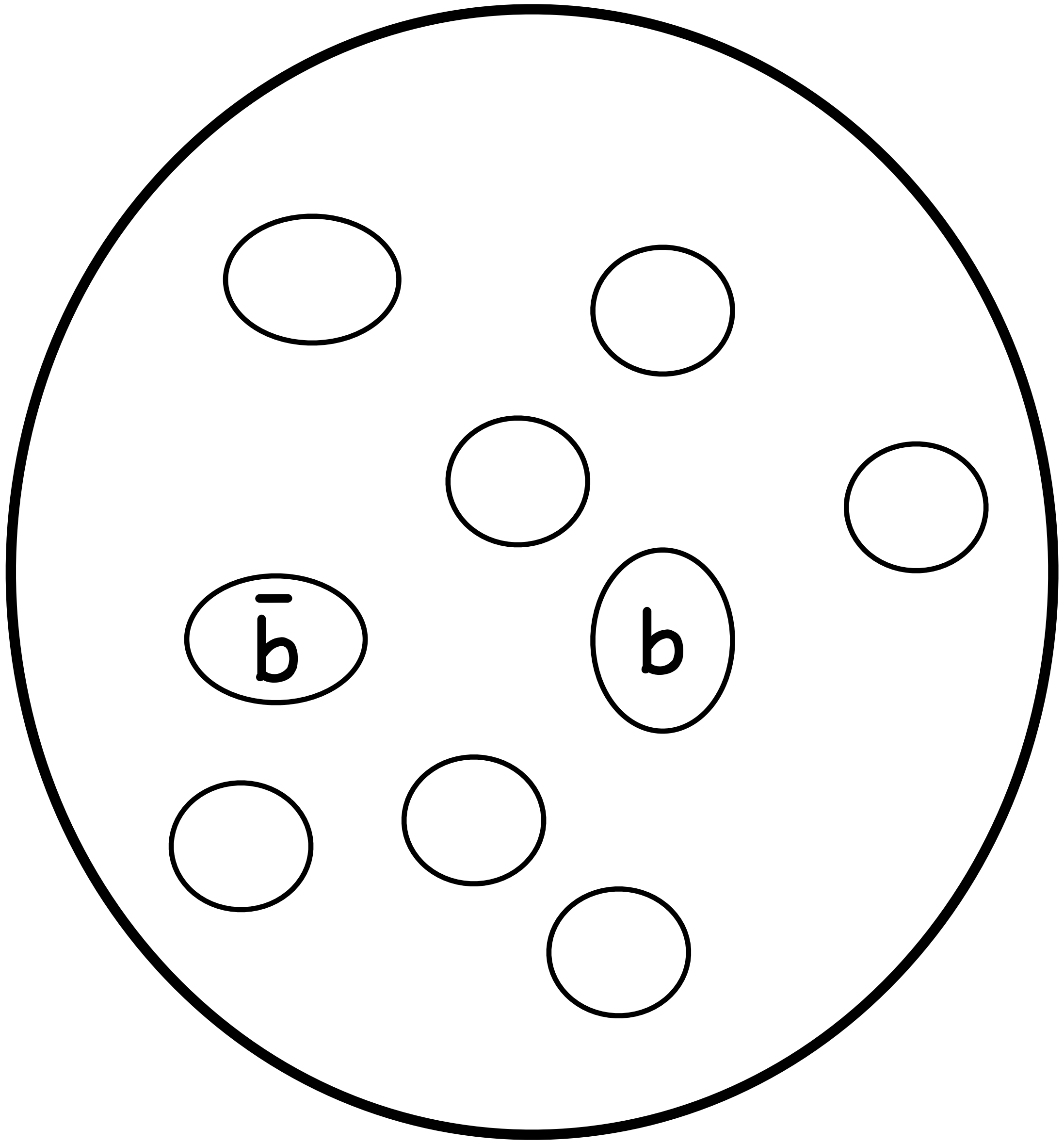
Recombine fat jet's constituents to microjets

(kT, R=0.15, pT > 1 GeV)

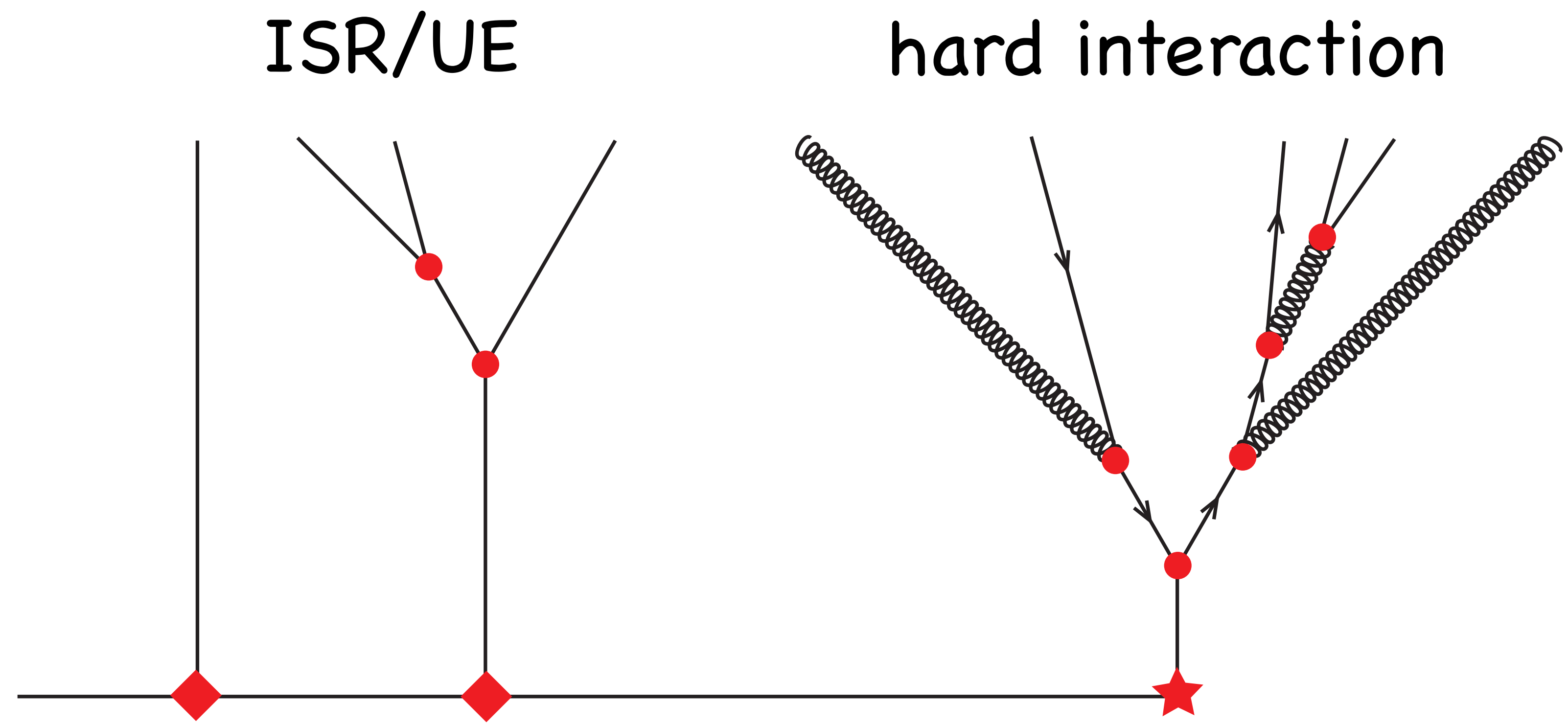
microjets are basic elements of event/fat jet



Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT

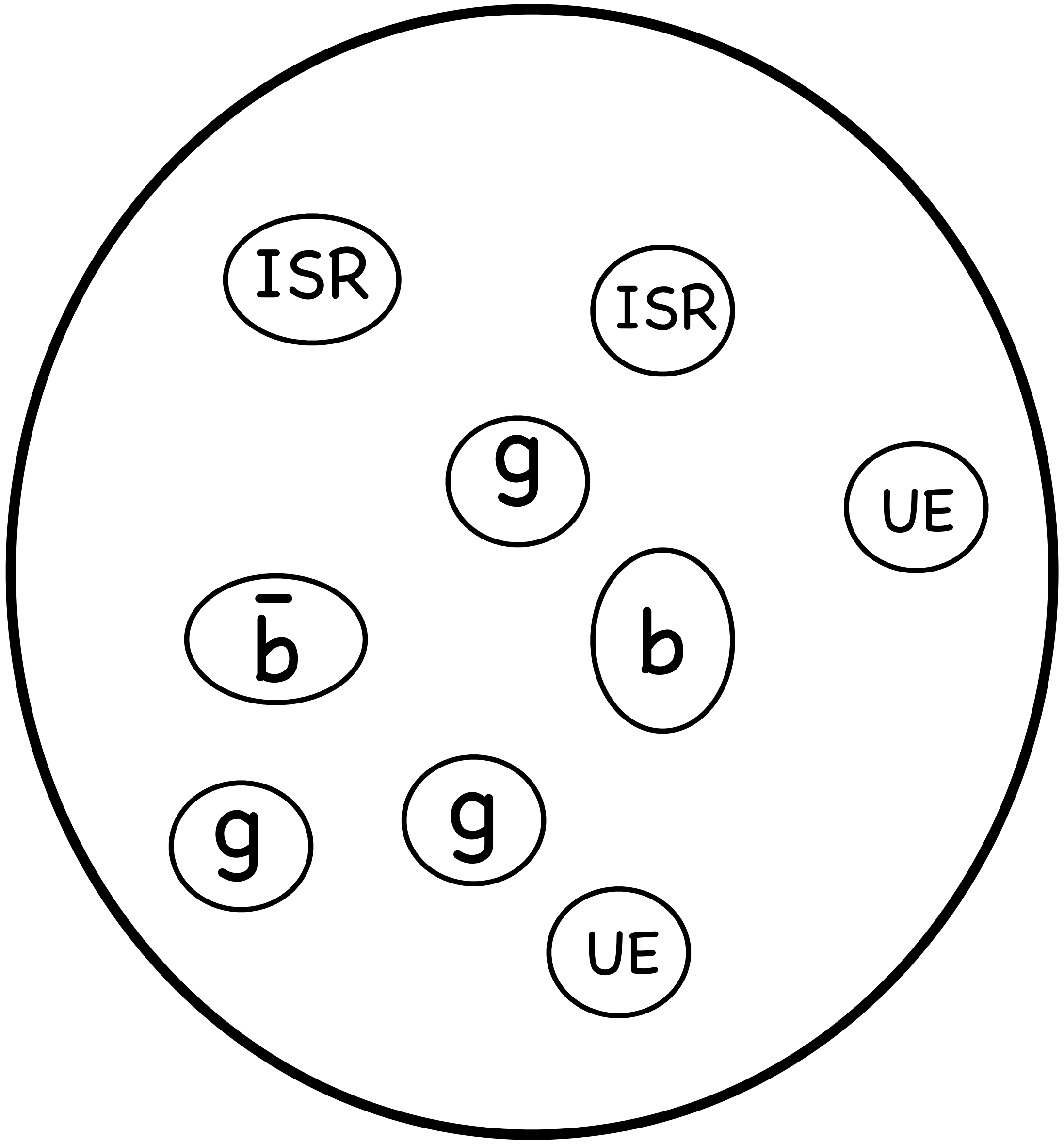


Build all possible shower histories

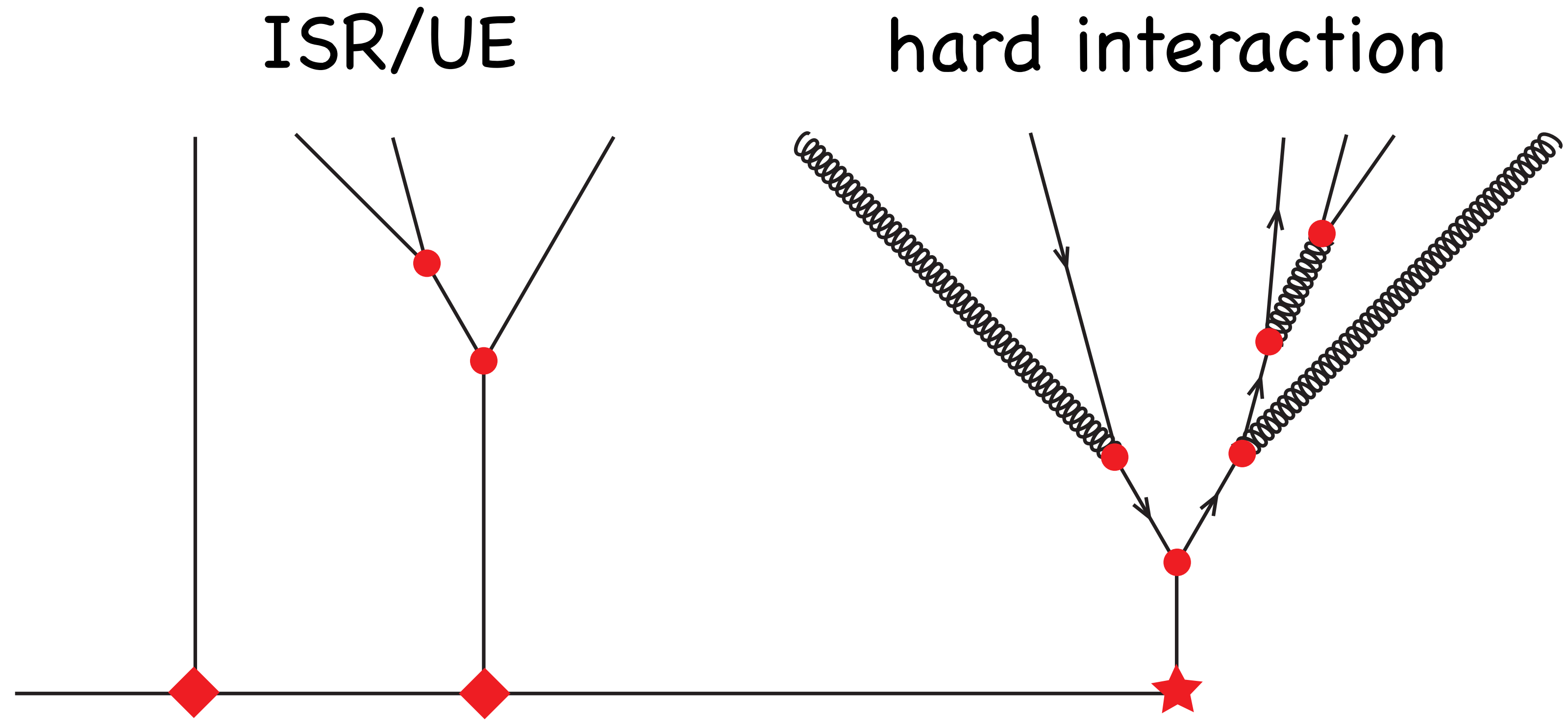
signal vs background hypothesis based on:

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

Fat jet: R=1.2, anti-kT



microjets
R=0.15, kT



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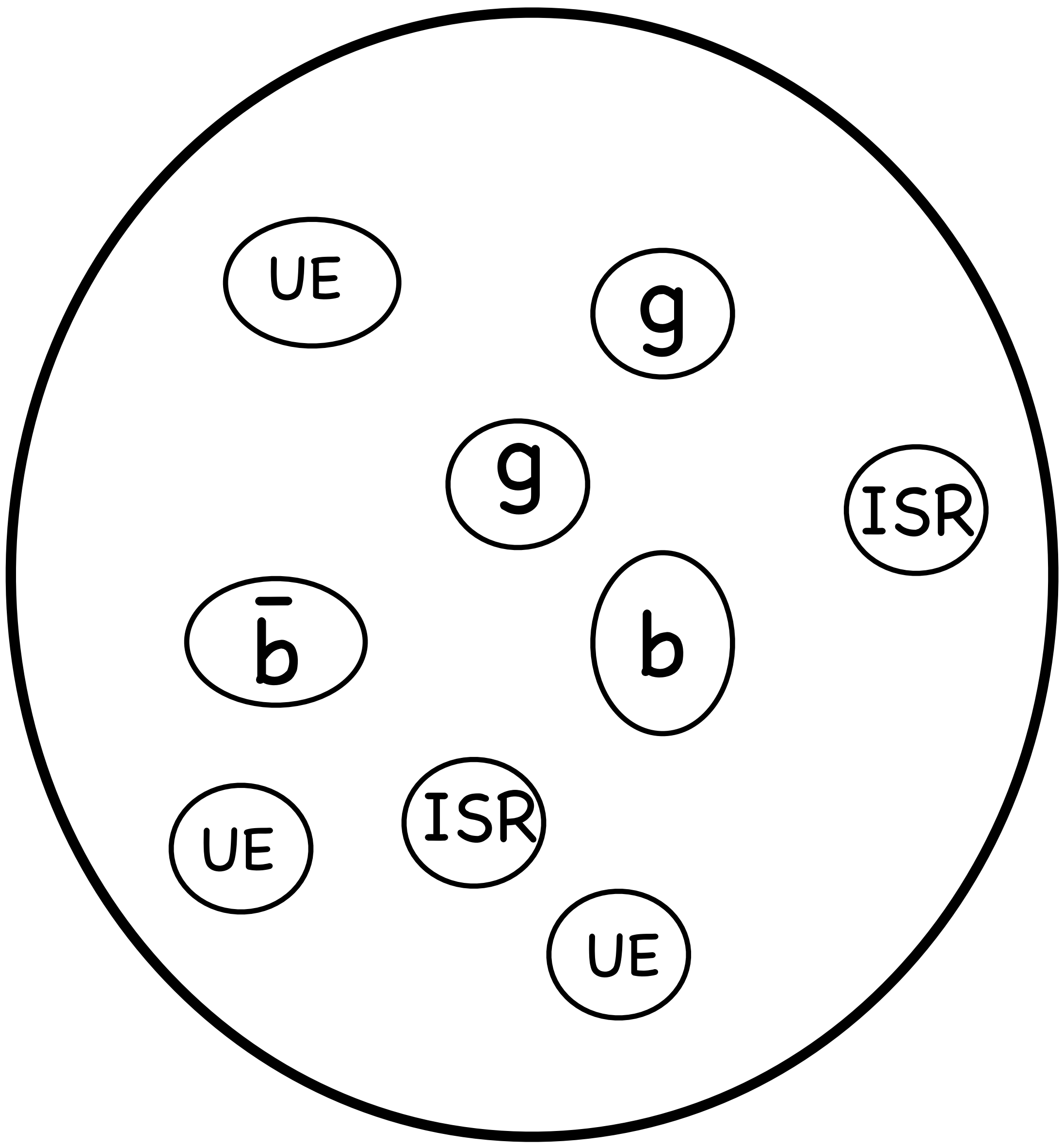
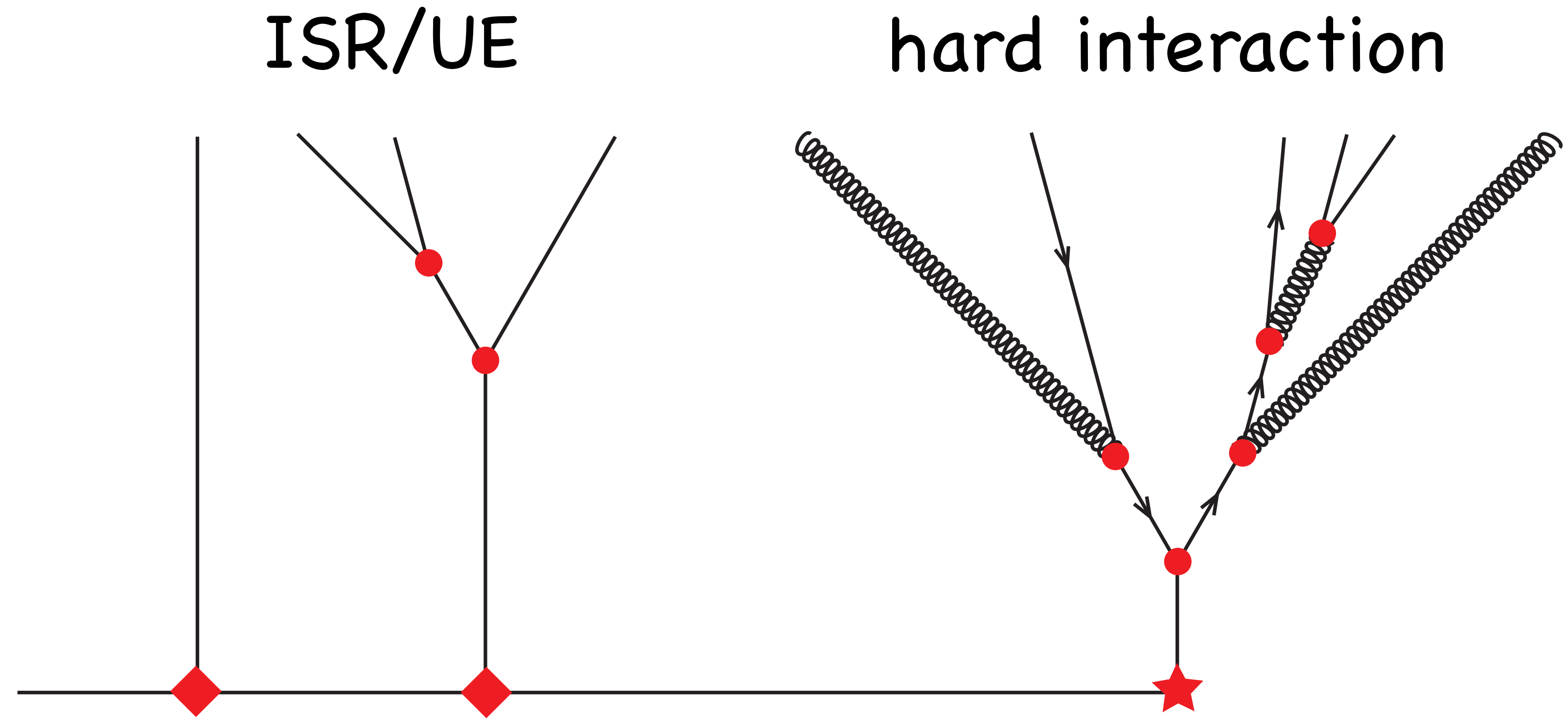


microjets
R=0.15, kT



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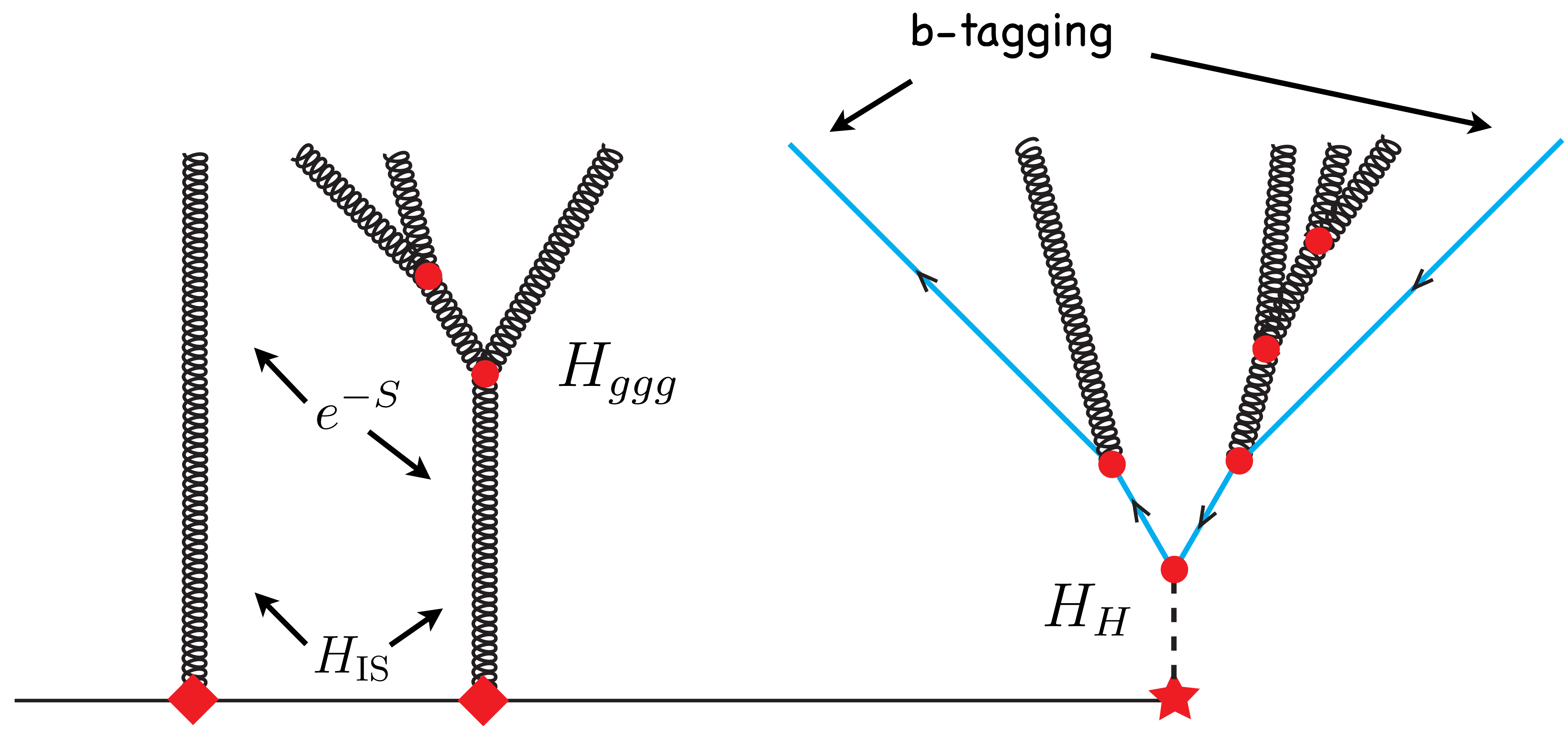
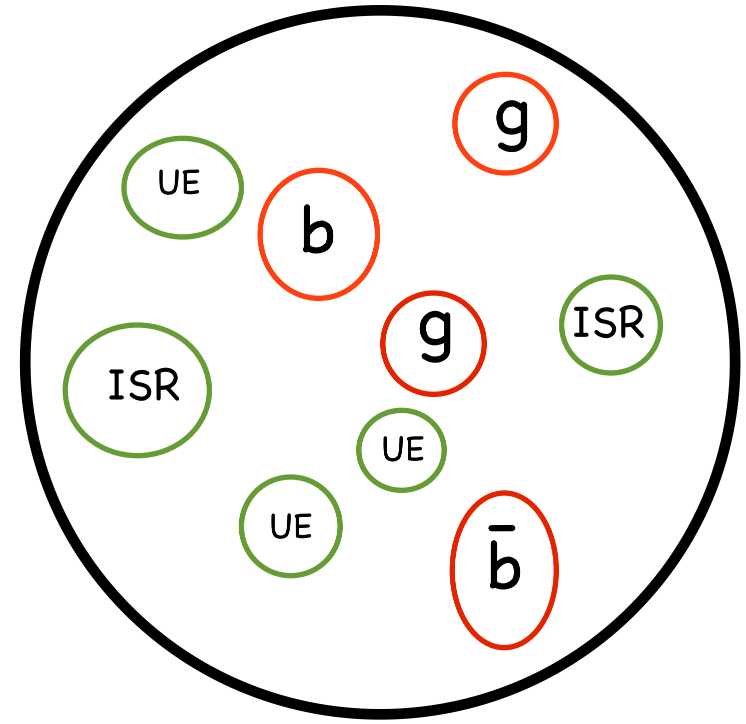


Want to convert the shower history into analytic expression

➡ Feynman Rules for Shower Deconstruction

$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})} = \frac{\sum_{\rm histories} H_{ISR} e^{-S_{I1}} \cdots \sum_{\rm histories} H_H e^{-S_{s1}} H^s_{bg} e^{-S_{s2}} \cdots}{\sum_{\rm histories} H_{ISR} e^{-S_{I1}} \cdots \sum_{\rm histories} H_{gbb} e^{-S_{b1}} H^b_{bg} e^{-S_{b2}} \cdots}$$

χ is the one analytic function to discriminate signal from background (for more detail see [Soper, MS 1102.3480])



$$Q^2 = \left(\sum_{i \in \text{fat jet}} \vec{p}_{T,i} \right)^2 + \left(\sum_{i \in \text{fat jet}} p_i \right)^2$$

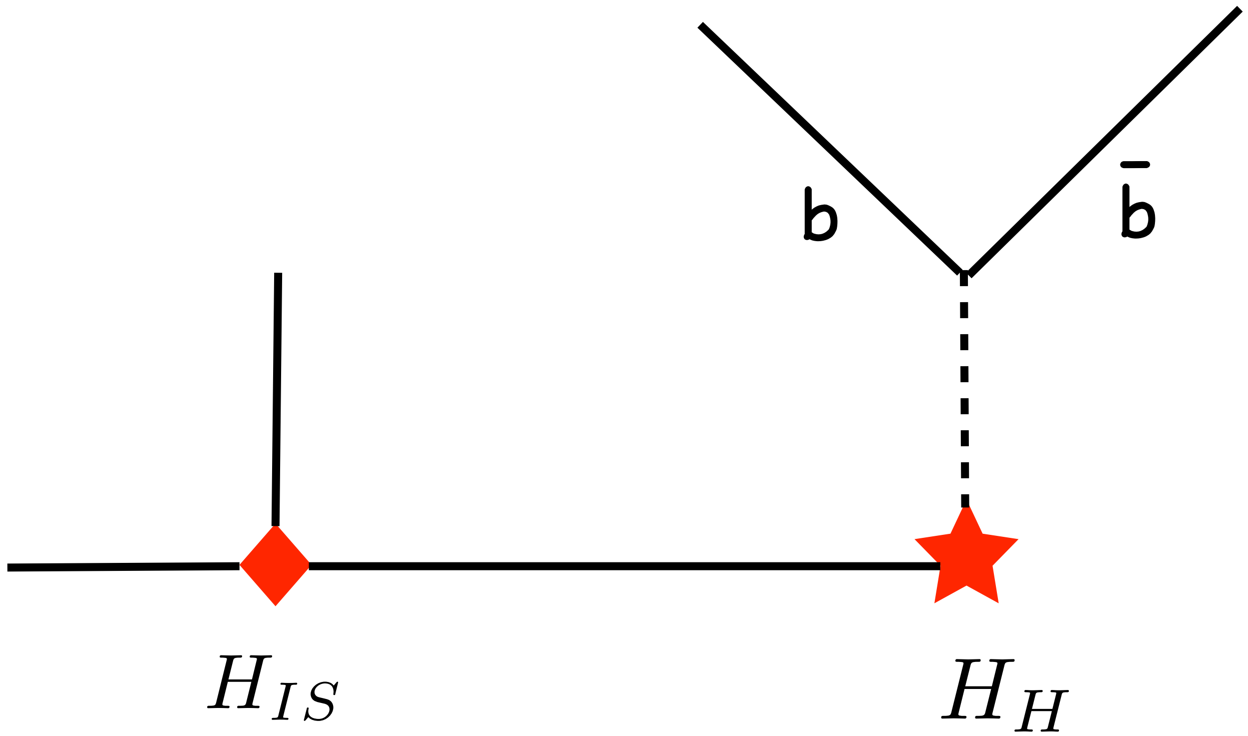
$$H_g = N_{\text{pdf}}^g \left(\frac{p_{T,\text{min}}^2}{k_0^2} \right)^{N_{\text{pdf}}^g} \frac{1}{k_0^2} \, \Theta(k_{T,\text{I}}^2 < Q^2/4)$$

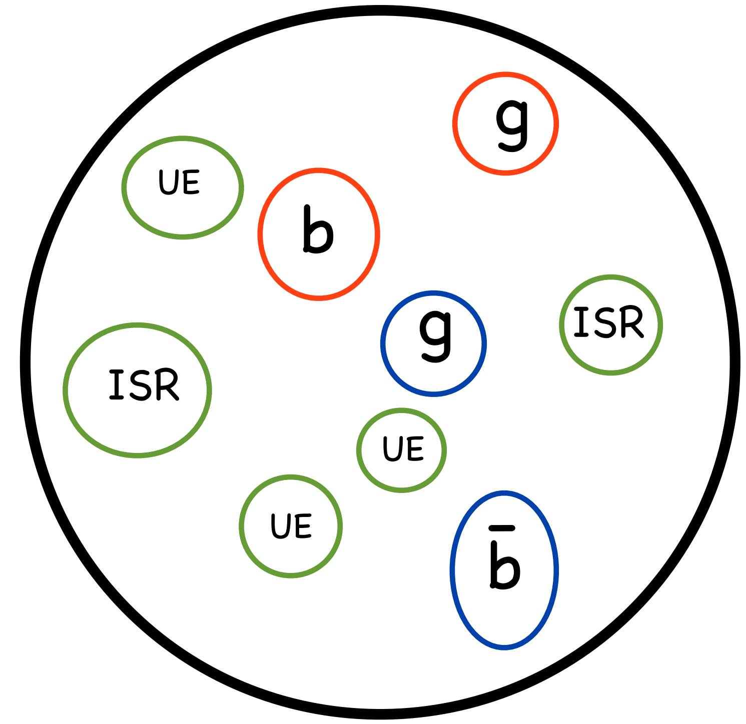
ISR vs Hard scale cut

$$H_H = N_{\text{pdf}}^H \left(\frac{p_{T,\text{min}}^2 + m_H^2}{k_H^2 + m_H^2} \right)^{N_{\text{pdf}}^H} \frac{1}{k_H^2 + m_H^2} \, \Theta(k_{T,\text{I}}^2 < Q^2/4)$$

$$H_{\text{IS}} = \frac{C_{\text{A}}}{2} \, \frac{\alpha_{\text{s}}(k_J^2 + \kappa_{\text{p}}^2)}{k_J^2 + \kappa_{\text{p}}^2} \, \frac{1}{(1 + c_R \, k_J/Q)^{n_R}} + \frac{c_{\text{np}} (\kappa_{\text{np}}^2)^{n_{\text{np}}-1}}{[k_J^2 + \kappa_{\text{np}}^2]^{n_{\text{np}}}}$$

(fitted to Pythia8)





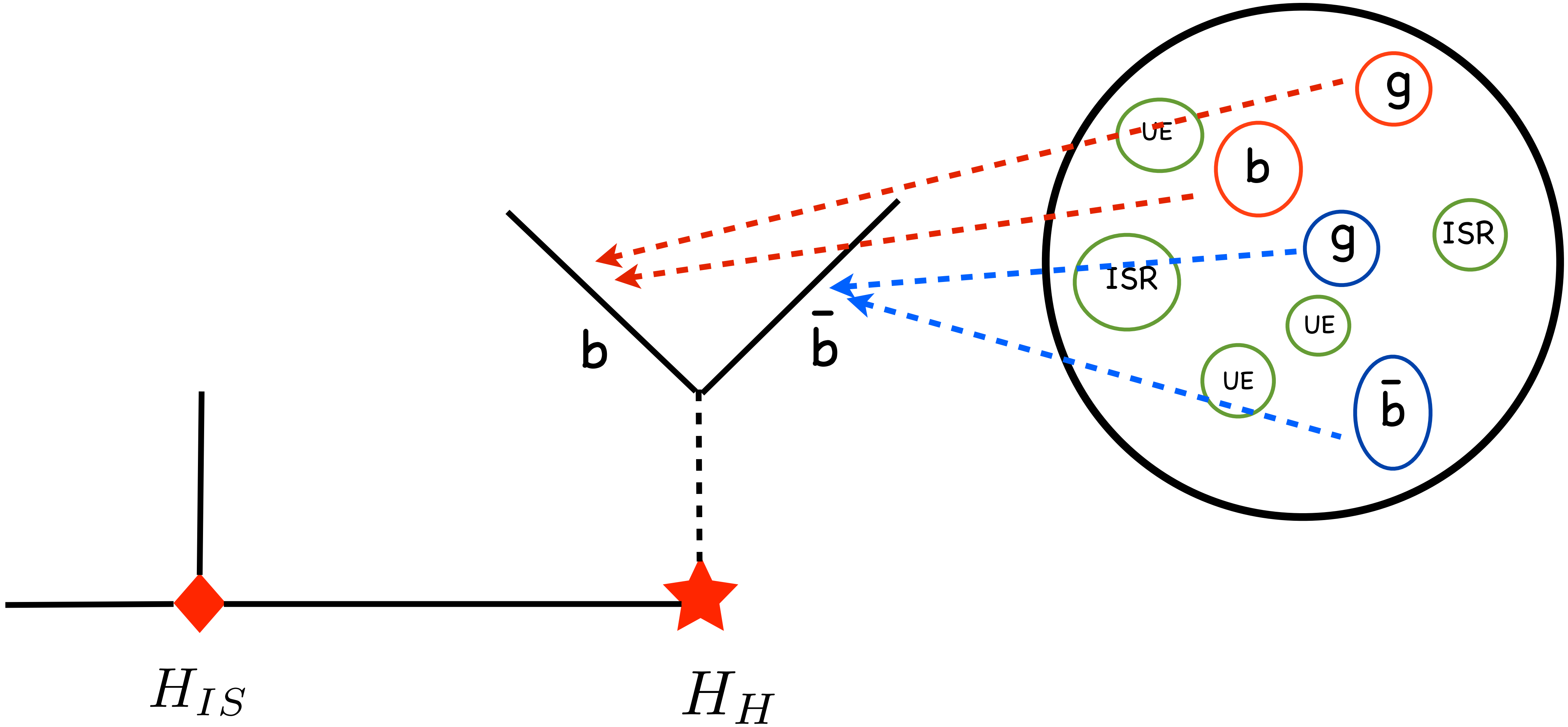
Higgs has to decay:

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

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

Mass window

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



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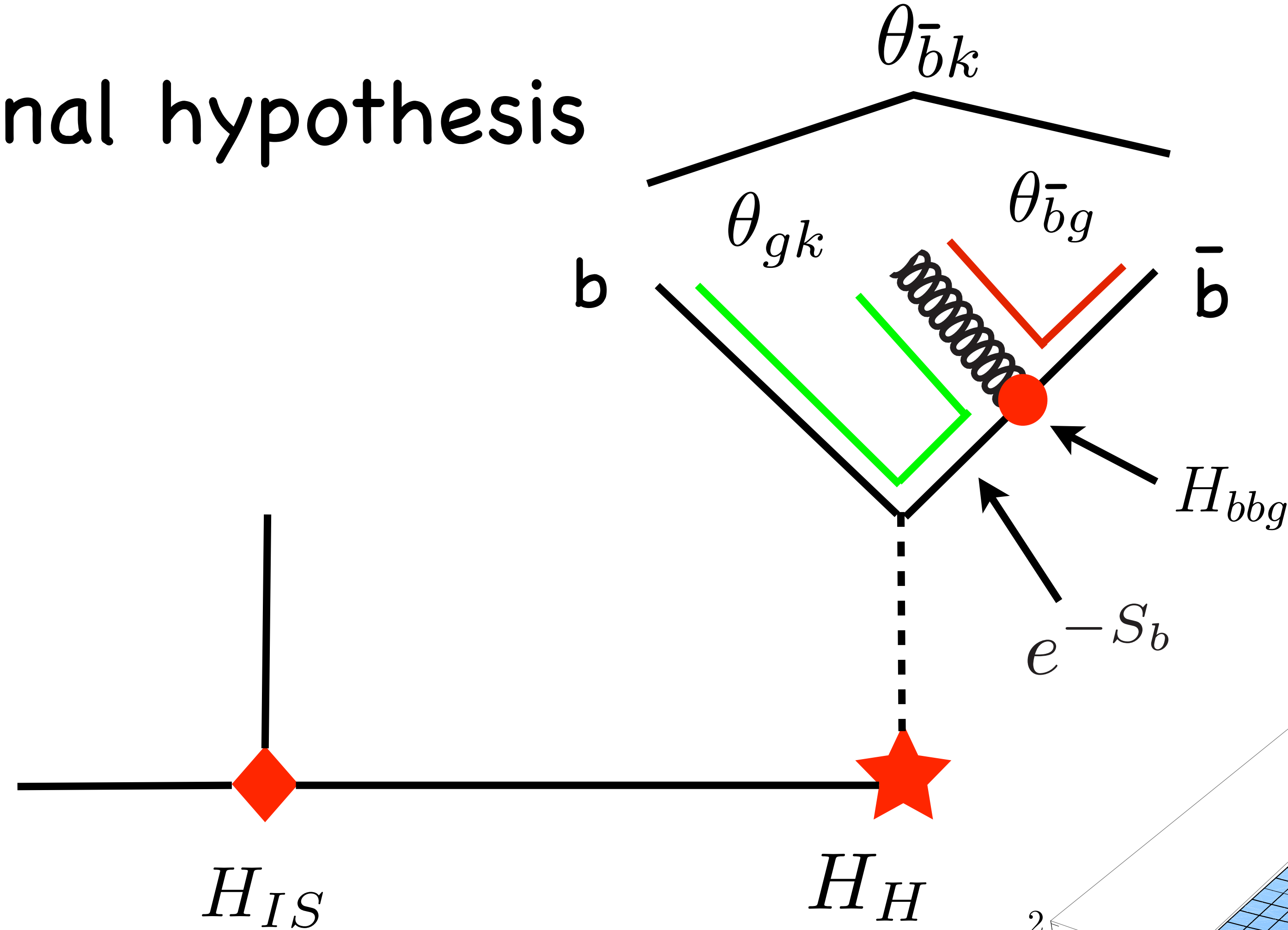
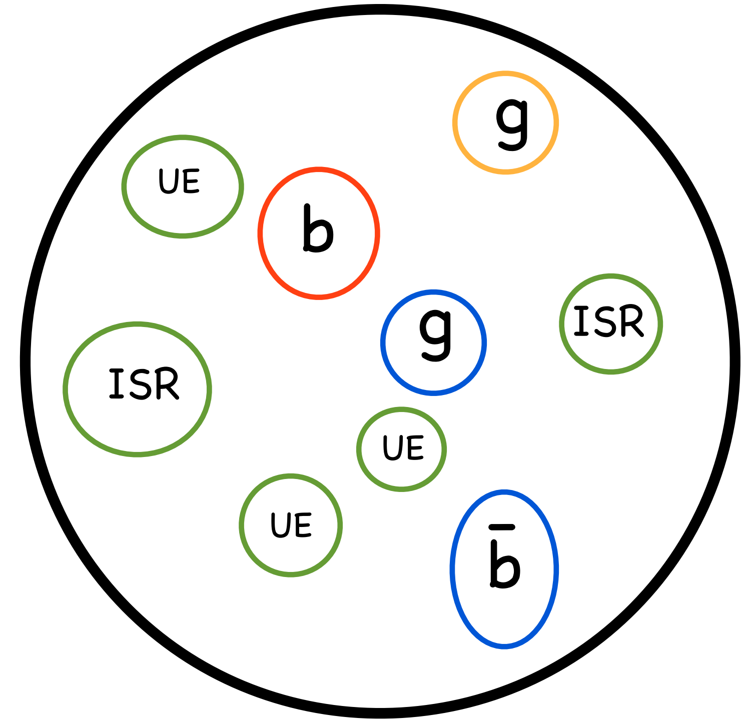
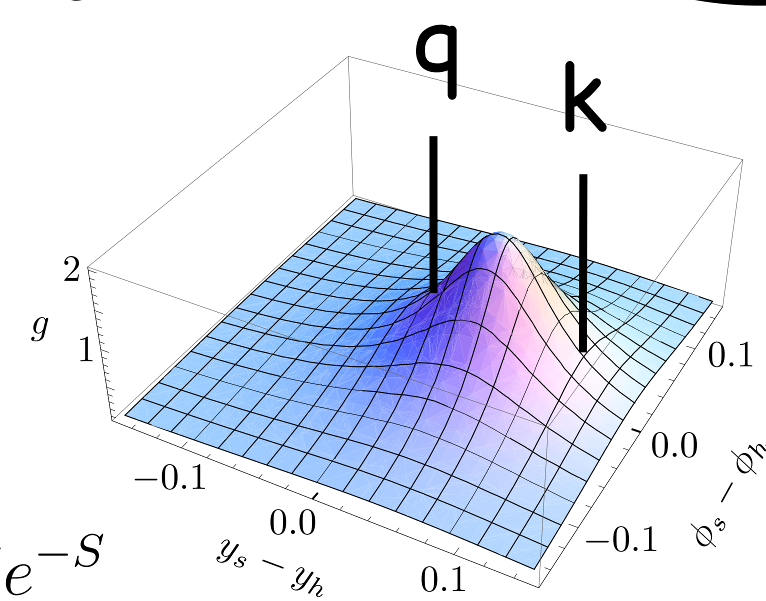
Signal hypothesis







[Marchesini, Webber, (1984)]

See talk by Marzani

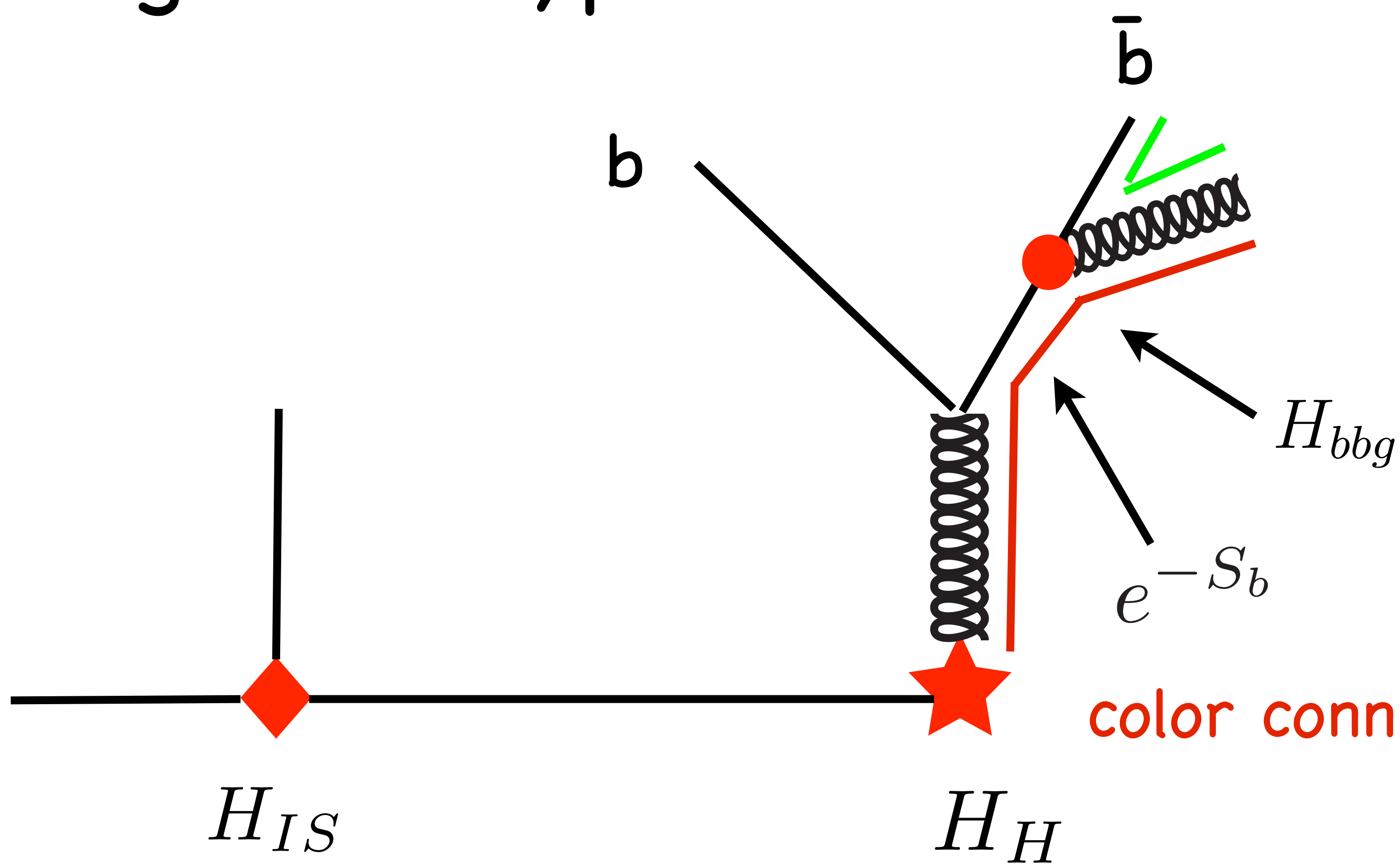
b-quarks radiate gluons

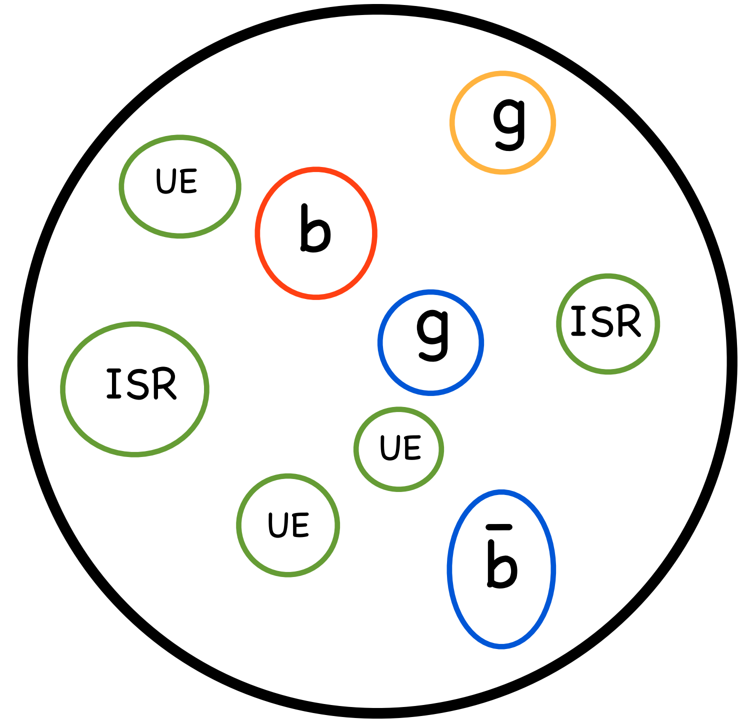
$$\int d\mathcal{P} = \int d\mu_J^2 \int d\Delta\phi \int d\Delta y \sum_s J\, H e^{-S}$$

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

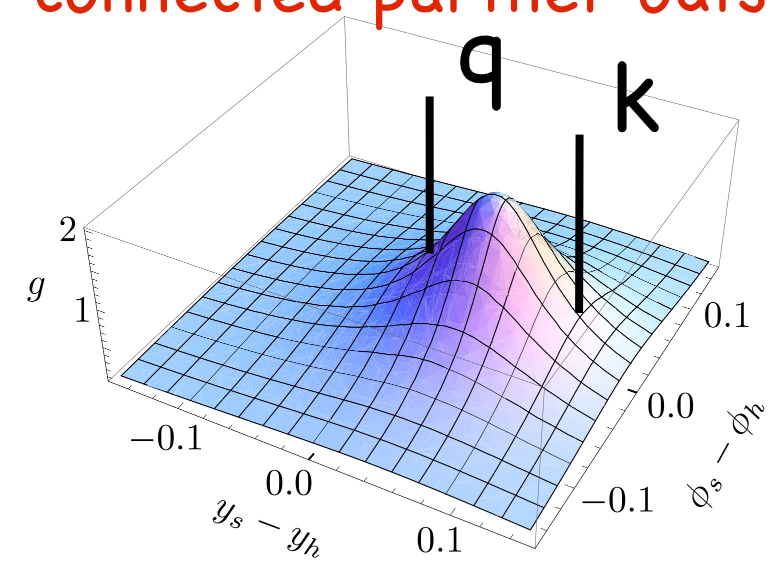
$$H_{qqg} = H_{\bar{q}g\bar{q}} = 8\pi C_{\rm F} \frac{\alpha_{\rm s}(\mu_J^2)}{\mu_J^2} \frac{k_J}{k_g} \left[1 + \left(\frac{k_q}{k_J}\right)^2\right] \frac{\theta_{qk}^2}{\theta_{gq}^2 + \theta_{gk}^2}\, \Theta\!\left(2\,\frac{\mu_J^2}{k_J} < \frac{\mu_K^2}{k_K}\right)$$

Background hypothesis





color connected partner outside fat jet



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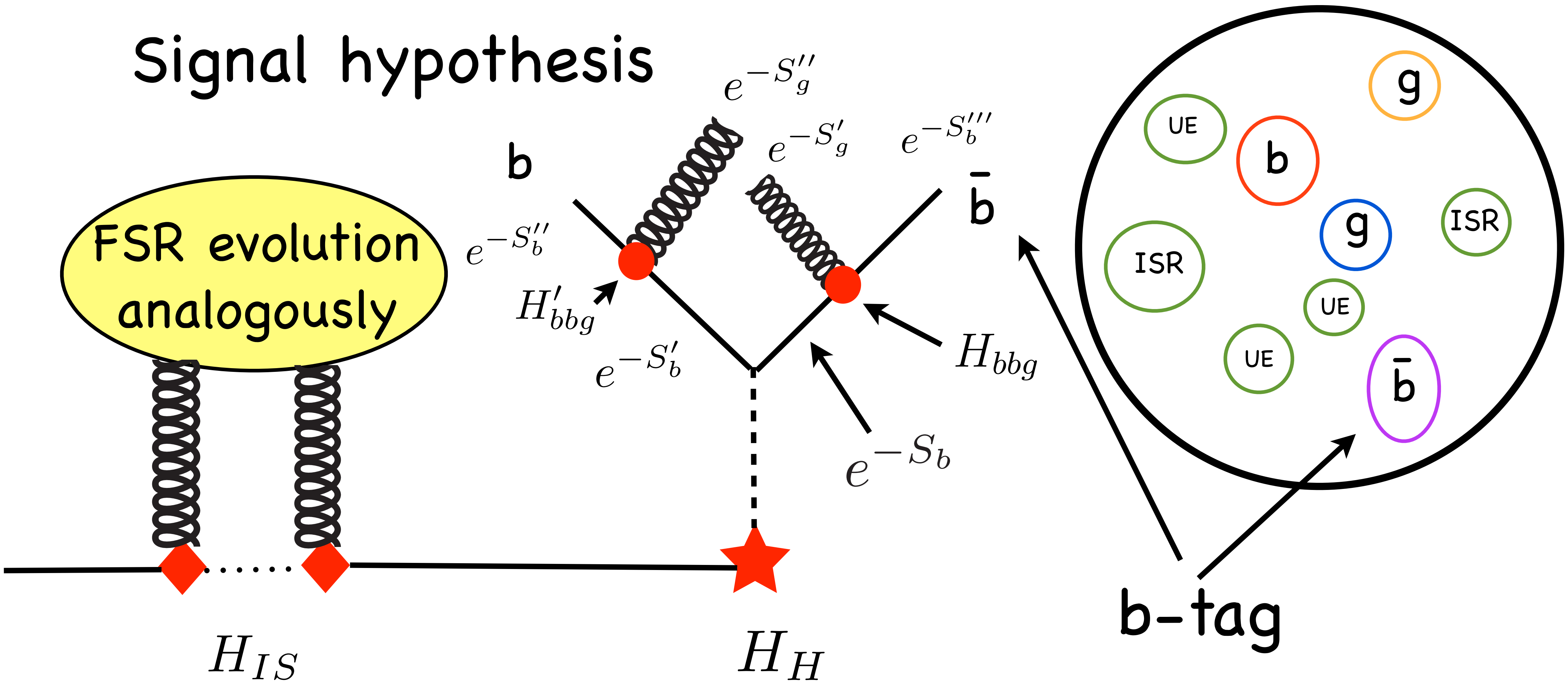
Signal hypothesis



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

Event selection cuts

- Cluster hadrons to ‘detector cells’ 0.1 x 0.1, ET > 0.5 GeV
- lepton pT > 15 GeV
- two hardest leptons mZ +- 10 GeV
- at least 1 fat jet (anti-kT, R=1.2, pT>200 GeV)

Normalize signal/background cross section
to the NLO results obtained from MCFM

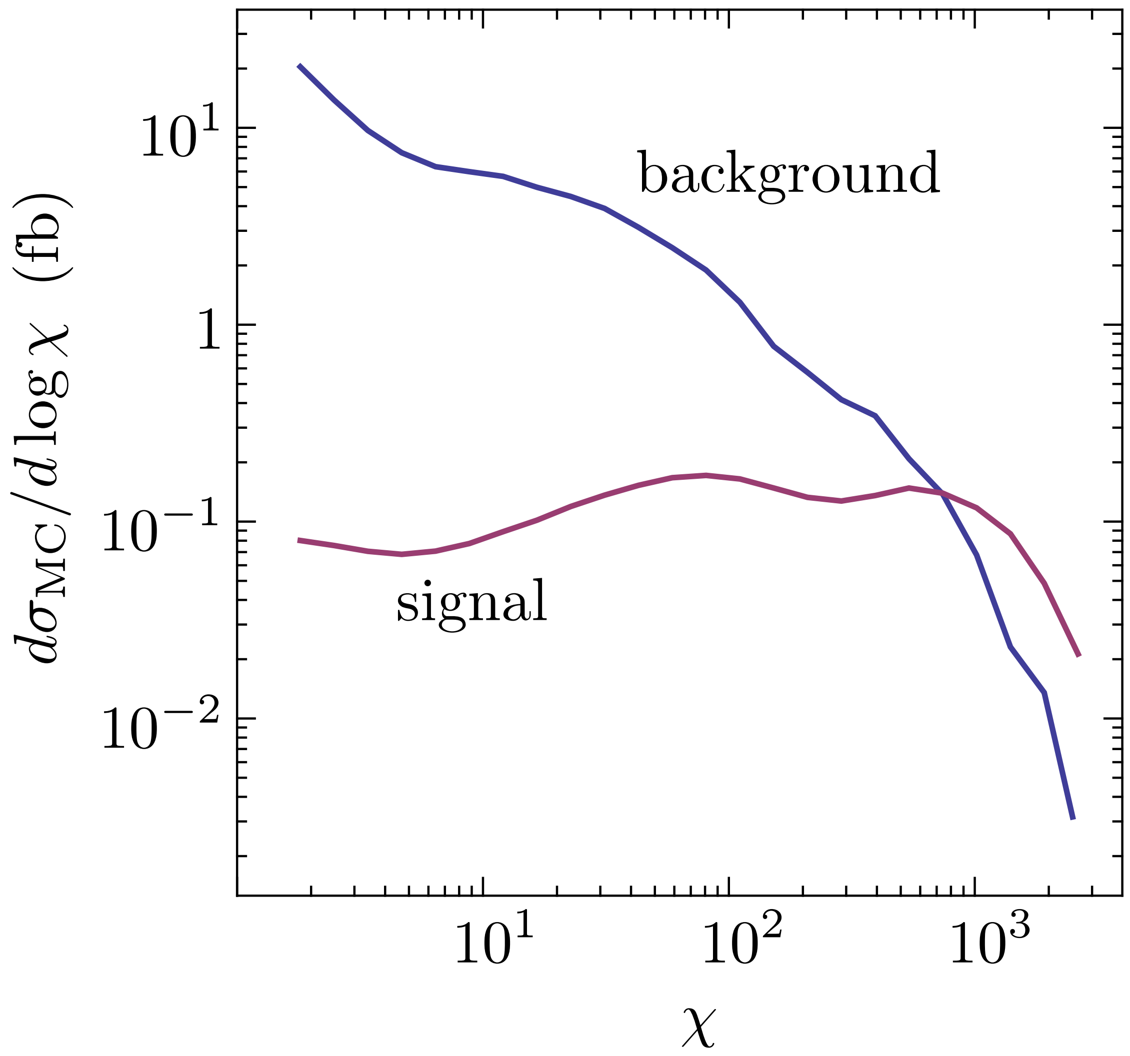
$$\sigma_{\mathrm{MC}}(\mathrm{S}) = 1.48\ \mathrm{fb}$$

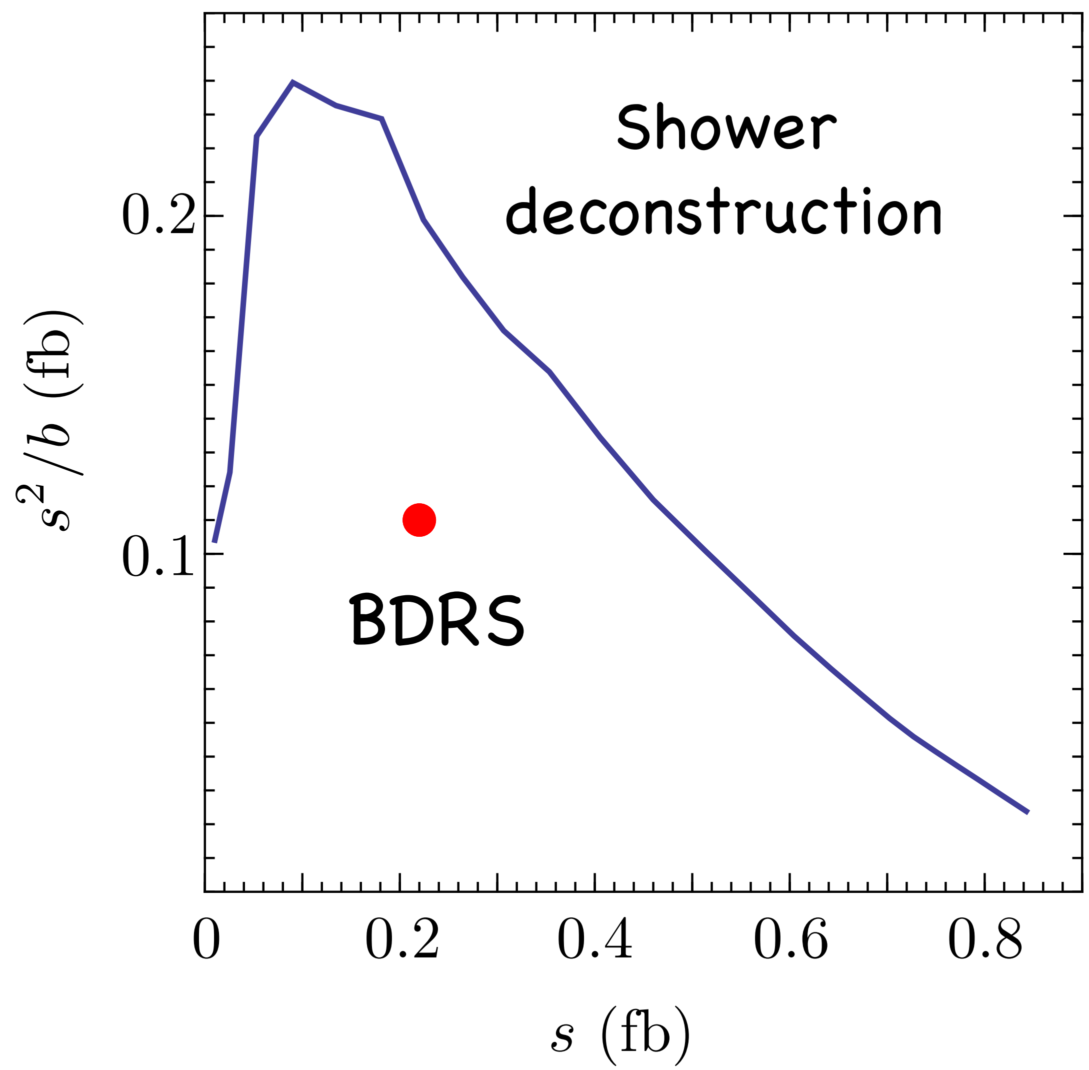
$$\sigma_{\mathrm{MC}}(\mathrm{B}) = 2610\ \mathrm{fb}$$

$$\frac{\sigma_{\mathrm{MC}}(\mathrm{S})}{\sigma_{\mathrm{MC}}(\mathrm{B})} = \frac{1}{1760}$$

Results of shower deconstruction (SD)

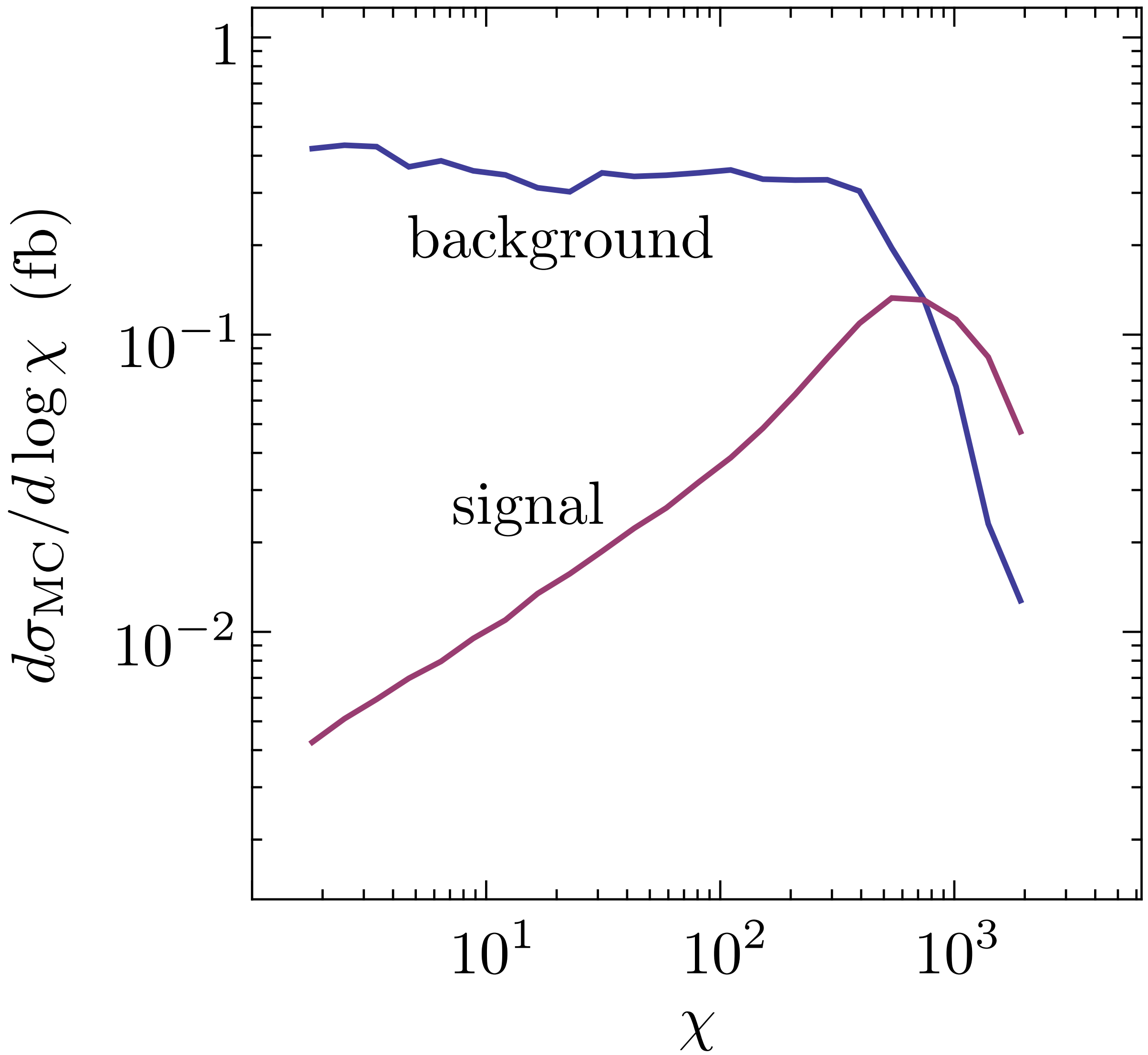
$$\chi(\{p,t\}_N) = \frac{P(\{p,t\}_N|\mathrm{S})}{P(\{p,t\}_N|\mathrm{B})}$$

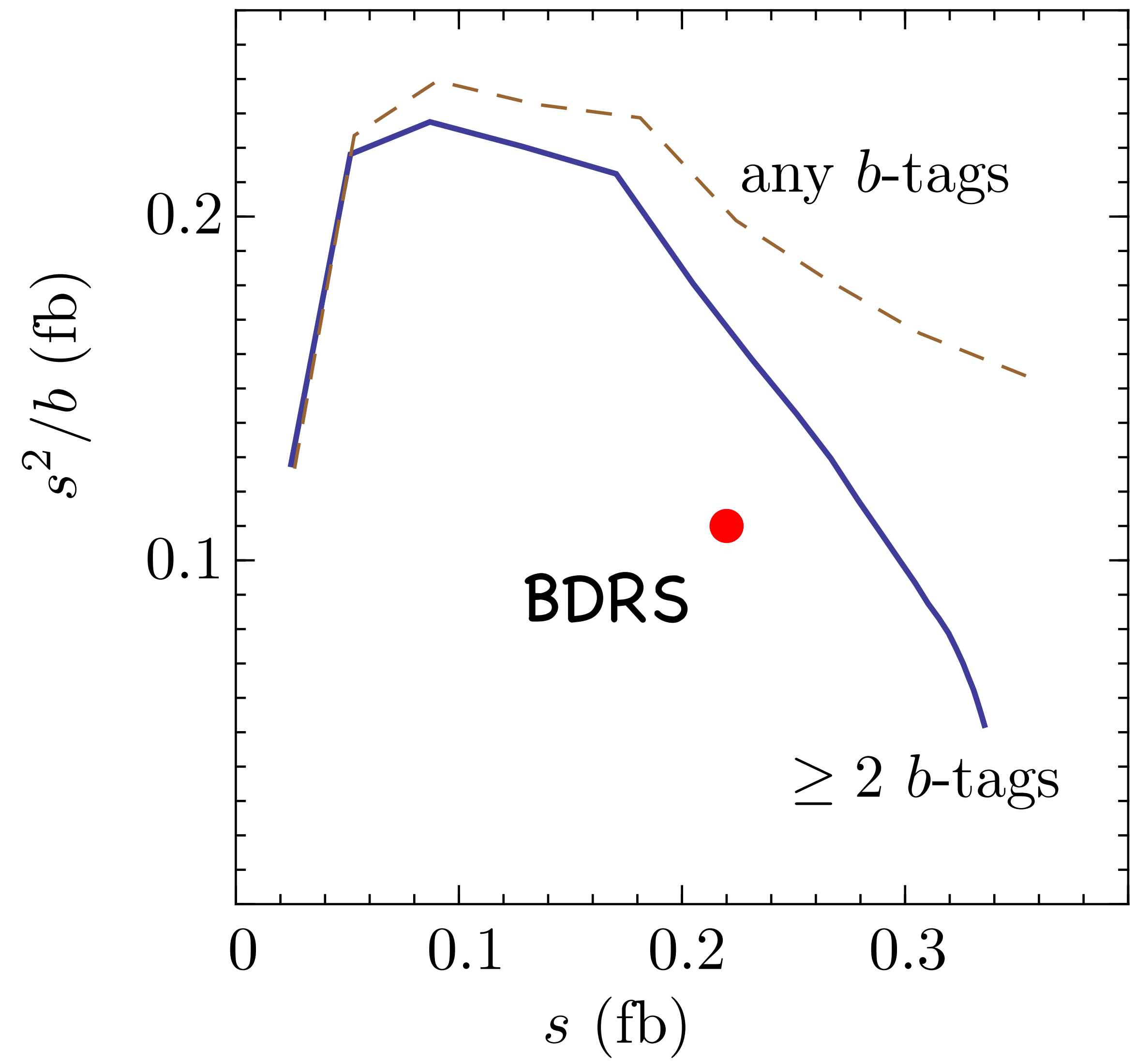




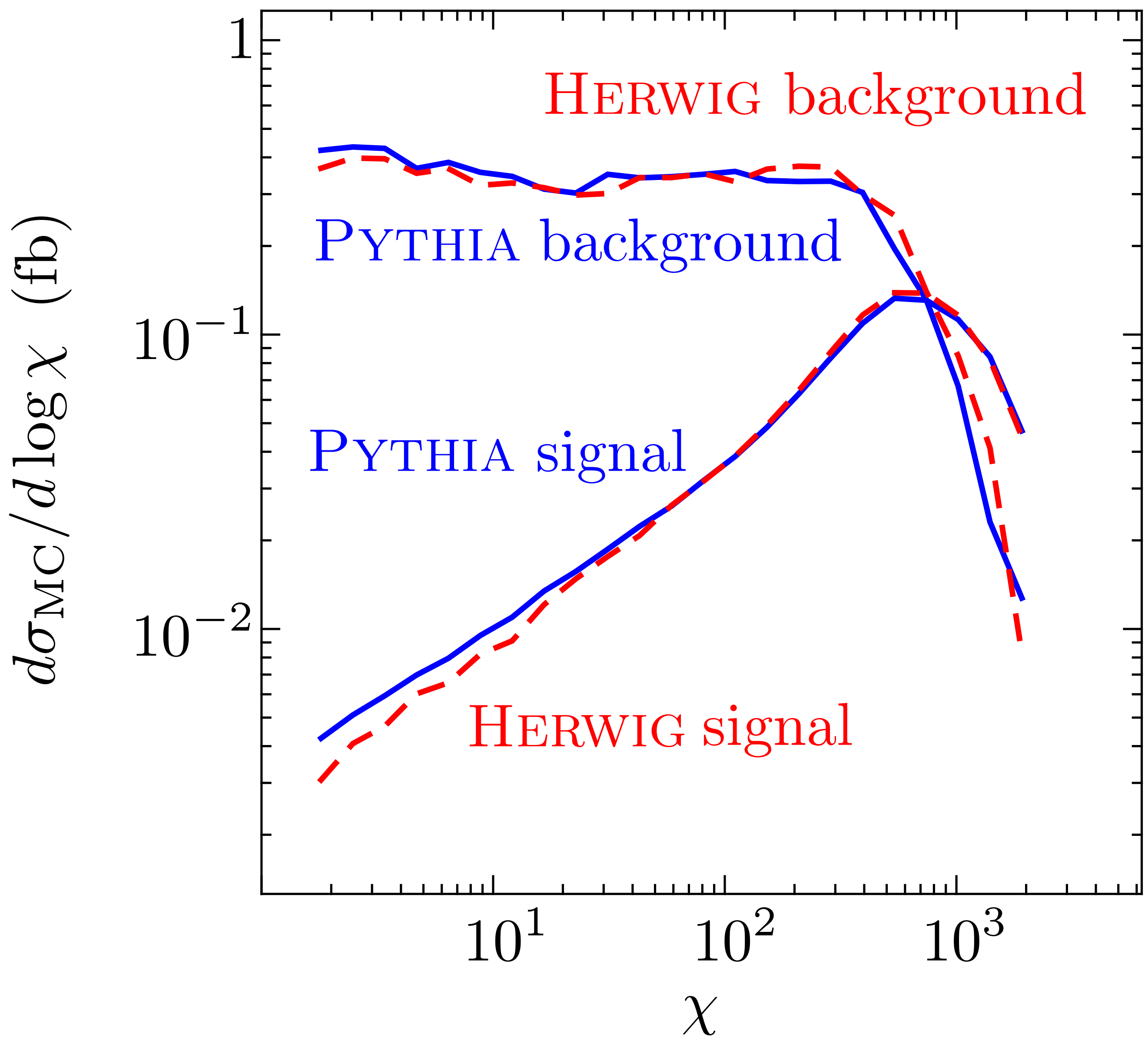
imperfect b-tagging (60%,2%) no b-tag required

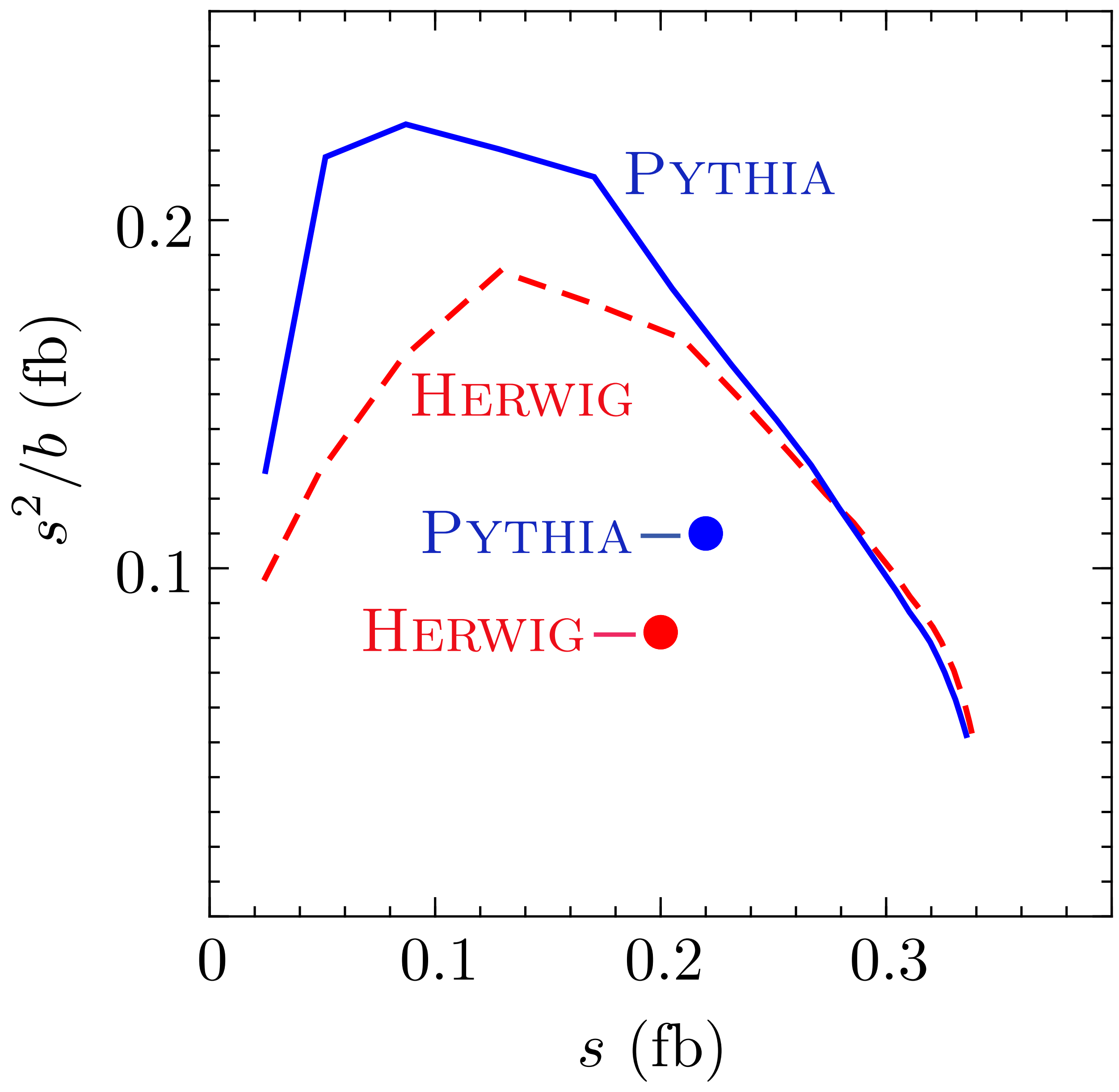
imperfect b-tagging but 2 b-tagged microjets





Monte-Carlo uncertainties





Lots of room for improvement:

FSR simulation

ISR simulation

Matrix element

Simulation of experimental issues, e.g. b-tagging

UE simulation

Modular build -> improvements are additive

Conclusions

- LHC is QCD and BSM machine -> new heavy particles? many jets!
- Boosted scenarios can be superior way to look for new physics
- Many different substructure approaches, very active field

- Shower deconstruction is maximum information approach
- Combines first principle QCD with BSM search
- Modular set-up -> parts can be improved independently