Constraining $h \to s\bar{s}$ at lepton colliders

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based on ongoing work with:

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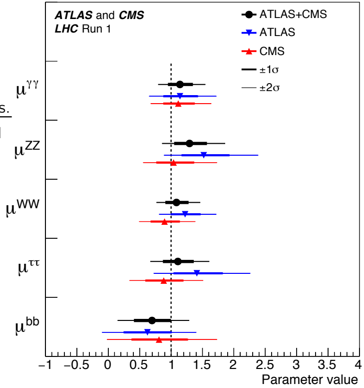
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Gauge boson masses

Higgs is main source of electroweak symmetry breaking!

$$\mu^X = \frac{\sigma \mathrm{BR}_X|_{\text{meas.}}}{\sigma \mathrm{BR}_X|_{\text{SM}}}$$

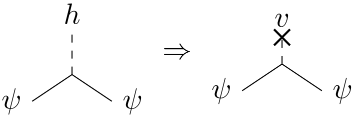


[1606.02266]

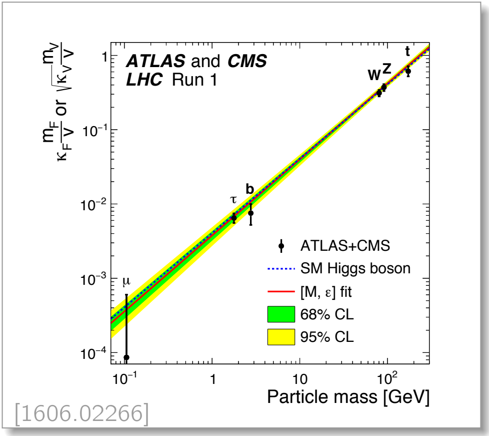
Higgs couples to gauge bosons as expected

What about fermion masses?

SM: economic solution, Higgs does it!



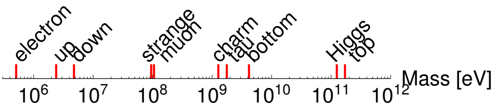
$$\Rightarrow \quad m_\psi \propto y$$

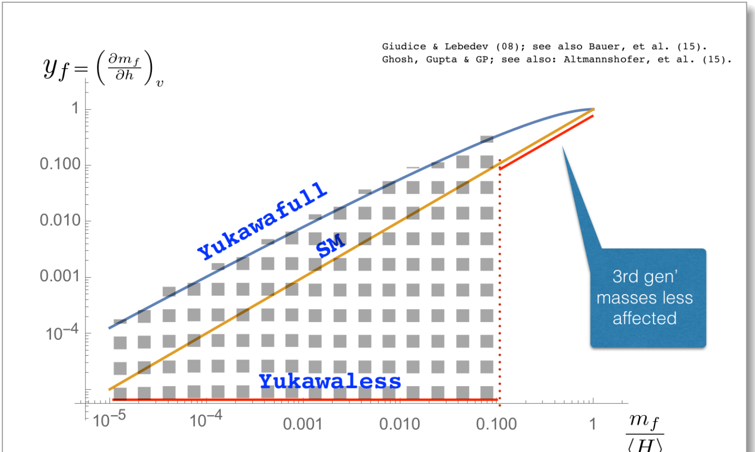


[1606.02266]

However

Large mass hierarchy





[Thanks to Gilad Perez]

Measurement of Yukawa couplings

Does the SM Higgs generate fermion masses?

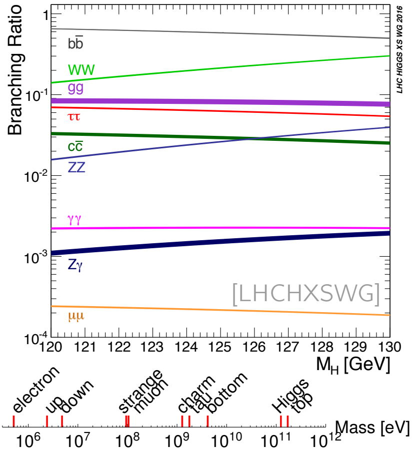
$$\mu_X = \frac{\sigma_{\text{prod}} \times \text{BR}(h \to X)}{\sigma_{\text{SM}} \times \text{BR}^{\text{SM}}(h \to X)}$$

- tth, $h \to \tau\tau$, $h \to bb > 5\sigma$ ✓
- $h \to \mu\mu$: $\mu_{\mu\mu} < 2.8$ at 95 % CL
  [ATLAS: 1705.04582, CMS: 1807.06325]

Lighter fermions even less constrained!

Difficulties

i) small branching ratio



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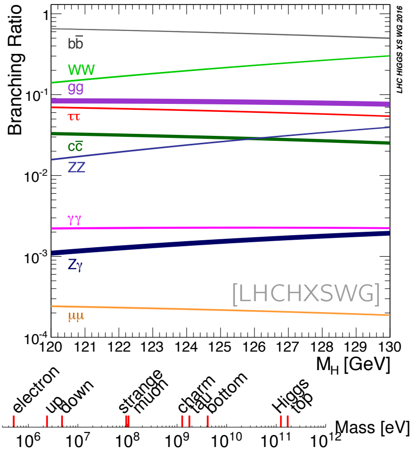


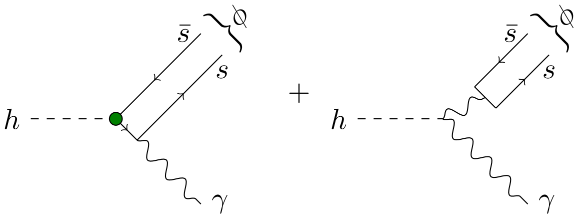
ii) difficult final state for quarks

- quarks appear as jets
- large background
- hard to distinguish

Nevertheless:
$h \to cc$ will be measured at % level at FCC-ee [1310.8361]

What about strange?

Exclusive decay $h \to \phi\gamma$ [1306.5770, 1406.1722]



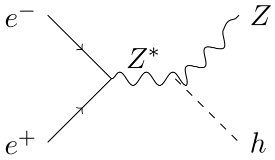
- Clean decay: BR($\phi(s\bar{s}) \to K^+(u\bar{s}) + K^-(\bar{u}s)) \approx 50\%$
- BUT: BR($h \to \phi\gamma) \approx 2 \times 10^{-6}$ [1505.03870]
- compare BR($h \to s\bar{s}) \approx 2 \times 10^{-4}$
- only weak limit at future (hadron) colliders [1406.1722]
- current limit: BR($h \to \phi\gamma) < 4.8 \times 10^{-4}$ [1712.02758]

Ideas to use differential distributions [see e.g. 1606.09253, 1606.09621, 1609.06592, 1611.05463]

Brute force method

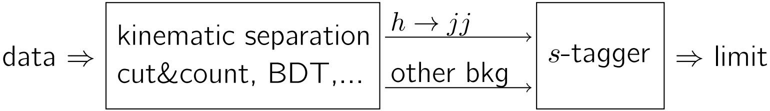
Alternative ansatz:

- FCC-ee will produce $\mathcal{O}(10^6 - 10^7)$ Higgses via



- $\mathcal{O}(200 - 2000)$ of which decay into strange quarks
- tag strange jets
- Done before in $Z \to s\bar{s}$
  - Measurement of the strange quark forward backward asymmetry around the Z0 peak
    [DELPHI Collaboration, Eur.Phys.J. C14 (2000)]
  - Light quark fragmentation in polarized Z0 decays
    [SLD Collaboration, Nucl.Phys.Proc.Suppl. 96 (2001)]

Setup and assumptions



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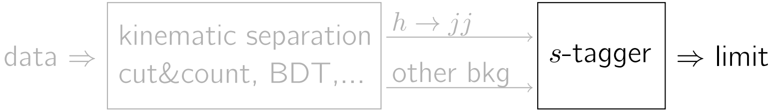

Part I:

- Clean sample with 10^7 Higgses
- Only background other Higgs decays ($h \to gg$, bb, cc)
- We know which jets originate from the Higgs decay
- Generate and shower with `PYTHIA`
- No detector simulation

Setup for an s-tagger

Ansatz: s-jets dominantly contain a prompt kaon that carries a large fraction of the jet momentum.

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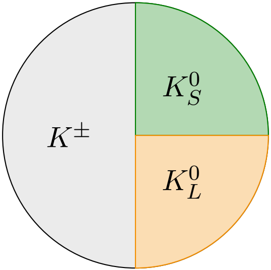
In which kaons can a s quark hadronize?



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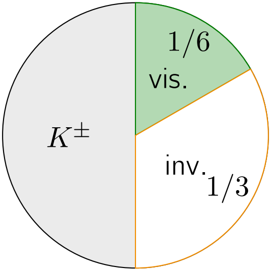

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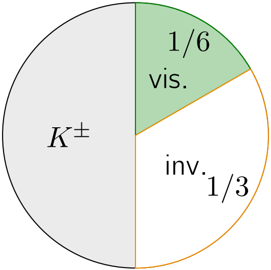
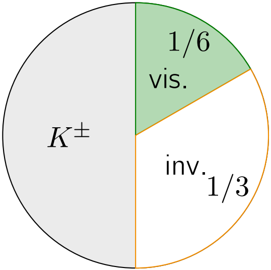




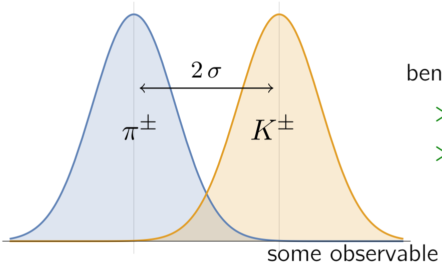
CC/NC/NN=9/6/1

Setup for an s-tagger

Ansatz: s-jets dominantly contain a prompt kaon that carries a large fraction of the jet momentum.

Charged kaon reconstruction:

- stable on detector scales
- tracking efficiency 95%
- Particle ID



bench marks e.g.:

- no ID
- $\epsilon_K = 95\%$
  $\epsilon_\pi = 12\%$

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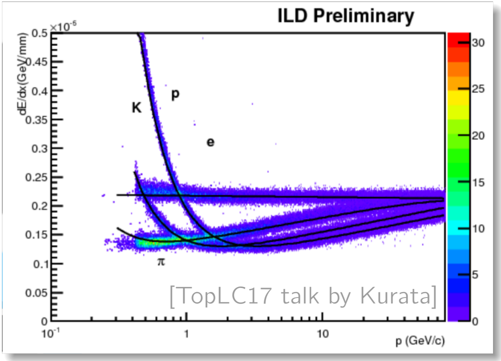

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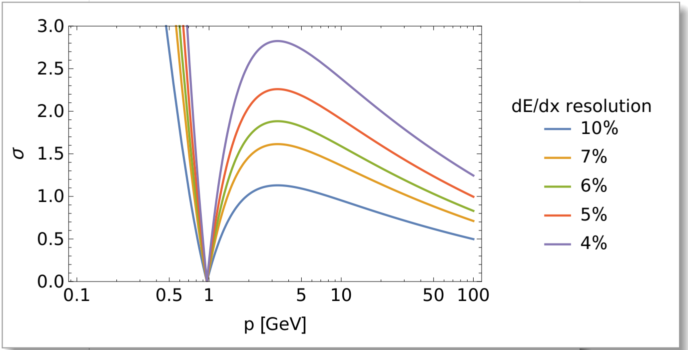

Setup for an s-tagger

Ansatz: s-jets dominantly contain a prompt kaon that carries a large fraction of the jet momentum.

Neutral K_s^0 reconstruction:

- Decay length $\sim 80\,\text{cm}$
- Needs to decay to $\pi^\pm$ within $5\,\text{mm} < R < 1\,\text{m}$
- reconstruction efficiency 80%

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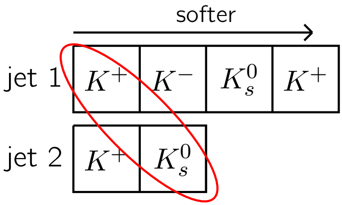

- Keep hardest pair of kaons with charge sum $|q_1 + q_2| < 2$
- Split into CC, NC and NN channel

Setup for an s-tagger

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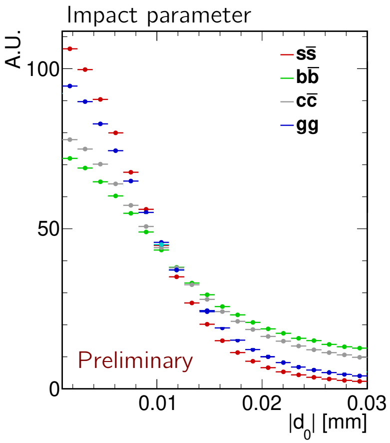
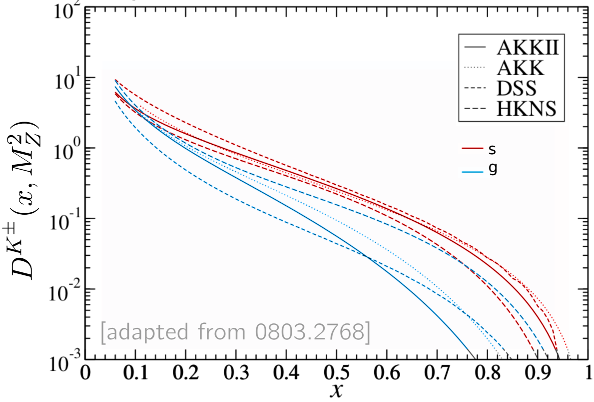


- straight extrapolation of tracks
- no vertexing
- $\mathcal{O}(60-80\%)$ of kaon candidates in b-jets stem from b-decays
- $\mathcal{O}(40\%)$ of kaon candidates in c-jets stem from c-decays
- smearing according to momentum and angle
- $5\,\mu$m uncertainty on IP

Setup for an s-tagger

Ansatz: s-jets dominantly contain a prompt kaon that carries a large fraction of the jet momentum.

Fragmentation functions



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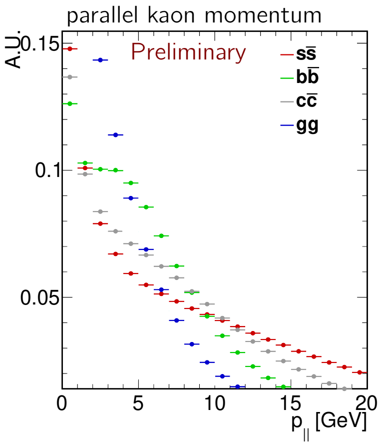
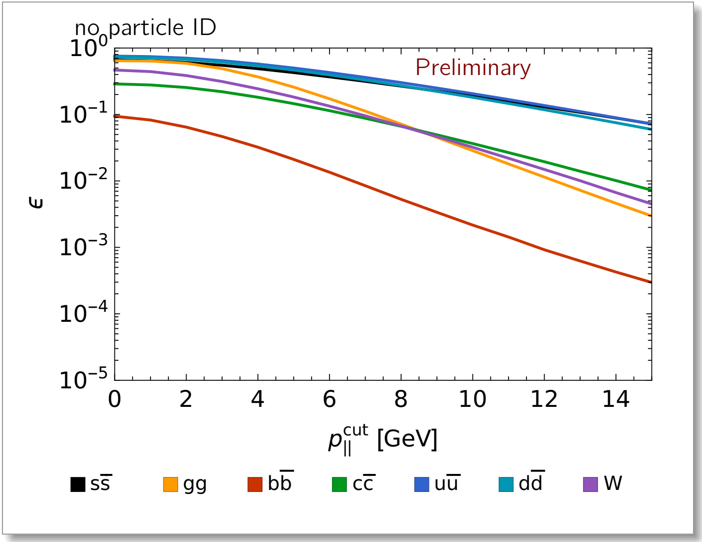


- candidates from non-s-jets are soft, especially in g-jets
- here: $p(\text{jet}) \approx 60$ GeV

s-tagging performance in CC channel

> impact parameter $d_0 < 15\mu$m



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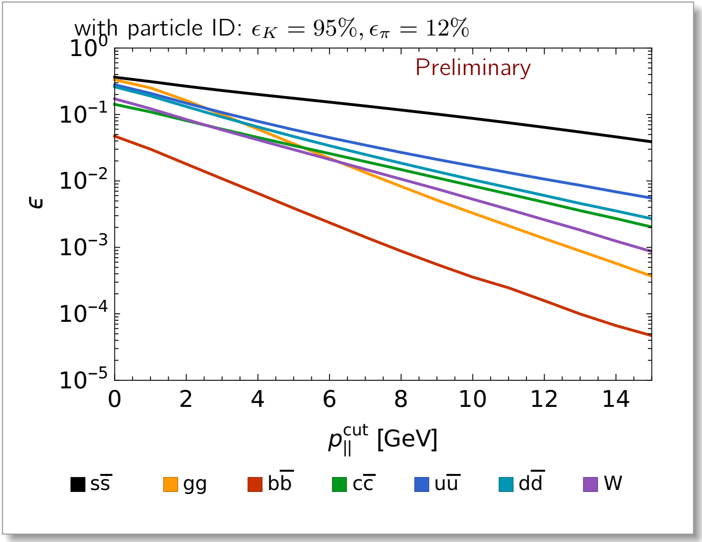
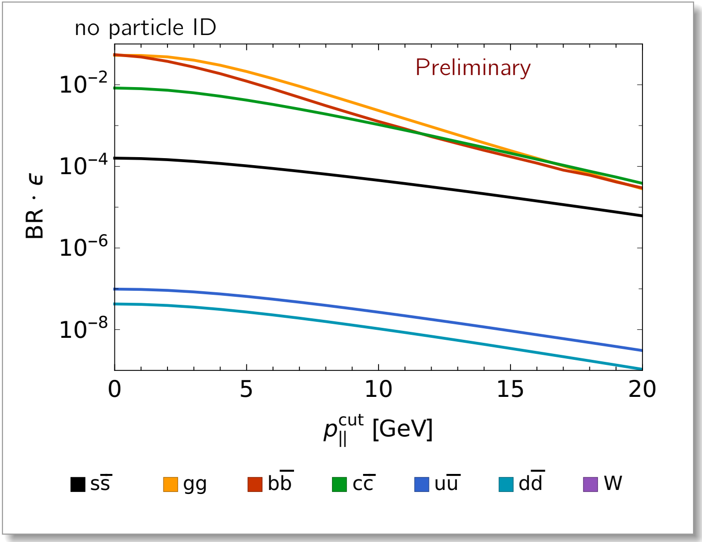


Number of events

> impact parameter $d_0 < 15\mu$m



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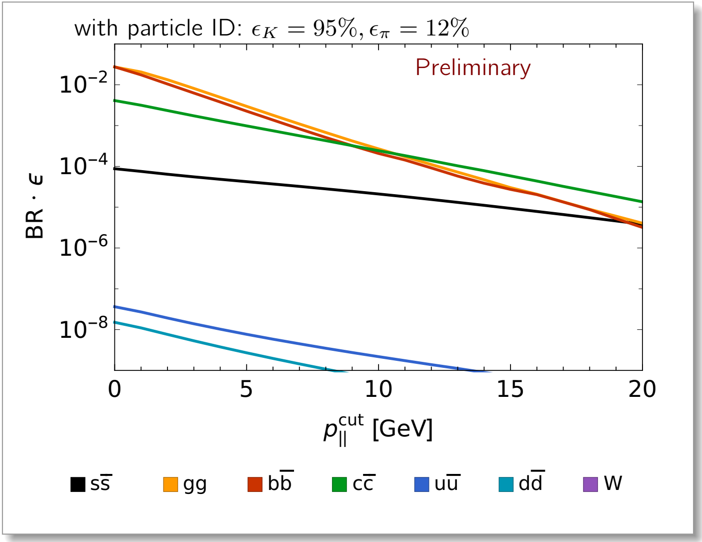
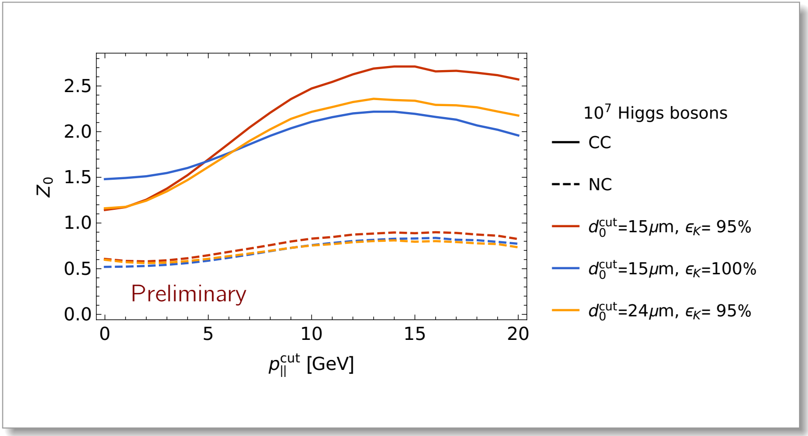


Results part I



- strange Yukawa within reach of FCC-ee!
- Improvements possible with vertexing

Realistic Collider

Existing studies for $h \to bb, cc, gg$:

- Cut&Count: $m_h = 120$ GeV [1207.0300]
- Cut&Count+BDT [Talk by Yu Bai @ CEPC meeting]

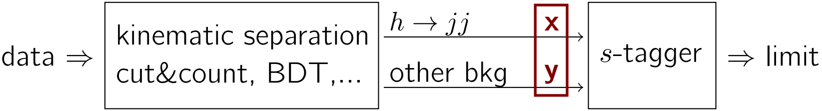
Assumptions:

- $h\nu\nu$ final state (don't consider $h\ell\ell$ or hjj)
- Only CC channel (no combination with NC)
- Non-$h \to jj$ flavor decomposition as in BDT study

flavor	W	bb	uu	dd	cc	ss	gg
relative abundance	65.3	9.8	6.1	6.0	6.4	6.0	0.2

- ϵ_W from $ee \to WW$
- Only statistical uncertainty

Results part II



x-Axis: $\dfrac{\#(h \to q\bar{q})}{\text{BR}(h \to q\bar{q})} \approx \dfrac{\#(h \to gg)}{\text{BR}(h \to g\bar{g})} \approx \mathcal{L}\sigma_h \epsilon_{h_{jj}}$

y-Axis: # of all events that are not $e^+e^- \to \nu\nu h, h \to jj$

$\approx \mathcal{L} \sum_{\text{bkg}} \sigma_{\text{bkg}} \epsilon_{h_{jj}}^{\text{bkg}}$

For each point (x,y) find best cut values to minimize upper limit

Results part II

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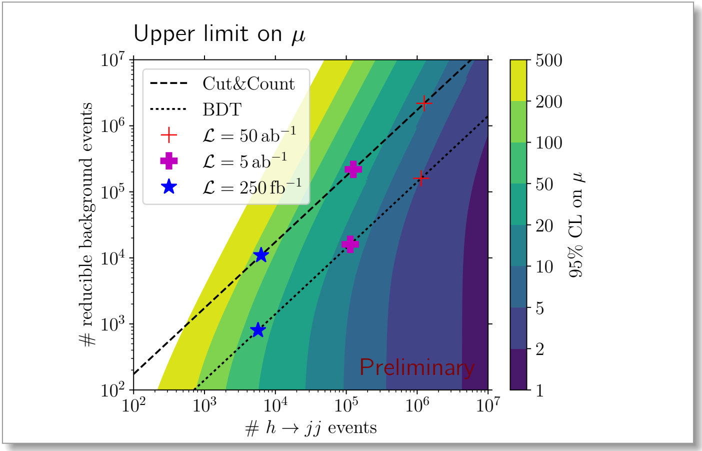

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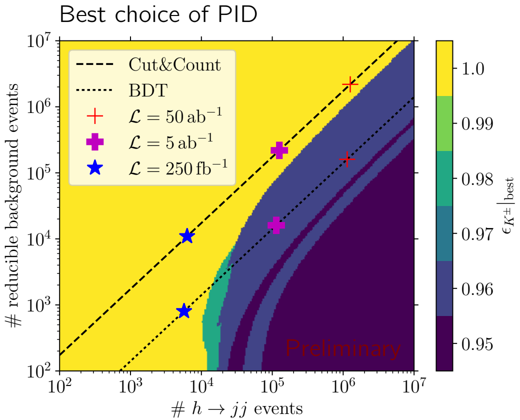

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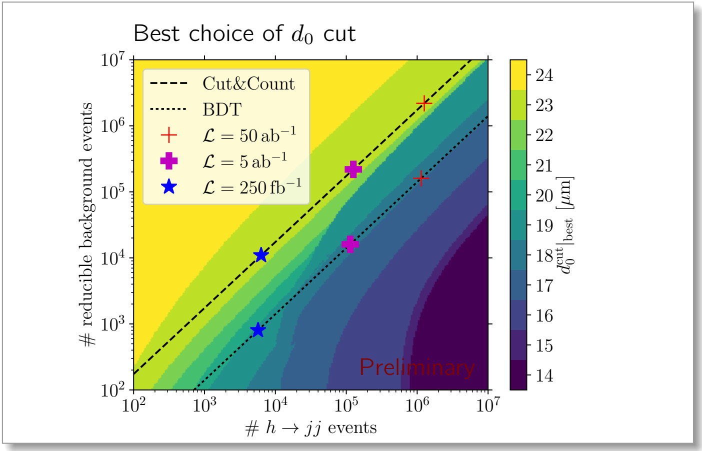

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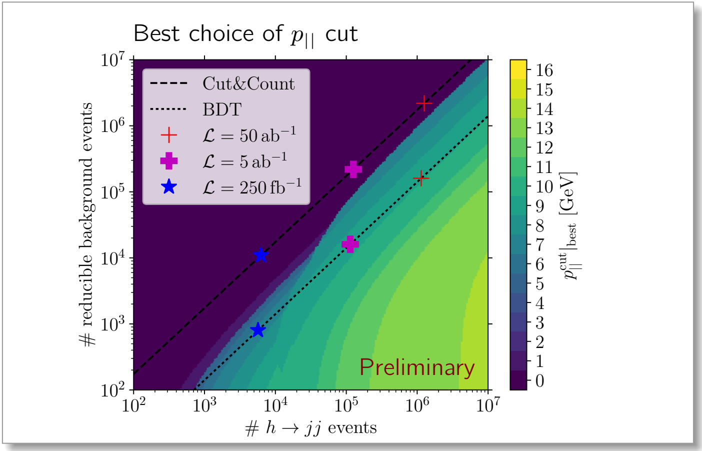

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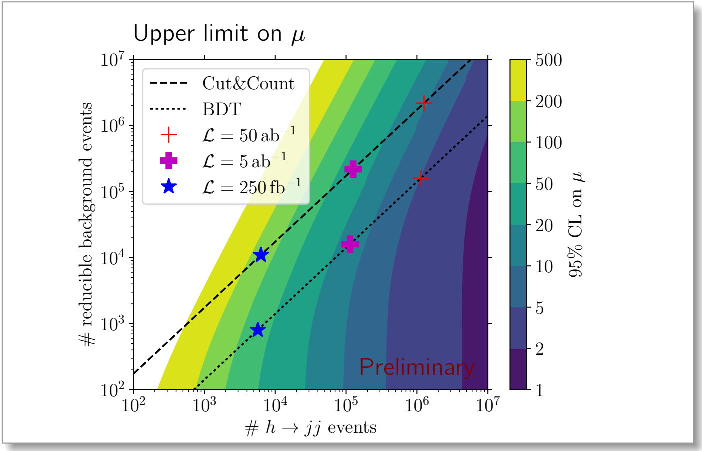


Conclusion

- s-tagger in the context of $h \to s\bar{s}$
- Proof-of-concept, can be improved
- with $\approx 50\ \mathrm{ab}^{-1}$ (FCCee): $\mu_s \lesssim 5$
- with $\approx 250\ \mathrm{fb}^{-1}$ (ILC): $\mu_s \lesssim \mathcal{O}(50)$
- applicable to other searches with s-jets (up to some modifications)

Thank You

BACKUP

non-Higgs background [1207.0300]

> $M^2_{\text{recoil}} = s + m_Z^2 - 2E_Z\sqrt{s}$ independent of Higgs decay

> signal-background separation in $h \to bb$, cc, gg

> with $m_h = 120\,\text{GeV}$

> $Z \to$ invisible (20%):

- $\epsilon_h = 33\%$
- $S/B = 0.58$

> $Z \to ee$ (3.4%):

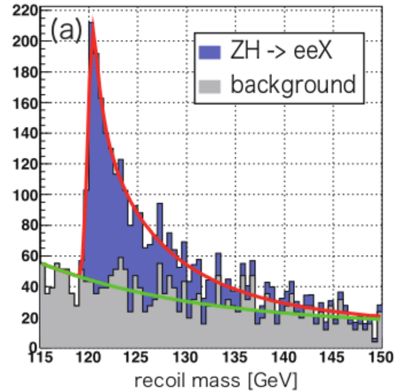
- $\epsilon_h = 38\%$
- $S/B = 0.74$

> $Z \to \mu\mu$ (3.4%):

- $\epsilon_h = 47\%$
- $S/B = 1.4$

> $Z \to$ hadrons (70%):

- $\epsilon_h = 26\%$
- $S/B = 0.08$



[0902.3035]

background flavor

$ee \to$ fs	WW $\tau\nu qq'$	$(ZZ, Z\gamma)$ $\nu\nu dd$	$\nu\nu h$ non-jj	$(ZZ, Z\gamma)$ $\nu\nu uu$	$\tau\tau h$ bb	qqh non-jj	WW $\mu\nu qq'$
rel. [%]	47.1	18.0	13.7	12.2	2.7	2.5	2.0