Soft Secondary Vertices in the diHiggs to 4b analysis

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Bad Honnef, 03.09.2026

HELMHOLTZ

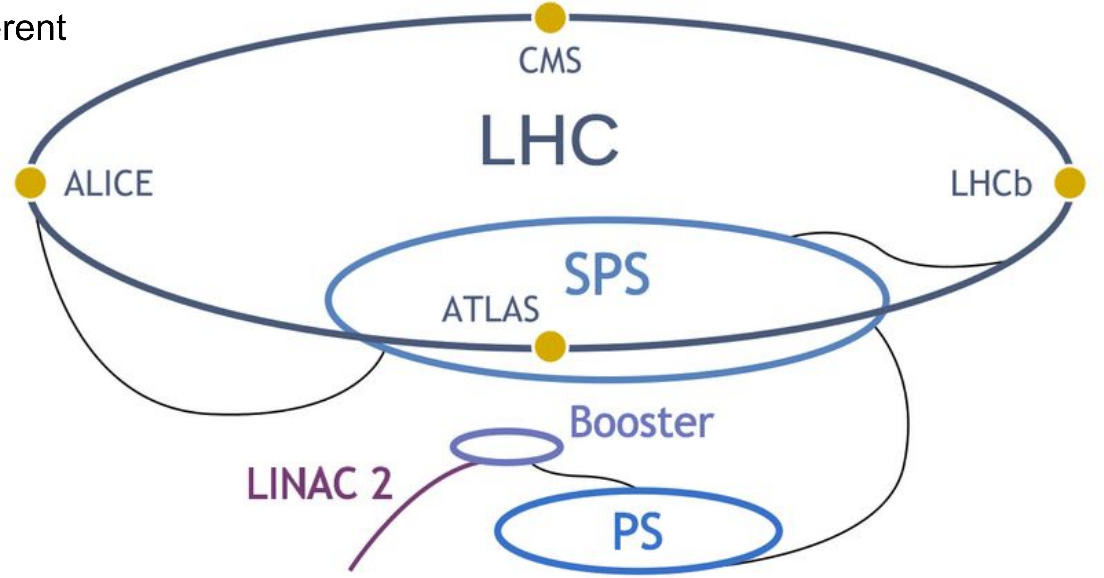
The Large Hadron Collider (LHC)

Overview

- 27km circular proton-proton collider located at CERN near Geneva

- collision energy of up to 13.6 TeV

- protons accelerated through chain of different accelerators



ATLAS detector

Overview

- largest experiment at the LHC (46m long, 25m diameter, 7000 tons!)

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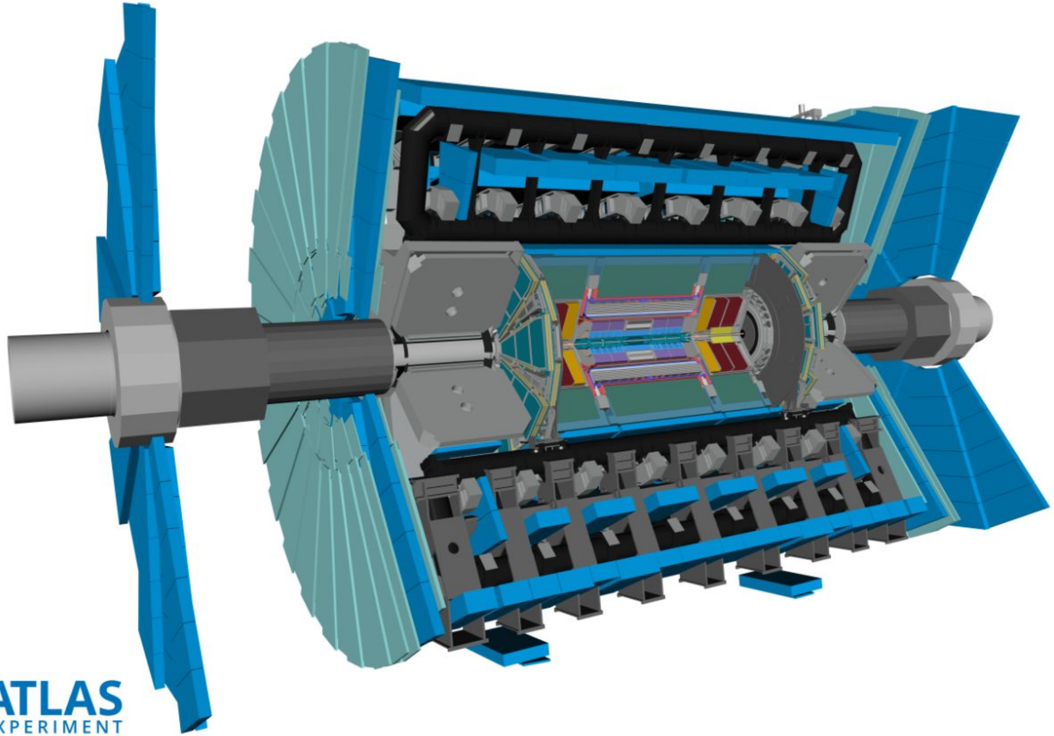


ATLAS EXPERIMENT

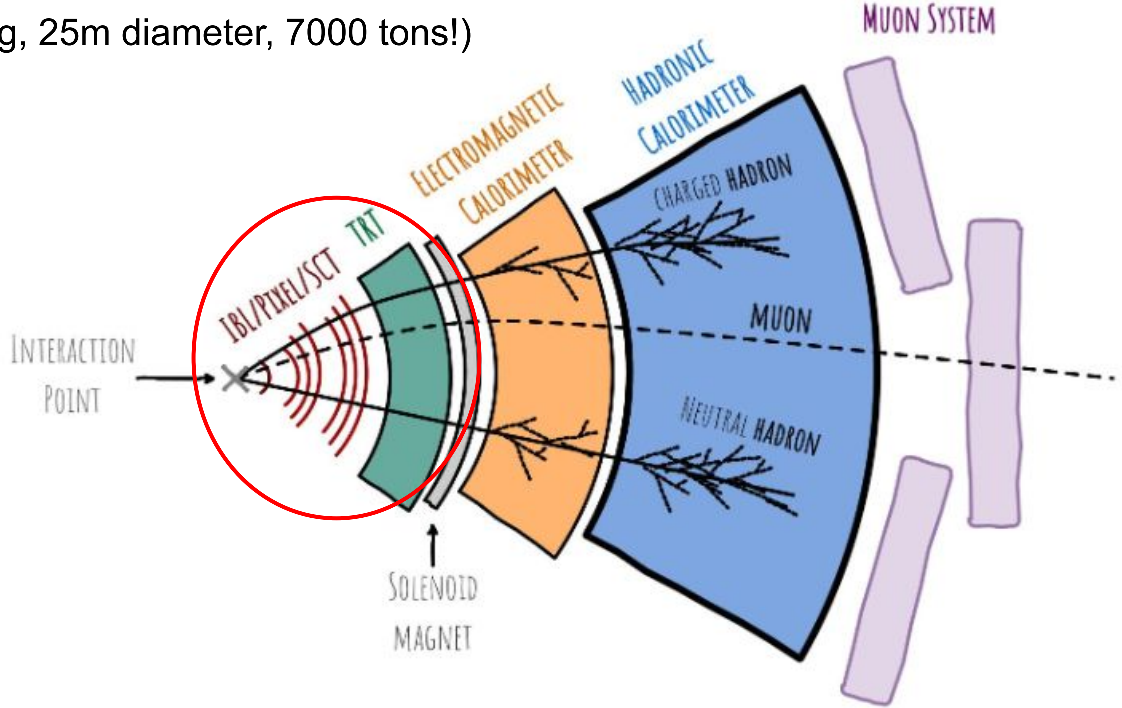
ATLAS detector

Overview

https://indico.global/event/11065/contributions/103255/attachments/47597/90117/seminar_s_paredes_s.pdf

- largest experiment at the LHC (46m long, 25m diameter, 7000 tons!)

- Inner Detector (ID)
    - Tracking & momentum measurement
    - consists of IBL, Pixel, SCT & TRT



ATLAS detector

Overview

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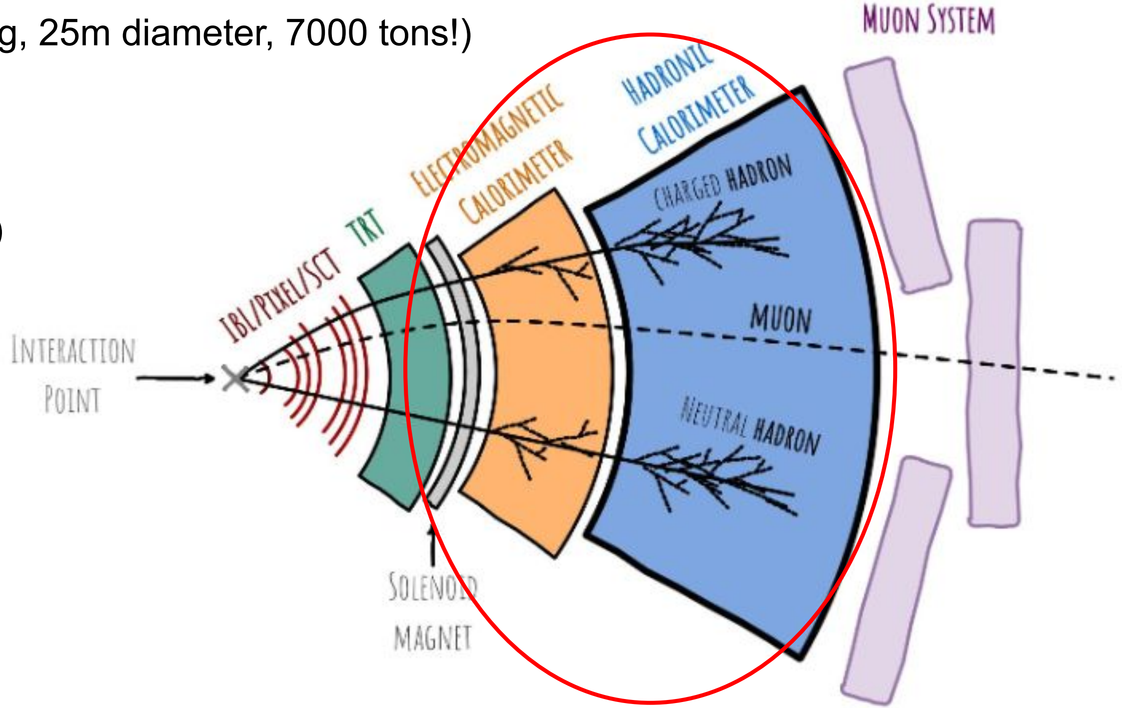
- largest experiment at the LHC (46m long, 25m diameter, 7000 tons!)

- Calorimeter System
    - energy measurement of electrons/ photons (ECAL) and hadrons (HCAL)



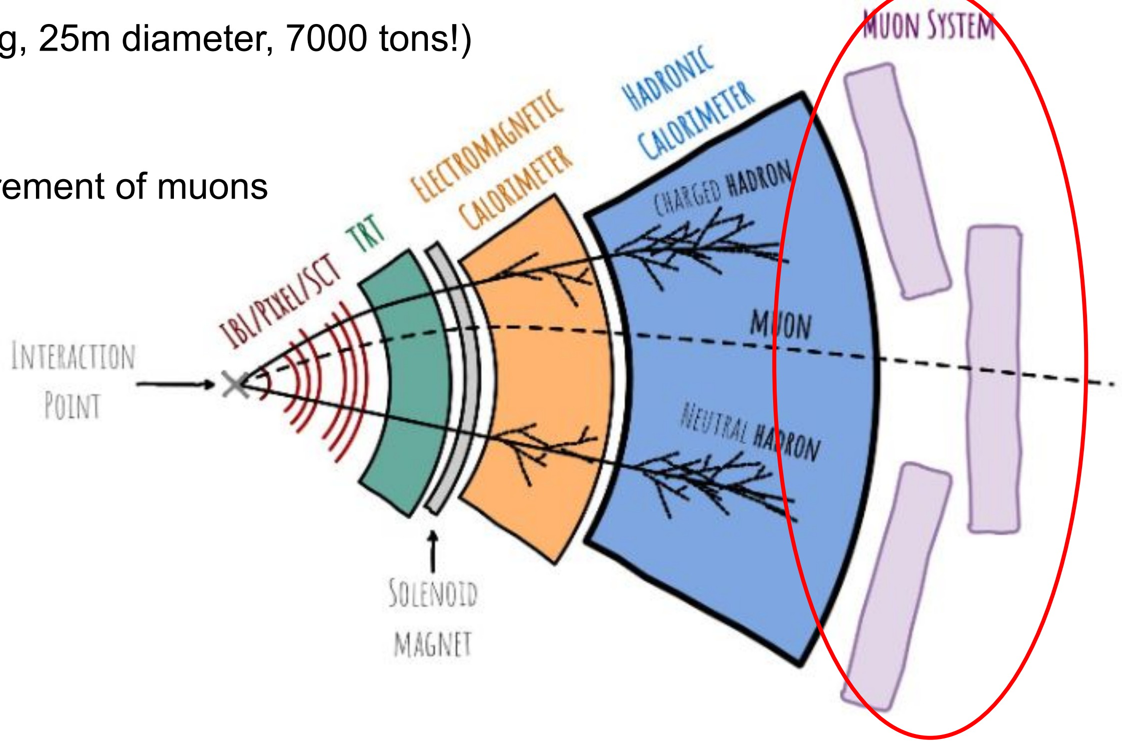
ATLAS detector

Overview

https://indico.global/event/11065/contributions/103255/attachments/47597/90117/seminar_s_paredes_s.pdf

- largest experiment at the LHC (46m long, 25m diameter, 7000 tons!)

- Muon System
    - Identification and momentum measurement of muons



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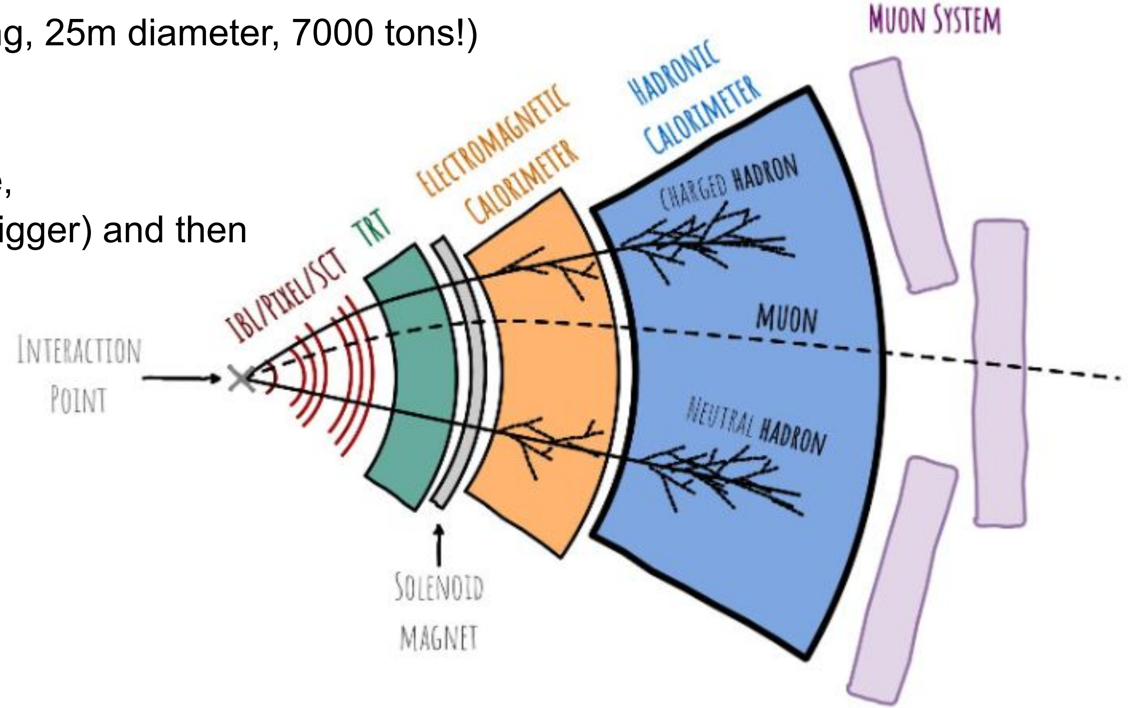
- largest experiment at the LHC (46m long, 25m diameter, 7000 tons!)

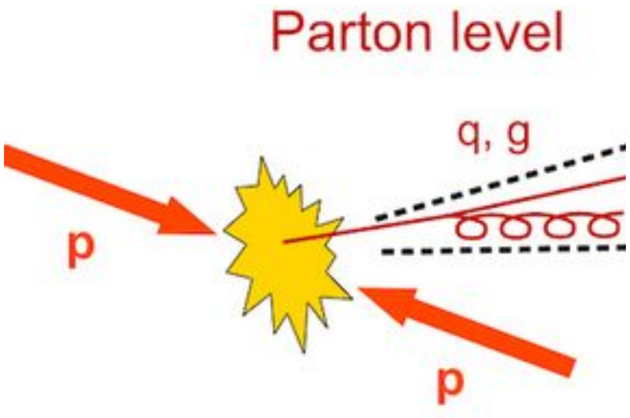
- Trigger System
    - Filter raw collision events in real time, once in custom hardware (Level-1 Trigger) and then in software (High-Level Trigger)



Jets and Tracks in the ATLAS detector

https://atlas-software.docs.cern.ch/analysis/analysis_tutorial/AnalysisSWTutorial/obj_jet_intro/

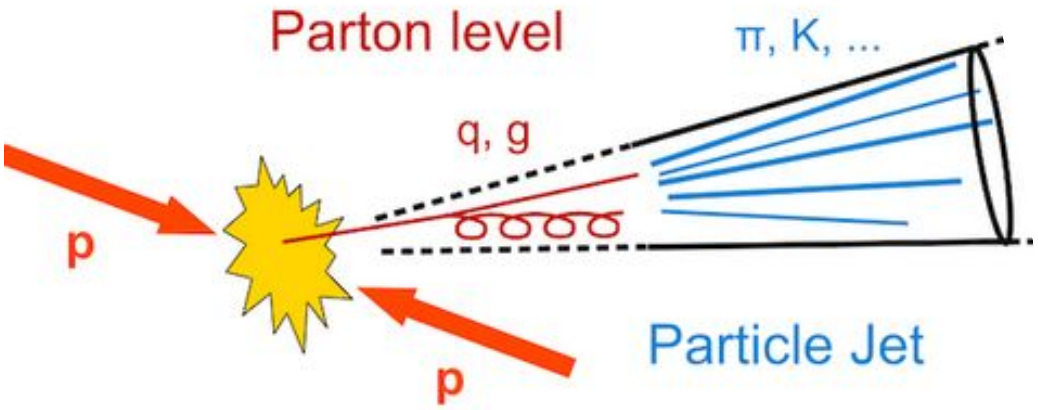
Partons



Jets and Tracks in the ATLAS detector

https://atlas-software.docs.cern.ch/analysis/analysis_tutorial/AnalysisSWTutorial/obj_jet_intro/

Hadronization

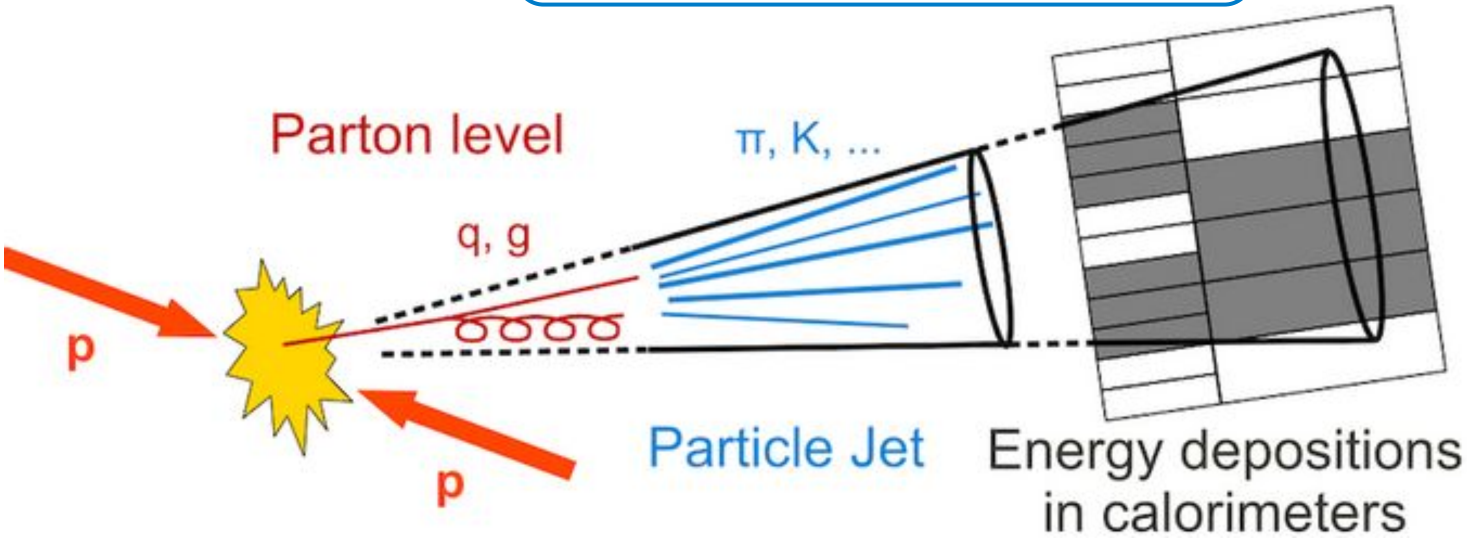


Jets and Tracks in the ATLAS detector

https://atlas-software.docs.cern.ch/analysis/analysis_tutorial/AnalysisSWTutorial/obj_jet_intro/

Object reconstruction in ATLAS

Jets are reconstructed and calibrated **only above** a transverse-momentum threshold! ATLAS: 20 GeV! Anything below: MISSED!

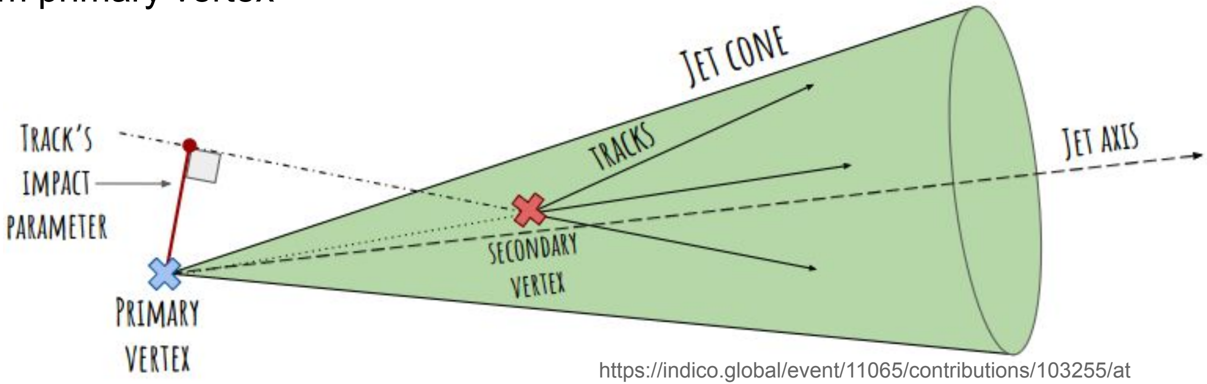


B tagging in the ATLAS detector

Why do we care about b quarks?

- A lot of interesting processes feature b-jets in the final state:
    - SM Higgs sector (*H -> bb*)
    - Top Quark physics (*t -> Wb*)
    - BSM searches (*X -> bY*)
    - Veto for many backgrounds

- *B* quarks have distinct properties
    - long lifetime ~ 1.5ps (generation changing decay suppressed by CKM)
      -> Displaced (secondary) vertex from primary vertex
    - Large impact parameters



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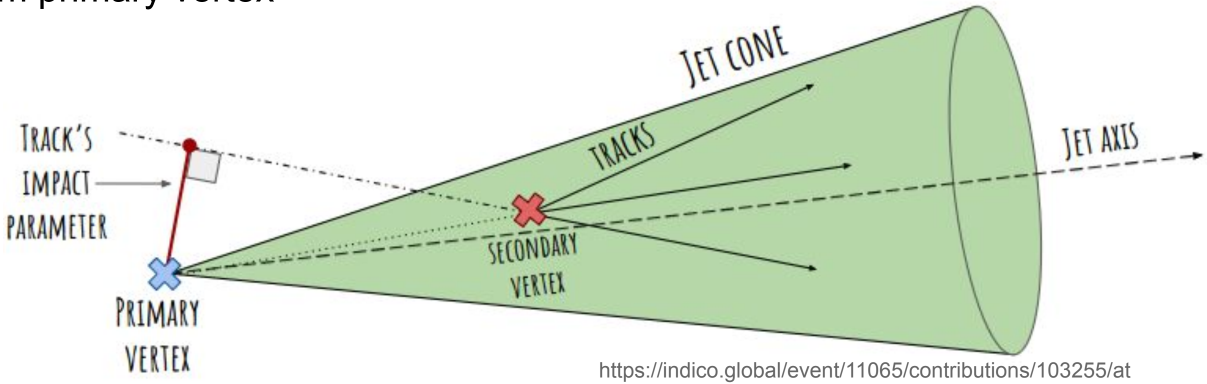
B-tagging algorithms analyze if jet contained a B-hadron decay (typical b-tagger efficiency used is 77%!)



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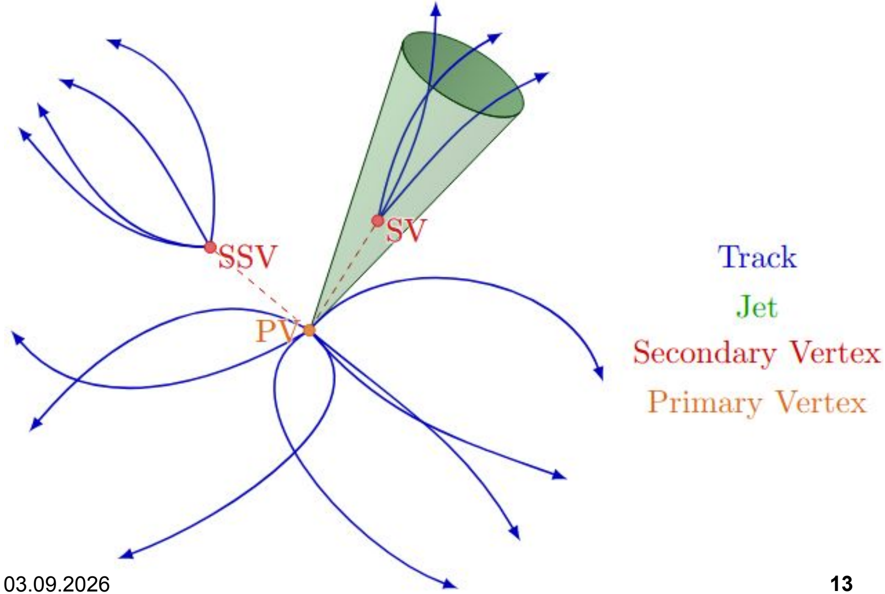
Soft Secondary Vertices (SSVs)

Recovering missed *B*-hadrons

- What happens when a b is too soft and not reconstructed in a jet?
  —> **the *B*-hadron is missed!** The event is not usable in our analysis

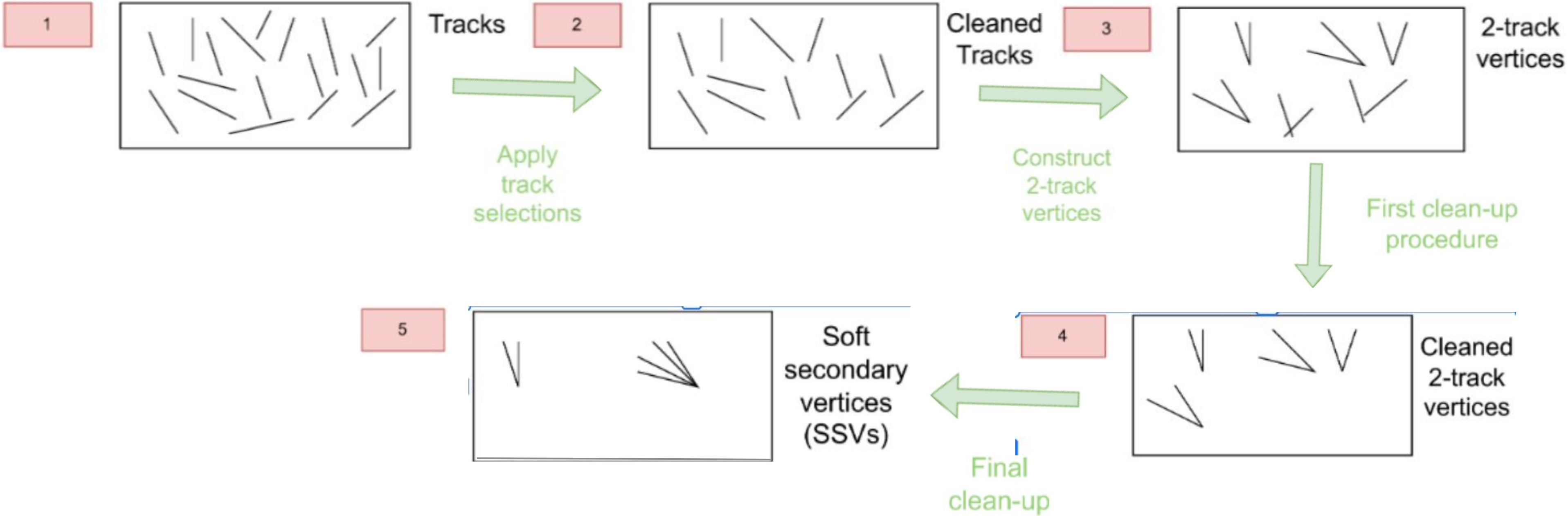
- Can we tag and “save” these *B*-hadrons outside of jets?
  —> yes! Via the soft-secondary-vertex tagger algorithm *NVSI*



SSV reconstruction

NVSI = NewVrtSecInclusive algorithm

- *Not restricted to jets by looking at all tracks!*



Higgs potential & self coupling

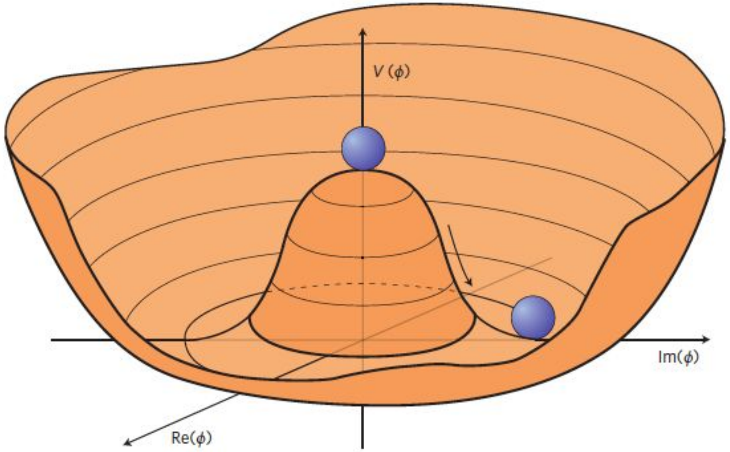
Motivation & goals for a diHiggs search

- The Higgs potential predicts both **trilinear** and **quartic** self-coupling

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2 H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^4$$

- value of λ unknown! SM predicts a value, BSM modifies it
  —> can access λ via Higgs pair production!

- Higgs pair production has not been observed yet!!
  —> Make the discovery and constrain couplings



DiHiggs production and decay in SM

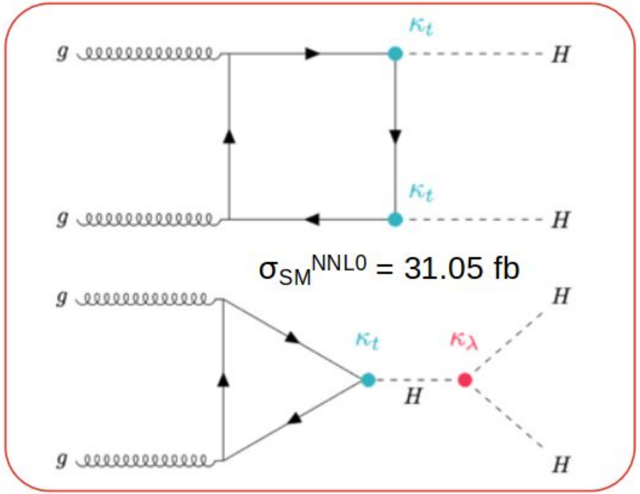
Overview

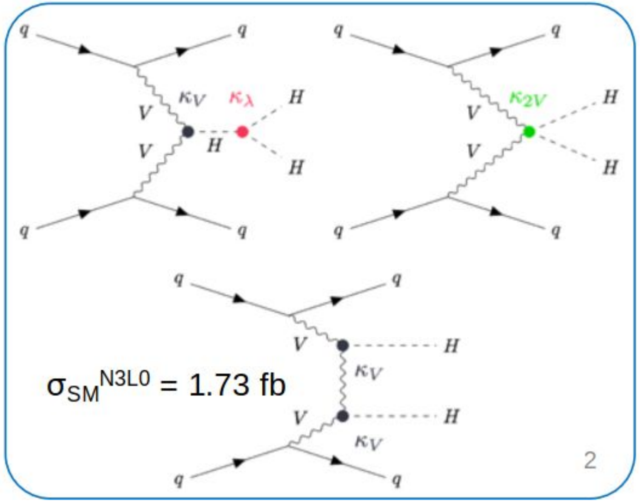
- The primary mechanism for Higgs pair production in the SM is gluon-gluon fusion (**ggF**) followed by vector-boson-fusion (**VBF**)

- couplings defined as e.g. $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$, where SM κ_λ = 1

- Highest branching ratio is the HH -> 4*b* decay (huge QCD background)
- HH -> *bbγγ* very clean signal, but very low statistics

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%





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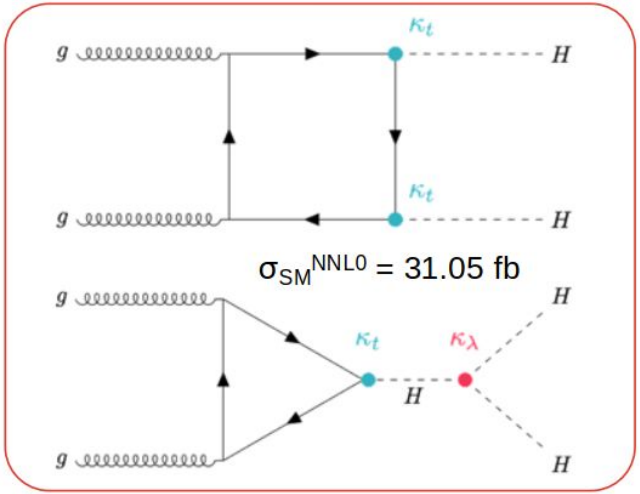
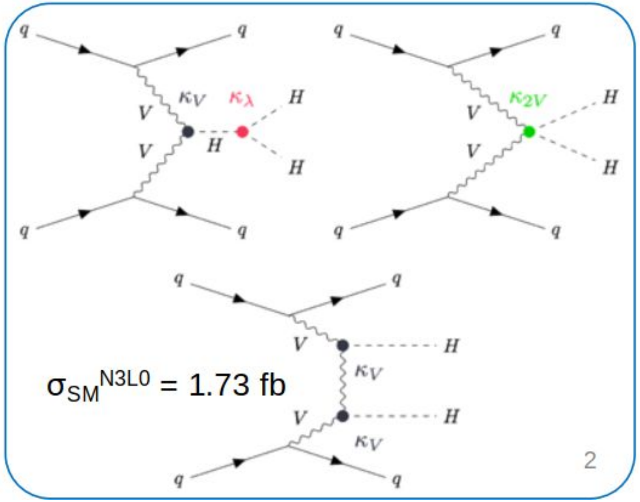
- Highe… …QCD background)
- HH -…

Can we add sensitivity to the analysis by "saving" events through SSV tagging where our *b*-tagging techniques fail?

				ZZ	YY
			…%	0.069%	
YY	0.26%	0.10%	0.028%	0.012%	0.0005%

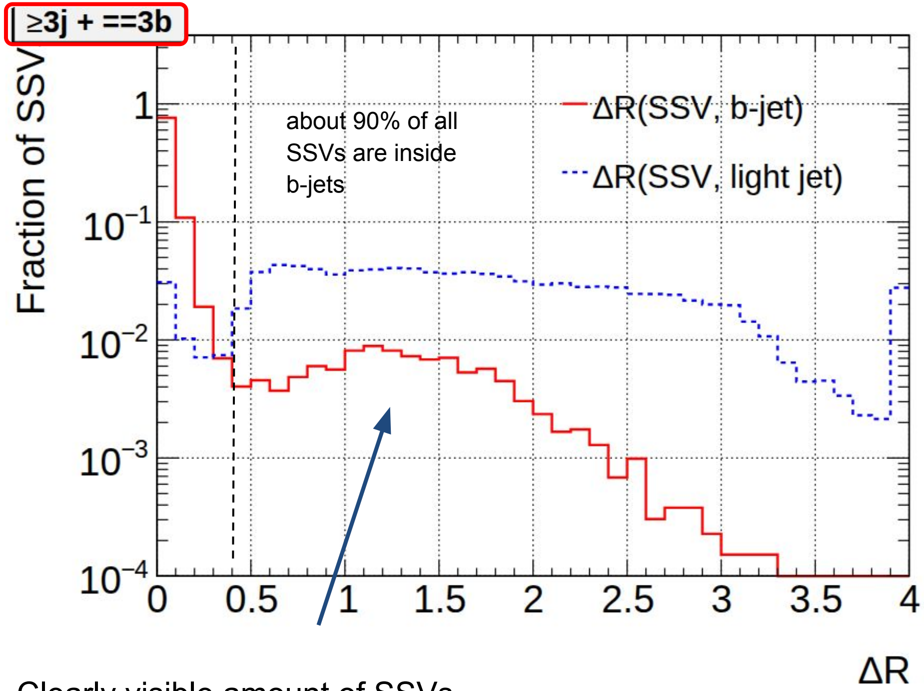




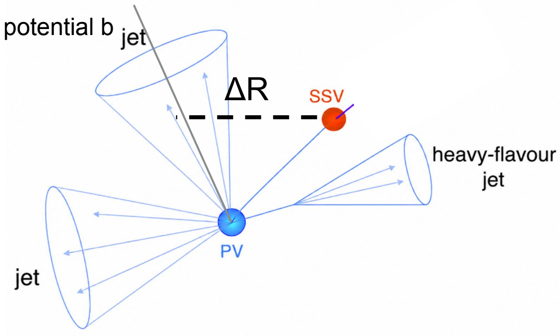
Where are the SSVs in our HH signal?

Distance to b-tagged and non b-tagged jets

- Do we have usable SSVs in our signal?

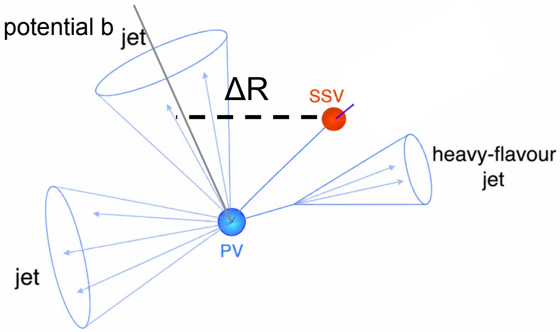


Clearly visible amount of SSVs
outside of *b*-jets!

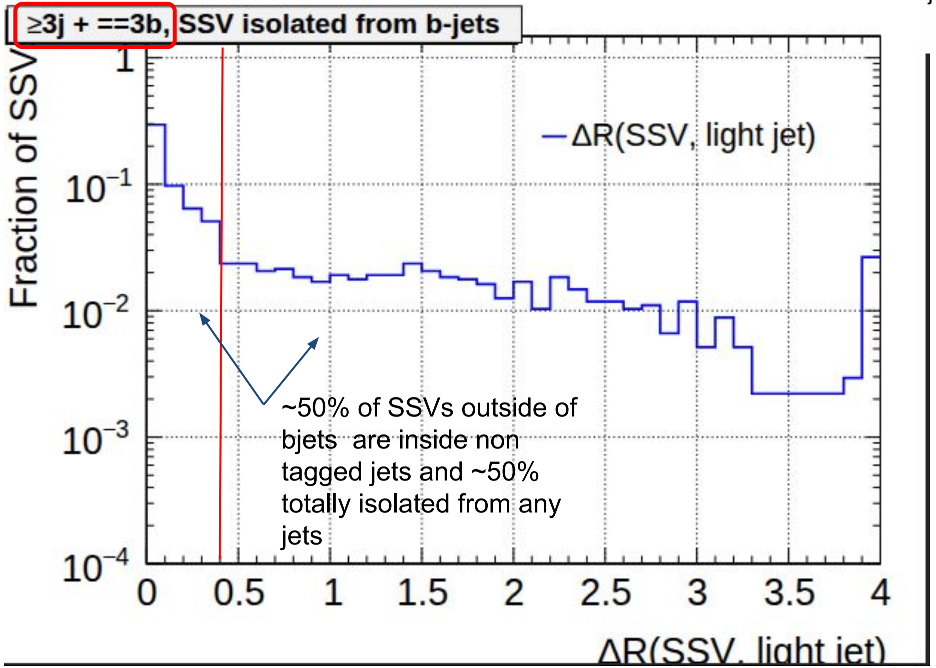


Where are the „good“ SSVs in our signal?

Only SSVs outside of bjets == “useful” or “good” SSVs



- Where are our SSVs?



How many events do we add?

Only for the signal HH to 4b sample

- Want events orthogonal to the current analysis

Selection type	N events	% of std analysis
Standard analysis (>=4j + >=4b)	2740	100.0%
+ Almost no outside-of-bjet SSVs here (see prev. plots)		
SSV *Selection* (>=3j + ==3b)	5343	195%
+ with >=1 good SSV	1270	46.3%
+ SSV from Higgs (truth)	**1110**	**40.5%**
split into:		
- SSV isolated from any jet		**51.1%**
- SSV inside non b-tagged jet		48.9%
- SSV inside jet passing loose b-jet WP		**22.1%**
- SSV inside jet failing loose b-jet WP		**26.8%**

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With the SSV region we can add up to 40% of events in addition to the standard analysis

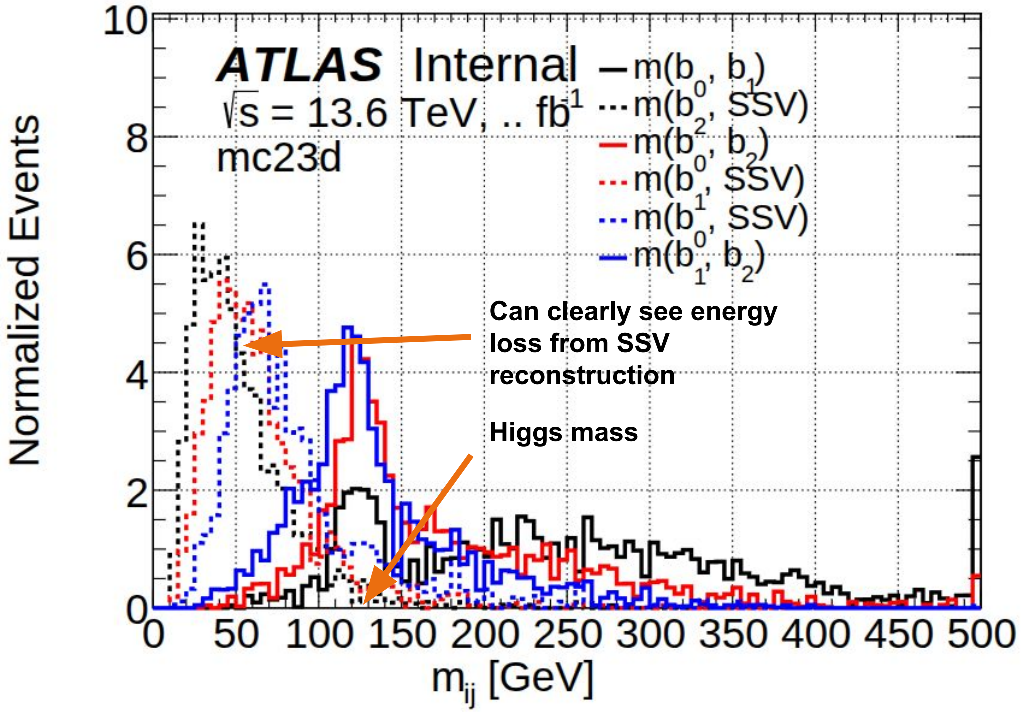
for m_{HH} < 400 GeV
~ 49% extra signal!

how does the background look?

Reconstructing the Higgs using SSVs

How do the invariant masses look with SSVs?

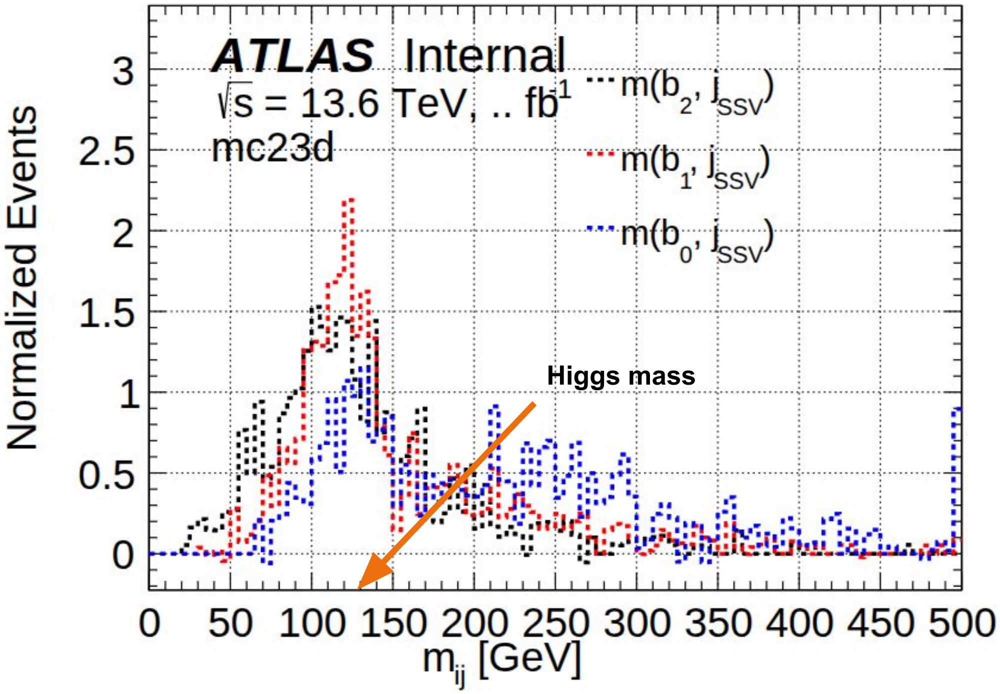
- 3 possible combinations in each event (j1+j2, j3+*j4*), (j1+j3, j2+*j4*), (j1+*j4*, j2+j3) (where SSV can be *j4*)



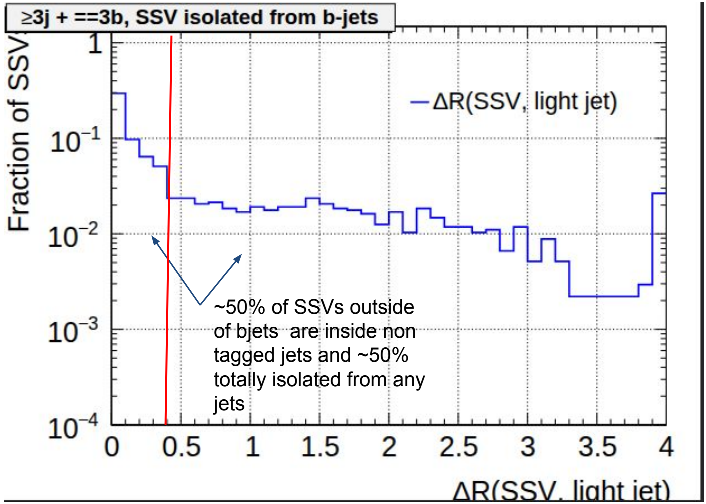
Reconstructing the Higgs using SSVs

Using SSVs as a “b-tag” for light jets

- For SSVs inside non-b-tagged jets, we can simply use the jet!



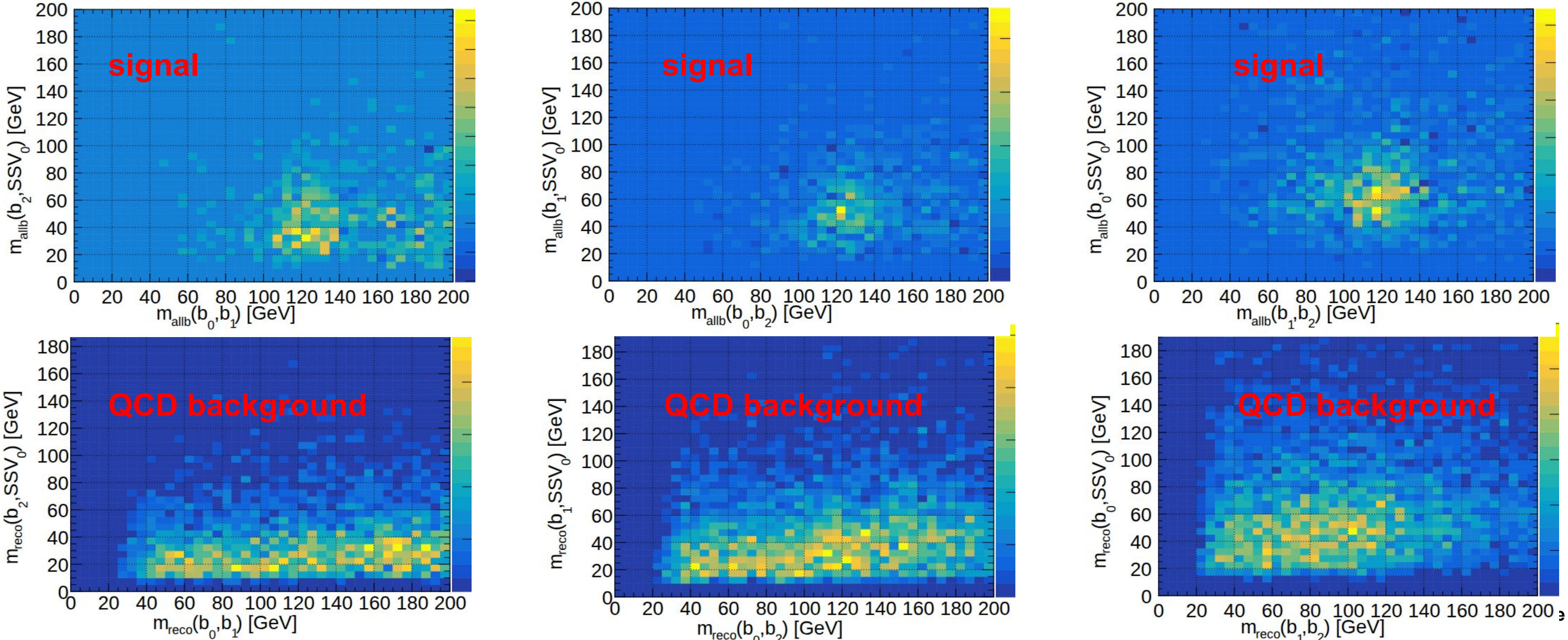
Remembering…



Reconstructing the diHiggs system

Invariant mass of both H_1 and H_2 in signal and background (QCD multijet)

- 3 possible combinations, this time in 2D massplane of the 2 Higgs

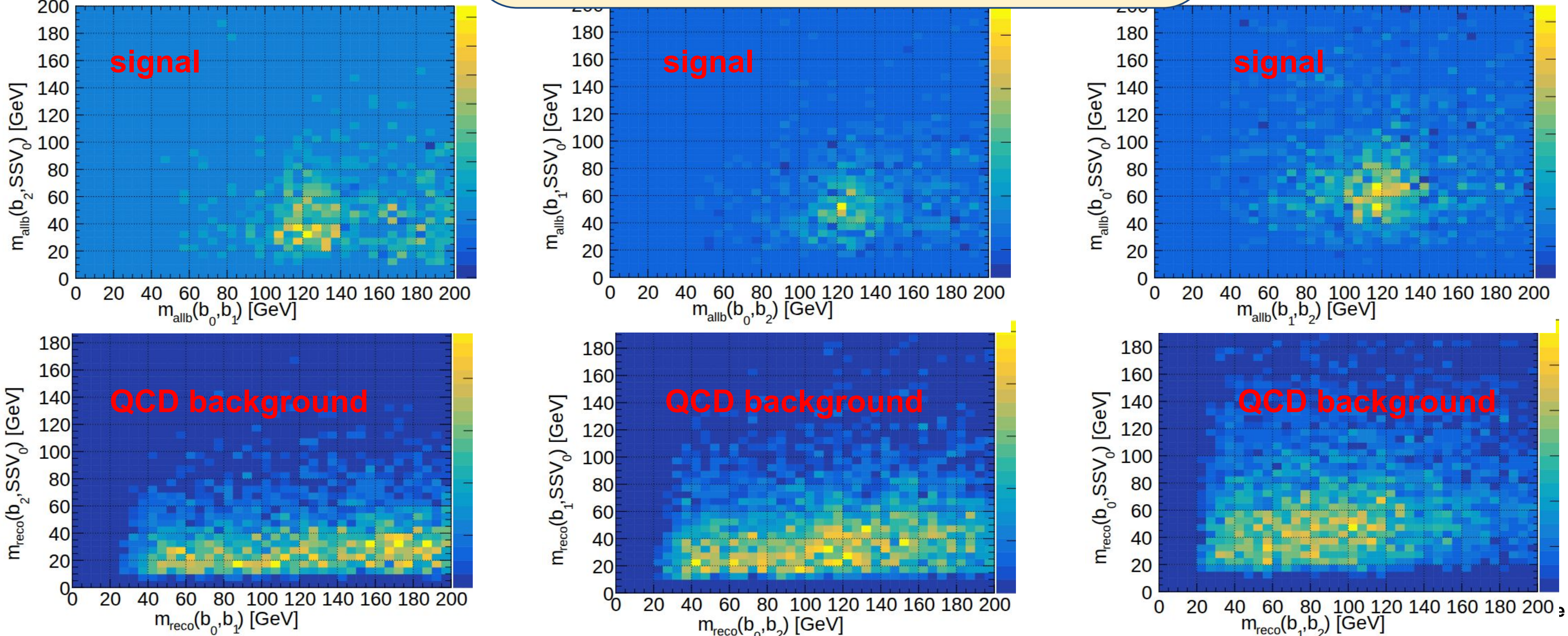


Reconstructing t

Invariant mass of both H1 ar

Which combination of the 3 is right???

- 3 possible combinations, this



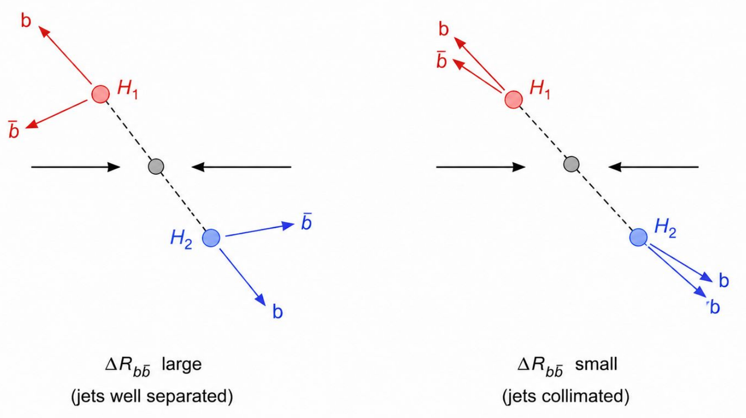
Correctly combining reconstructed jets to the Higgs

Which combination of jet pairing to the Higgs is correct?

- A huge challenge is the pairing of b-jet pairs to the Higgs (at low m_{HH})

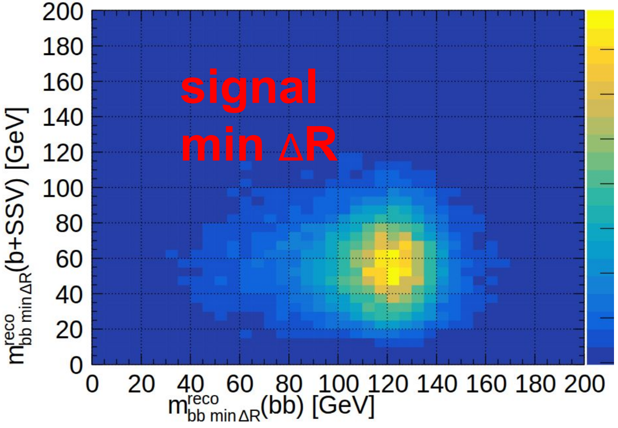
- only one combination out of the 3 per event can be true
  —> Pairing efficiency (*how often are we picking the right combo?)*
  —> whole range of m_{HH}?

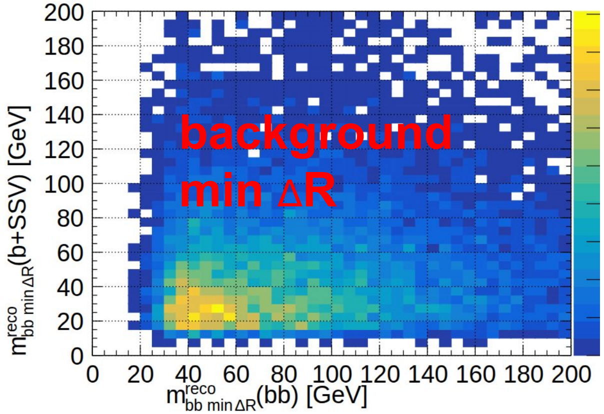
- Possibilities for pairing the jets
    - minimum angular distance between b jets
    - take pairs closest to higgs mass (background sculpting!)



Combining reconstructed jets to the Higgs

Comparing the "minimum(ΔR)" and "target mass minimization" strategies





Combining reconstructed jets to the Higgs

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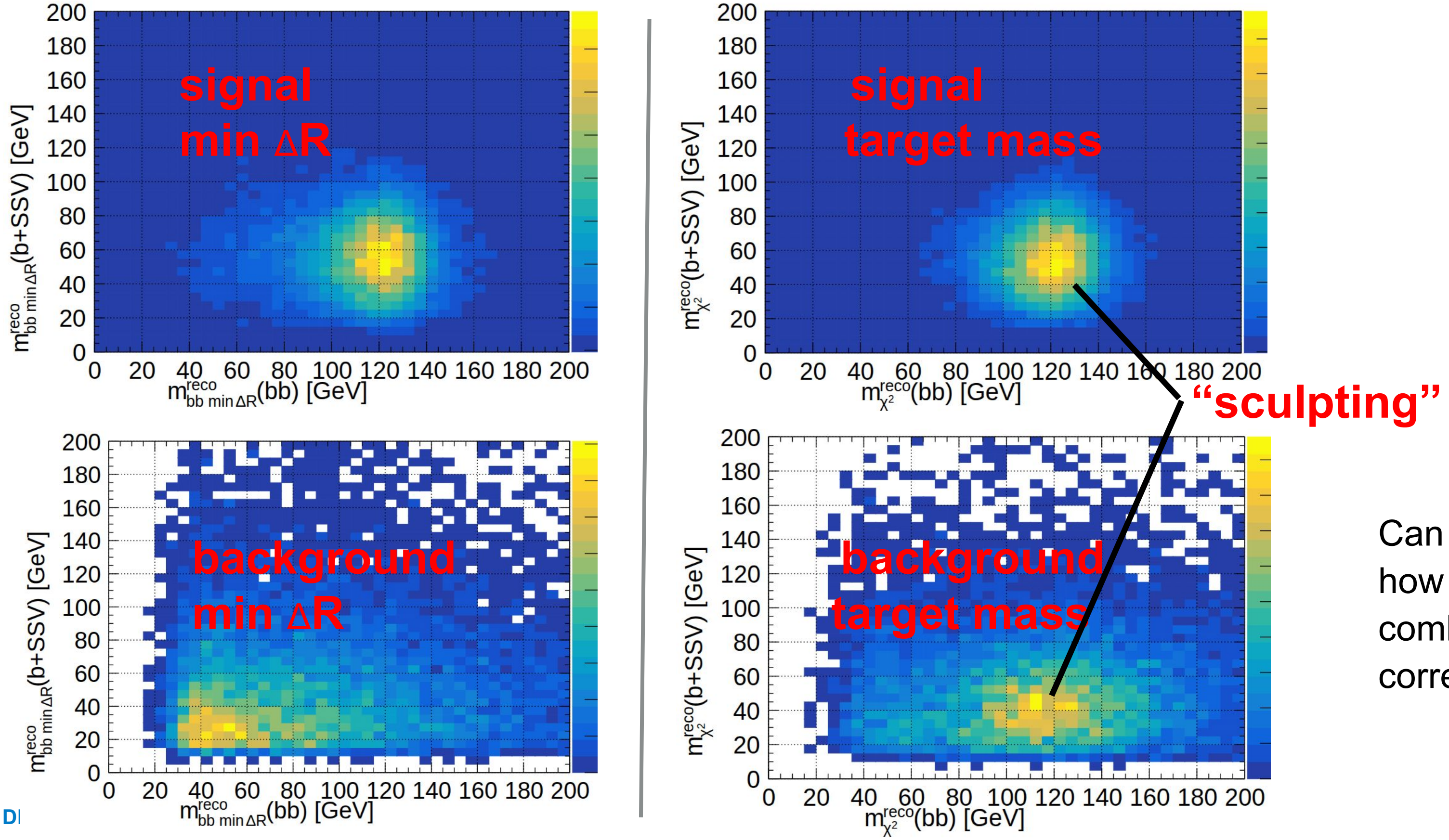


Can we quantify how often the picked combination is correct?

Combining reconstructed jets to the Higgs

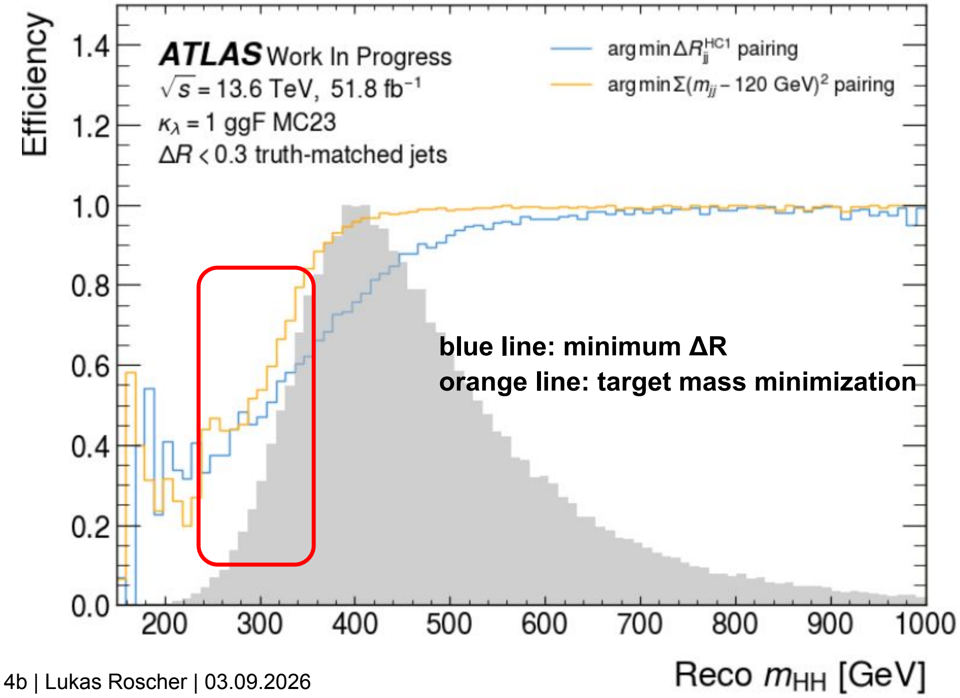
Pairing efficiency vs m_{HH}

- Pairing efficiency "*how often is the picked combination the correct one?*" vs m_{HH}

- blue line: "minimum ΔR", orange line: "target mass minimization"

- Both clearly weak for low m_{HH}
  —> These events are most relevant for the Higgs self coupling!

- Major studies going on for this
  —> use e.g. *maximum* ΔR instead until m_{HH} ~ 300 GeV (how to combine this?)



Summary and Outlook

HH to bbbb analysis and SSVs

- SSVs can recover signal events (for m_{HH} < 400 GeV ~ 49% extra signal) that are missed by the standard b-tagging techniques
  —> Isolated SSVs need energy correction
  —> Using an inclusive “3b1SSV” would define another region for the final statistical fit (combine before? After?), splitting region into “isolated” and “inside non b-tagged jets” needed even

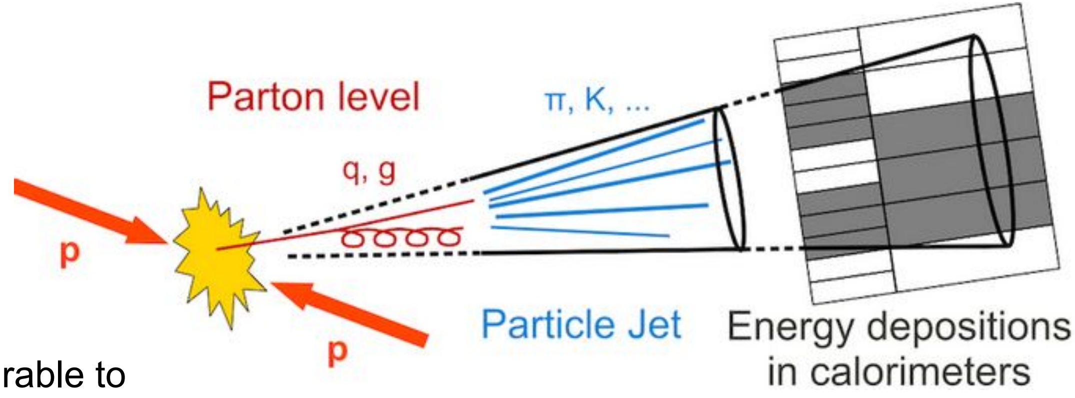
- Combining the jets (or SSV) into the 2 Higgs is a major challenge at low m_{HH}
  —> We are currently **blind** to events that are crucial to restrict Higgs self-coupling!
  —> One solution might be to combine different pairing strategies for different ranges of m_{HH}

Backup

Jets and Tracks in the ATLAS detector

https://atlas-software.docs.cern.ch/analysis/analysis_tutorial/AnalysisSWTutorial/obj_jet_intro/

Object reconstruction in ATLAS



- A lot of hard processes of interest contain quarks and gluons (partons) in the final state

- Partons carry color charge
  - can’t be observed in isolation
  - as partons separate, it’s energetically favourable to pull new quarks from the vacuum and quickly recombine (hadronization)

  —> this forms a spray of stable hadrons that enter ATLAS leaving tracks and energy deposits

- “Hadronic jets” combine grouped energy deposits into one object that serves as a proxy for the partons

  —> different algorithms use different criteria building jets from calorimeter clusters and tracks

- Jet energy is never fully measured (neutral hadrons/decays, detector limits, pile-up, …)

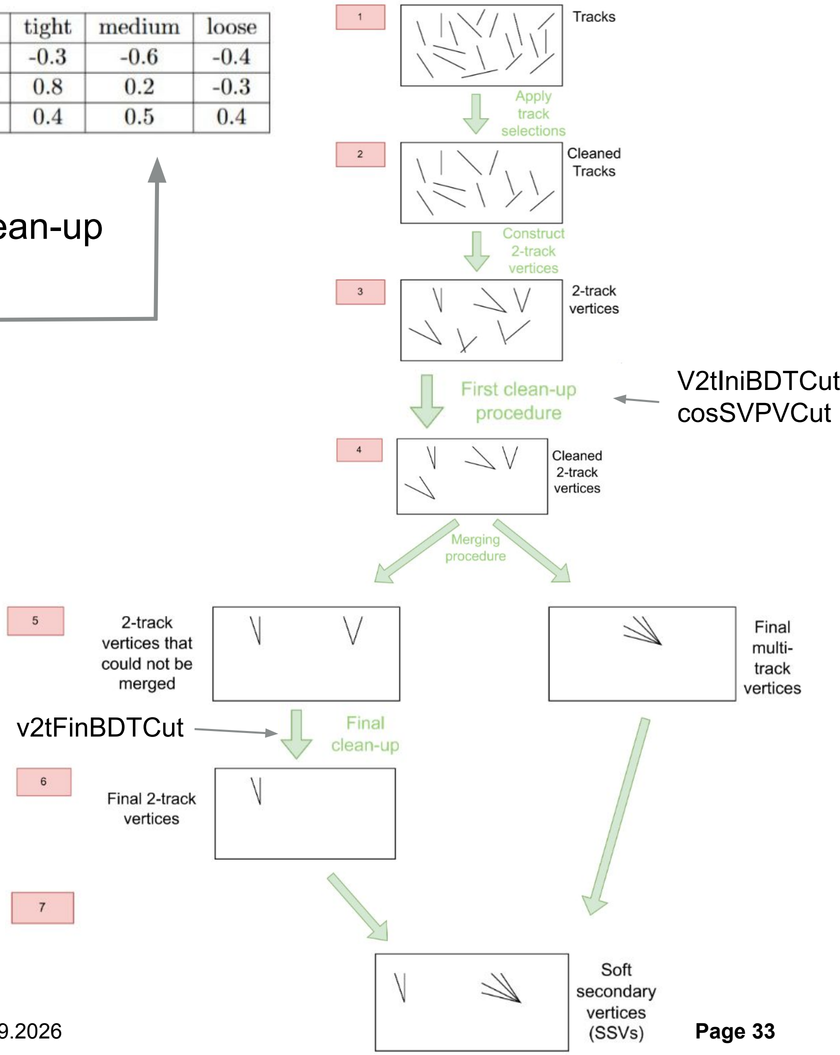
  —> Necessary to apply corrections to jets in simulation and in detector data

SSV reconstruction

NVSI = NewVrtSecInclusive algorithm

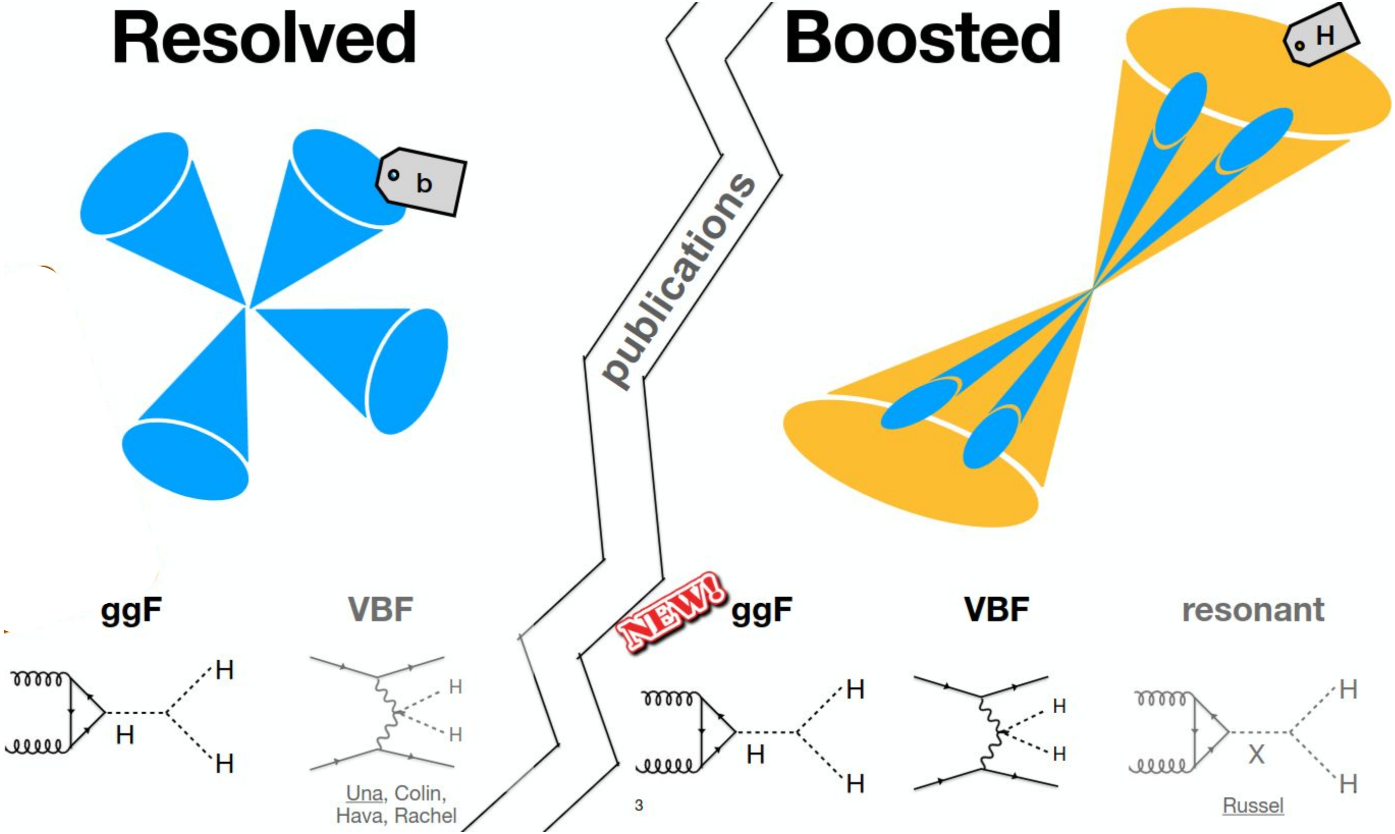
	tight	medium	loose
v2tIniBDTCut	-0.3	-0.6	-0.4
v2tFinBDTCut	0.8	0.2	-0.3
cosSVPVCut	0.4	0.5	0.4

- The NVSI algorithm uses track information and combines clean-up and merging steps to reconstruct soft secondary vertices
- Three working points for the cleaning steps (BDTs)
- Not restricted to jets by looking at all tracks



The HH to 4b analysis 2/2

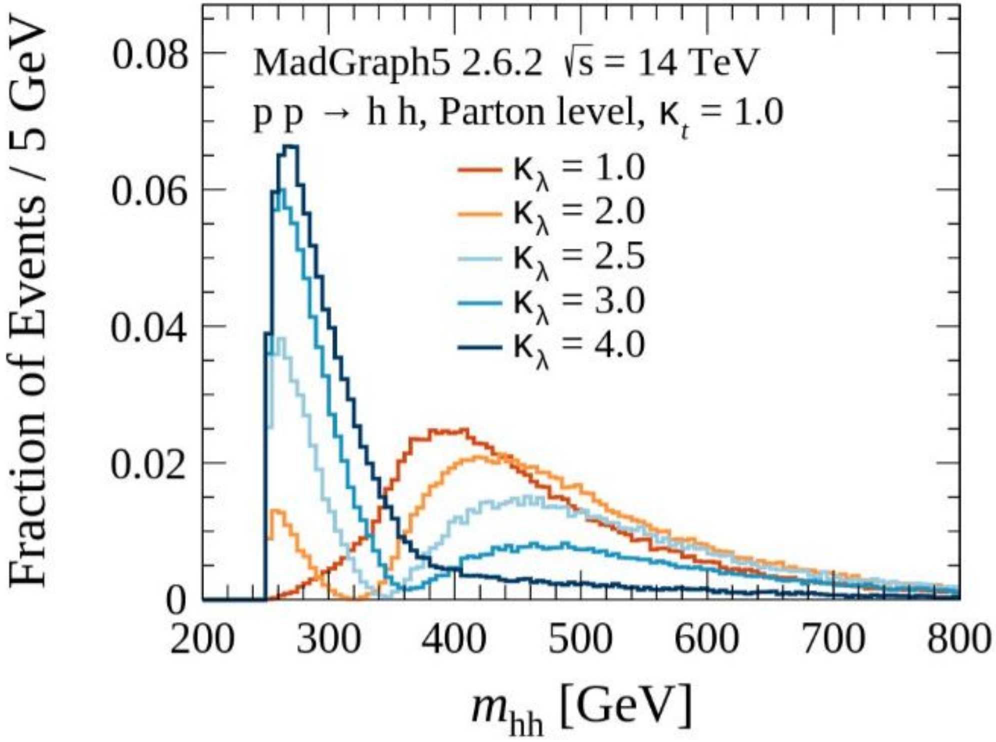
Object reconstruction in ATLAS



Effect of kappa lambda on higgs mass distribution

...

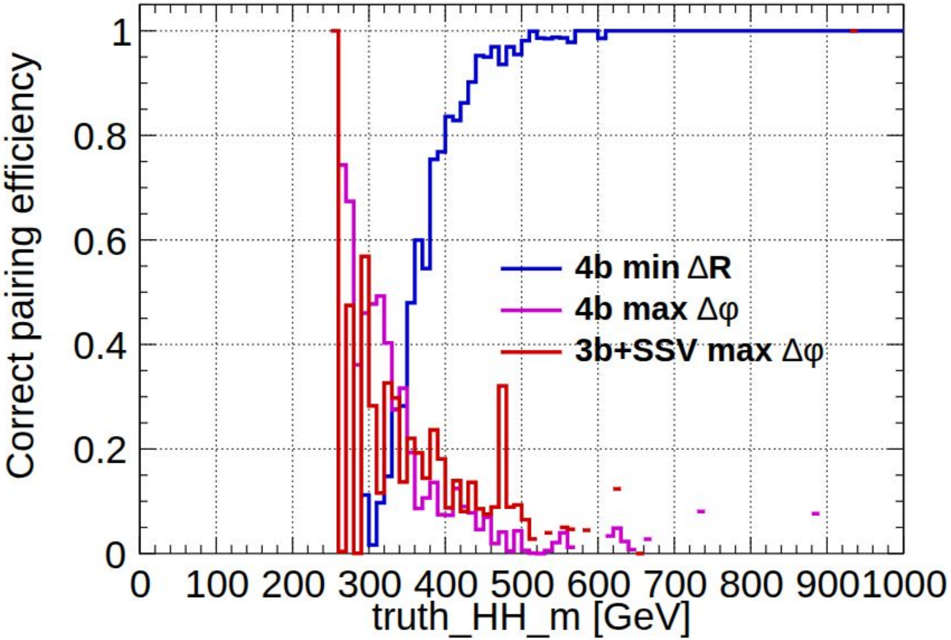
...



Jet pairing to Higgs candidates efficiency 3/3

Different m_{HH} regimes

- At low m_{HH}, maximum angular separation would work much better
- Even SSVs should keep direction information (but much worse energy resolution)
- One could split m_{HH} into “low” and “high” and use different pairing methods
- Example: max($\Delta\phi$) between jet pairs for $m_{HH} < 350$ GeV, min(ΔR) for high $m_{HH} > 350$ GeV



max($\Delta\phi$) good at HH threshold
-> κ_λ sensitivity?

things can be improved to just using min(ΔR) for the whole m_{HH}

3b1SSV vs 3b1l (l=loose btag WP)

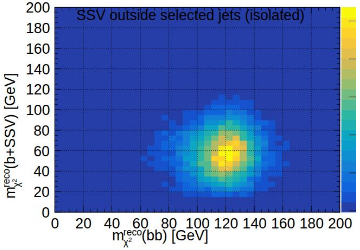
Plot mH1 vs mH2 for signal and background, split in the 3 SSV categories

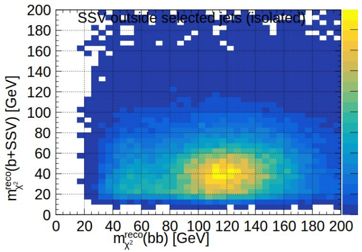
<u>target mass minimization</u>

signal

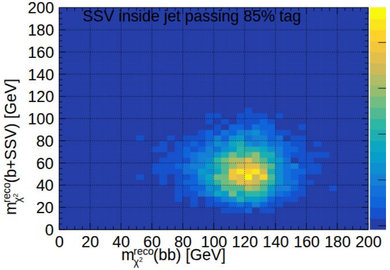
background

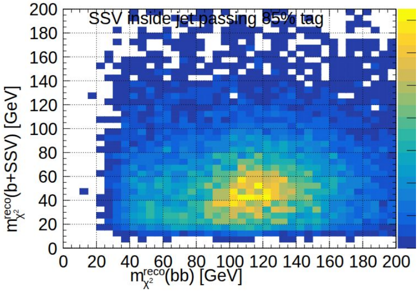
isolated SSVs



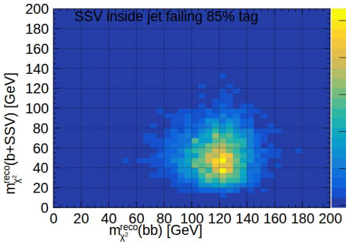


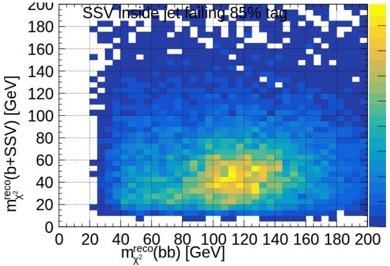
SSVs inside passing 85% jet





SSVs inside failing 85% jet





Signal Region for 4b, 3b1SSV, 3b1L region

Scanning X_HH and significance

- X_HH for 4b:

$$X^{4b}_{\mathrm{HH}}(m_{\mathrm{H1}}, m_{\mathrm{H2}}) = \sqrt{\left(\frac{m_{\mathrm{H1}} - 124\ \mathrm{GeV}}{0.10\, m_{\mathrm{H1}}}\right)^2 + \left(\frac{m_{\mathrm{H2}} - 117\ \mathrm{GeV}}{0.10\, m_{\mathrm{H2}}}\right)^2}$$

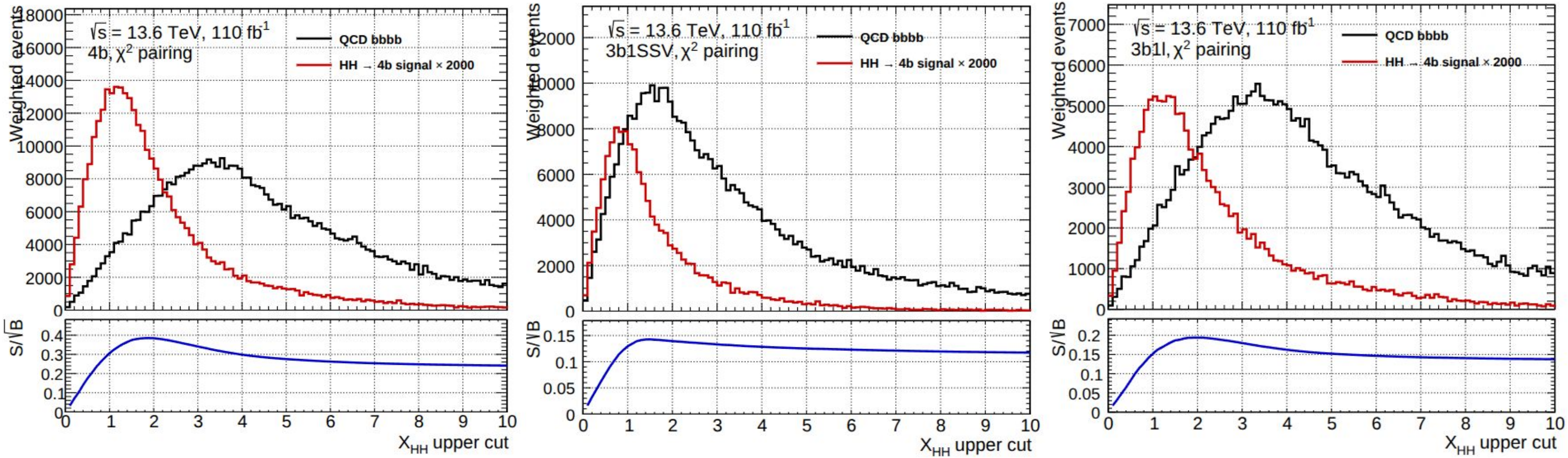
with X_HH < 1.6 for SR (4b)

- X_HH for 3b1SSV:

$$X^{3b1SSV}_{HH}(m_{H1}, m_{H2}) = \sqrt{\left(\frac{m_{H1} - 120\ \mathrm{GeV}}{0.15\, m_{H1}}\right)^2 + \left(\frac{m_{H2} - 60\ \mathrm{GeV}}{0.35\, m_{H2}}\right)^2}$$

  - mass region broader (witdh of ellipse)
  - mH2 needs different target, because SSV

- 2 Higgs paired by **minimum mass target difference** (SSV belongs to H2)



Summary table for yields SSV selection

Signal and background weighted yields

Event content	Signal yield (% of 3b)	bbbb yield (% of 3b)	Relative \S/B vs. all 3b
All exactly 3b events	348.40 (100.00%)	2,857,260.74 (100.00%)	1.000
Good SSV + loose jet	20.16 (5.79%)	86,409.30 (3.02%)	1.913
↳ Leading SSV inside pass-85/fail-77 jet	15.75 (4.52%)	65,029.51 (2.28%)	1.986
↳ Loose jet doesn’t contain the leading SSV	4.41 (1.27%)	21,379.79 (0.75%)	1.692
Good SSV, no loose jet	51.37 (14.74%)	307,080.87 (10.75%)	1.372
Loose jet, no good SSV	54.08 (15.52%)	258,877.82 (9.06%)	1.713
Neither good SSV nor loose jet	222.79 (63.95%)	2,204,892.75 (77.17%)	0.829

Category	Signal yield (share)	bbbb yield (share)	S/S_4b	B/B_4b
>=4b	168.33	588,484.60	1.000	1.000
Inclusive 3b1SSV	71.53 (100% SSV)	393,490.17 (100% SSV)	0.425	0.669
↳ SSV inside pass-85/fail-77 jet	15.75 (22.0% SSV)	65,029.51 (16.5% SSV)	0.094	0.111
↳ SSV inside jet failing 85%	19.20 (26.8% SSV)	78,644.02 (20.0% SSV)	0.114	0.134
↳ SSV outside all selected jets	36.58 (51.1% SSV)	249,816.65 (63.5% SSV)	0.217	0.425
Inclusive 3b1l@85	74.24 (100% 3b1l)	345,287.12 (100% 3b1l)	0.441	0.587
↳ 3b1l with no good SSV	54.08 (72.8% 3b1l)	258,877.82 (75.0% 3b1l)	0.321	0.440