b/c-quark flavor tagging and identification: past, present and future

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Weizmann Institute Of Science - “Flavor of Higgs” workshop

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Experimental status

- Higgs boson discovery established by ATLAS and CMS at $m(H) \sim 125$ GeV.
- Discovery relies on clear signal observation in bosonic channels ($\gamma\gamma$, WW, ZZ).
- Fermionic channels:
  - Recently $>3\sigma$ signal in H to tau tau
  - No $3\sigma$ observation yet in H to bb
- The main question today:
  - is it the Standard Model Higgs boson?
  - can we find deviations from SM predictions which hint at physics beyond SM?
Higgs couplings

- Deviations from SM are presently looked for by defining multiplicative scale factors \( \kappa \) for the coupling parameters (SM expectation = 1), leaving the tensor structure unchanged.

\[
\mathcal{L} = \kappa_W \frac{2m_W^2}{v} W^+ W^- H + \kappa_Z \frac{m_Z^2}{v} Z\mu Z\mu H - \sum_f \kappa_f \frac{m_f}{v} f \bar{f} H + c_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{\mu\nu}_{\mu\nu} H + \frac{c_\gamma}{\pi v} A_{\mu\nu} A^{\mu\nu} H
\]

- Test of absolute couplings difficult
  - Total decay width not directly accessible at LHC.
  - A measurement of absolute couplings is possible if the total width is bound
    - NEW! Measurement through interferometry, but has assumptions!
    - Upper limit from fulfilling unitarity in \( WW \) scattering (valid for SM and a large class of BSM models)

\[
\left[ \begin{array}{cccc}
W & \gamma & Z & W \\
\gamma & Z & \gamma & Z \\
Z & \gamma & Z & H \\
W & W & W & W
\end{array} \right]^2 < \infty
\]

\[ \kappa_W \leq 1, \kappa_Z \leq 1 \]
Higgs couplings (II)

- Lower limit from sum of all “visible” decay modes

\[ \Gamma_H \geq \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\tau + \Gamma_b \]

- At ~125 GeV Higgs boson width is expected to be dominated by H to bb (BR ~ 60%)
  - Precise determination of H to bb would be important for extracting absolute couplings!
- Most sensitive channel is VH, H to bb (V=W/Z)
  - Leptonic signature to trigger / reduce backgrounds
  - Excellent b-quark ID required to reject light- and c-jets
  - Expected sensitivity at the end of Run-I LHC:
    - ~2\(\sigma\) (CMS), ~1.7\(\sigma\)* (ATLAS)
    - <15% error on H to bb signal foreseen by CMS with 300 inv. fb. of data

*Final ATLAS Run-I result not public yet

![CMS Projection](image-url)
Higgs couplings (III)

- Direct evidence of coupling to top-quarks implies observation of ttH production
  - at least 2 b-quarks in final state
- Most promising channel ttH, H to bb
  - Very challenging due to high backgrounds
  - Excellent b-quark ID required to suppress tt+light-jet backgrounds
  - 4 b-jets means it’s hard to reconstruct an even broad Higgs mass peak
- Presently 0.7σ/0.5σ sensitivity (ATLAS / CMS) (~1σ combining all decay modes)
- Measurement will become competitive in Run-II.
b/c-quark flavor ID

• Important role in Higgs physics:
  • H to bb searches
  • ttH production
  • as a handle to veto b-jets from top production (e.g. VBF H to WW)

• Will review:
  • What b-tagging is about and how it works
  • What we have achieved @ LHC in Run-I (performance + calibration)
  • What we can improve in the next run (upgraded detector, improved techniques)

• Will refer mainly to ATLAS, with a few comparisons to CMS.
We don’t see b-quarks…

- A b-quark fragments typically (~87% of times) into:
  - B*, B** (excited b-hadrons)

- These decay strongly or electromagnetically ($c\tau < 10^{-16} \text{ s}$) into:
  - a b-hadron + few additional particles (which form a jet)

### b-hadron types

<table>
<thead>
<tr>
<th>Mesons:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+_u = \bar{b}u$</td>
<td>$B_s^0 = \bar{b}s$</td>
<td>$B_c^+ = \bar{b}c$</td>
</tr>
<tr>
<td>$B_s^0 = \bar{b}d$</td>
<td>$B_s^0 = \bar{b}s$</td>
<td>$B_c^+ = \bar{b}c$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Baryons:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 = bud$</td>
<td>$\Xi_b^{0,-} = bus, bds$</td>
<td>$\Omega_b^- = bss$</td>
</tr>
</tbody>
</table>

### Relative production rates

<table>
<thead>
<tr>
<th>b-hadron</th>
<th>Branching fraction ($\Gamma_i/\Gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+$</td>
<td>(40.0 ± 1.2)%</td>
</tr>
<tr>
<td>$B^0$</td>
<td>(40.0 ± 1.2)%</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>(11.4 ± 2.1)%</td>
</tr>
<tr>
<td>$b$-baryon</td>
<td>(8.6 ± 2.1)%</td>
</tr>
</tbody>
</table>

- The b-quark fragmentation function is hard: in average most of the energy of the original b-quark (~70%) goes into the b-hadron
B-hadron decays

- A b-hadron undergoes a weak decay with:
  \[ cT \sim 1.5 \times 10^{-12} \text{ s} \]

- Decay properties:
  - For a b-hadron with \( p_T \sim 30 \text{ GeV} \), \( \beta \gamma \sim 6 \Rightarrow L = \beta \gamma cT \sim \sim5 \text{ mm} \)
    \( \rightarrow \) Measurable displaced secondary vertex!
  - B-hadron mass is \( \sim 5 \text{ GeV} \)
  - Since \( |V_{cb}| \gg |V_{ub}| \), in most of the cases also a c-hadron is produced out of the b-hadron. \( cT \text{ (c-hadron)} \sim 0.4-1 \times 10^{-12} \text{ s} \). This creates an additional tertiary vertex.
  - In \( \sim42\% \) of the cases the b-hadron decays semi-leptonically, in \( \sim11\% \) directly \( (b \rightarrow \ell) \) and in \( \sim10\% \) indirectly \( (b \rightarrow c \rightarrow \ell) \) where \( \ell=e \) or \( \mu \).
  - All these properties can be exploited to identify b-jets and separate them from u,d,s-jets (light) and gluon-jets.
Typical topology in light-jets

- Most of the tracks really come directly from the quark fragmentation process.

- Few light jets present a real displaced vertex due to:
  - Hadronic interactions in the detector material (mostly on beam pipe and first pixel layers)
  - Photons converting into an electron-positron pair (track pair emitted collinearly)
  - Long lived particles: $K_s/\Lambda$ decaying to $\pi^+ \pi^- / p \pi^-$
    
    $\tau(K_s) = 2.7 \text{ cm} / \tau(\Lambda) = 7.9 \text{ cm} >> \tau(B)=0.46 \text{ mm}$
  - Badly measured tracks (hard scatter, nuclear interactions,...) / tracks with shared hits in the first pixel layers can significantly increase the rate of fake tracks / fake vertices.
Ingredients to b-tagging

1. **Tracks**
   - Can only measure trajectory of charged particles
   - Tracks associated to jets based on:
     \[ \Delta R(\vec{p}_{jet}, \vec{p}_{trk}) < \Delta R_{cut} \]
     \( (\Delta R \text{ cut } pT \text{ dependent}) \)

2. **Jets**
   - **Direction**: allows to assign a “lifetime sign” to tracks
   - **Transverse momentum/rapidity**: exploit dependence of physics properties and detector resolution on jet kinematics

3. **Leptons**
   - Muons are used to identify semi-leptonic b-decays.
• Impact parameter resolution of tracks determined by first layers of pixel detector

• Crucial to distinguish displaced tracks from b-hadron decays ($c\tau \sim 0.5\text{mm}$) from tracks from fragmentation (compatible with the primary vertex).
Impact parameter resolution

- Can be parameterized as:

\[ \sigma_X(p_T) = \sigma_X(\infty)(1 + \frac{p_X}{p_T}) \]

- Measured in data
- After improvements in alignment iterations \sim reached nominal resolution goal (wasn’t the case in 2011).
Primary vertex reconstruction

- The main challenge is the reconstruction of multiple vertices due to pile-up.
- Present strategy: iterative vertex finder. Outliers of first vertex used to find further vertices
- “Adaptive” vertex fitter used. Downweights outliers smoothly iteration after iteration.

Event reconstructed in 2011 data with 20 vertices!

The PV error ellipses are magnified by 20x.
B-tagging algorithms

• Two main categories:
  • “Lifetime” based
    • Impact parameter based
      → exploit (in)compatibility of single tracks to PV
    • Inclusive secondary vertex based
      → determination of weak B hadron decay vertex + production / decay properties
  • PV → b- → c-hadron decay chain based
    → more detailed determination of vertex topology
  • “Lepton-ID” based
    → Exploit identification of muons from B or B → D decay
Impact parameter algorithm

- For each track define 2d likelihood with IP significance in $r\phi$ and $z$

- Assign lifetime sign to both of them

- Compute LH as:

  $$LR(IP_1, IP_2, \ldots, IP_N) = \prod_{i=1}^{N} \frac{PDF_b(IP_i)}{PDF_l(IP_i)}$$

  $$weight(IP_1, IP_2, \ldots, IP_N) = \log(LR(IP_1, IP_2, \ldots, IP_N))$$
### Inclusive SV algorithm

- **Finding strategy:**
  - Find all displaced 2-track vertices within the jet
  - Remove all vertices with di-track mass compatible with KS, Lambda decay, or photon conversion.
  - Remove all vertices in correspondence of pixel layers (likely to stem from material interactions).
  - Using only tracks from any of the non-vetoed 2-track vertices, form a single inclusive secondary vertex (only require “loose” vertex with $\text{Prob}(\chi^2) > 0.1\%$)

- **Combine variables:**
  - invariant mass at vertex
  - # of non-vetoed 2-trk vertices
  - energy fraction of tracks at vertex w.r.t. all tracks in jets
  - into a 2d+1d likelihood function.
JetFitter

- Constraints all tracks stemming from both B/D-hadron vertices to intersect B-flight axis
- Basically a new Kalman Filter relying on the “ghost track” method first introduced in SLD [SLAC-PUB-8225 (1999)]
- Two vertices or 1 vertex + 1 single track reconstructed in ~6%/~14% of cases in real b-jets
- Can be used to better separate b- from c- jets
### Combination of “lifetime” algorithms

- Combines the three discriminators into a single final Neural Network.

### Performance against light- and c-jets:

- For VH optimized b-tagging cut yields:
  - 70% b-tagging efficiency
  - ~5 c-jet rejection
  - ~130-150 light-jet rejection

<table>
<thead>
<tr>
<th>Discriminator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight_IP3D</td>
<td># 2-trk vertices</td>
</tr>
<tr>
<td></td>
<td>Energy(vtx) / Energy (tot)</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
</tr>
<tr>
<td>LH(IP3D)</td>
<td># vertices with &gt;1 track</td>
</tr>
<tr>
<td></td>
<td># tracks at vertices</td>
</tr>
<tr>
<td></td>
<td># 1-track vertices</td>
</tr>
<tr>
<td>LH(SV1)</td>
<td>Mass</td>
</tr>
<tr>
<td>NN(JetFitter)</td>
<td>DeltaPhi(b-momentum, b-axis)</td>
</tr>
<tr>
<td></td>
<td>DeltaEta(b-momentum, b-axis)</td>
</tr>
</tbody>
</table>

\[ \text{Rejection} = \frac{1}{\text{efficiency}} \]
And in CMS?

- Very similar geometry of pixel detector (despite all-silicon tracker). Pixel size 100x150 \(\mu m\) instead of 50x400 \(\mu m\).
- 3D impact parameter resolution very similar to ATLAS (momentum resolution much better in CMS, but doesn’t impact b-tagging)
- Most advanced algorithm “CSV” (Combined Secondary Vertex)
  - Combination of impact parameter, “pseudo-vertex” and vertex algorithm
- Comparison of c-jet and light-jet rejection factors for 70% efficiency working point:
  - c-jets: \(\sim 5\) (ATLAS) vs \(\sim 5\) (CMS)
  - light-jets: \(\sim 130\) (ATLAS) vs \(\sim 50\) (CMS)
- Take comparison with some care (depends a bit on sample/cuts)
Where does it matter? ttH…

- Light jet rejection is for example critical in ttH, H to bb
- Below a comparison of the tt+light jet contamination in the main 1-lepton channel signal regions
- Light jet rejection is a bit less critical in VH, H to bb.

**CMS analysis**

<table>
<thead>
<tr>
<th></th>
<th>5 jets ≥4 b-tags</th>
<th>≥6 jets ≥4 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH(125)</td>
<td>5.2 ± 1.4</td>
<td>8.3 ± 2.3</td>
</tr>
<tr>
<td>tt+lf</td>
<td>79 ± 34</td>
<td>71 ± 36</td>
</tr>
<tr>
<td>tt+b</td>
<td>29 ± 17</td>
<td>33 ± 20</td>
</tr>
<tr>
<td>t¯t + b¯b</td>
<td>38 ± 21</td>
<td>78 ± 47</td>
</tr>
<tr>
<td>t¯t + c¯c</td>
<td>32 ± 18</td>
<td>52 ± 31</td>
</tr>
<tr>
<td>t¯tV</td>
<td>2.5 ± 0.7</td>
<td>5.8 ± 1.8</td>
</tr>
<tr>
<td>Single t</td>
<td>10.3 ± 5.3</td>
<td>7.3 ± 3.1</td>
</tr>
<tr>
<td>V+jets</td>
<td>1.9 ± 1.7</td>
<td>1.2 ± 1.3</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.1 ± 0.1</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Total bkg</td>
<td>193 ± 62</td>
<td>249 ± 90</td>
</tr>
<tr>
<td>Data</td>
<td>219</td>
<td>260</td>
</tr>
</tbody>
</table>

**ATLAS analysis**

<table>
<thead>
<tr>
<th></th>
<th>5 jets, ≥ 4 b-tags</th>
<th>≥ 6 jets, ≥ 4 b-tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH (125)</td>
<td>11 ± 1 ± 9</td>
<td>28 ± 2 ± 23</td>
</tr>
<tr>
<td>tt+ light</td>
<td>78 ± 9</td>
<td>78 ± 11</td>
</tr>
<tr>
<td>t¯t + c¯c</td>
<td>45 ± 12</td>
<td>75 ± 19</td>
</tr>
<tr>
<td>t¯t + b¯b</td>
<td>149 ± 20</td>
<td>300 ± 40</td>
</tr>
<tr>
<td>t¯t + V</td>
<td>3.3 ± 1.0</td>
<td>8.9 ± 2.7</td>
</tr>
<tr>
<td>non-t¯t</td>
<td>23.2 ± 2.5</td>
<td>18.8 ± 2.2</td>
</tr>
<tr>
<td>Total</td>
<td>309 ± 11</td>
<td>507 ± 27</td>
</tr>
<tr>
<td>Data</td>
<td>283</td>
<td>516</td>
</tr>
</tbody>
</table>
Rejecting c-jets

- Historically, most effort invested in light-jet rejection.
- More recently, dedicated algorithms to reject c-jets.
- Explicitly train NN / BDT against c-jets.
- Take advantage of secondary vertex properties and topology from JetFitter (decay chain fit).

<table>
<thead>
<tr>
<th>ε(B)</th>
<th>R(c)</th>
<th>R(light)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>~3</td>
<td>~27</td>
</tr>
<tr>
<td>70%</td>
<td>~5.0</td>
<td>~150</td>
</tr>
<tr>
<td>60%</td>
<td>~8.0</td>
<td>~650</td>
</tr>
<tr>
<td>50%</td>
<td>~14</td>
<td>~2500</td>
</tr>
<tr>
<td>30%</td>
<td>~78</td>
<td>~40k</td>
</tr>
</tbody>
</table>

- Table with values for MVI and MVIc.
Where does it matter? VH…

- In the VH, H to bb analysis, in the 1-lepton channel (WH)
- ttbar is the leading background (and will be more so at 14 TeV)

**low pT(V)**

**high pT(V) - “boosted” analysis**

**b-tagging doesn’t help!**

**b+c-jets: c-jet rejection crucial!**
From c-jet rejection to c-tagging

- Neural Network trained against both light- and c-charm jets, with three output nodes (Pb, Pc, Pu)
- Uses combination of cuts on $\log(Pb/Pc)$ and $\log(Pc/Pu)$
- Presently used for SUSY analysis with c-quarks in the final state
- Presently proposed working points:
  - c-tag eff: 20% $\rightarrow$ b-jet eff: 20%, light-jet eff: $\sim$0.7%
  - c-tag eff: 95% $\rightarrow$ b-jet eff: 50%, light-jet eff: $\sim$100%
- Algorithm being refined through the use of Deep Neural Networks
- But main problem is that in most of the discriminant variables c-jets are always between light- and b-jets.
Higgs to cc?

- Higgs to cc BR is ~2.9%, against ~57% of bb (20 times smaller)

- “C”-tagging for now is not able to reduce b-jet much more than c-jets:
  - Efficiency for c-jets significantly lower than for b-jets ($\varepsilon_c^2$)
  - Background from b-jets not significantly suppressed
  - Additional backgrounds from c+b and c+c (e.g. top rejection at high pT won’t work anymore)

- Without really a significant improvement in b-tagging, Higgs to cc seems out of reach.
Performance calibration

- Performance is not everything
- Efficiencies/rejections need to be calibrated with data
- The calibration uncertainty can be a limiting systematics in analysis with b-jets (dominant systematics in the VH EPS 2013 analysis!)
- Both ATLAS and CMS have developed a complete set of calibration measurements, for b-, c- and light-jets
- Will briefly describe the main techniques

*Standard tagger missing in this plot*
B-jet calibration in ATLAS

- Previously main calibration method was “pTrel”, based on having two nearly independent taggers, a “muon” and a “lifetime” based one.

- The dominant systematics with this method is the extrapolation of the MC-to-data Scale Factor from b-jets with $B \rightarrow \mu + X$ to inclusive b-jets.
  - ATLAS estimated such uncertainty to be $\sim 4\%$, but no good way to rigorously justify it (+ no correlation model vs pT).
  - CMS claims this is a percent level effect and therefore negligible.
B-jet calibration in ATLAS (II)

- Will present most precise of the calibrations based on ttbar events.

- Within the H to bb analysis group, we designed a new calibration method, based on applying a maximum likelihood fit to di-leptonic ttbar events with 2 jets:

\[
L(\sqrt{s}, \sqrt{s}, \sqrt{s}, \sqrt{s}) = \begin{bmatrix}
  f_{bb} PDF_{bb}(\sqrt{s}, \sqrt{s}) PDF_{bb}(\sqrt{s}, \sqrt{s}) \\
  + f_{bl} PDF_{bl}(\sqrt{s}, \sqrt{s}) PDF_{bl}(\sqrt{s}, \sqrt{s}) \\
  + f_{ll} PDF_{ll}(\sqrt{s}, \sqrt{s}) PDF_{ll}(\sqrt{s}, \sqrt{s}) \\
  + 1 \leftrightarrow 2
\end{bmatrix} / 2,
\]

where:
- \( f_{bb}, f_{bl}, f_{ll} \) and \( f_{ll} = 1 - f_{bb} - f_{bl} \) are the overall two jet flavour fractions.
- PDF_{f} (\sqrt{s}, \sqrt{s}) is the PDF (probability density function) for the b-tagging weight for a jet of flavour \( f \), conditionally dependent on \( \sqrt{s} \).
- PDF_{f_{1} f_{2}}(\sqrt{s}, \sqrt{s}) is the two-dimensional PDF for [\( \sqrt{s}, \sqrt{s} \)] for the flavour combination [\( f_{1}, f_{2} \)].
B-jet calibration in ATLAS (III)

- Flavor fractions and non b-jet efficiencies from MC.
- Fit extracts from data b-jet efficiency in bins of $p_T(jet)$.
- B-efficiency uncertainty reduced from ~5% to ~2% in intermediate $p_T$ region.
- Leading systematics:
  - Top pair modeling
  - Amount of residual non-top background ($Z$+jets, diboson)
  - Jet energy scale, jet energy resolution
- Uncertainty on $p_T$ dependence still significantly impacts ATLAS top mass measurement.

$$SF = \frac{\text{eff(data)}}{\text{eff(MC)}}$$

![Graph showing b-jet efficiency scale factors](attachment:Graph.png)

| $p_T$ region | SF
|-------------|-----|
| 20-30 GeV   | 0.979
| 30-40 GeV   | 0.986
| 40-50 GeV   | 0.985
| 50-60 GeV   | 0.980
| 60-75 GeV   | 0.971
| 75-90 GeV   | 0.980
| 90-110 GeV  | 0.965
| 110-140 GeV | 1.000
| 140-200 GeV | 1.008
| 200-300 GeV | 1.000

See graphs for b-jet efficiency scale factors obtained from the combination of SF~0.98.

**Integral:** $\int L dt = 20.3 \text{ fb}^{-1}$

**Energy:** $s = 8 \text{ TeV}$
B-jet calibration in CMS

- Main calibration provided by multi-jet events:
  - Either using muon in jets
  - Or using cross-calibration of different taggers (e.g. Jet Probability (JP) based on impact parameters before/after applying a cut on the algorithm to calibrate)

- While these methods introduce some MC dependence, they have the advantage that they allow to calibrate jets well above 200 GeV (for which ATLAS right now only uses MC extrapolation).

- At lower pT (20-200 GeV) a precision of 2-4% is obtained. Still relies mostly on multijet events, while the top based measurement has still larger uncertainties.
Light-jet calibration

- Relying mainly on negative tag method
  - Hypothesis: tracks from light jets are symmetric with respect to their lifetime sign.
  - Procedure: use “fake tracks or vertices” with negative lifetime sign to emulate the ones with positive sign
- However two corrections are needed to $\varepsilon(\text{neg})$:
  - $k_{hf} = \frac{\varepsilon_{\text{neg}}}{\varepsilon_{\text{inc}}}$ due to the contamination of tracks from b- and c-jets
  - $k_{ll} = \frac{\varepsilon_{l}}{\varepsilon_{l}^{\text{neg}}}$, because of tracks in light jets which are not symmetric in lifetime sign (e.g. from conversions, Ks, $\Lambda$s, …)
- Mistag rate determined as:
  \[ \varepsilon_{l} = \varepsilon_{\text{inc}} k_{hf} k_{ll} \]
- Errors of the order of $\sim 30\%$
- CMS uses $\sim$same method, but ends up with smaller uncertainties.
**Upgrade for Run-II**

- **Insertable B Layer:** new pixel layer, closer to interaction point
- It is installed on top of a new (thinner) beam pipe
- Was inserted into ATLAS on May 7th 2014.
- Planar sensors in central region, 3d sensors in forward region.

**IBL:**
- Additional pixel layer $R \approx 3.3 \text{ cm}$
- Pixel size $50 \times 250 \mu\text{m}$

**ATLAS “b”-layer:**
- $R \approx 5.1 \text{ cm}$, pixel size $50 \times 400 \mu\text{m}$
B-tagging performance with IBL

- Tracking resolution: multiple scattering term reduced by ~70%, intrinsic resolution in z improved by ~80% for |η|<0.4

- B-tagging (top pair events):
  - factor 2 improvement in light-jet rejection
  - counteracts degradation due to up to ~50 additional pile-up interactions

- More detailed studies show:
  - Improvement mostly at low pT (up to x3-4).
  - Performance for pT>200 GeV nearly unchanged.
Tracking in the core of high pT jets

- Degradation due to collimated tracks in core of high pT jets: for R~3cm already relevant at pT \(\sim O(200 \text{ GeV})\)
- Relevant for VH analysis at high pT(V)

- Neural Network based clustering: allows to identify and split correctly most of the shared clusters
- Status: already commissioned with present pixel detector, now being retuned for IBL.
- Aim: be able to exploit the improved track resolution also at high pT!
Beyond Run-II

- **Phase-I Upgrade**
  - Instantaneous luminosity up to $\sim 2.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mu \sim 50\%$)
    - Run from 2019 to 2022 to get $\sim 300 \text{ fb}^{-1}$

- **Phase-II Upgrade (High Lumi - LHC)**
  - Instantaneous luminosity up to $\sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($\mu \sim 140\%$)
    - Run from 2023 to 2034 to get $\sim 3000 \text{ fb}^{-1}$

- **Inner Detector Upgrade**
  - **CMS**: for Phase-I (ATLAS plans to live with present detector + IBL) [TDR 2012]
  - **ATLAS**: for Phase-II, all-silicon Inner Detector [LoI 2012]
Upgrade of ATLAS Inner Detector (ITK)

- Present pixel detector designed to survive until ~400 fb⁻¹, IBL until ~850 fb⁻¹
- SCT and TRT not be able to cope with High Lumi occupancy → build more granular all-silicon detector

- Barrel:
  - Presently: 3 pixel, 4 SCT, TRT
  - Proposed: 4 pixel, 3 short-strip, 2 long-strip layers
  - 3 → 6 pixel discs
  - Plan to use ID earlier in trigger chain (100 kHz → 200-500 kHz, challenging!)

- New pixel detector
  - Withstand $10^{16} \text{n}_{\text{eq}} / \text{cm}^2$
  - 60M → 600M channels
  - 25x150 μm pixels
  - Planar, 3d or diamond
Projected performance

- **9 → 11** hits per track, to suppress fakes

<table>
<thead>
<tr>
<th>Track parameter</th>
<th>Existing ID with IBL no pile-up</th>
<th>Phase-II tracker 200 events pile-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 0.5$</td>
</tr>
<tr>
<td>Inverse transverse momentum ($q/p_T$) [TeV]</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Transverse impact parameter ($a_0$) [\mu m]</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Longitudinal impact parameter ($z_0$) [\mu m]</td>
<td>65</td>
<td>50</td>
</tr>
</tbody>
</table>

- First b-tagging studies show improvement $x4$ in light-jet rejection with no pile-up w.r.t. present ID
- Much less degradation due to pile-up
- Algorithms not yet optimized for pile-up
(Some) alternative layouts

- **Five pixel barrel layers**
  - More robust pattern recognition
  - But more material

- **Alpine layout**
  - Make sensors more perpendicular to incoming particles
  - Reduces traversed material
CMS upgrade for Phase-I

- Also move to 4 pixel layers in barrel (as in ATLAS after addition of IBL)
- First layer 4.4 → 3 cm
- Pixel size still 100x150 μm

- Much less material
B-tagging performance

- Without pile-up 3x better light-jet rejection @ 70% efficiency
- Better with respect to the current ATLAS upgrade with IBL because of the significant decrease in material budget
- Will allow to efficiently counteract the effect of pile-up.
Prospects for Higgs couplings...

- Projections publicly available for CMS, which rely on the performance of the upgraded detector (to counteract the effect of pile-up).

![CMS Projection Diagram]

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>300 fb$^{-1}$</td>
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<tr>
<td></td>
<td>Scenario 1</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>6.5</td>
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<tr>
<td>$\kappa_V$</td>
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<tr>
<td>$\kappa_0$</td>
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<tr>
<td>$\kappa_b$</td>
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<tr>
<td>$\kappa_t$</td>
<td>14</td>
</tr>
<tr>
<td>$\kappa_T$</td>
<td>8.5</td>
</tr>
</tbody>
</table>

- Predictions are hard, as the main problem is controlling the backgrounds to levels of accuracy of per mille, which is VERY challenging!
  - Here the assumption is made that systematic uncertainties also scale with luminosity. So these are rather indications of the maximum ultimative precision one could reach, rather than solid predictions.

- Nevertheless it shows the incredible potential of 300 or 3000 fb$^{-1}$ of LHC data.
Summary and outlook

• Identification of b-quark jets in LHC Run-I matched and exceeded expectations
  → Can select 70% of b-jets, with well below 1% light-jet fake rates

• Calibration for b-jets reached a precision of 2-4% over most of the pT spectrum (against ~5% of most optimistic assumptions before start of data taking)

• Rejection of c-jets has been significantly improved, but more work needed to reach decent c-tagging performance

• The insertion of IBL in ATLAS or, in the future, the tracker upgrades of ATLAS and CMS will further improve the performance, despite the more and more demanding high pile-up conditions.

• Exciting times are (still!) ahead of us!