Jet physics at colliders

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A jet definition is a systematic procedure that projects away the multiparticle dynamics, so as to leave a simple picture of what happened in an event:

Jets are as close as we can get to a physical single hard quark or gluon: with good definitions their properties (multiplicity, energies, [flavour]) are

- finite at any order of perturbation theory
- insensitive to the parton → hadron transition

NB: finiteness ←→ set of jets depends on jet def.
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NB: finiteness ↔ set of jets depends on jet def.
Jet (definitions) provide central link between expt., “theory” and theory
And jets are an input to almost all analyses
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And jets are an input to almost all analyses
1. Infrared and Collinear unsafe jet algorithms have been with us for a long time

It’s time to relegate them to where they belong

20th century history
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It’s time to relegate them to where they belong.

20th century history
Jet-finding has been painless at HERA, but not at Tevatron. **WHY?**

I don’t know the true answer, but here are some guesses

<table>
<thead>
<tr>
<th><strong>HERA</strong></th>
<th><strong>Tevatron</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inherited JADE-type algorithms</td>
<td>Inherited <em>pp</em> cone algs</td>
</tr>
<tr>
<td>Problematic/complex from the start</td>
<td></td>
</tr>
<tr>
<td>Much QCD, some searches</td>
<td>Many searches, some QCD</td>
</tr>
<tr>
<td>Jet-finding had to be decent</td>
<td>Jet-finding relevance is more subtle</td>
</tr>
<tr>
<td>Complexity $\sim$ that of LEP</td>
<td>Complexity $\gg$ that of LEP</td>
</tr>
<tr>
<td>Moderate multiplicites</td>
<td>Multiplicites higher</td>
</tr>
<tr>
<td>UE small, $dp_t/d\eta \sim 0.5 - 1$ GeV</td>
<td>UE large, $dp_t/d\eta \sim 2.5 - 5$ GeV</td>
</tr>
<tr>
<td>$e^+e^-$-inspired solutions work</td>
<td>$e^+e^-$-inspired solutions have issues</td>
</tr>
</tbody>
</table>

NB: LHC more like Tevatron than HERA
<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Type</th>
<th>IRC status</th>
<th>Notes</th>
</tr>
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<tr>
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<tr>
<td>Run II Seedless cone</td>
<td>SC-SM</td>
<td>OK</td>
<td>slow: $N2^N$ !!</td>
</tr>
<tr>
<td>CDF JetClu</td>
<td>$IC_{r-SM}$</td>
<td>IR$^{2+1}$</td>
<td>for top physics, searches</td>
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<tr>
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$SR = \text{seq.rec.};\ IC = \text{it.cone};\ FC = \text{fixed cone};$

$SM = \text{split–merge};\ SD = \text{split–drop};\ PR = \text{progressive removal}$

$IR_{n+1}$: for $n$ nearby hard partons, 1 soft emitted gluon can change hard jets

$Coll_{n+1}$: for $n$ nearby hard partons, 1 collinear splitting can change hard jets
### What's out there?

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**SR** = seq.rec.; **IC** = it.cone; **FC** = fixed cone;  
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**IR$_{n+1}$**: for $n$ nearby hard partons, 1 soft emitted gluon can change hard jets  

**Coll$_{n+1}$**: for $n$ nearby hard partons, 1 collinear splitting can change hard jets
Does lack of IRC safety matter?

I do searches, not QCD. Why should I care about IRC safety?

- If you’re looking for an invariant mass peak, it’s not 100% crucial
  
  IRC unsafety \( \sim R \) is ill-defined
  
  A huge mass peak will stick out regardless

Well, actually my signal’s a little more complex than that...

- If you’re looking for an excess over background you need confidence in backgrounds
  
  E.g. some SUSY signals

  - Check \( W+1 \) jet, \( W+2 \)-jets data against NLO in control region
  - Check \( W+n \) jets data against LO in control region
  - Extrapolate into measured region

- IRC unsafety means NLO senseless for simple topologies, \( LO \) senseless for complex topologies
  
  Breaks consistency of whole
  
  Wastes \( \sim 50,000,000 \) $/£/CHF/€

But I like my cone algorithm, it’s fast, has good resolution, etc.

- Not an irrelevant point
  
  \( \rightarrow \) has motivated significant work
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If you're looking for an invariant mass peak, it's not 100% crucial. IRC unsafety $\approx R$ is ill-defined. A huge mass peak will stick out regardless.

The complex than that... Of course, if you're looking for a signal over background you need confidence in your background estimation. E.g. some SUSY signals. Check $W + n$ jets data against NLO in control region. Check $W + 1 \text{ jet}$, $W + 2 \text{-jets}$ data against LO in control region. Extrapolate into measured region.

IRC unsafety means NLO senseless for simple topologies, LO senseless for complex topologies. Breaks consistency of whole.

Wastes $\sim 50,000,000$ $\text{\$}/\text{\£}/\text{\CHF}/\text{\€}$.

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But I like my cone algorithm, it’s fast, has good resolution, etc.

- Not an irrelevant point \( \rightarrow \) has motivated significant work
CDF hep-ex/0512062 & hep-ex/0701051 inclusive-jet measurements show that basic behaviour of $k_t$ algorithm is as good as that of cone.

**Crucial difference relative to HERA is use of $R < 1$ (NB $R \equiv D$)**

Why? Because of different scale of UE

Lesson adopted by LHC experiments in past couple of years
## #2: fixing available algs

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<tr>
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<th>Evolution</th>
</tr>
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<tbody>
<tr>
<td>exclusive $k_t$</td>
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</tr>
<tr>
<td>D0 Run II cone</td>
<td>IC$_{mp}$-SM</td>
<td>IR$_{3+1}$</td>
<td>$\rightarrow$ SISCone [with $p_t$ cut?]</td>
</tr>
<tr>
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<td>IC-SM</td>
<td>IR$_{2+1}$</td>
<td>$\rightarrow$ SISCone</td>
</tr>
<tr>
<td>PxCone</td>
<td>IC$_{mp}$-SD</td>
<td>IR$_{3+1}$</td>
<td>[little used]</td>
</tr>
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SR = seq.rec.; IC = it.cone; FC = fixed cone;
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A full set of IRC-safe jet algorithms

Generalise inclusive-type sequential recombination with

\[ d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \Delta R_{ij}^2 / R^2 \quad d_{iB} = k_{ti}^{2p} \]

<table>
<thead>
<tr>
<th>Alg. name</th>
<th>Comment</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p = 1 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( k_t )</td>
<td>Hierarchical in rel. ( k_t )</td>
<td>( N \ln N ) exp.</td>
</tr>
<tr>
<td>CDOSTW '91-93; ES '93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p = 0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambridge/Aachen</td>
<td>Hierarchical in angle</td>
<td>( N \ln N )</td>
</tr>
<tr>
<td>Dok, Leder, Moretti, Webber '97</td>
<td>Scan multiple ( R ) at once</td>
<td></td>
</tr>
<tr>
<td>Wengler, Wobisch '98</td>
<td>( \leftrightarrow ) QCD angular ordering</td>
<td></td>
</tr>
<tr>
<td>( p = -1 )</td>
<td></td>
<td>( N^{3/2} )</td>
</tr>
<tr>
<td>( \text{anti-}k_t )</td>
<td>Hierarchy meaningless.</td>
<td></td>
</tr>
<tr>
<td>Cacciari, GPS, Soyez '08</td>
<td>Behaves like IC-PR</td>
<td></td>
</tr>
<tr>
<td>( \sim ) reverse-( k_t )</td>
<td>Delsart, Loch et al.</td>
<td></td>
</tr>
<tr>
<td>SC-SM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SISCone</td>
<td>Replacement for IC-SM</td>
<td>( N^2 \ln N ) exp.</td>
</tr>
<tr>
<td>GPS Soyez '07 + Tevatron run II '00</td>
<td>notably “MidPoint” cones</td>
<td></td>
</tr>
</tbody>
</table>

Compromise between having a limited set of algs. and a good range of complementary properties

See talk by G. Soyez about the newer algs., SISCone & anti-\( k_t \)
anti-$k_t$ v. Cone (ICPR) jets
2.

Let’s ask *useful* questions about jets

- When a jet is 1 parton
- When a jet is 2, 3 partons
- When a jet is 0 partons
Traditional use of jets: as a stand-in for a single parton

Basic questions:

- Which jet algorithms work best?
- What value of jet angular radius $R$ is best?
- How does answer depend on the momentum scale? LHC ranges from 25 GeV to 5 TeV
- How does answer depend on pileup?
- What logic behind all of this?
How to establish jet-def\textsuperscript{n} quality?

Partons are not physical objects
divergent, meaningless @ NLO, etc.
Parton-jet matching is \textit{not} the way to go

\textbf{Instead:} use physical decays (imaginary narrow $Z'$, H) to investigate question rigorously.

Cacciari et al.; Büge et al., LH'07

How do you measure quality?

- Look at invariant mass peak
- Do not fit a Gaussian!
- \textbf{Instead} measure minimal width containing 40\% (say) of invariant mass peak

See talk by J. Rojo in final-states session
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\begin{itemize}
  \item $M_{Z'} = 100$ GeV
  \item $R = 0.7$
\end{itemize}

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What’s the “best” jet-def?

Jet definition $\equiv$ jet-alg + choice of parameters

Try all options

- $R$ dependence is crucial
- Non-trivial interplay with hard scale $\text{high-}p_t \rightarrow \text{large } R$
- Qualitative understanding based on analytical arguments

Knowledge of $R$-dep of PT, Hadr, UE effects is key to good choice of jet def.

See talks by L. Magnea and M. Dasgupta

Pythia 6.4 + DWT tune + FastJet
Cacciari, Rojo, GPS & Soyez ’08
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Crude analytical estimates
Dasgupta, Magnea & GPS '07

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Crude analytical estimates
Dasgupta, Magnea & GPS '07

See talks by L. Magnea and M. Dasgupta
$R$ is a free parameter — a bit like “focus” in a camera.

Measuring several $R$-values helps inform our understanding of non-perturbative effects & contributes to a habit of **flexible jet finding**.

![Graphs showing jet production and $R$-dependence](image)

**Powerful cross check on theoretical ideas & MCs;**  
Please: more like this, also with larger range of $R$!
Pushing jets to their limit:
when a $W$, $Z$, $H$ or a top $\rightarrow$ a single jet

Not unusual at LHC: $m_W, m_t \ll 14$ TeV
Illustrate LHC challenges with a recently widely discussed class of problems:

Can you identify hadronically decaying EW bosons when they’re produced at high $p_t$?

$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Significant discussion over years: heavy new things decay to EW states

- Seymour '94 [Higgs $\rightarrow WW \rightarrow \nu \ell$jets]
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Using jets @ LHC

1 jet $\gtrsim 2$ partons

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![Diagram of boosted X decaying into single jet](image)

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Brooijmans ’08 ATL-PHYS-CONF-2008-008, based on $k_t$ algorithm

Use subjet relative transverse-momentum scale (”y-scale”) & correlation with jet mass to pick out top quarks from background

**top quarks** $p_t \sim 1$ TeV

**normal jets**
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*Efficiencies*

*Normal jets*

*Top quarks*
Using jets @ LHC

$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

[Herwig 6.5 + Jimmy 4.31 + FastJet Cam/Aa R=1.2]

Butterworth, Davison, Rubin & GPS ’08

Possible new (light) Higgs discovery channel
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[SIGNAL]

$Z_{bb}$ BACKGROUND

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arbitrary norm.
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 возможный новый (легкий) конечный канал обнаружения Хиггса

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Предполагаемый новый (легкий) канал обнаружения Хиггса
Using jets @ LHC

1 jet $\gtrsim$ 2 partons

$pp \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

SIGNAL

Final filtered result, $p_t=227.257$ m=117.211

[Herwig 6.5 + Jimmy 4.31 + FastJet Cam/Aa R=1.2]

Butterworth, Davison, Rubin & GPS '08

Much to be learnt still about extracting boosted W/H/Z/top from bkgd; NB HERA has extensive experience with subjets.
Jets without hard partons:

Most jet algorithms give you \( \sim 50 \rightarrow 100 \) “jets,” mostly not hard.

*provide window on UE and min-bias*
Usual approach to UE

Marchesini-Webber idea:
look at transverse region to measure underlying event

Topological selection
The jets are classified as belonging to the noise on the ground of their position

So far mostly average quantities
But full tuning of UE models needs point-to-point fluctuations & correlations, as well as event-to-event fluctuations
And difficult to use in complex events, e.g. top
Using jets @ LHC
1 jet \approx 0 \text{ partons}

Making use of all jets

Approximate linear relation between $P_t$ and area for minimum bias jets.

Can be used on an event-by-event basis to correct the hard jets.
E.g. take dijet events with $p_t > 50$ GeV, extract $\rho$ from the soft jets. Look at the distribution of $\rho$ across events:

Result for $\rho$ consistent in topological and jet-based methods;
But also get event-by-event dist.
Jet-based method works in complex events too (e.g. $t\bar{t}$)
E.g. select quiet events for clean studies

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Conclusions
Unlocking the power of jets at LHC means going beyond stale discussions of whether we really need IRC safe algorithms. For each IRC unsafe alg., there’s a good safe alternative. HERA offers a good example in its approach to jets.

The questions we face on jets cover LHC’s whole dynamic range:

- From $\sim 1$ GeV to multi-TeV
- The scales mix: UE with pileup with EW with TeV
- Understanding of low scales, substructure $\leftrightarrow$ HERA

The key to focusing with clarity on LHC events will be **flexibility**. Powerful ideas that rely on flexibility are here; more will come. LHC experiments’ ongoing efforts to build in flexibility are essential.

**Much more material & discussion in parallel session!**
EXTRAS
Real life does not have infinities, but pert. infinity leaves a real-life trace

$$\alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \infty \rightarrow \alpha_s^2 + \alpha_s^3 + \alpha_s^4 \times \ln p_t/\Lambda \rightarrow \alpha_s^2 + \alpha_s^3 + \alpha_s^3$$ BOTH WASTED

Among consequences of IR unsafety:

<table>
<thead>
<tr>
<th>Last meaningful order</th>
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NB: $30 − 50M investment in NLO

Multi-jet contexts much more sensitive: **ubiquitous at LHC**

And LHC will rely on QCD for background double-checks, extraction of cross sections, extraction of parameters
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Multi-jet contexts much more sensitive: **ubiquitous at LHC**

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extraction of cross sections, extraction of parameters
Many cone algs have two main steps:

- **Find some/all stable cones**
  \[
  \equiv \text{cone pointing in same direction as the momentum of its contents}
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- **Resolve cases of overlapping stable cones**
  By running a ‘split–merge’ procedure [Blazey et al. ‘00 (Run II jet physics)]
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**Qu: How do you find the stable cones?**

Until recently used iterative methods:

- use each particle as a starting direction for cone; use sum of contents as new starting direction; repeat.

**Iterative Cone with Split Merge (IC-SM)**

- e.g. Tevatron cones (JetClu, midpoint)
- ATLAS cone
Iterative Cone [with progressive removal]

Procedure:

- Find one stable cone
  By iterating from hardest seed particle
- Call it a jet; remove its particles from the event; repeat
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**Iterative Cone with Progressive Removal (IC-PR)**

- e.g. CMS it. cone, [Pythia Cone, GetJet], …
- **NB: not same type of algorithm as Atlas Cone, MidPoint, SIScone**
Jet contours – visualised

Different cone types

- $k_t$, $R=1$
- Cam/Aachen, $R=1$
- SISCon, $R=1$, $f=0.5$
- anti-$k_t$, $R=1$
One last reason sometimes quoted for using IRC unsafe algs:

“Our trigger uses the XYZ cone, and we want to have the same algorithm in the trigger and the physics analyses”

And our trigger people are very conservative and will never change algorithm

A possible response:

- Low-level and high level triggers often use different algs anyway
- Algs like anti-$k_t$ are definitely fast enough (1ms [20ms] at low [high] lumi) to fit comfortably within the time per event, $O(1\text{s})$, in the HLT
- anti-$k_t$ and plain (trigger) cones should give similar jets: you can trigger if jets from either pass the cuts — increase in bandwidth should be negligible and if you really want your old trigger cone, you’ve still got it.
Status in 2005

Single package, **FastJet**, to access all developments, natively ($k_t$, Cam/Aachen) or as plugins (SISCone): Cacciari, GPS & Soyez ’05–07

http://www.lpthe.jussieu.fr/~salam/fastjet/
Status in 2007

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E.g.: WH/ZH search channel @ LHC

- Signal is $W \to \ell \nu, H \to b\bar{b}$.
- Backgrounds include $Wb\bar{b}$, $t\bar{t} \to \ell \nu b\bar{b}j$, . . .

Difficulties, e.g.

- $gg \to t\bar{t}$ has $\ell \nu b\bar{b}$ with same intrinsic mass scale, but much higher partonic luminosity
- Need exquisite control of bkgd shape

Try a long shot?

- Go to high $p_t$ ($p_{tH}, p_{tV} > 200$ GeV)
- Lose 95% of signal, but more efficient?
- Maybe kill $t\bar{t}$ & gain clarity?
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Searching for high-$p_t$ HW/HZ?

High-$p_t$ light Higgs decays to $b\bar{b}$ inside a single jet. Can this be seen?

**Butterworth, Davison, Rubin & GPS '08**

Cluster with Cambridge/Aachen

1. Find a high-$p_t$ massive jet $J$
2. Undo last stage of clustering ($\equiv$ reduce $R$)
3. If $m_{\text{subjets}} \lesssim 0.67m_J$ & subj $p_t$’s not asym. & each $b$-tagged $\rightarrow$ Higgs candidate
4. Else, repeat from 2 with heavier subjet

Then on the Higgs-candidate: *filter* away UE/pileup by reducing $R \rightarrow R_{\text{filt}}$, take *three hardest subjets* (keep LO gluon rad$^n$) + require $b$-tags on two hardest.
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combine HZ and HW, $p_t > 200$ GeV

Leptonic channel

- $p_t V, p_t H > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_t, \ell > 30$ GeV, $|\eta_\ell| < 2.5]$
- No extra $\ell, b$'s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 18 GeV window

Leptonic channel

$Z \rightarrow \mu^+ \mu^-, e^+ e^-$

- $80 < m_{\ell^+ \ell^-} < 100$ GeV

At 5.9$\sigma$ for 30 fb$^{-1}$ for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. Deserves serious exp. study!
combine HZ and HW, $p_t > 200$ GeV

**Missing $E_T$ channel**

- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
- $[p_{t,\ell} > 30$ GeV, $|\eta_{\ell}| < 2.5]$
- No extra $\ell$, $b$’s with $|\eta| < 2.5$
- Real/fake $b$-tag rates: 0.7/0.01
- $S/\sqrt{B}$ from 18 GeV window

**Common cuts**

- $S/\sqrt{B} = 4.0$ in 112-128 GeV

**Extra** Higgs

- $Z \rightarrow \nu \bar{\nu}, W \rightarrow \nu[\ell]$

- $E_T > 200$ GeV

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**Common cuts**
- $p_{tV}, p_{tH} > 200$ GeV
- $|\eta_H| < 2.5$
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- No extra $\ell, b$’s with $|\eta| < 2.5$
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**Semi-leptonic channel**
- $W \rightarrow \nu\ell$
  - $E_T > 30$ GeV (\& consistent $W$.)
  - no extra jets $|\eta| < 3, p_t > 30$

---

At 5.9\(\sigma\) for 30 fb\(^{-1}\) for $m_H = 115$ GeV this looks like a possible new channel for light Higgs discovery. **Deserves serious exp. study!**
combine HZ and HW, $p_t > 200$ GeV

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3 channels combined

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