NMSSM Higgs and Hidden Valleys at DØ

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for the DØ Collaboration

DPF 2009 - Wayne State University
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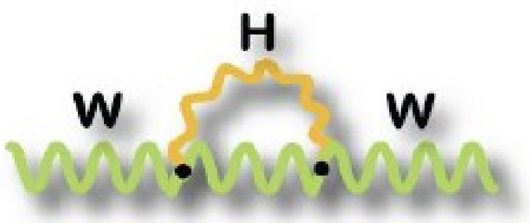
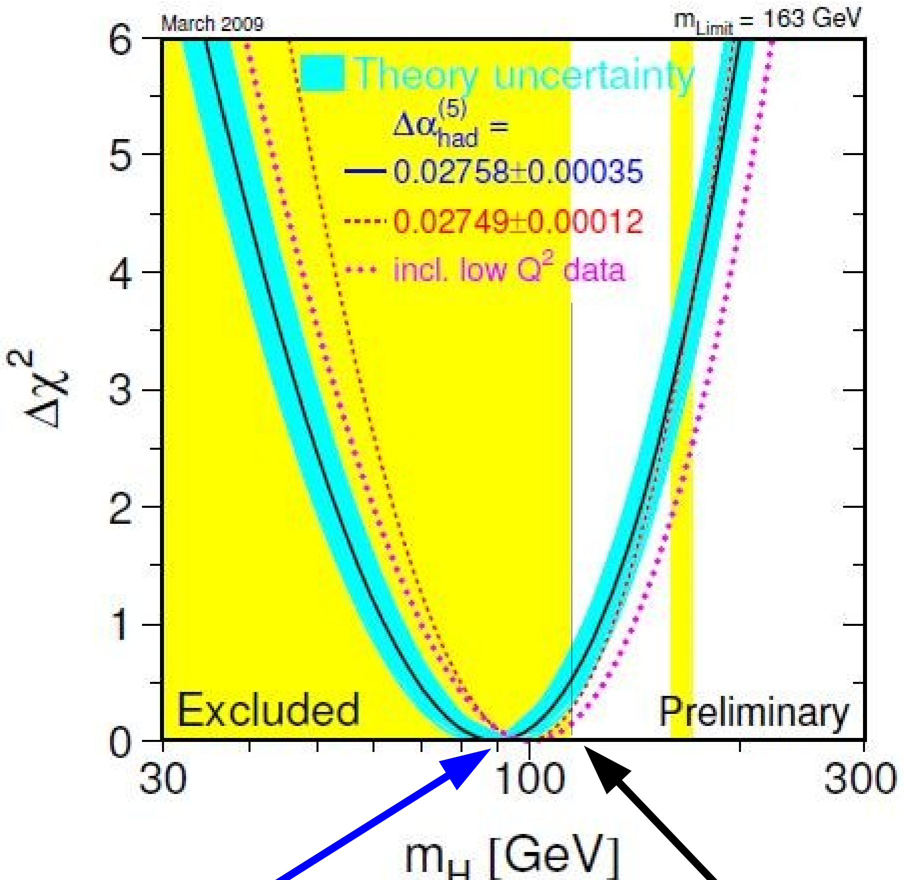
SLAC NATIONAL ACCELERATOR LABORATORY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Where's the Higgs ?



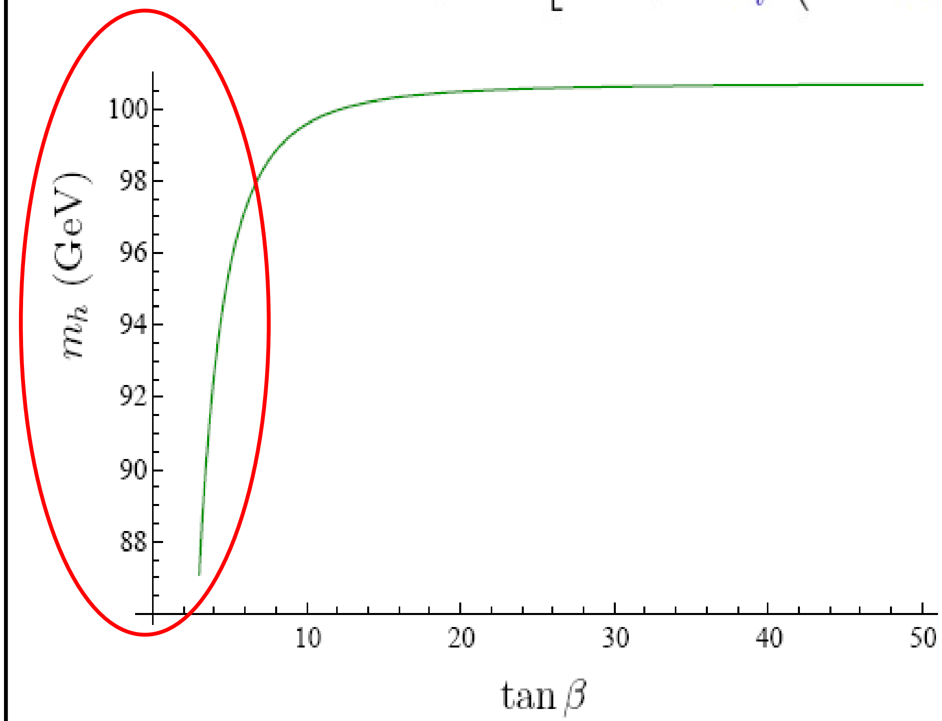
$$\sim \log \frac{m_H}{m_W}$$



M_h~95 GeV

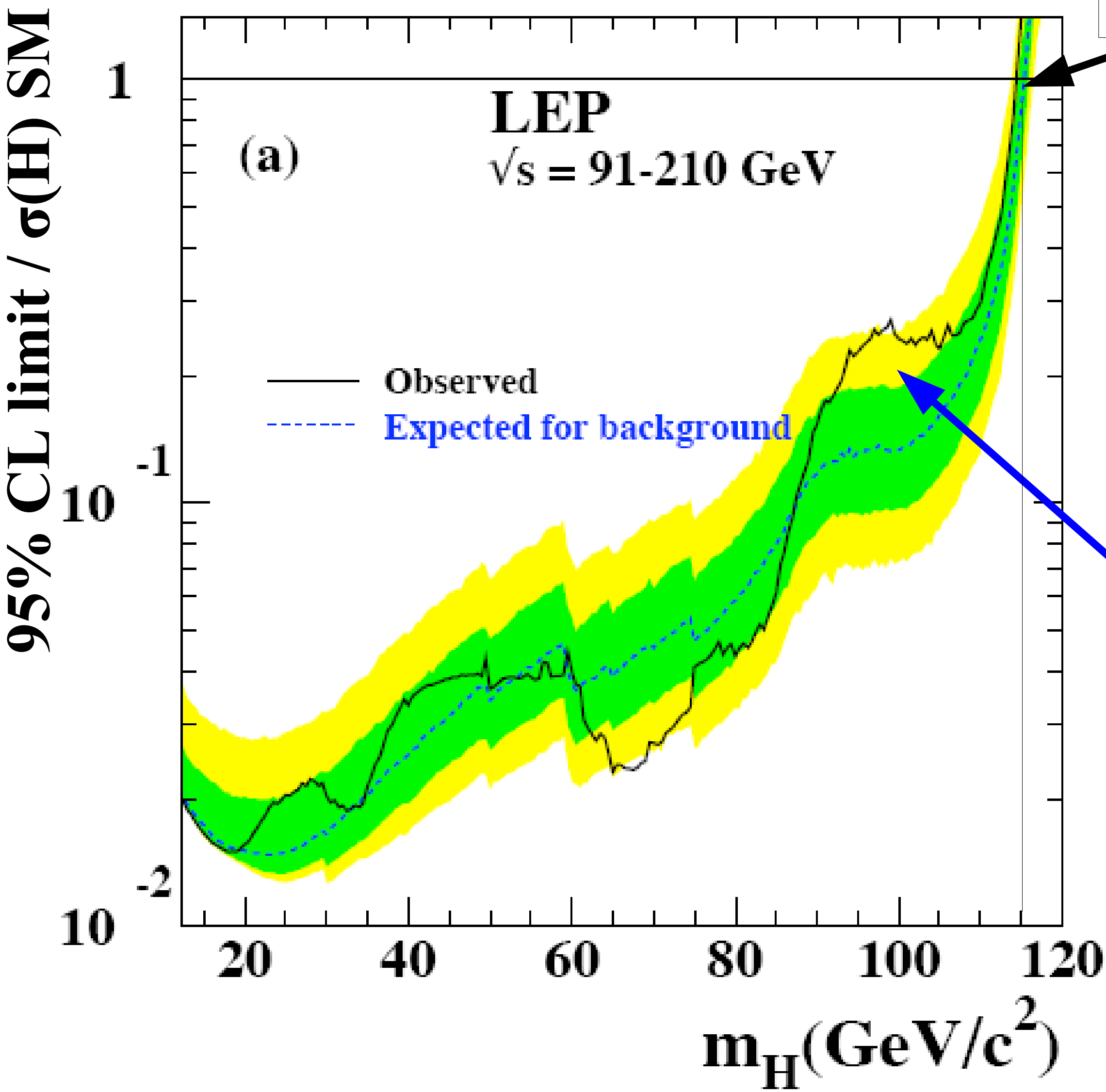
M_h>114.4 GeV

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$



SM-like Higgs mass typically <100 GeV in SUSY

Maybe LEP *did* see the Higgs ?



M_h>114.4 GeV

$h \to b\bar{b},\ \tau^+\tau^-$

2σ excess at M_H~95GeV

Consistent with BR(h→bb)~10%!

SM Higgs **decay** is *vulnerable*

Light Higgs decays to b quarks
but coupling is small ~1/60

New decay can easily dominate!

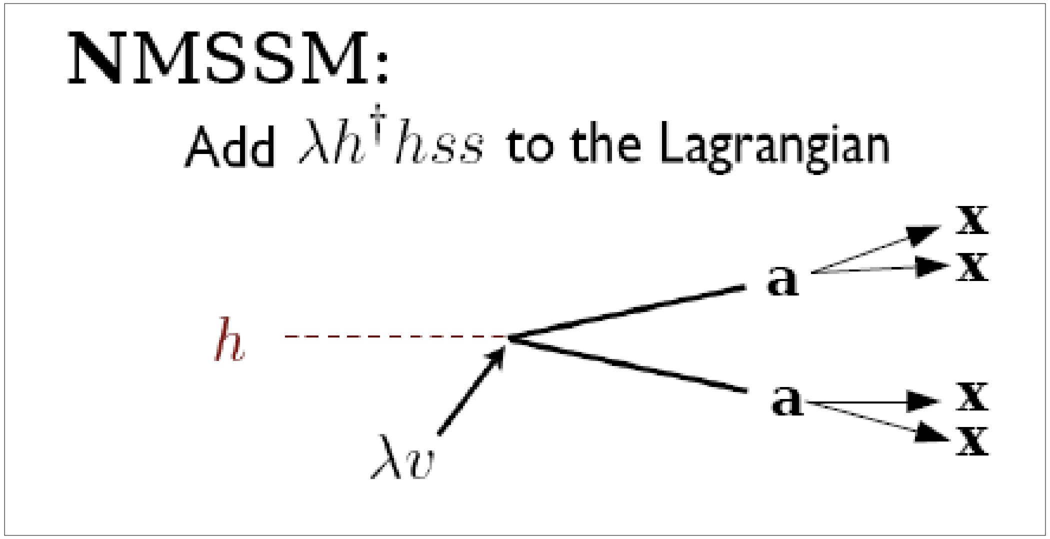
m_H > ~~114.4~~ GeV

4 b : 110 GeV

4 tau : 86 GeV

4 mu : 82 GeV ?

4 e : ?

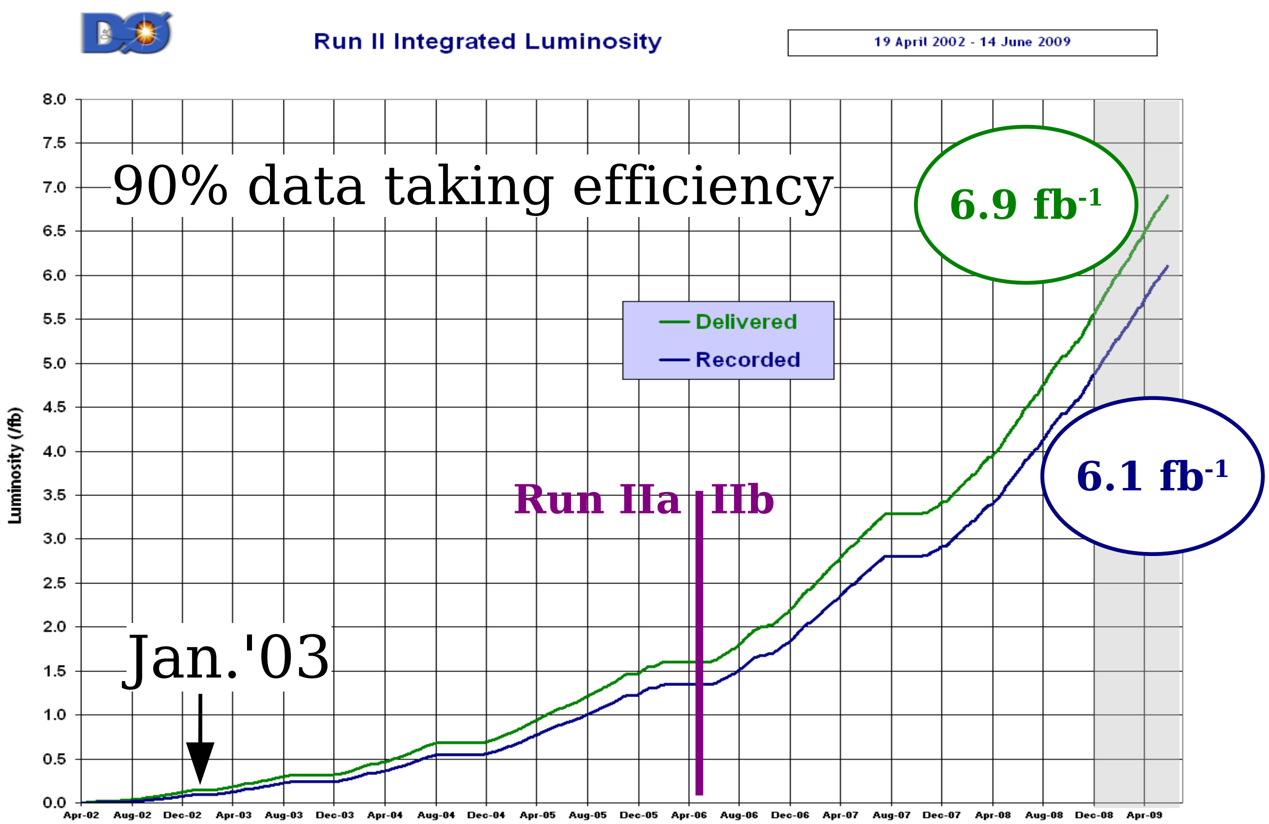


R. Dermisek and J.F. Gunion, Phys.Rev.Lett.95:041801 (2005).
“Non-standard Higgs Decays”: hep-ph/0801.4554 (2008).

Data at DØ

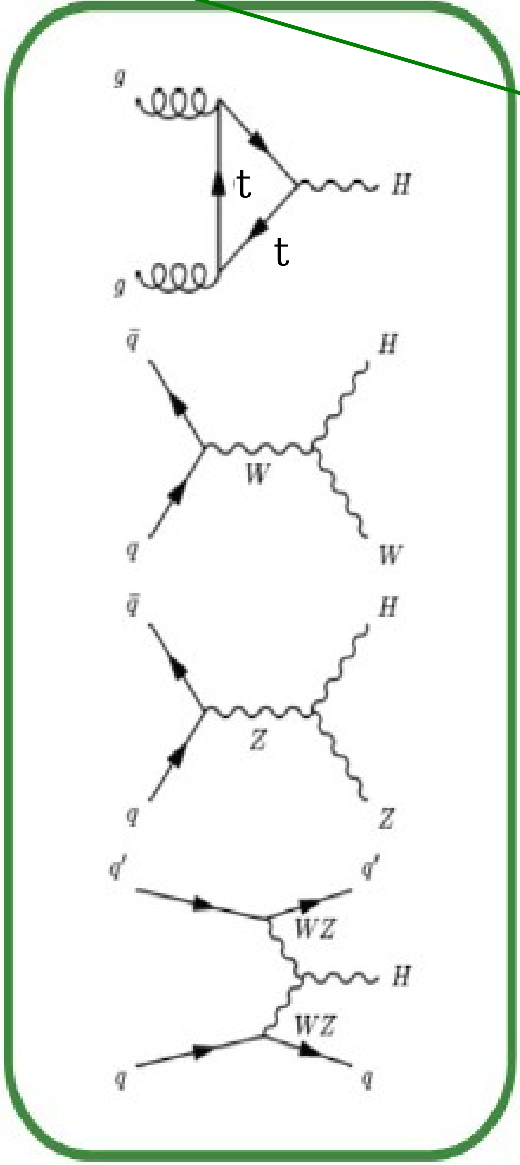
$p\bar{p}$ collider at 1.96 TeV

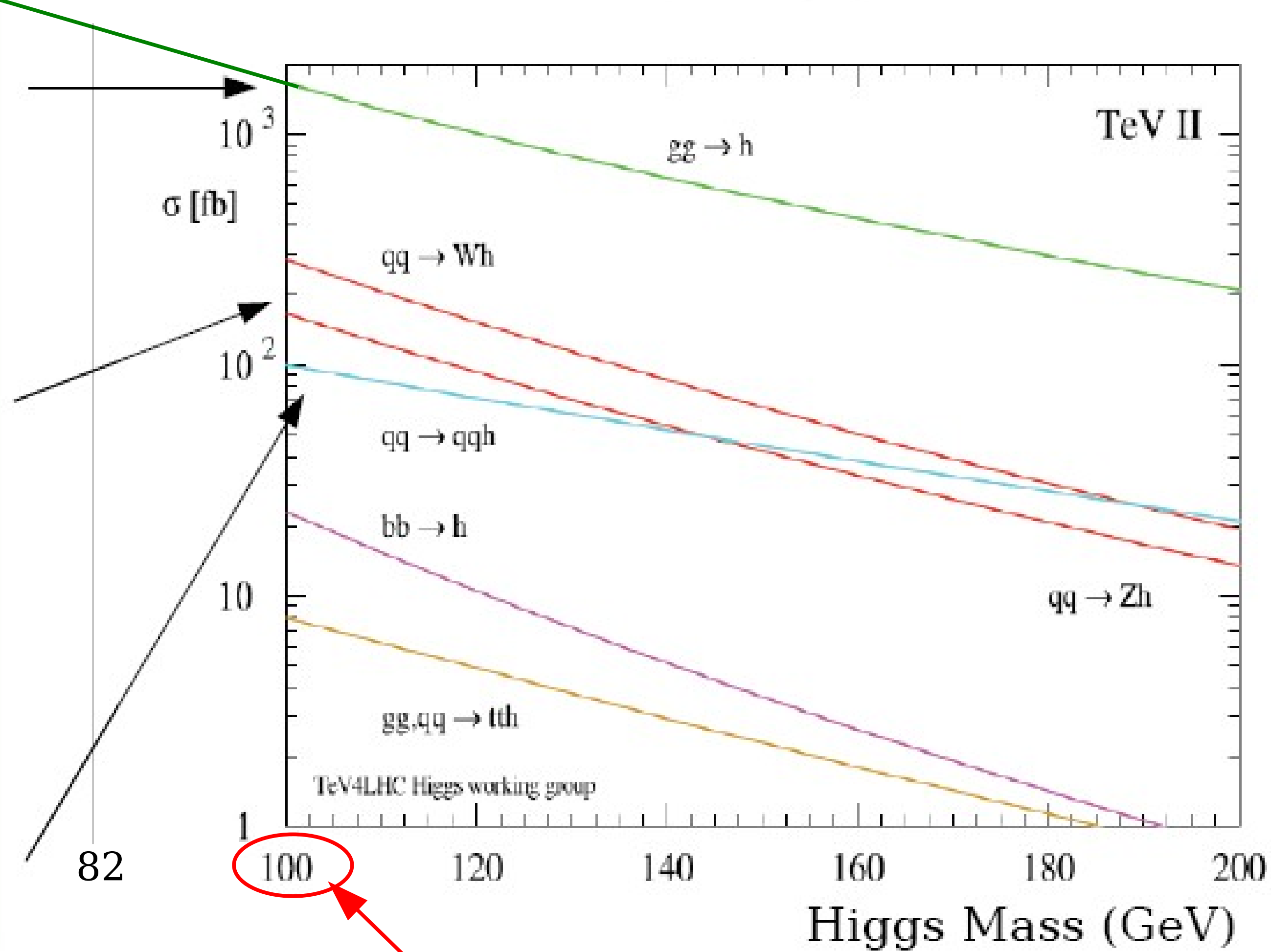
Up to **4.2 fb^{-1}** analyzed in this talk



Tevatron and DØ both performing very well!

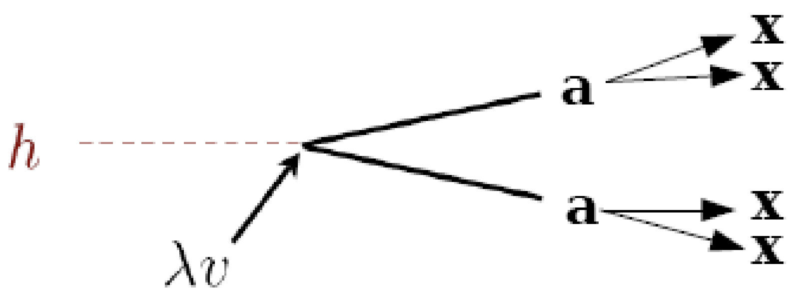
Higgs Production at the Tevatron





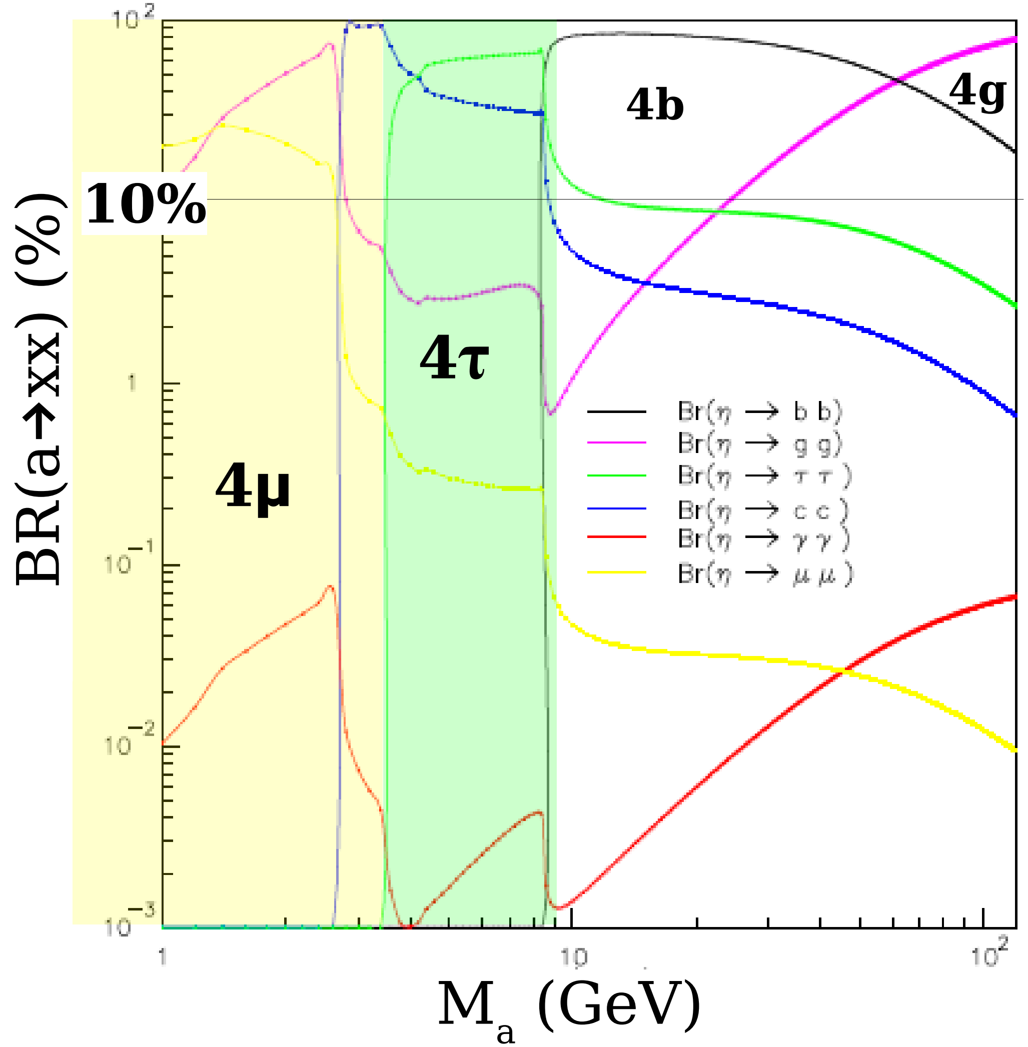
~10,000 Higgs events at the Tevatron (so far)!

Search for Higgs in the **N**MSSM



For $M_a < 2M_{tau}$, BR(a→μμ)~10%
(charm decays are typically suppressed in the NMSSM)

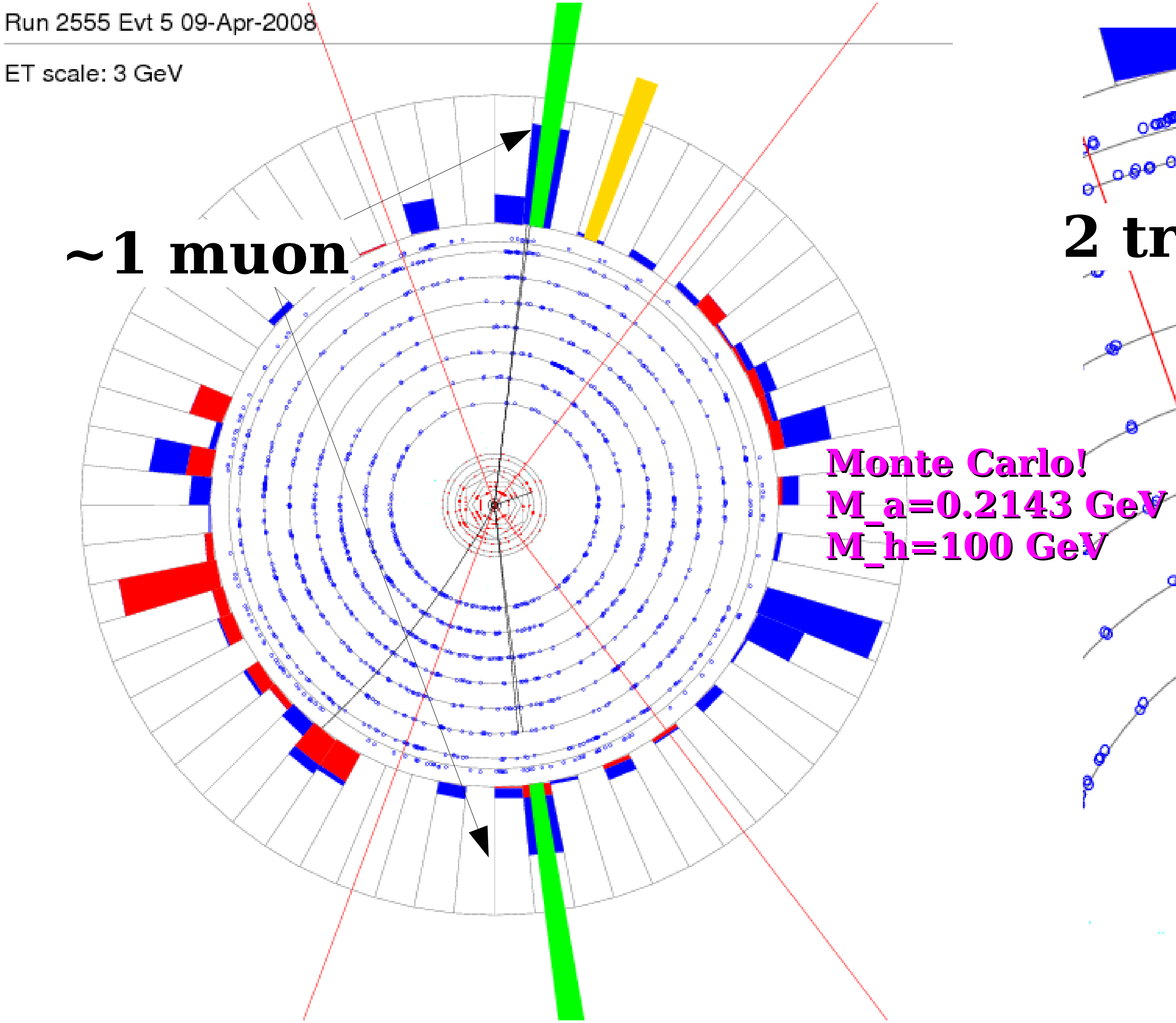
h→aa→4μ ~ 1%, but *clean*!

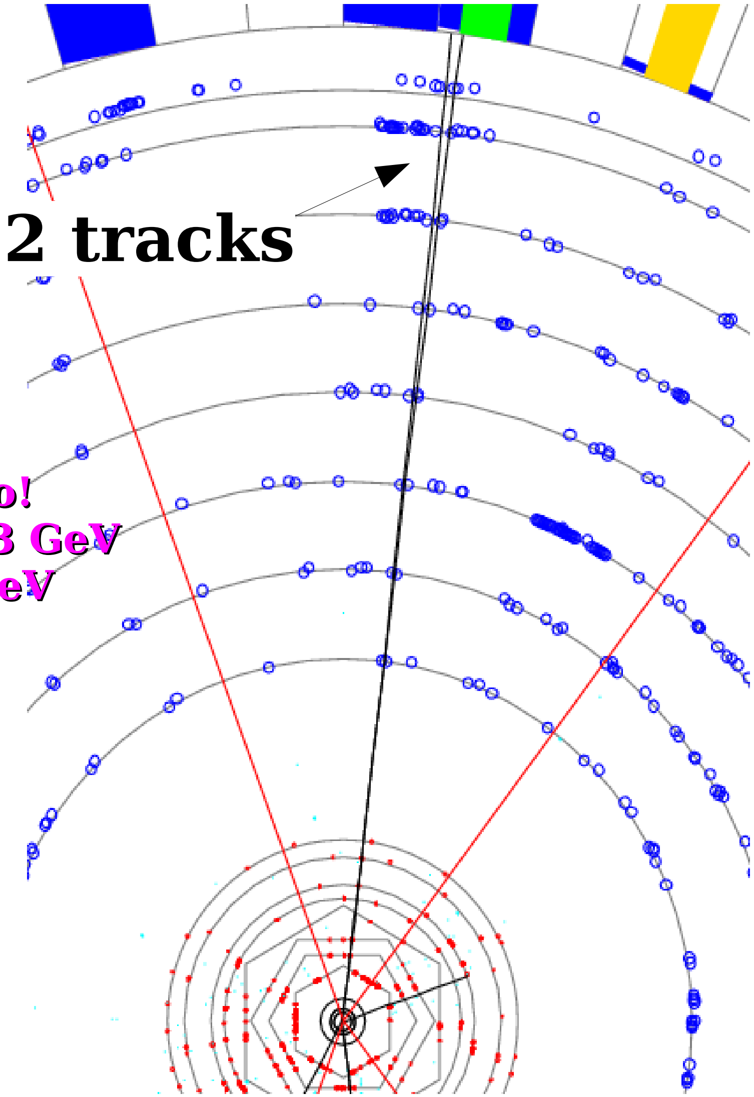


K. Cheung, J. Song, P. Tseng and Q.S. Yan, Phys. Rev. D78, 055015 (2008).

h→aa→4μ

Muon pairs can be extremely collinear !

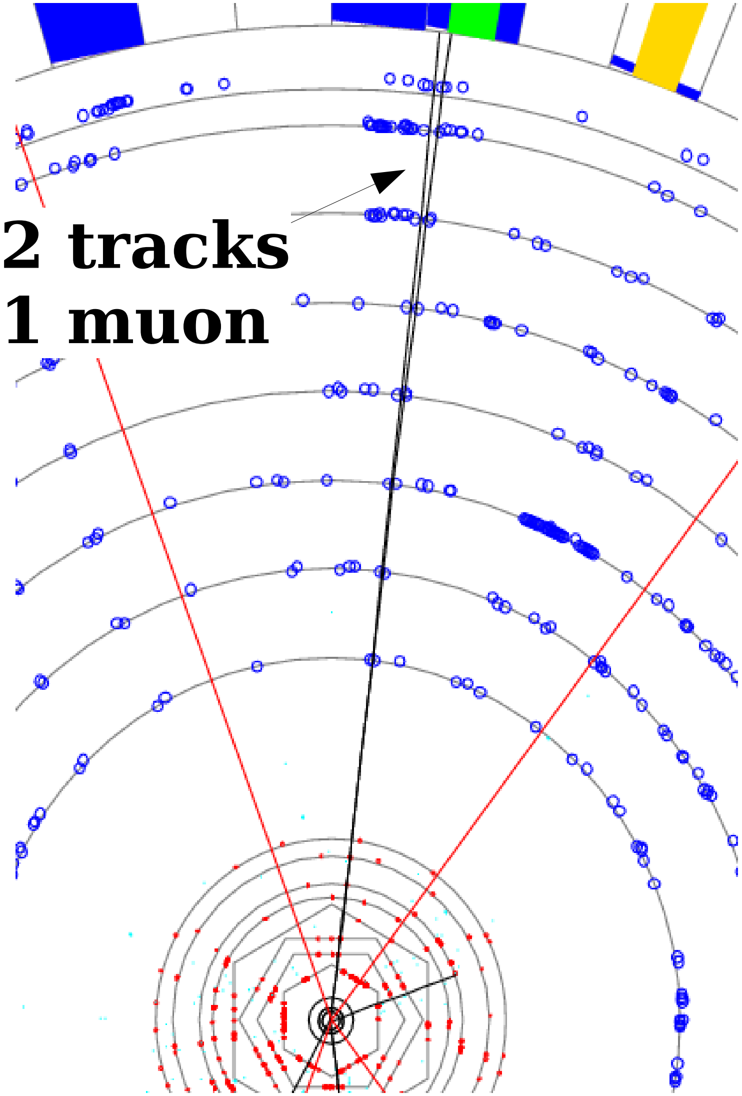




h→aa→4μ

2 muons (out of 4), p_T*>10 GeV*

Not relying on muon system to distinguish both muons of a pair



Reconstruction efficiency for muon?

- Uncertainty rises, from ~2% to ~10%

Multiple muon hits in drift tubes…

- Trigger efficiency per muon is ~20% lower, but have 2 of them

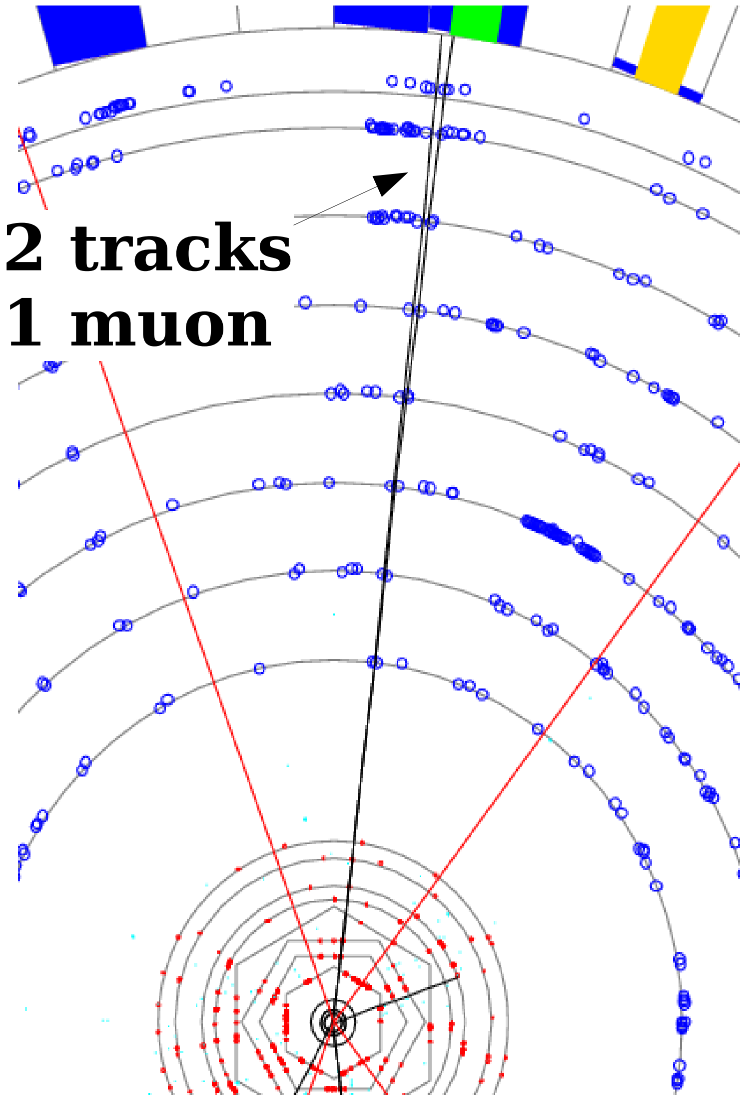
h→aa→4μ

"Companion track", p_T>4 GeV

Efficiency?
- high p_T K_s *in data*

Also see data/MC agreement in
- 3-prong tau decays
- photon conversions

Uncertainty: 20-50%



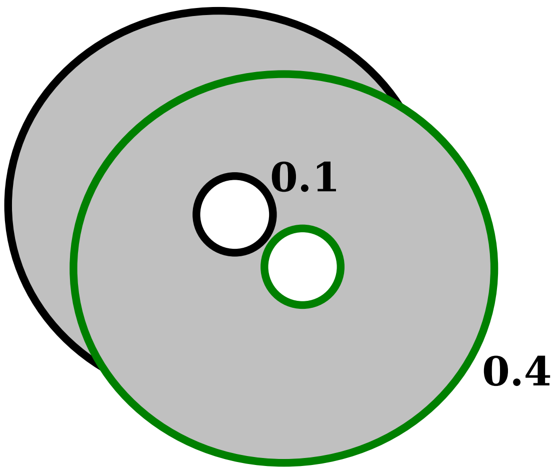
h→aa→4μ

Muon isolation in calorimeter

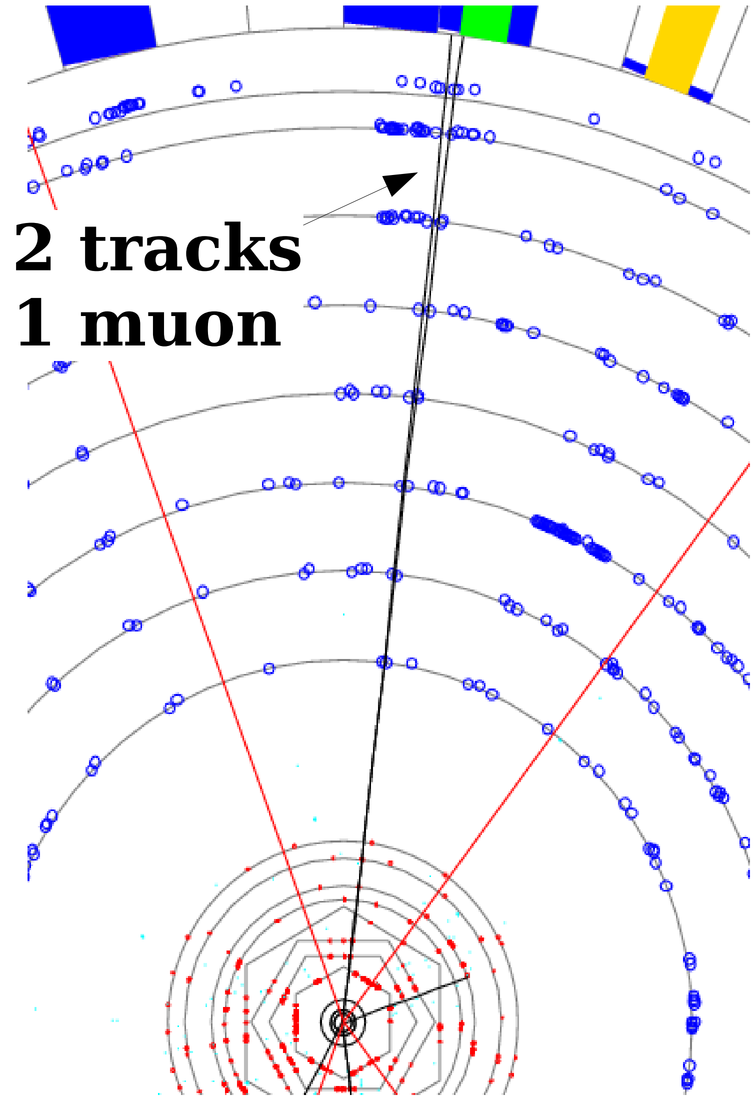
- reduces jet background

But muons overlap!

Custom muon isolation definition...



Higher M_a (~3 GeV)



h→aa→4μ

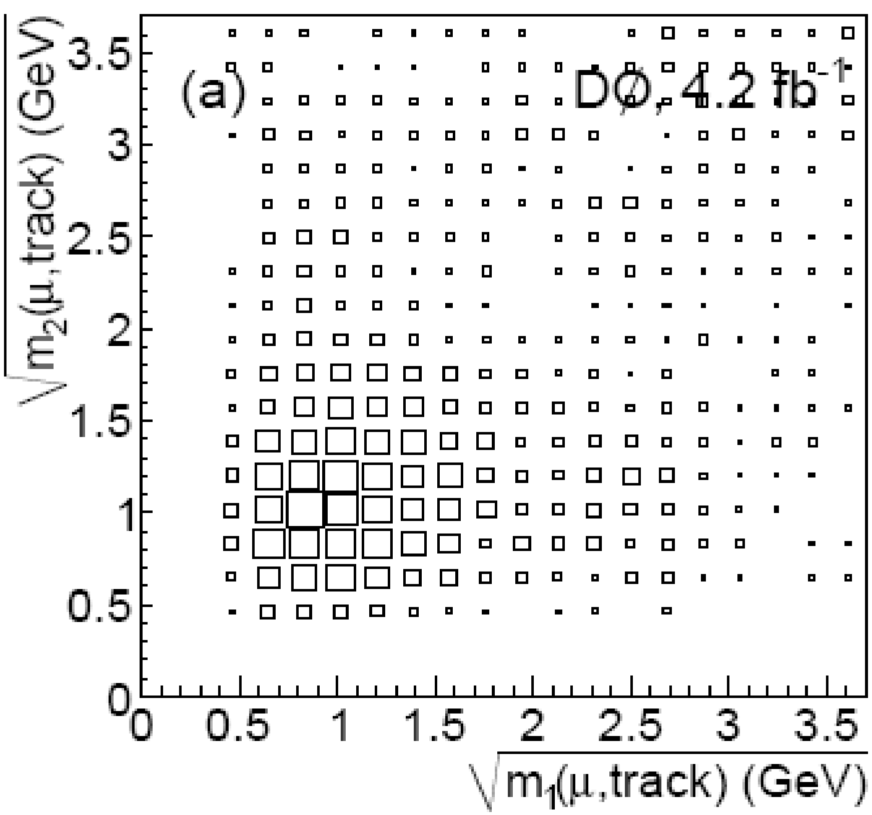
Backgrounds measured from (less isolated) data

- 1.9 events from QCD, 0.3 from Z→μμ

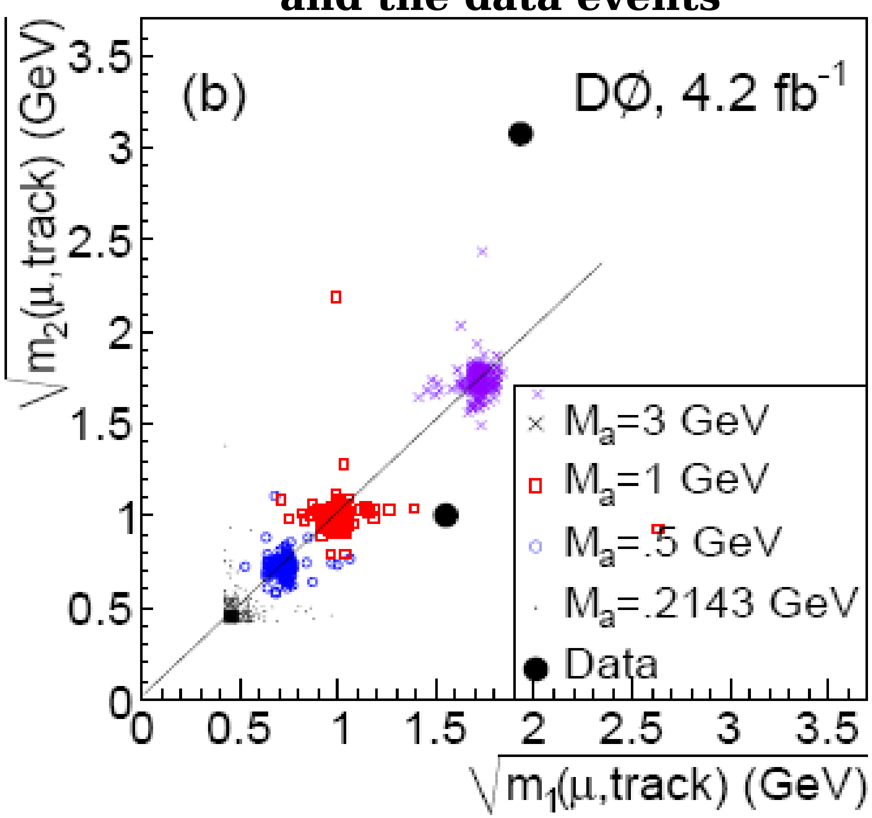
2 events are observed

- Don't have matching μ-track masses
- Also don't have >2μ, vs. ~50% of signal events

Estimated background



Signals for various M_a and the data events



h→aa→4μ

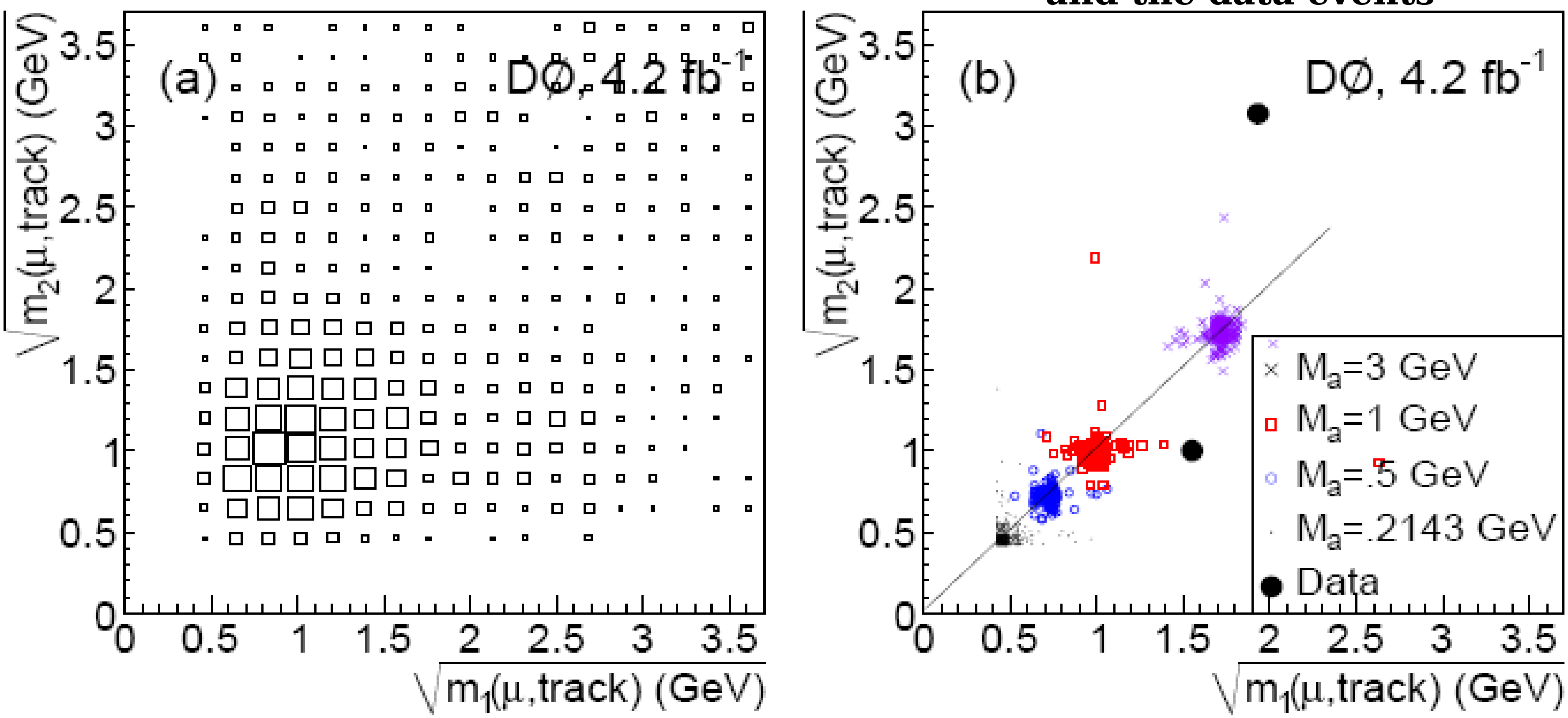
Count events within μ-track mass windows

For M_h=~100 GeV, BR(h→aa)=~90% : **exclude BR(a→μμ)>~10%**

Severely constrains NMSSM for $M_a < 2M_{tau}$!

Estimated background

Signals for various M_a and the data events



h→aa, $M_a > 2M_{tau}$

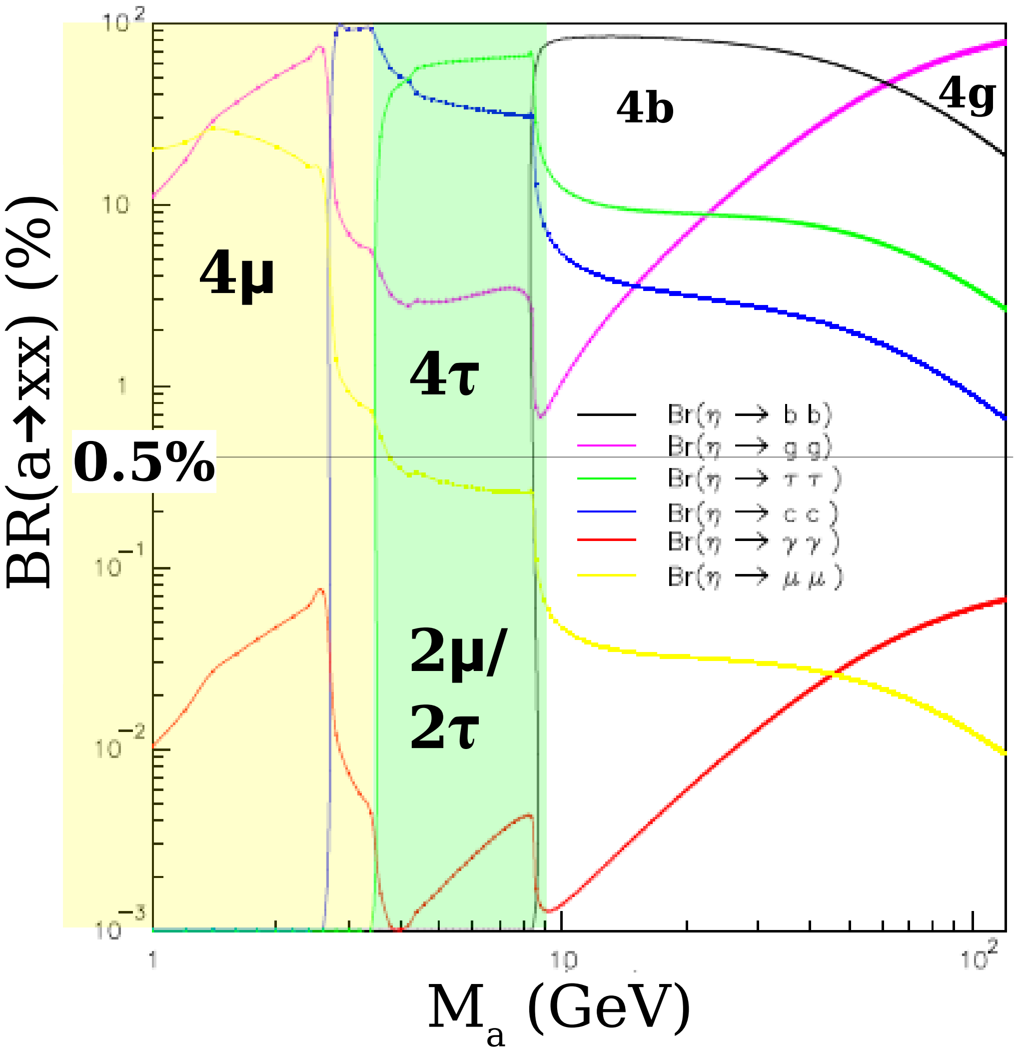
h→aa→4τ is hard !

- **τ**'s in overlapping pairs
- Need **τ** →μ,e decays
- e, μ will be low p_T

Easier to do h→aa→2μ2**τ**

- a→μμ mass peak
- high p_T muons

2μ2τ smaller by ~1/100, but *cleaner*



M. Lisanti and J. G. Wacker, arXiv:0903.1377 [hep-ph].

h→aa→2μ2τ

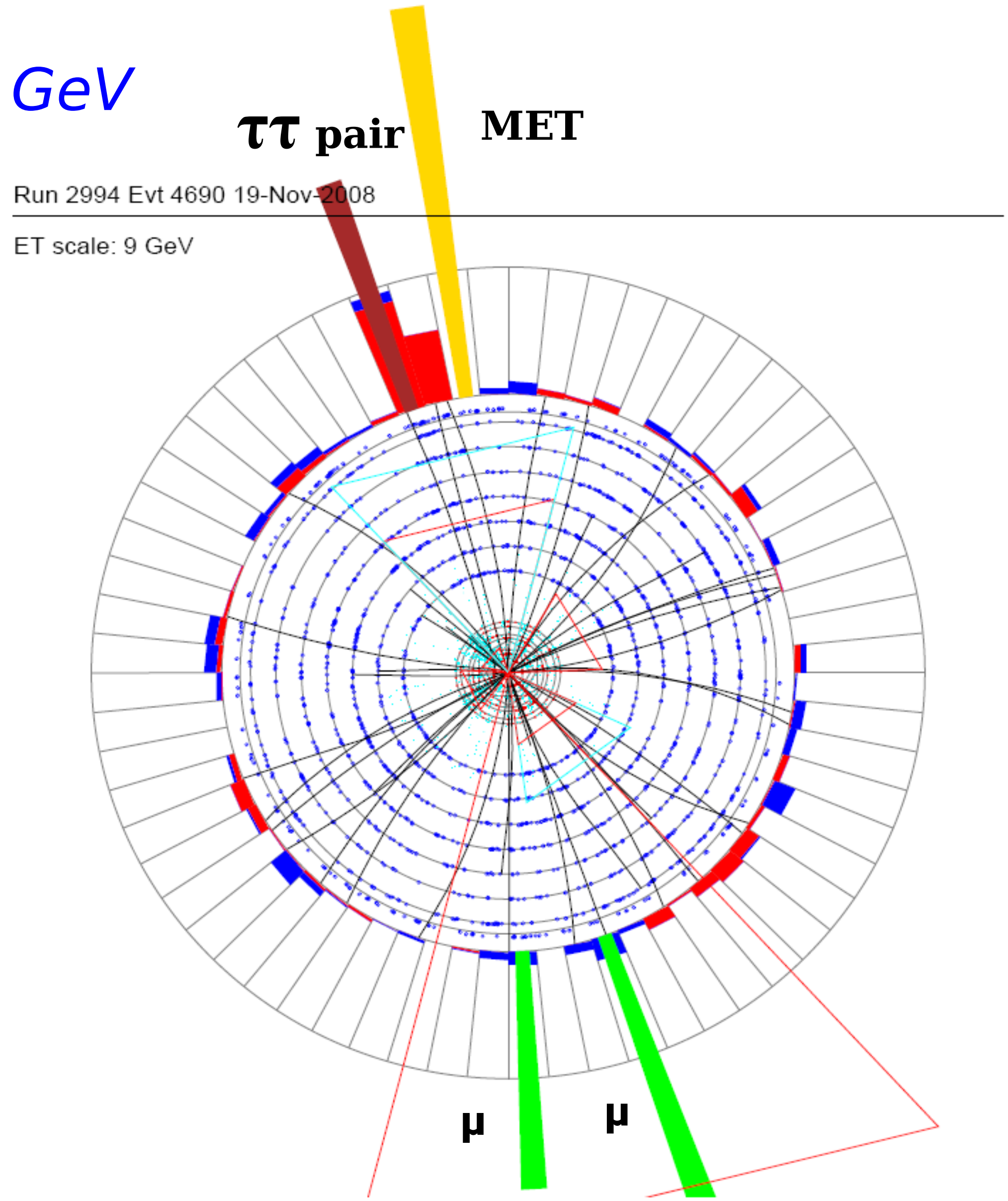
2 nearby, isolated muons, p_T>10 GeV

Tighter muon criteria

- just a jet on the other side

Scalar sum muon p_T > 35 GeV

- Reduces background (QCD multijet, Drell-Yan)



h→aa→2μ2τ

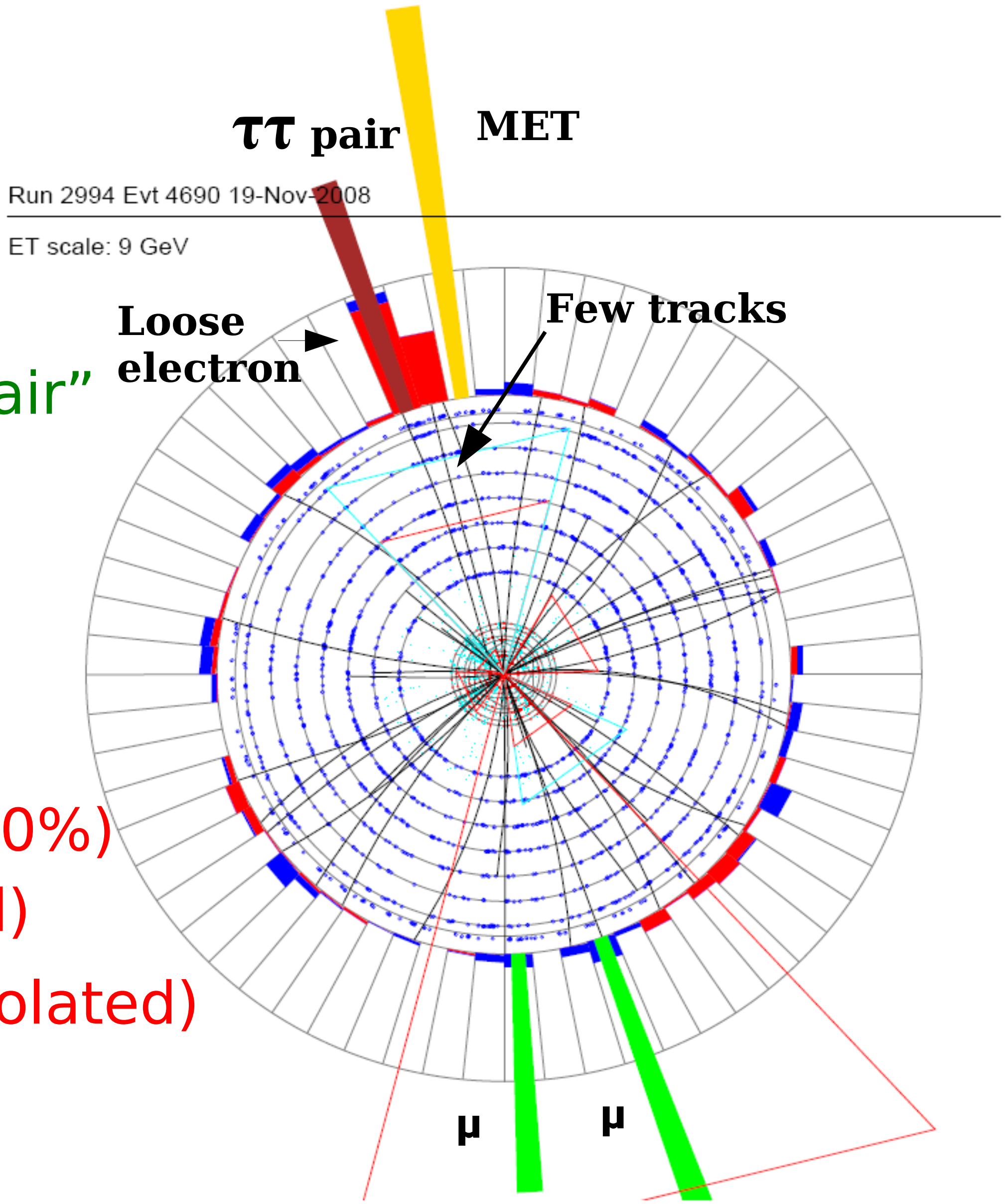
τ's overlap, ruining standard τ-ID criteria (isolation, N_{track}, etc.)!

1) Set of cuts selects "MET in τ pair"

- MET, "jet" ET, N_{track}
- *additional muon criteria to minimize fake MET (track χ^2, etc.)*

2) Additional muon or electron (40%)

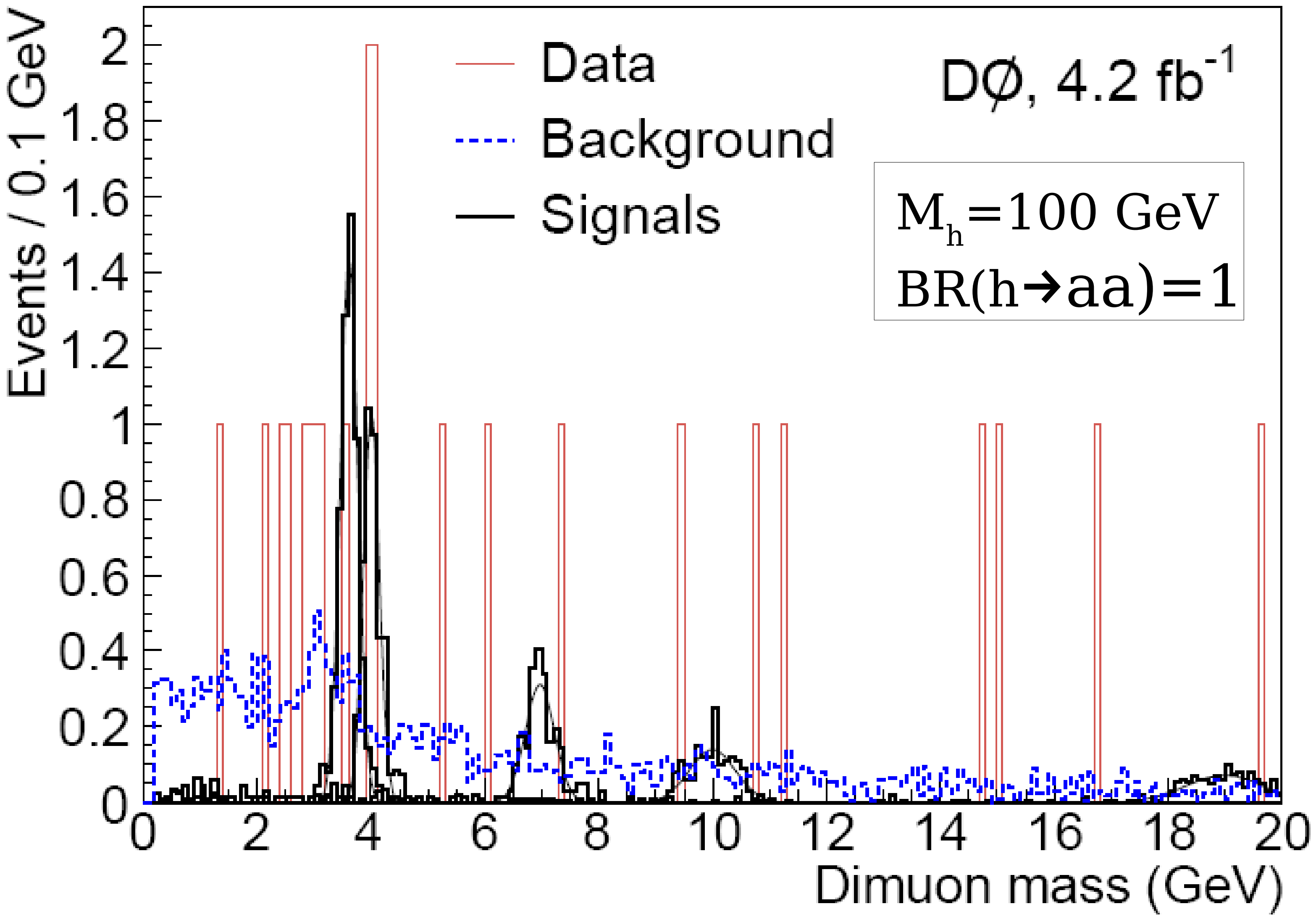
- muon in τ pair (non-isolated)
- electron in τ pair (loosely-isolated)



h→aa→2μ2τ

Background shape from less-isolated (di-muon) data

- normalized to isolated data

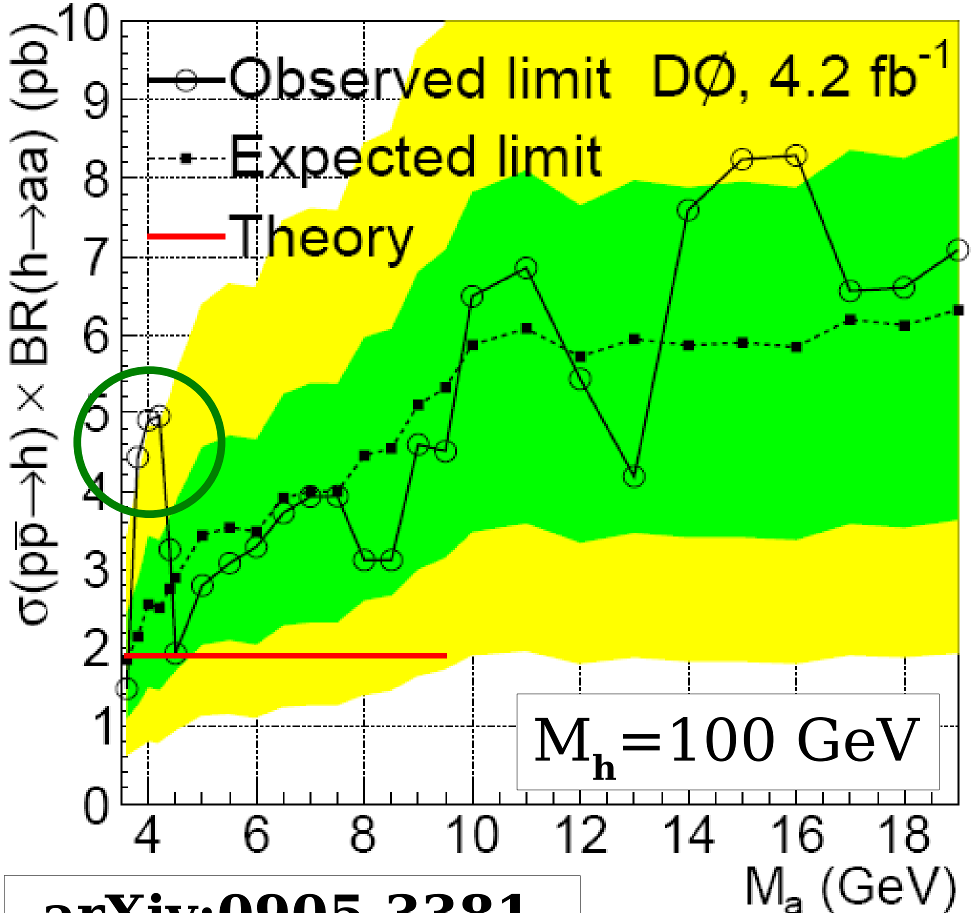


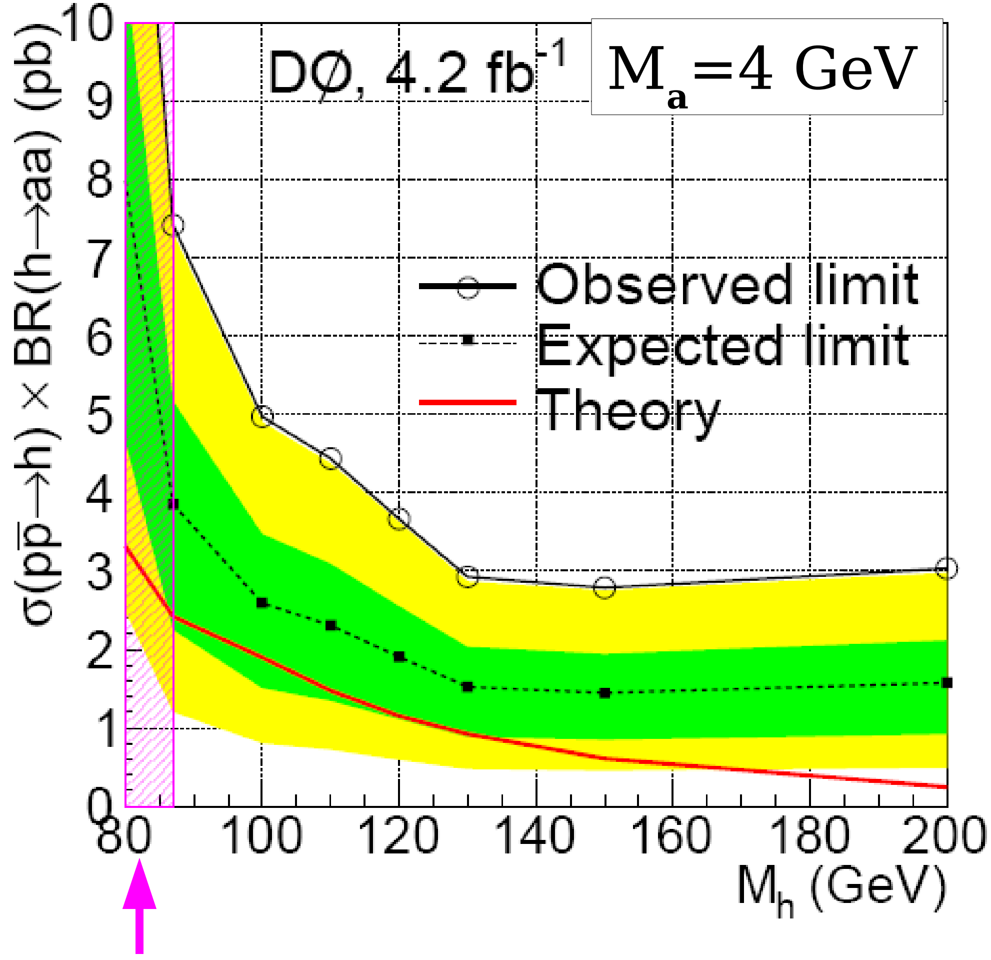
h→aa→2μ2τ

Currently exclude ~1-3 times $p\bar{p}$→h cross-section

- **2 sigma excess at 4 GeV**

Tevatron can cover the full M_a range: more data, CDF





arXiv:0905.3381
Accepted by PRL

Zh→Zaa→Z4τ bound from OPAL (LEP)

Hidden Valley

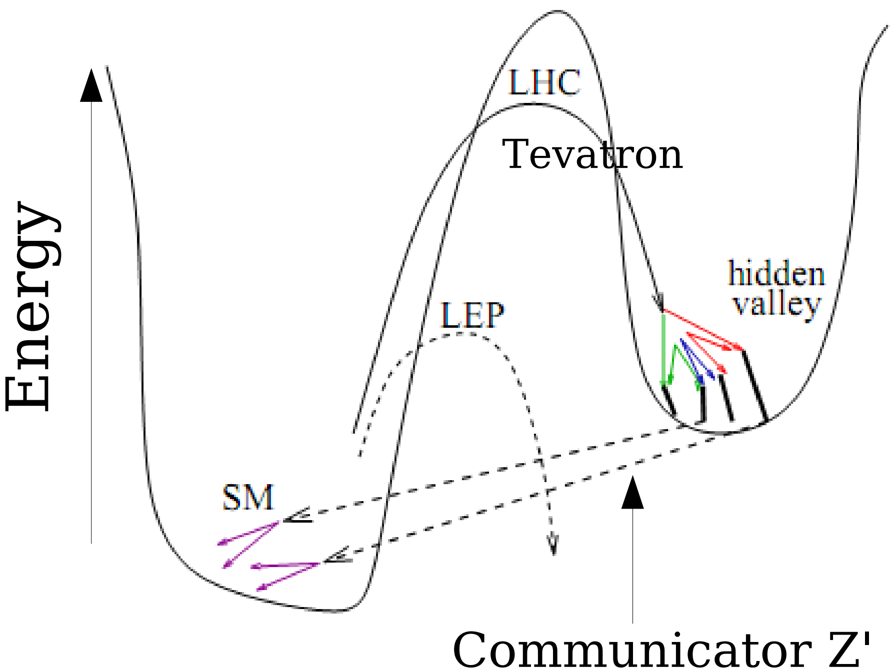
Hidden sector (weakly interacting with the SM)

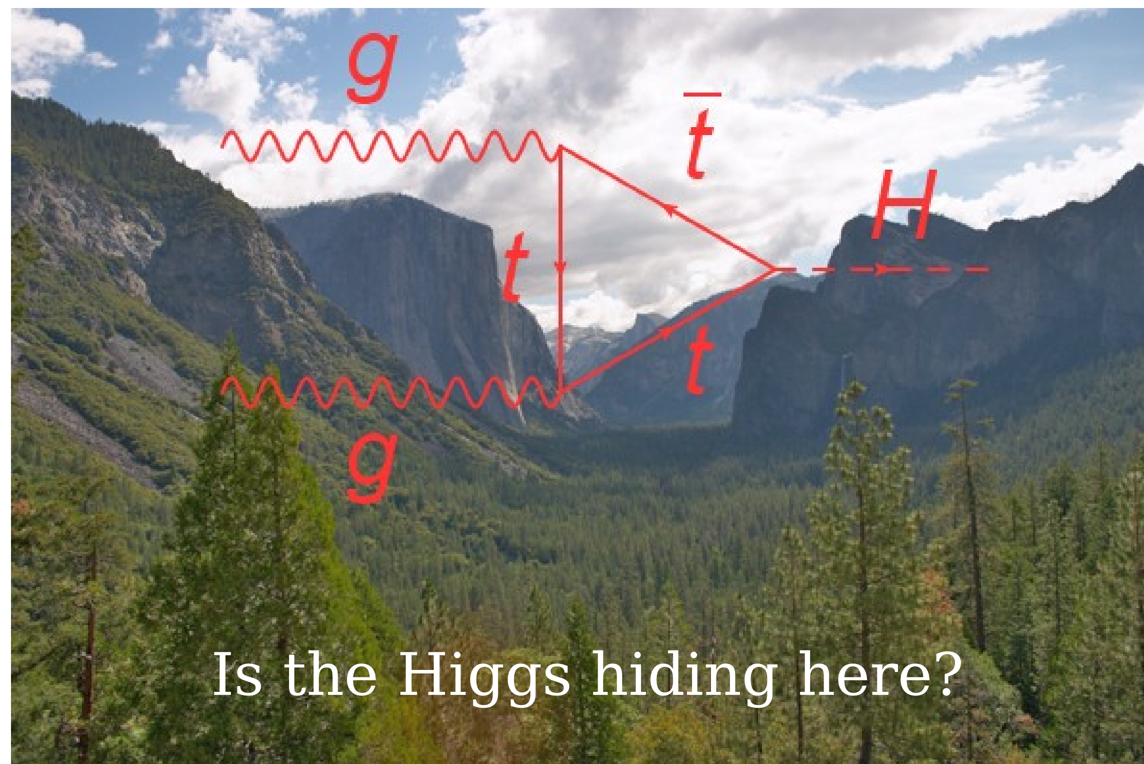
Strongly coupled: v-hadrons, v-pions, etc.

Strassler and Zurek, Phys. Rev. Lett. B651:374 (2007).

v-particles could be long-lived

- but < 1 second, (big-bang nucleosynthesis)



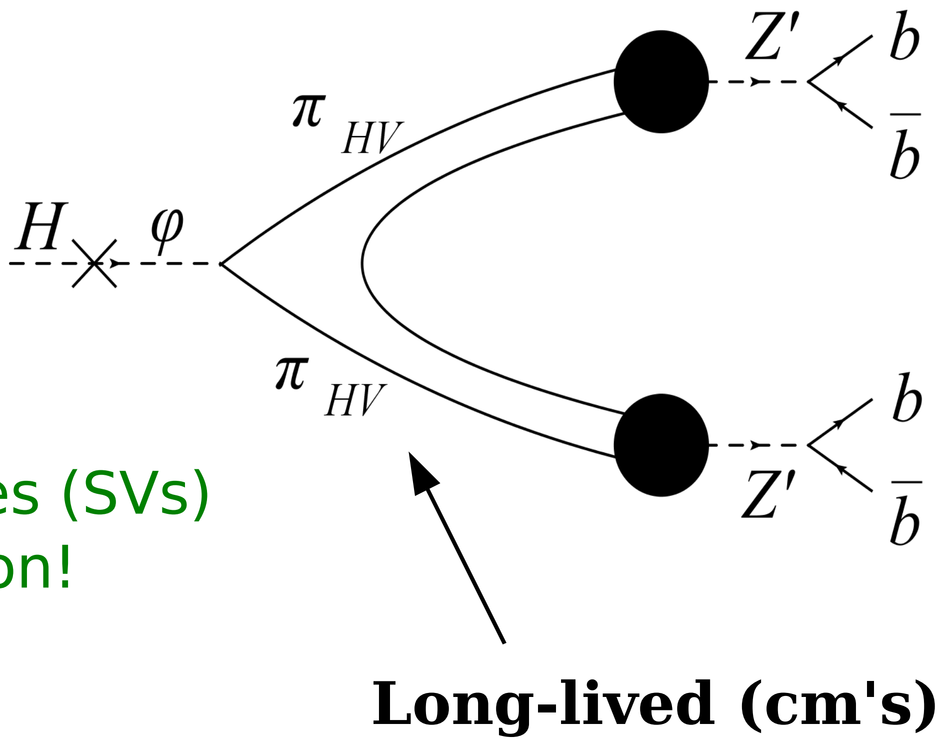


Higgs → HV HV → bb bb

SM Higgs mixes with HV Higgs
- BR(H→ HV HV) could be large

HV prefers to decay to b$\bar{b}$
(due to helicity suppression)

Highly displaced secondary-vertices (SVs)
- never searched for at Tevatron!



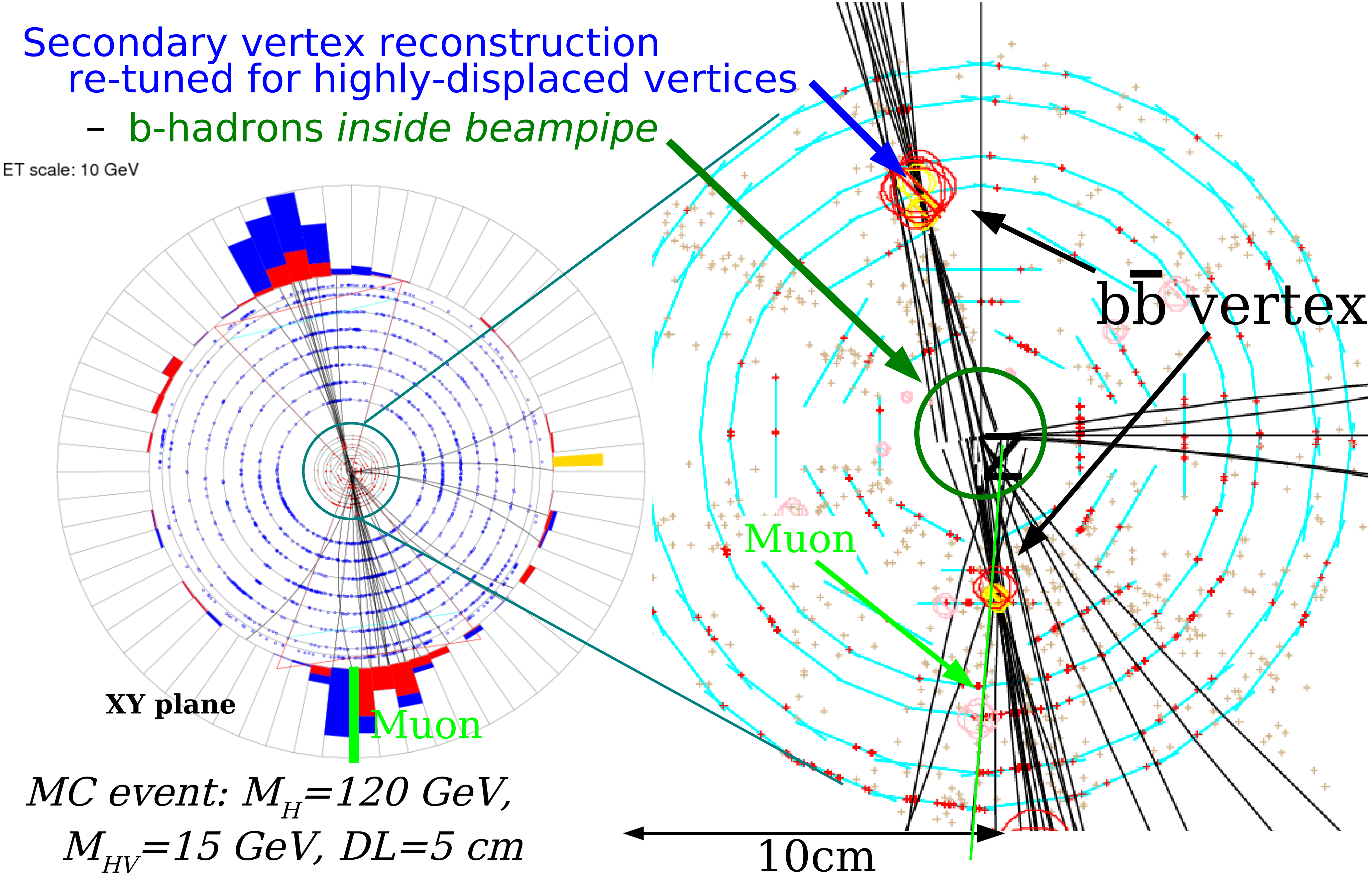
Evades most LEP limits, m_H>82 GeV

Another way to *hide the Higgs*!

Higgs → HV HV → bb bb

Secondary vertex reconstruction
re-tuned for highly-displaced vertices

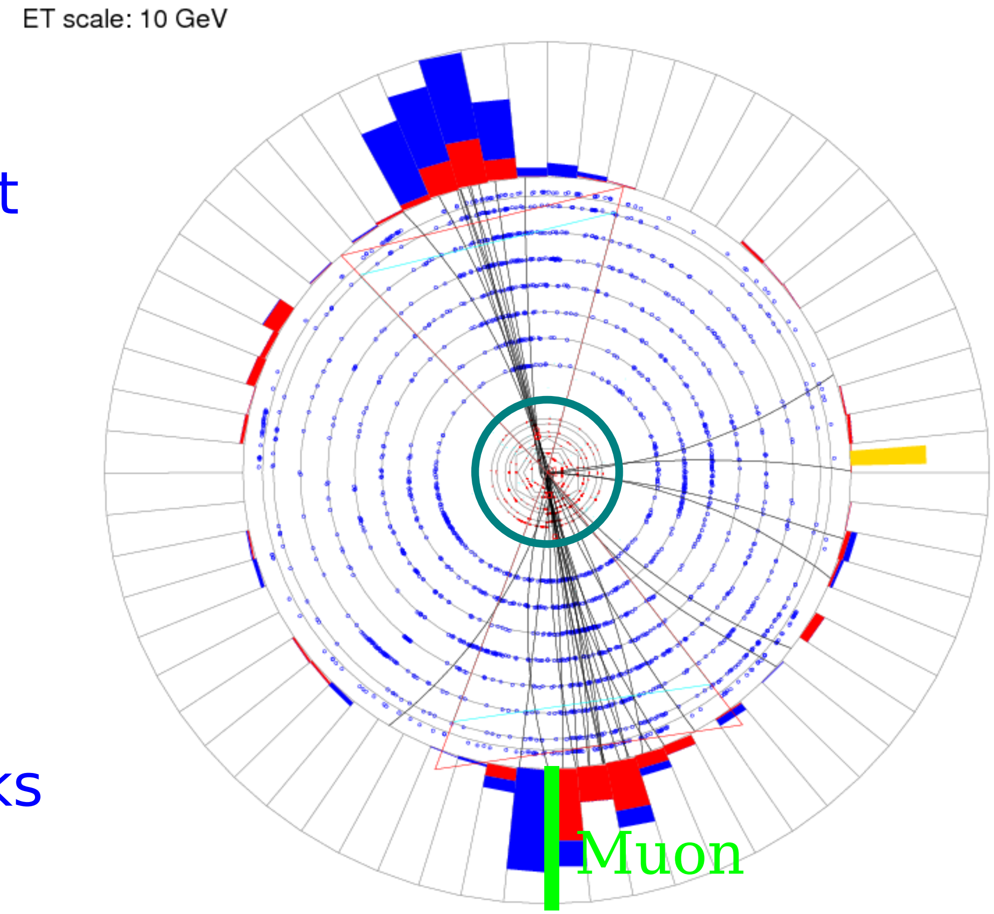
– b-hadrons *inside beampipe*



MC event: M_H=120 GeV,
M_{HV}=15 GeV, DL=5 cm

Higgs → HV HV → bb bb

- 2 jets with p_T>10GeV
- muon, p_T>4 GeV, matched to jet
- central primary vertex and <3 additional pp interactions
- 1.6cm< SV radius < 20cm
  - remove b-decays
  - fiducial volume



Require **2** SVs with at least 4 tracks

Use "OR" of all triggers
(mostly muon+jet)

3.6 fb^{-1} analyzed

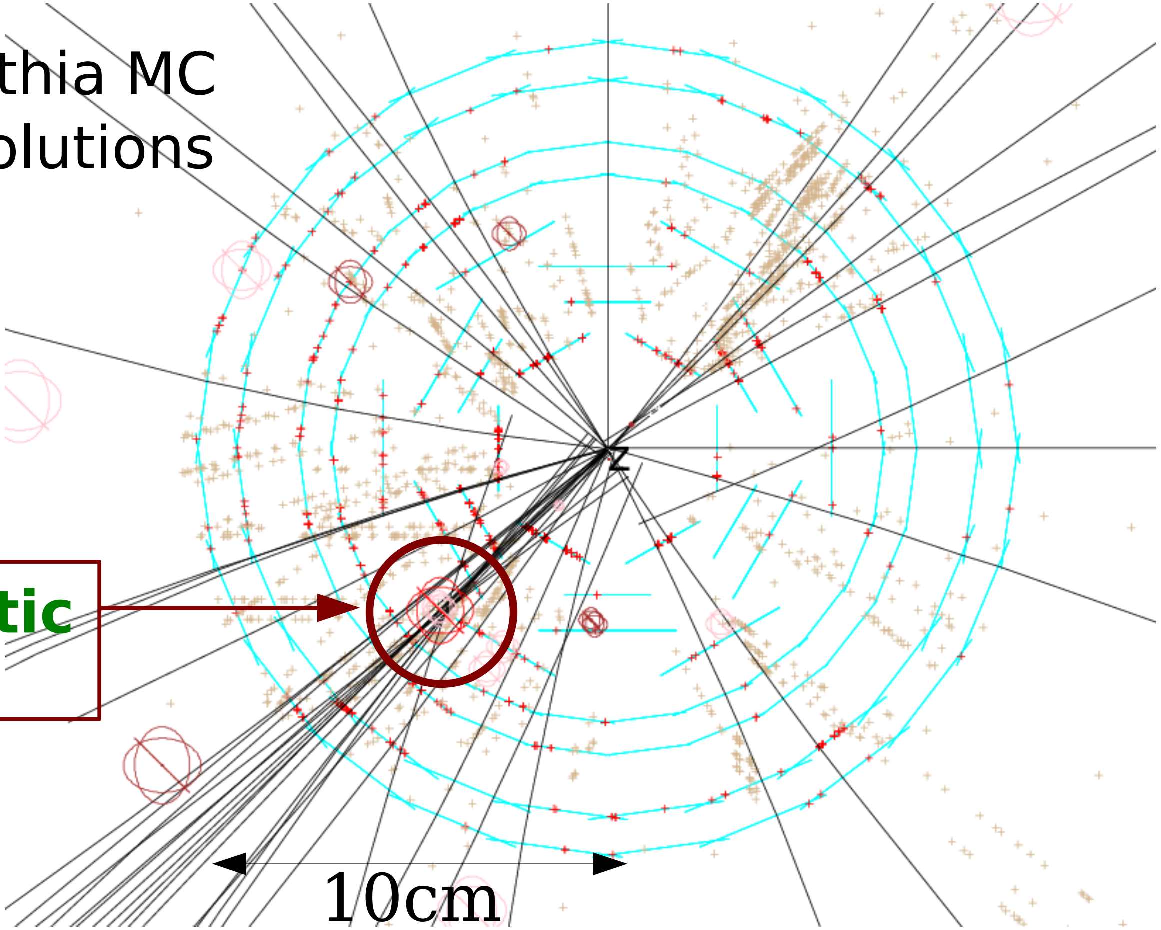
Higgs → HV HV → bb bb

Background simulated with Pythia MC
- SVs smeared to data resolutions

In-flight decays (pion, kaon)

Material interactions
- photon conversions
- **hadron-nucleus inelastic scattering**

Pattern recognition errors

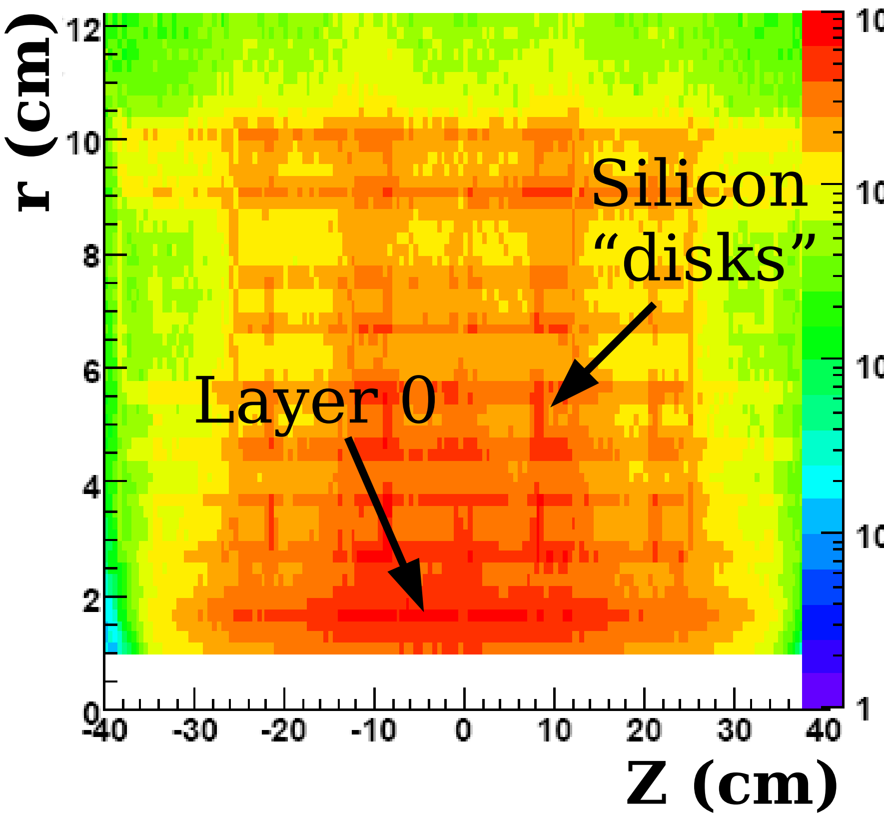


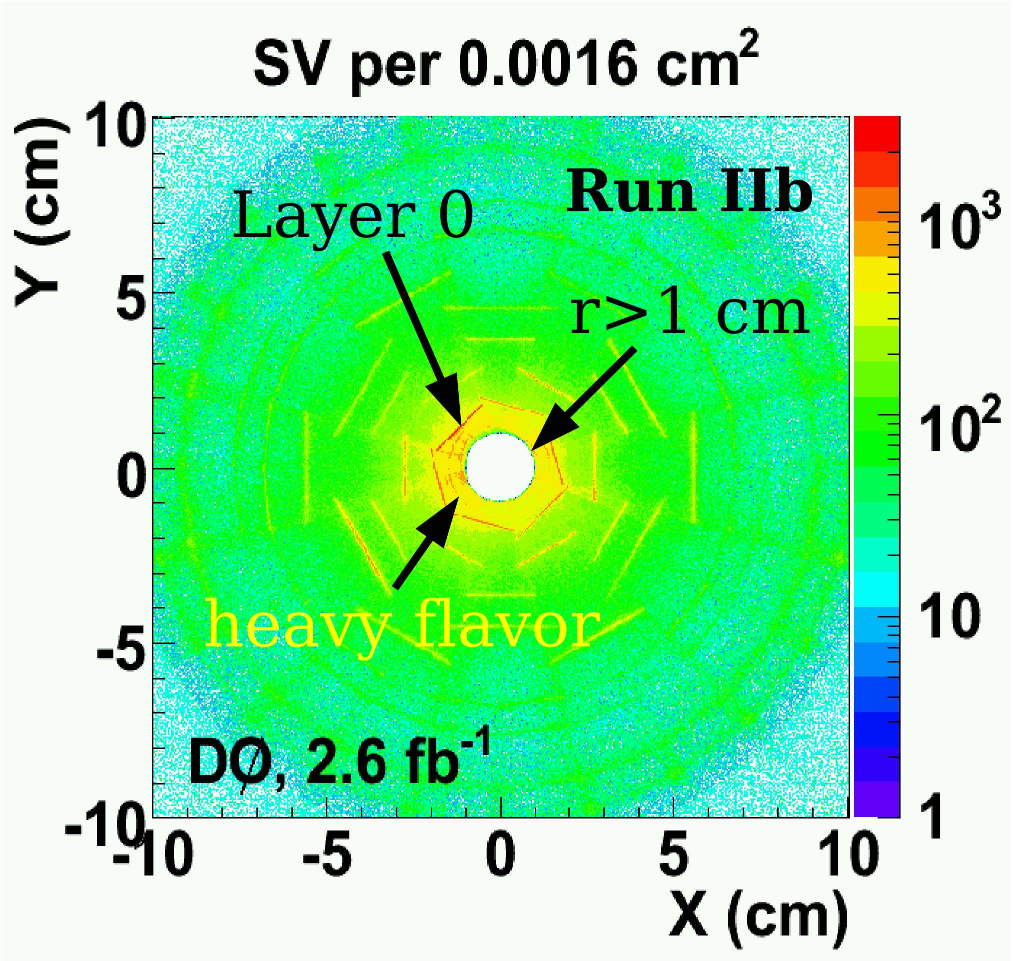
QCD MC event:
6 reconstructed tracks,
material interaction

Higgs → HV HV → bb bb

Material "map" using vertices with 3 tracks

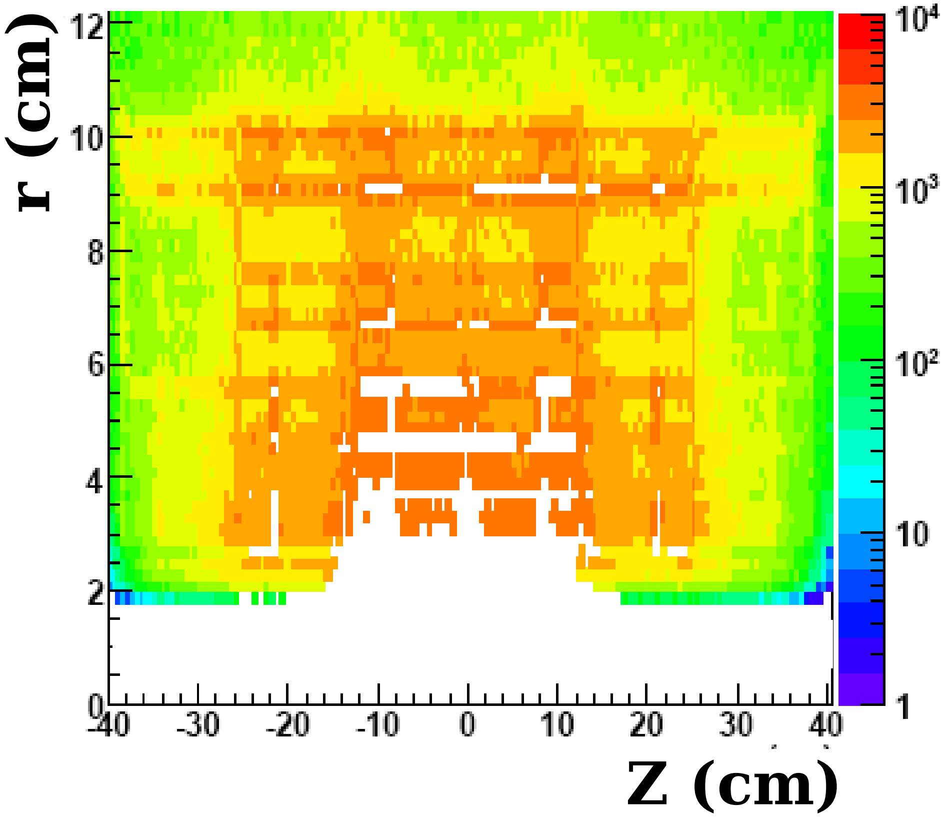
(RZ and XY projections)

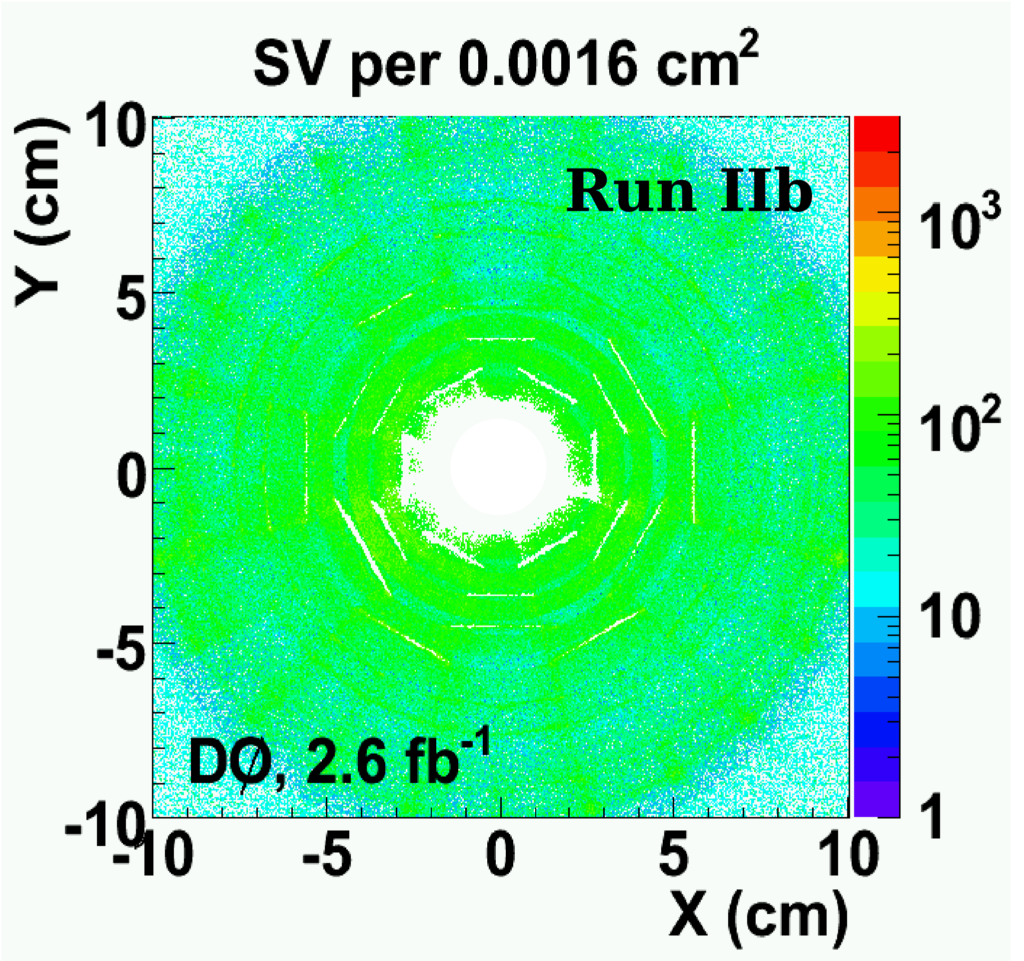




Higgs → HV HV → bb bb

Reject SVs that occur in high material density regions





Higgs → HV HV → bb bb

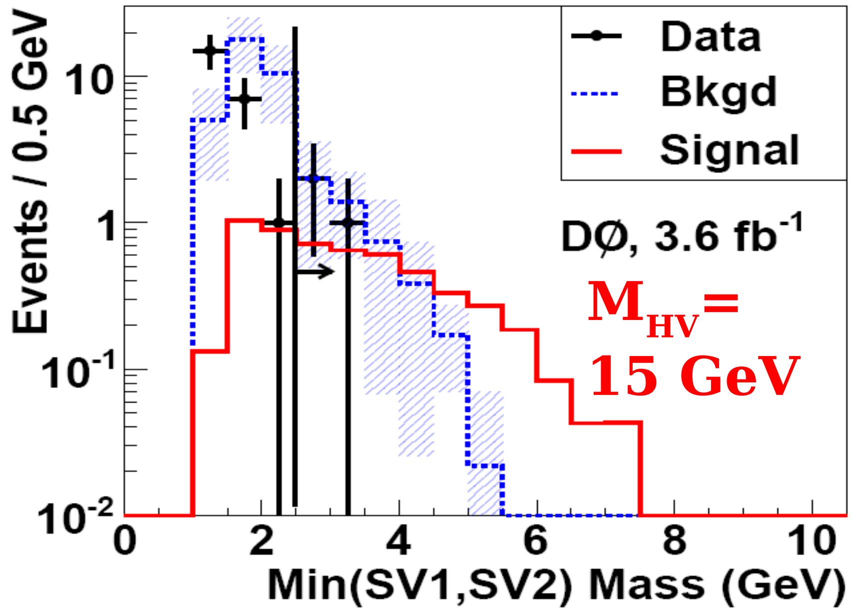
Cut on minimum of the mass OR maximum of the collinearity (depending on M_{HV})

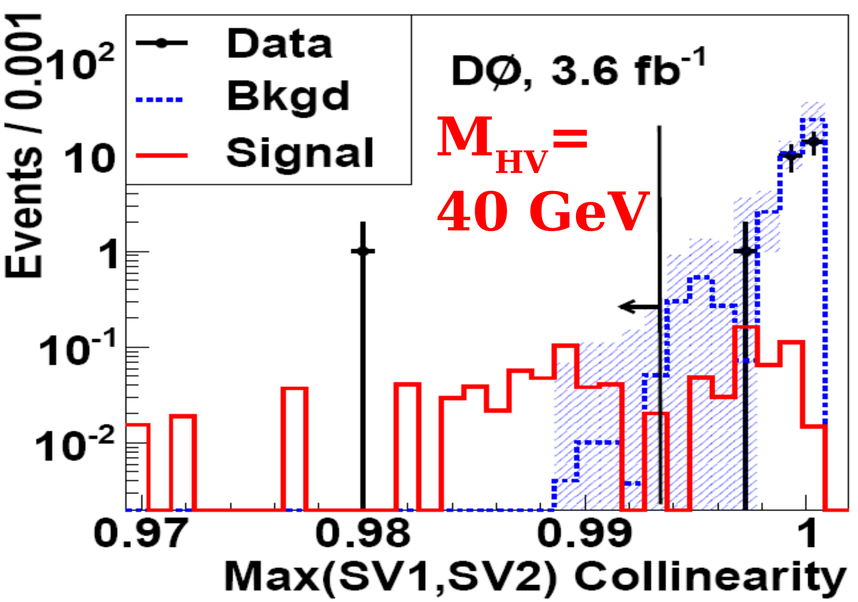
Signal efficiency uncertainty:

- Trigger efficiency, ~17%
- Luminosity, 6.1%

Background uncertainty:

- MC statistics, ~100%
- Tracking efficiency, ~28%
- Smearing, ~18%
- Material density, ~15%



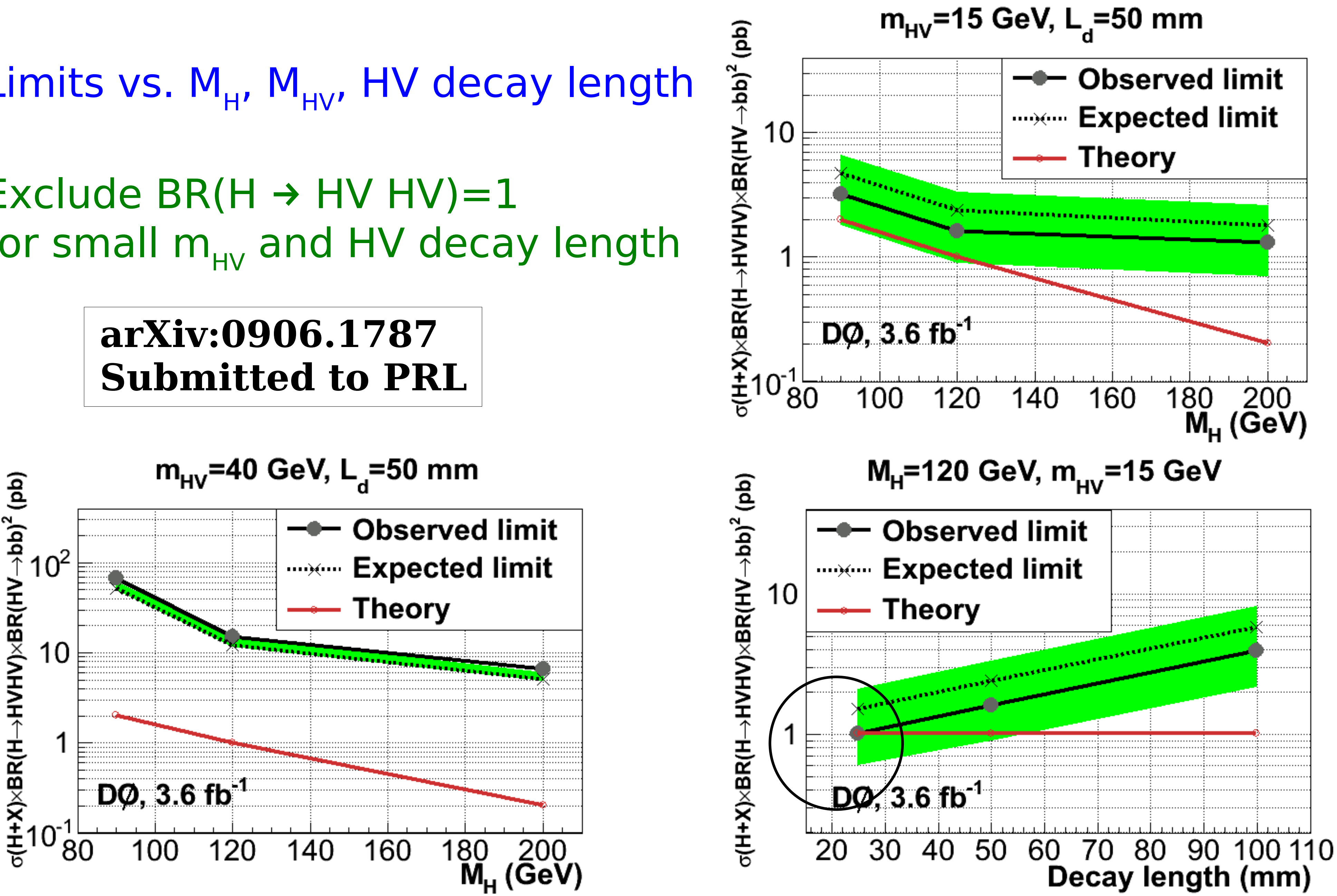


Higgs → HV HV → bb bb

Limits vs. M_H, M_{HV}, HV decay length

Exclude BR(H → HV HV)=1
for small m_{HV} and HV decay length

arXiv:0906.1787
Submitted to PRL



Conclusions

Well-motivated extensions of the SM:

- **N**MSSM
- Hidden Valley

Predict <u>challenging</u> *new signatures*

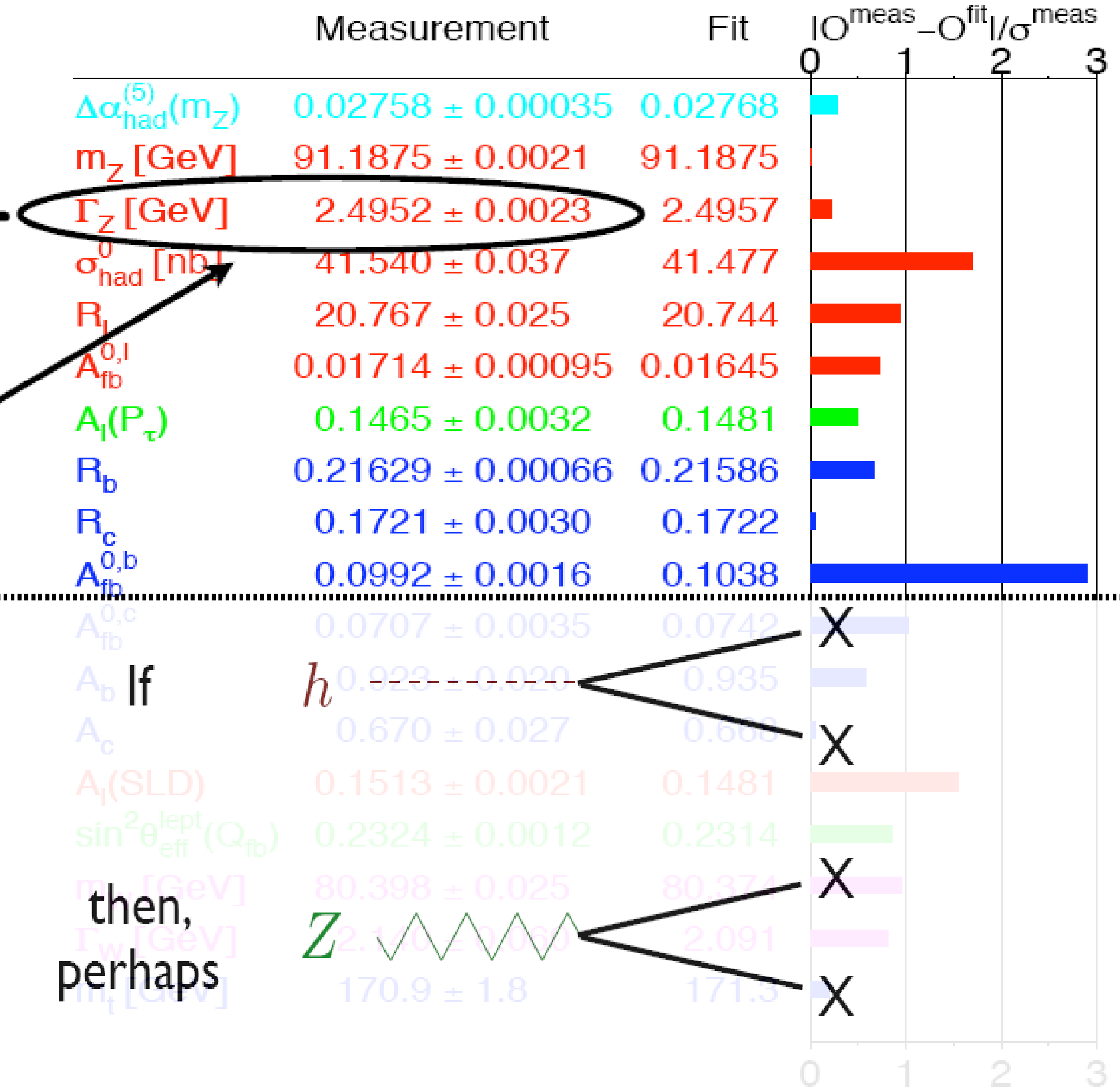
- collinear lepton pairs
- long-lived particles → (b-)jets

New DØ analyses probe these signatures for the first time...

No evidence for new physics yet...
but we could be on the right track!

Backup

Precision Constraint



Error bar is about 1 per mil

but $\Gamma_Z \simeq 1000 \times \Gamma_h(m_h = 115\ \mathrm{GeV})$

OPAL (LEP) h→aa→4τ Search

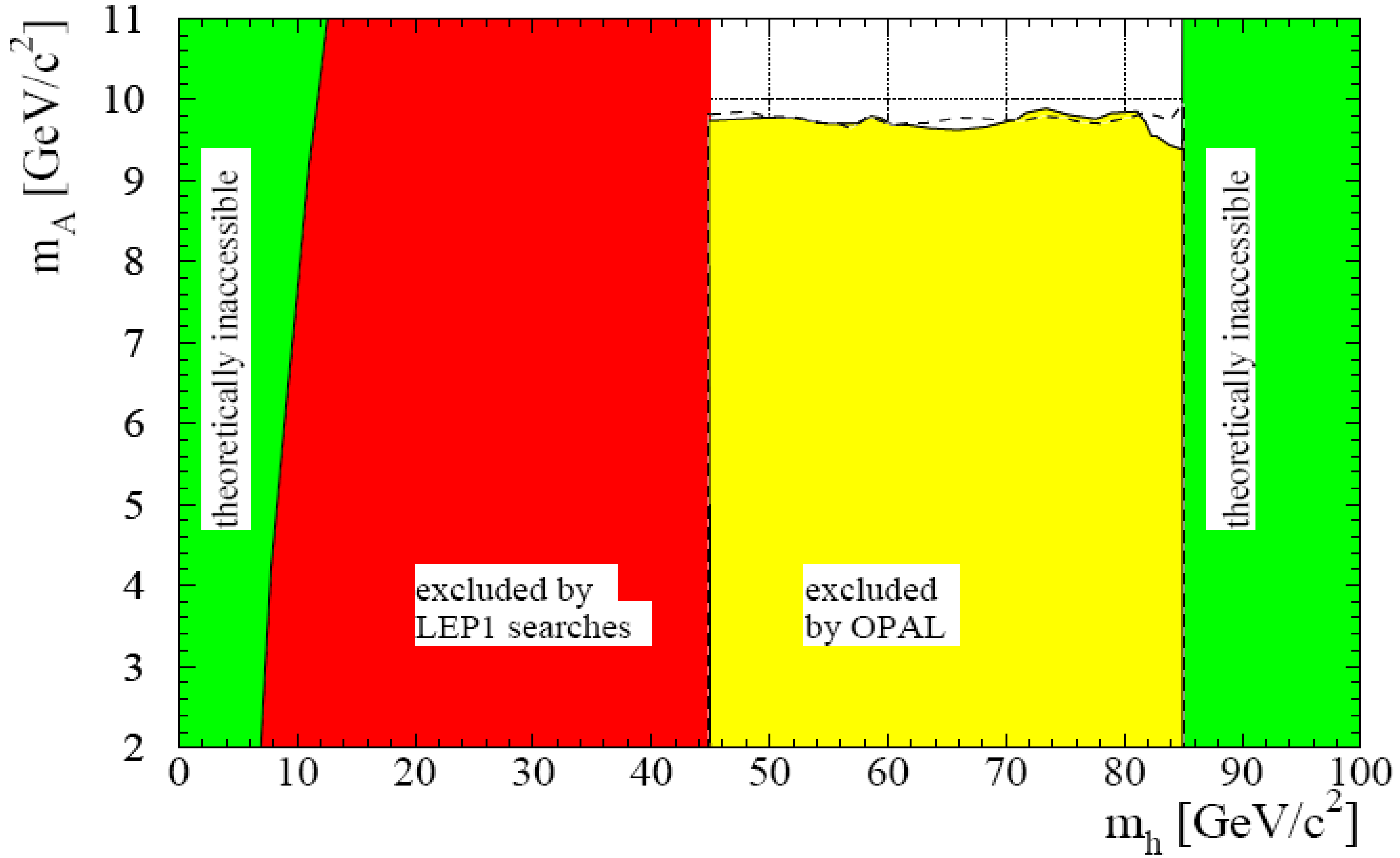
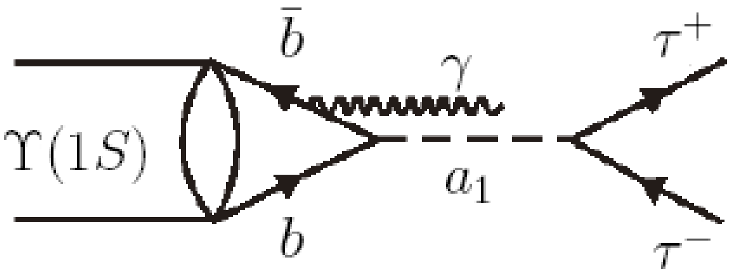
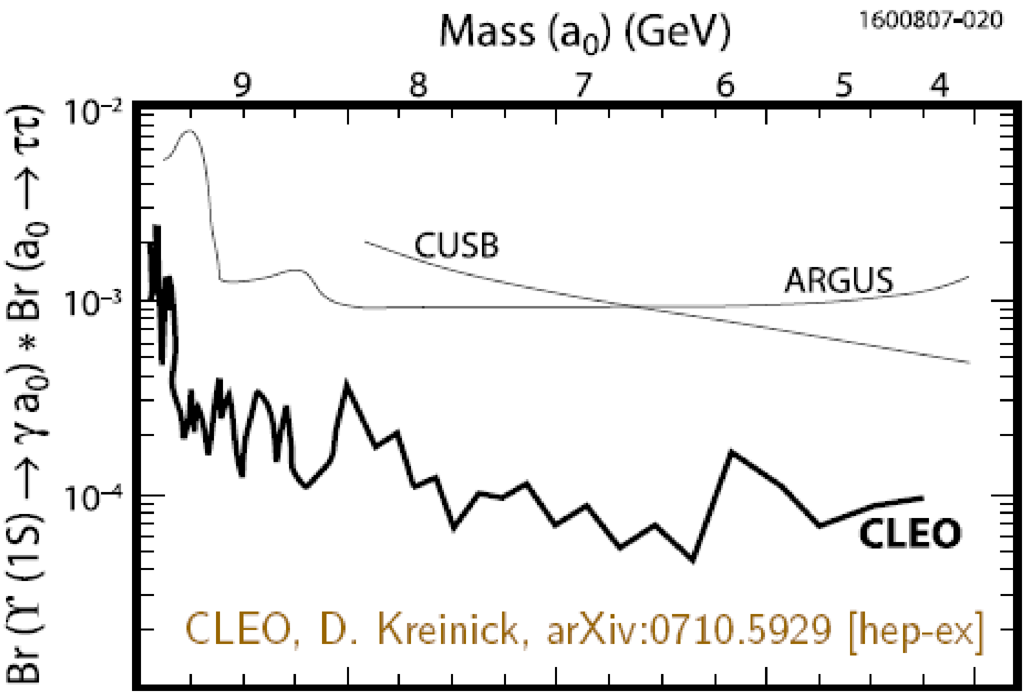
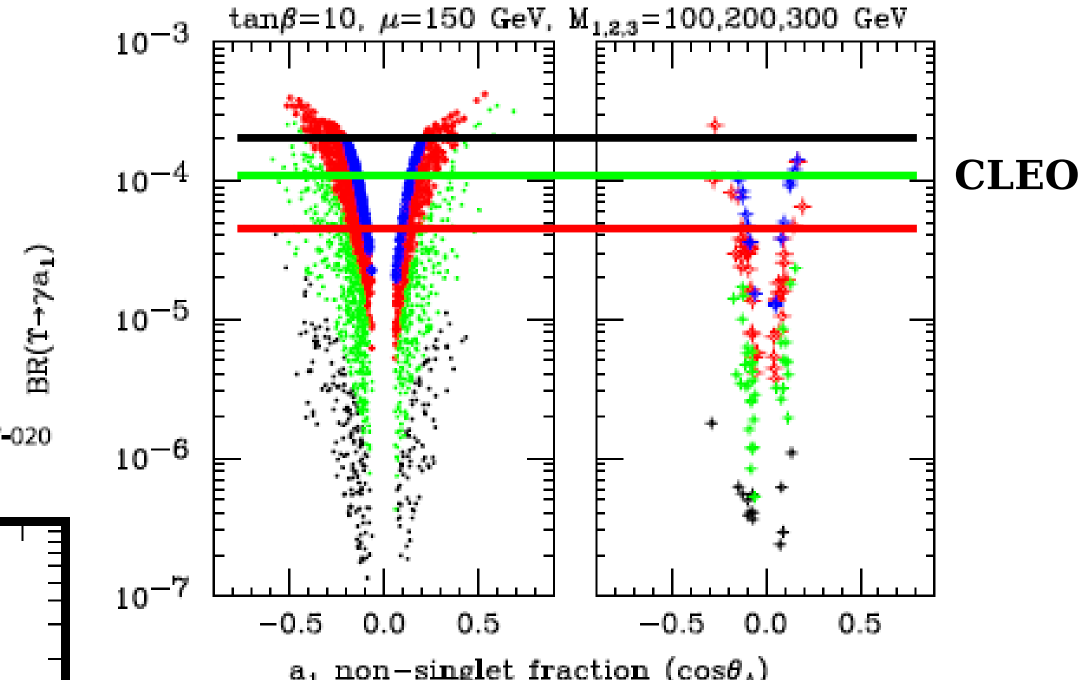


Figure 8: *Expected (dashed contour) and observed (light grey area) excluded regions at 95% CL in the m_A versus m_h plane for the MSSM no-mixing benchmark scenario. These limits are derived using the combined results from* $Z^0 \to \nu\bar{\nu}$, $Z^0 \to \mu^+\mu^-$ *and* $Z^0 \to e^+e^-$ *channels and for centre-of-mass energies between 189 and 209 GeV. The theoretically inaccessible regions and the region excluded by LEP 1 are also shown by darker areas.*

Light CP-odd Higgs at B factories







A_κ, A_λ, κ, λ scan $F < 15$ scan

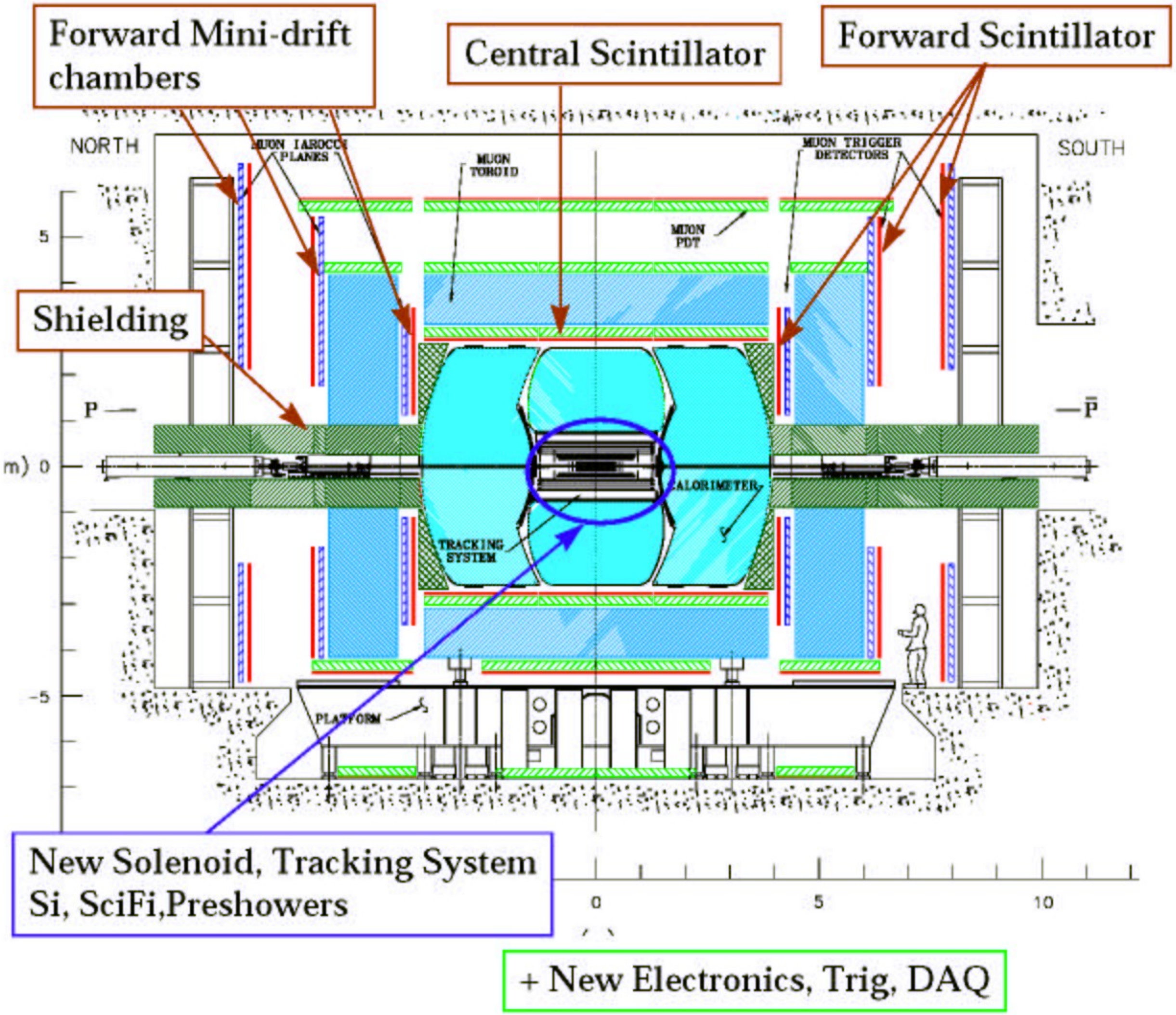
$m_{a_1} < 2m_\tau$

$2m_\tau < m_{a_1} < 7.5\,GeV$

$7.5\,GeV < m_{a_1} < 8.8\,GeV$

$8.8\,GeV < m_{a_1} < 9.2\,GeV$

DØ



Electrons / photons
Muons
Jets / b-jets / taus
MET

Collaboration of ~550 physicists

a→μμ?

HyperCP experiment at Fermilab reported evidence for

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4}(\text{stat}) \pm 5.5(\text{syst})] \times 10^{-8}.$$

SM expectation between 1.6 – 9 x 10^{-8}, so could just be SM...

But strange $M_{\mu\mu}$ distribution!

Is this the "a"?

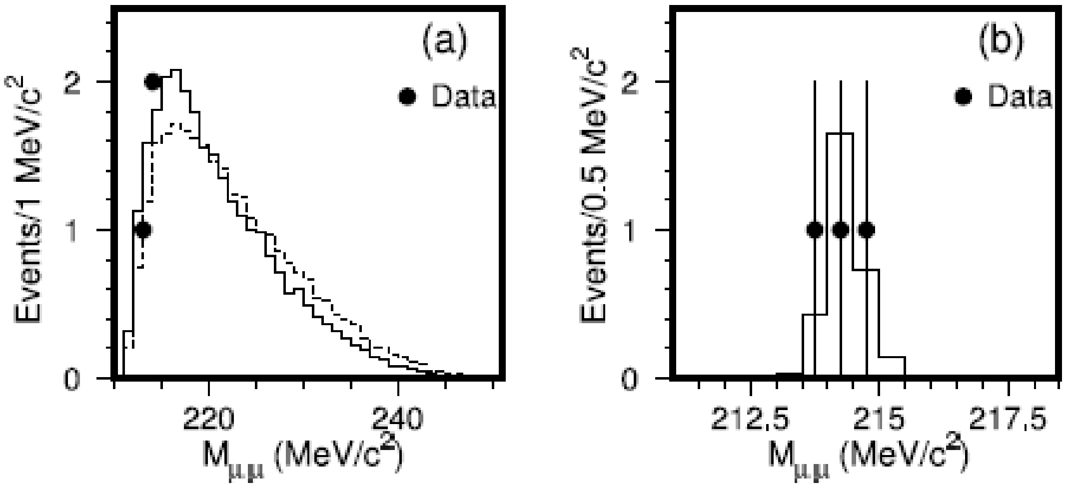
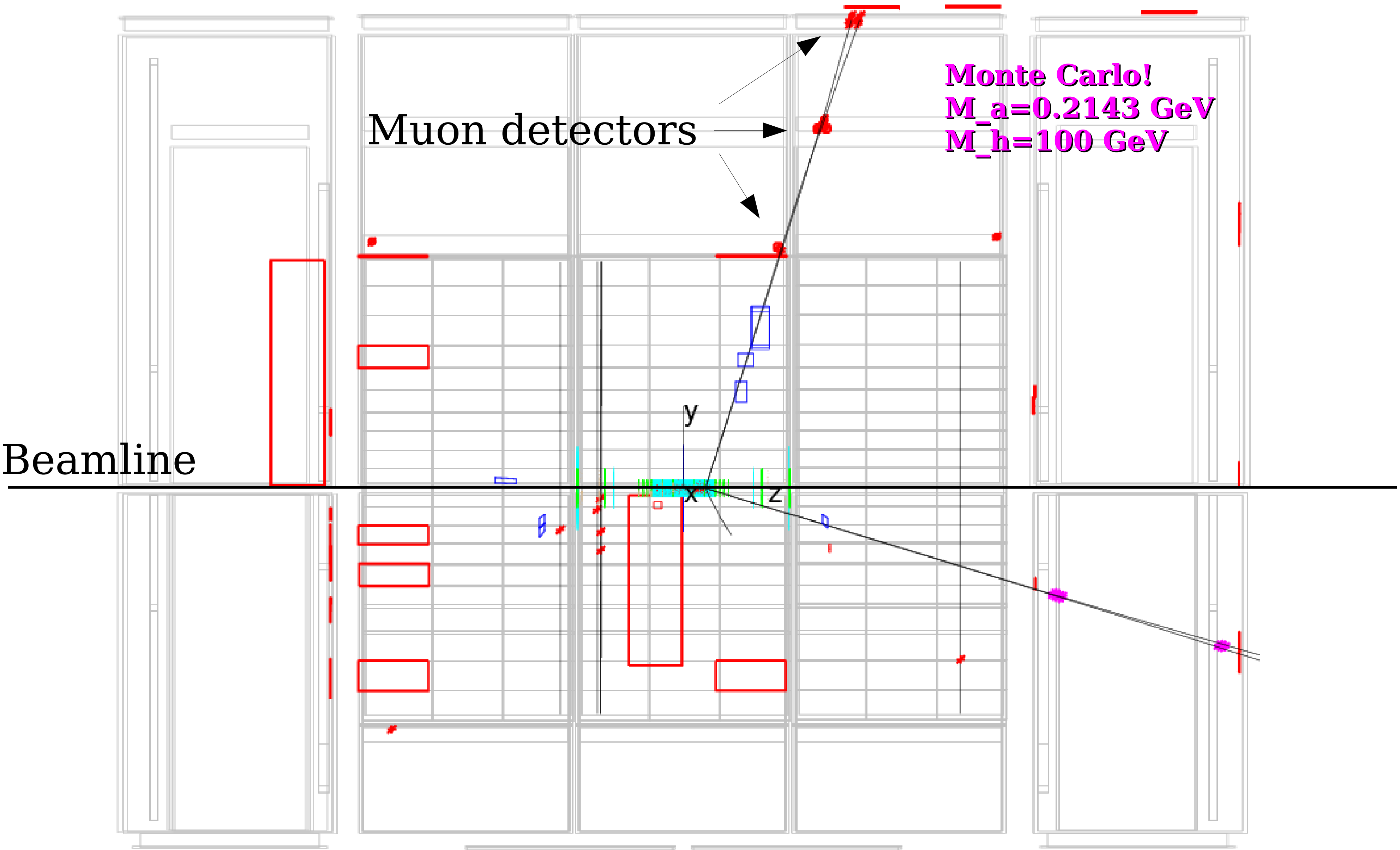


Figure 4: The $\mu^+\mu^-$ invariant mass of the three signal events with superimposed (a) Monte Carlo form factor decays (solid histogram) and uniform phase-space decays (dashed histogram), and (b) Monte Carlo $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$ events generated with $m_{X^0} = 214.3\text{MeV}/c^2$.

h→aa→4μ


Muon detectors
Monte Carlo!
M_a=0.2143 GeV
M_h=100 GeV
y
x
z
Beamline

h→aa→4μ

M_a (GeV)	Window (MeV)	Eff.	N_{bckg}	N_{obs}	$\sigma\times$BR [exp] obs (fb)
0.2143	±15	17%	0.001±0.001	0	[10.0] 10.0
0.3	±50	16%	0.006±0.002	0	[9.5] 9.5
0.5	±70	12%	0.012±0.004	0	[7.3] 7.3
1	±100	13%	0.022±0.005	0	[6.1] 6.1
3	±230	14%	0.005±0.002	0	[5.6] 5.6

h→aa→2μ2τ

Count total events in +-2 sigma windows

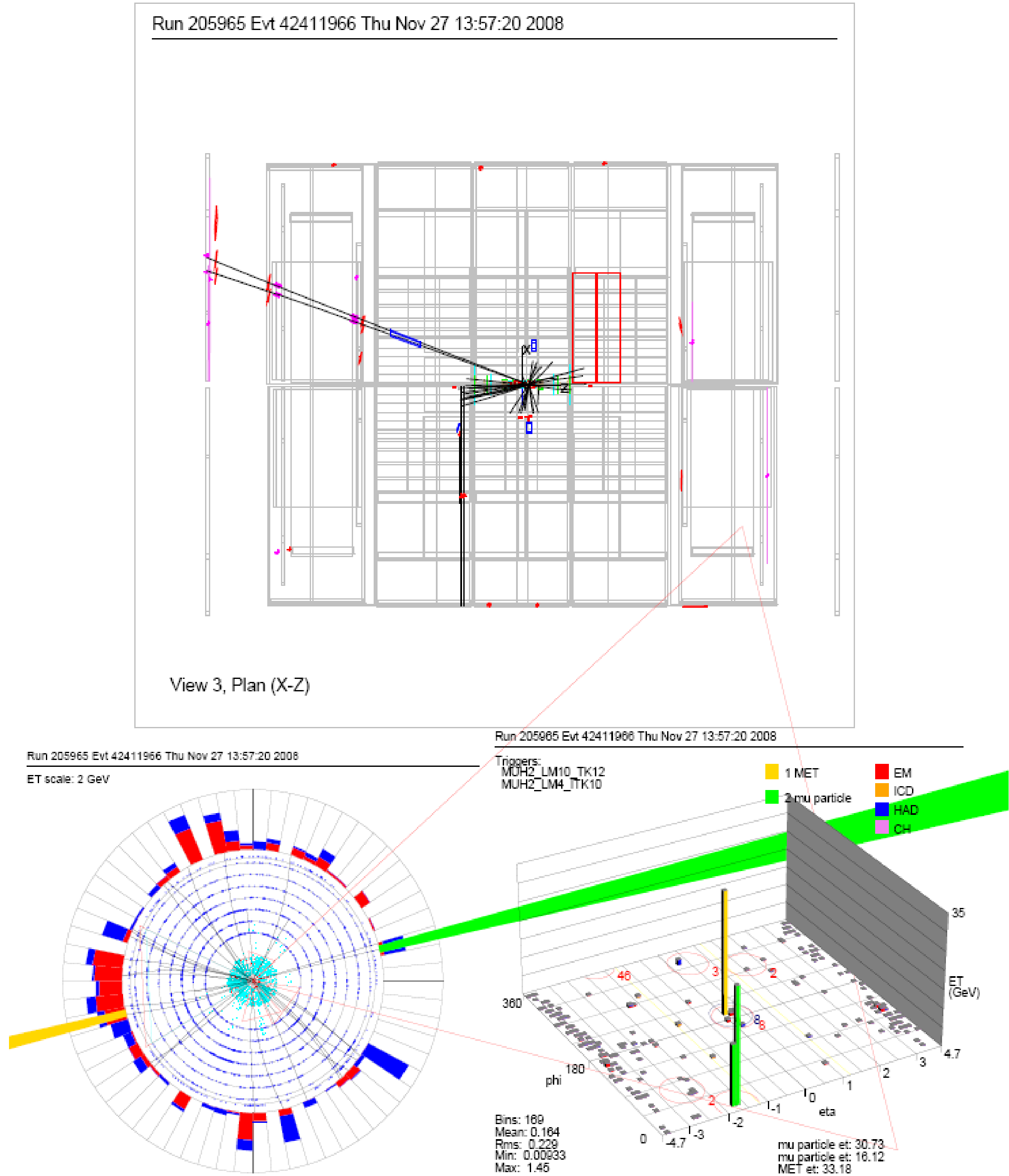
– Extrapolate efficiencies between simulated MC points

Set limits using Bayesian technique

Sample	N pre.	N iso.	(ref.) "$\not\!\!E_T$"	"Mu"	"EM"	Window	$N_{\rm sig}$ (Eff.)	$N_{\rm bckg}$	$N_{\rm obs}$	[exp] obs	$\sigma \times 2{\times}$BR
Data	95793	2795	(1085) 15	4	4						
M_a=3.6 GeV	53.1	28.0	(14.5) 3.5	1.9	0.8	±0.30 GeV	5.2 (0.066%)	1.9±0.4	1	[1.8] 1.5 pb	[23.8] 19.1 fb
M_a=4 GeV	33.6	15.3	(8.1) 2.5	1.2	0.4	±0.32 GeV	3.3 (0.042%)	1.1±0.2	4	[2.6] 4.9 pb	[23.9] 45.9 fb
M_a=7 GeV	20.6	8.7	(4.5) 1.7	0.8	0.3	±0.54 GeV	2.1 (0.027%)	1.1±0.2	1	[4.0] 3.9 pb	[25.0] 24.6 fb
M_a=10 GeV	19.3	7.5	(4.2) 1.1	0.6	0.3	±0.95 GeV	1.5 (0.020%)	1.6±0.3	2	[5.9] 6.5 pb	[24.7] 27.3 fb
M_a=19 GeV	14.6	5.4	(2.9) 0.8	0.4	0.2	±1.37 GeV	1.2 (0.015%)	0.6±0.1	1	[6.3] 7.1 pb	[30.0] 33.7 fb

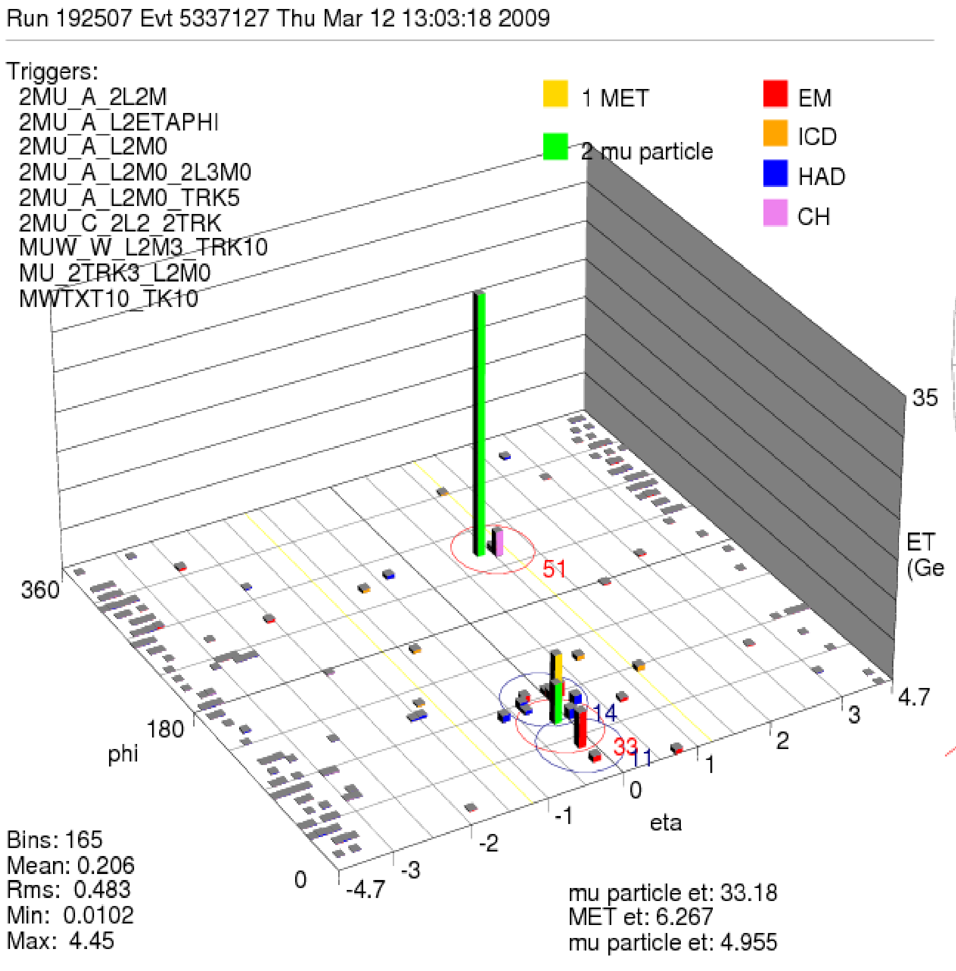
h→aa→2μ2τ

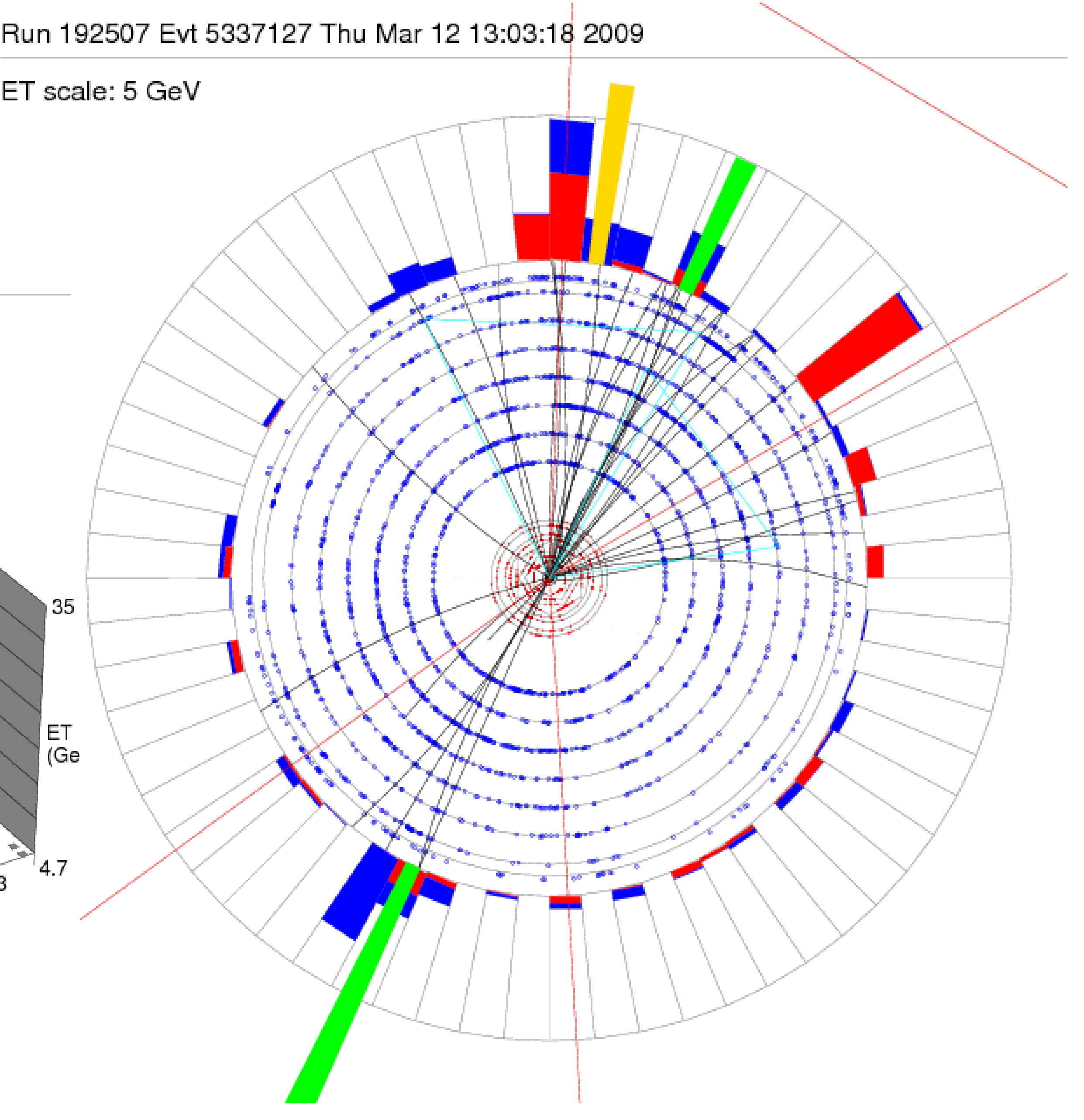
"MET" event in data



h→aa→2μ2τ

"Muon" event in data





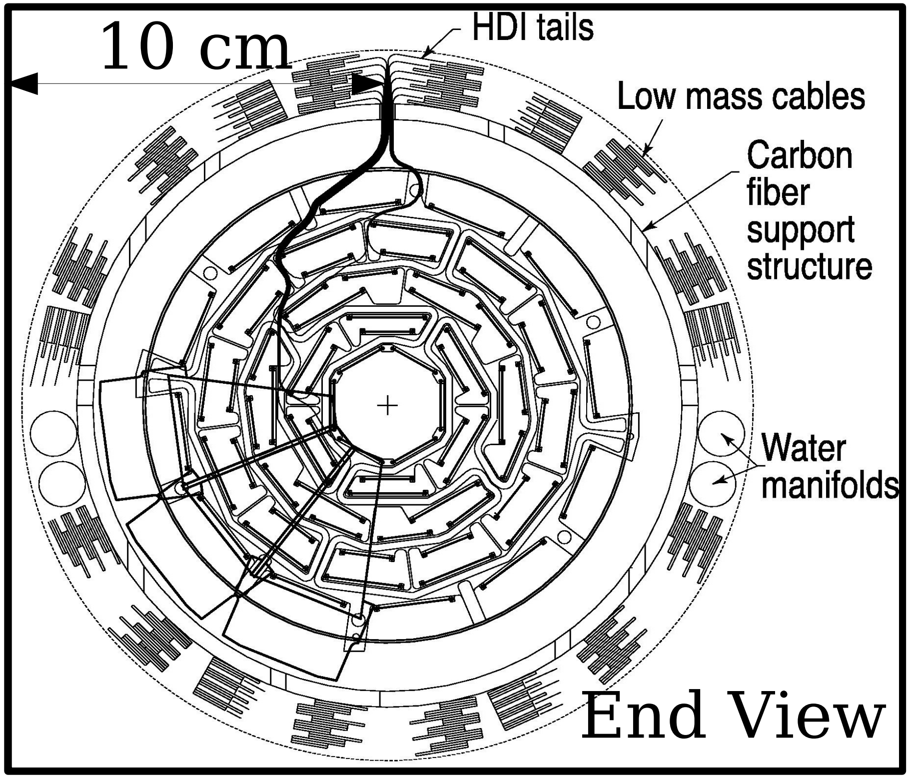
Tracker – position & momentum

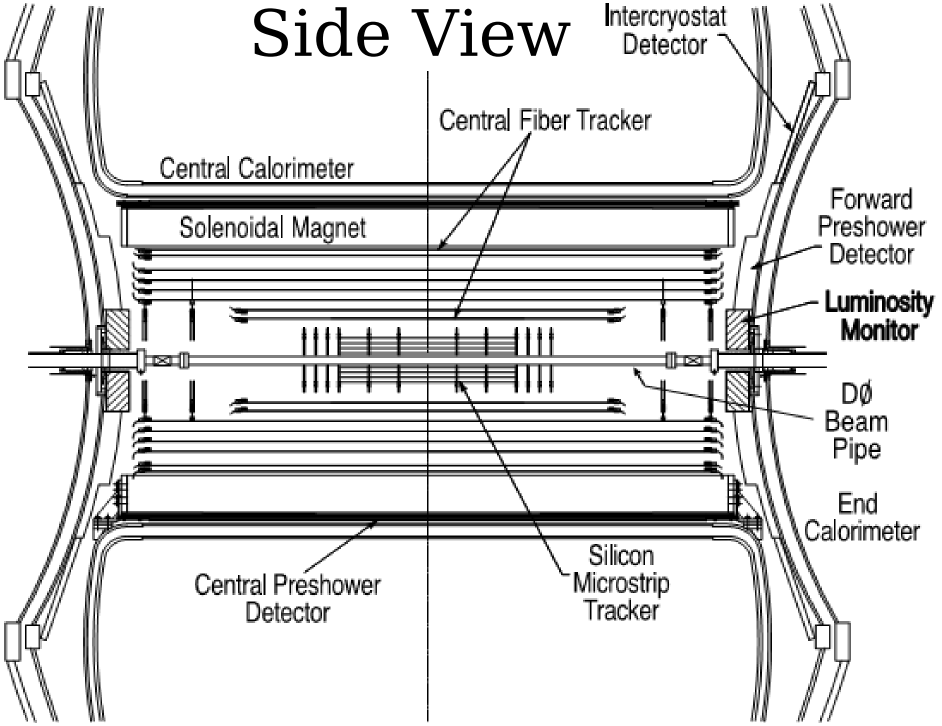
Inside in a 2T solenoid

Silicon Microstrip Tracker (SMT)

- very high resolution (~10μm)

Central Fiber Tracker (CFT)

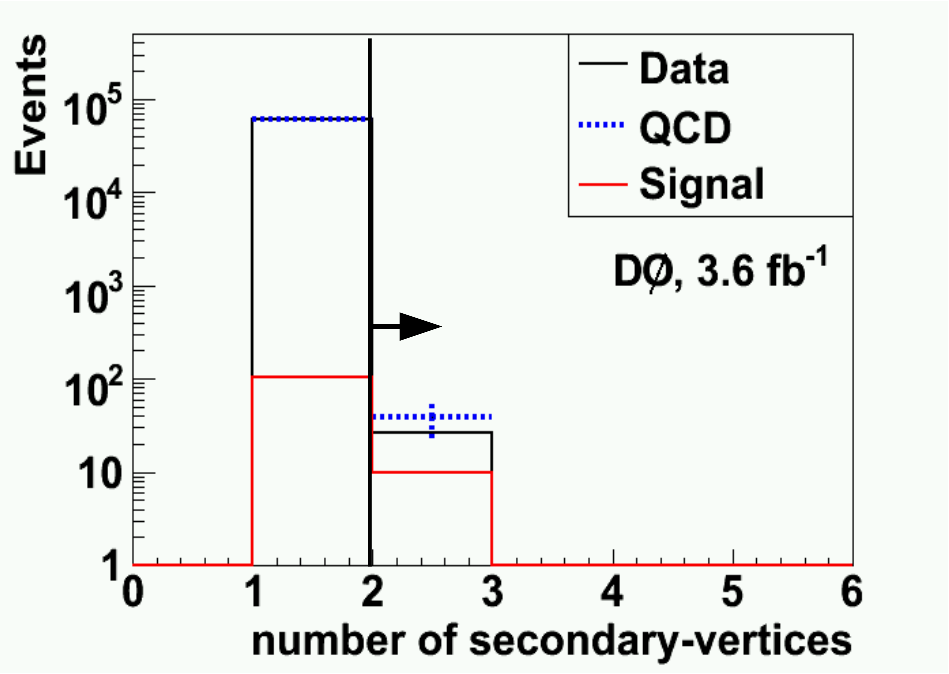


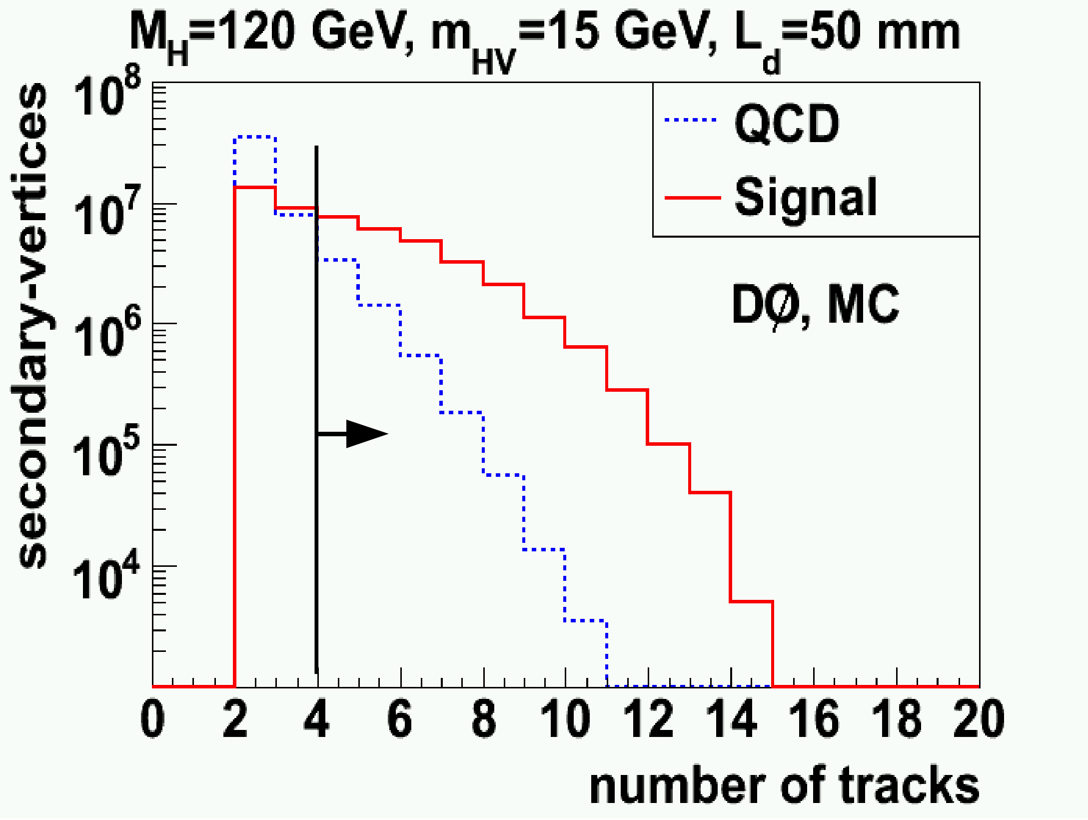


Higgs → HV HV → bb bb

2 SVs per event

SV track multiplicity>=4

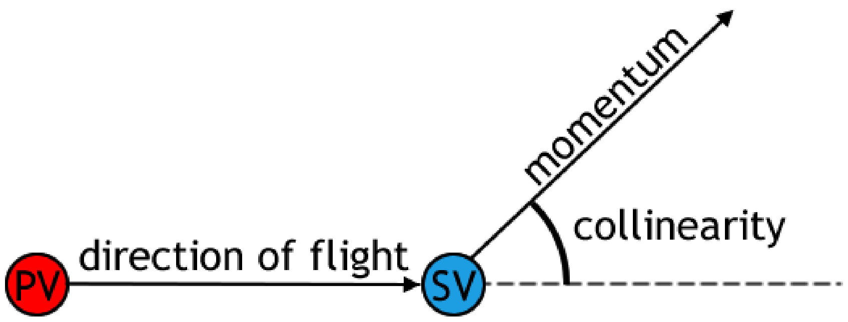


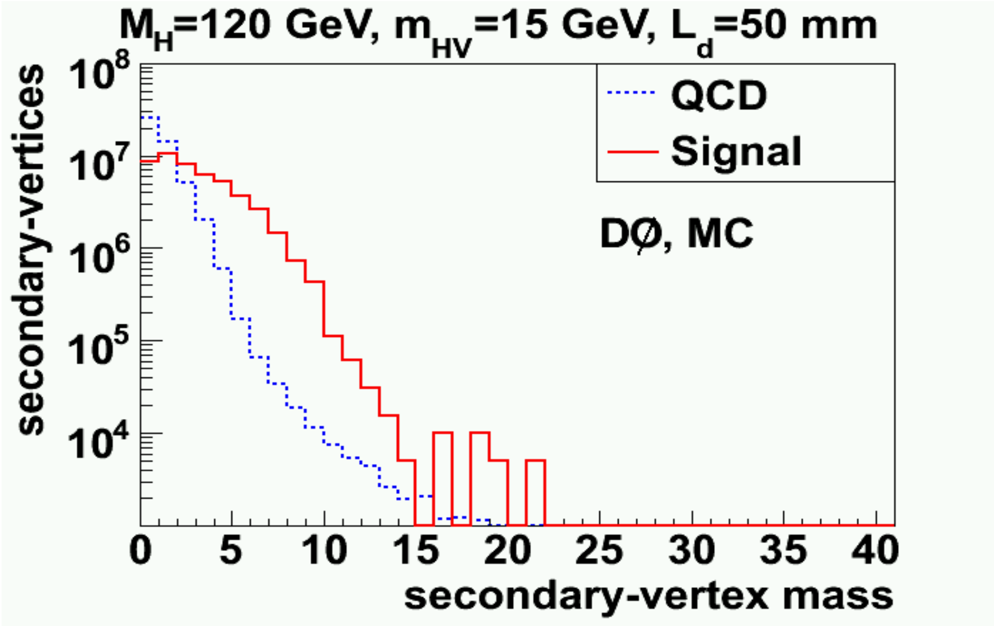


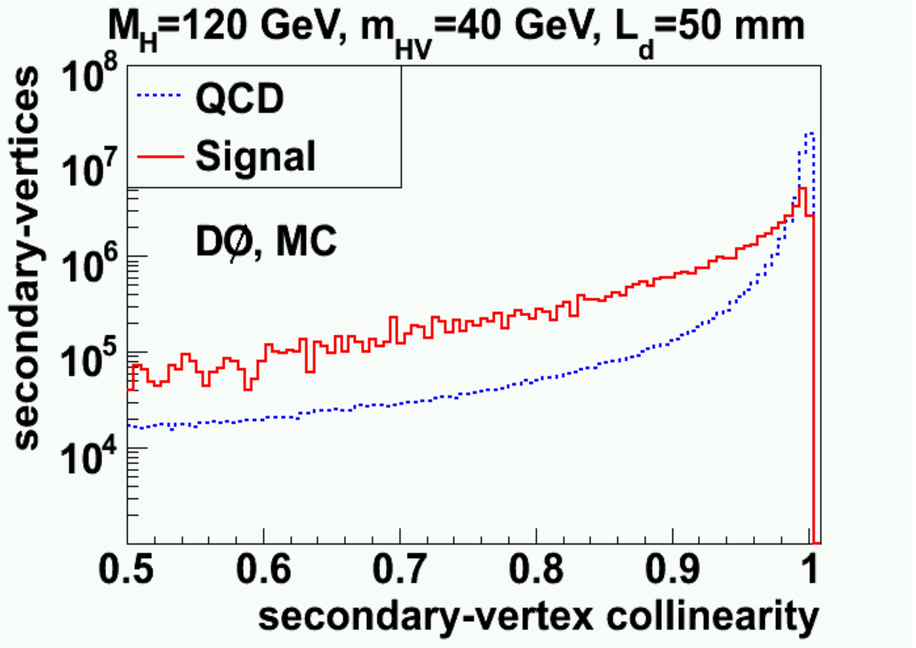
Higgs → HV HV → bb bb

SV mass and collinearity

Final handles to separate signal from background

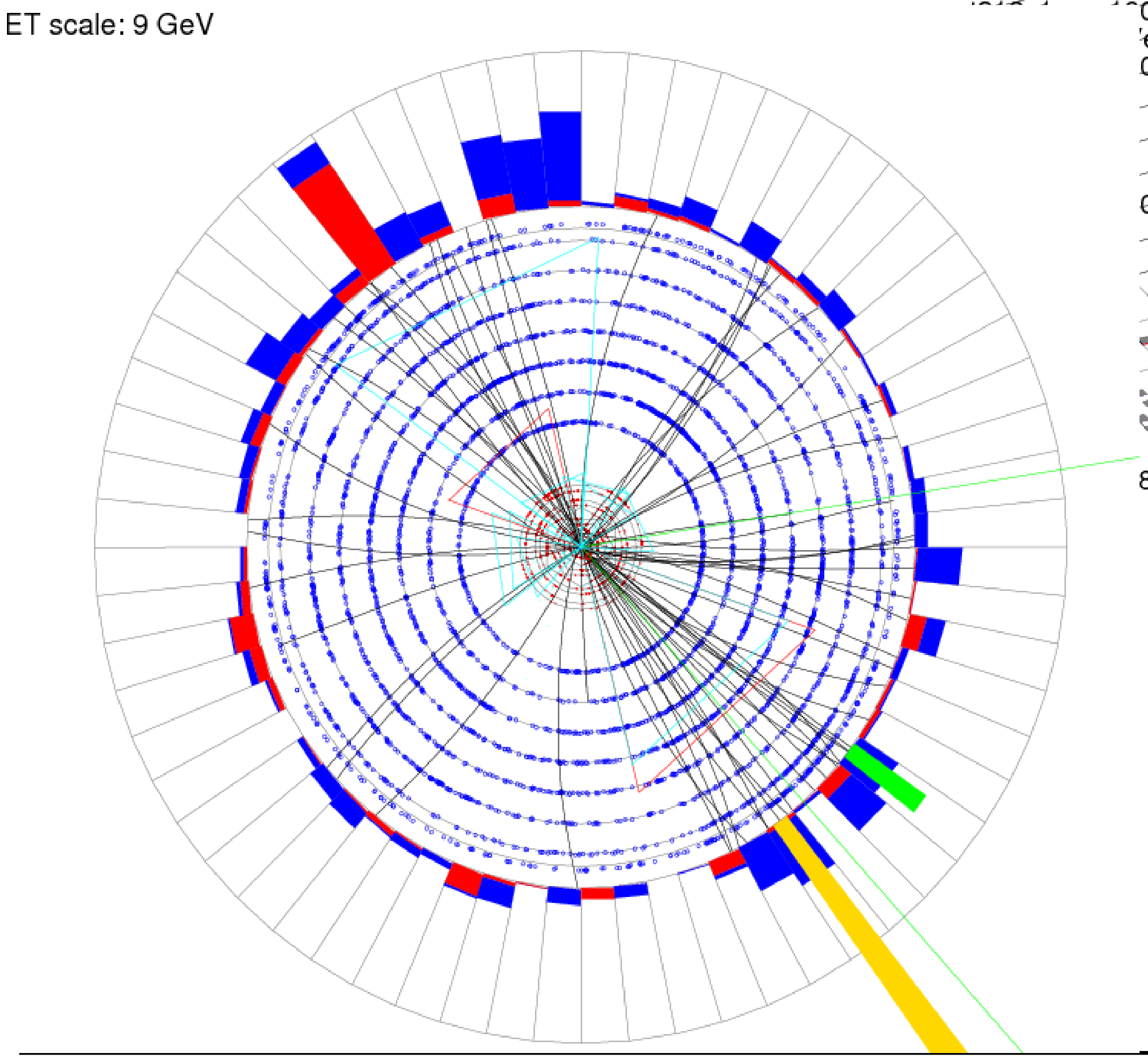


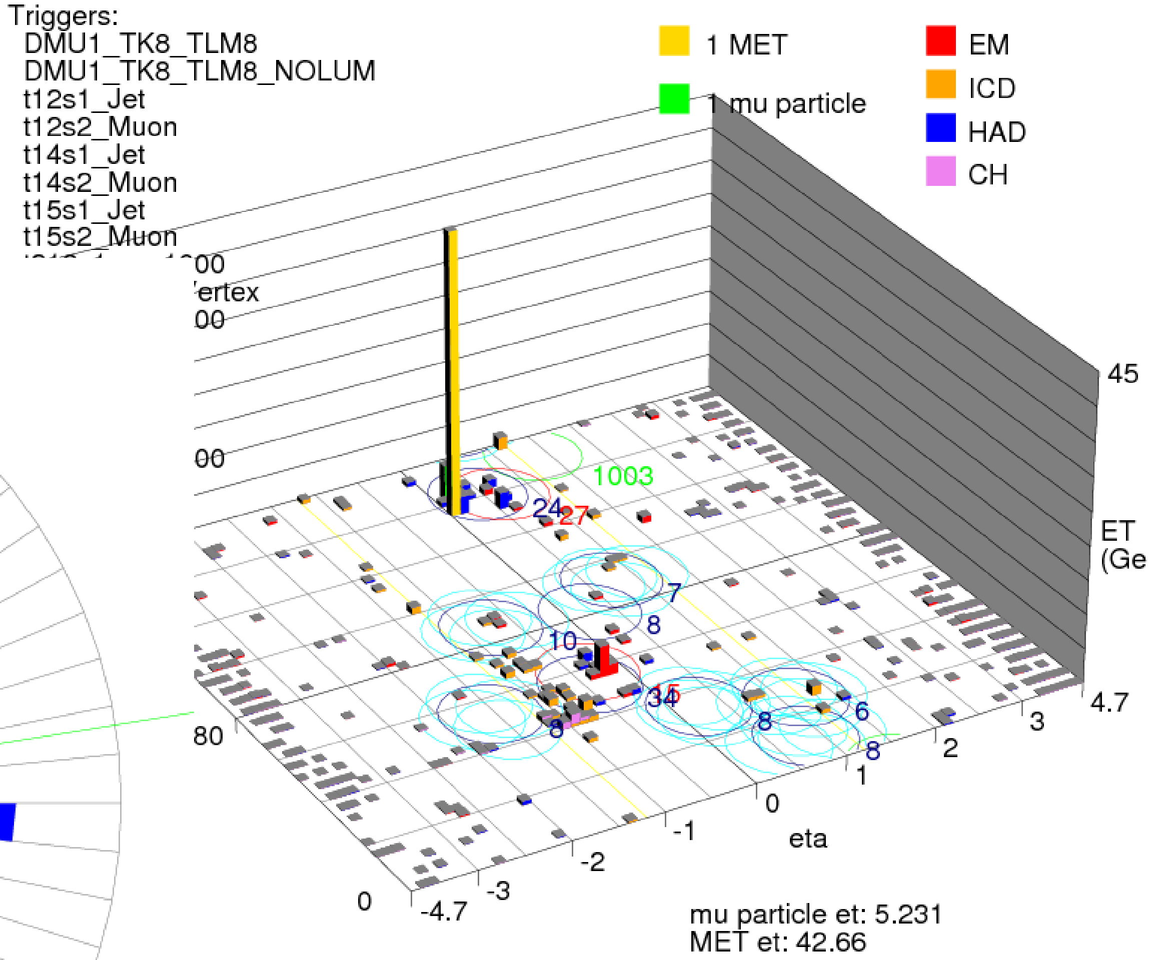




Higgs → HV HV → bb bb

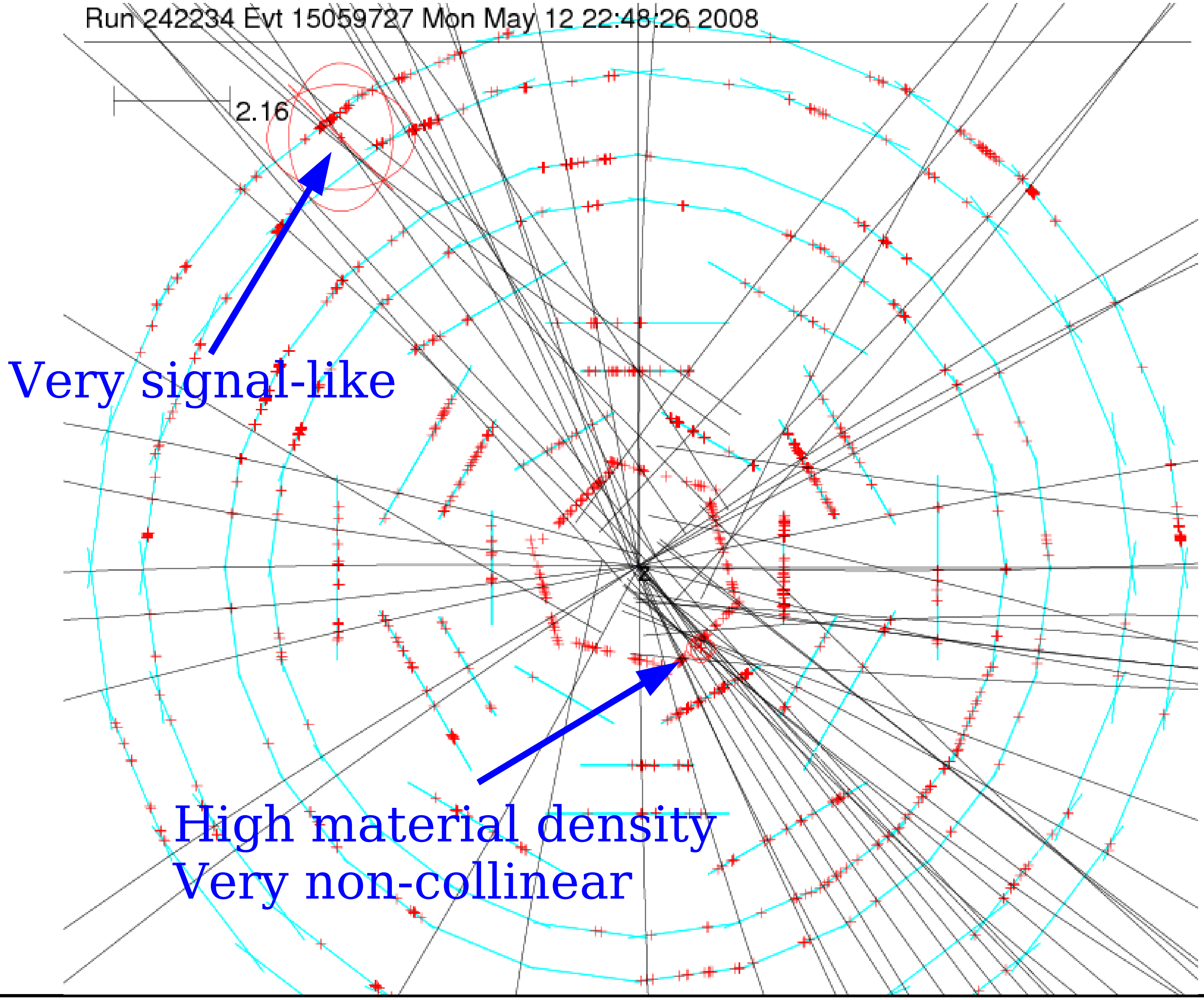
The event with
largest significance:





Higgs → HV HV → bb bb

The event with
largest significance:



Higgs → HV HV → bb bb