Searches for Long-Lived Particles with a Displaced-Vertex Signature

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Cornell University Journal Club
February 2016

Outline

- Motivation and general comments
- Search at ATLAS: **PRD 92 072004**
  - Scenarios
  - Analysis & results
- Search at BABAR: **PRL 114, 171801**
  - Scenarios
  - Analysis & results
- Summary & outlook

The usual introduction

- The standard model works really well
- But:
  - The hierarchy problem
  - Dark matter
  - The baryon asymmetry
  - Origin of flavor
  - Smallness of m_ν
  - Dark energy (?)

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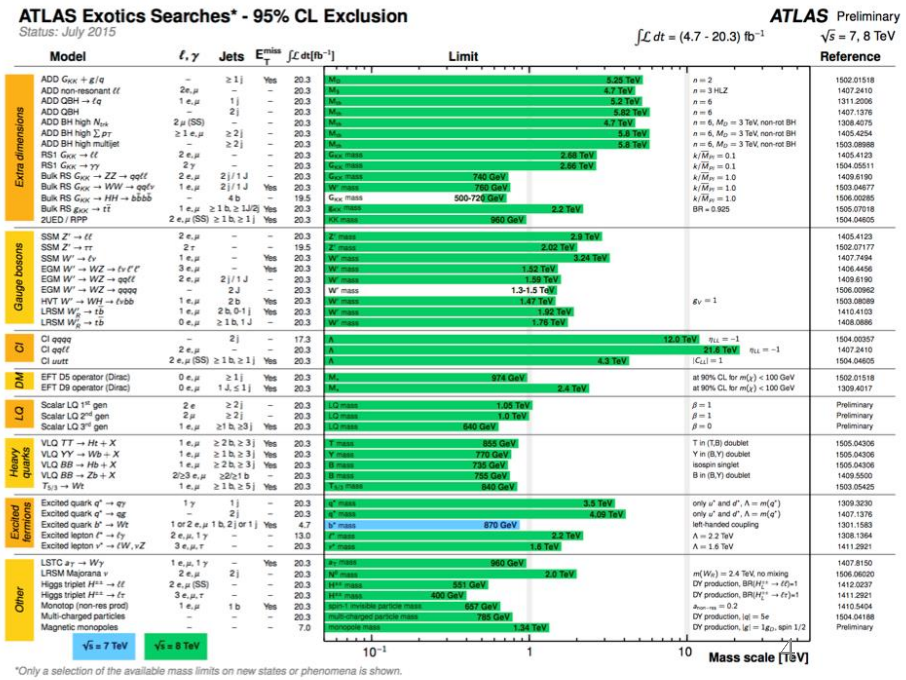
- The standard model works really well
- But:
  - The hierarchy problem
  - Dark matter
  - The baryon asymmetry
  - Origin of flavor
  - Smallness of m_ν
  - Dark energy (?)
- So we search everywhere we can for new physics



Another angle

- Discovering the SM involved steady and slow progress
  - Discovery of the c, τ, b (1970s)
  - Discovery of the W and Z (1983)
  - Precision EW measurements (1990s)
  - Discovery of the t quark (1995)
  - Direct observation of ν_τ (2000)
  - Precision CP violation (2000s)
  - Neutrino oscillations (→2000s)
  - Discovery of the Higgs boson (2012)

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  - Precision CP violation (2000s)
  - Neutrino oscillations (→2000s)
  - Discovery of the Higgs boson (2012)
- What (and when) will the next discovery be?
  - Search everywhere
  - Think of new ideas and new techniques

New long-lived particles (L)

- Why:
  - Unambiguous signature for new physics
- Who:
  - L decay should be suppressed (long lifetime)
  - L production should be relatively strong (produced in colliders)
- How:
  - For displacements of 100s of μm to 10s of cm, use the tracker – the innermost part of the detector.
  - Other methods for decays in outer detector regions

Other searches
(hopefully missing only a few)

ATLAS:

- 1210.0435: displaced lepton jets
- 1304.6310, 1409.5542: non-pointing γ
- 1310.6584: R-hadrons stopped in CAL
- 1411.6795: detector-stable “muons”
- 1501.04020: decays in HCAL
- 1504.03634: vertices in MS or ID (in jet)
- 1506.05332: high dE/dx

CMS:

- 1211.2472 , 1409.4789, 1411.6977: displaced dileptons (different flavors)
- 1411.6530: displaced $q\bar{q}$
- 1506.00424: possibly displaced muons

LHCb:

- 1412.3021: displaced jet pairs
- 1508.04094 displaced μ's in $B \to K^{*}\mu^{+}\mu^{-}$

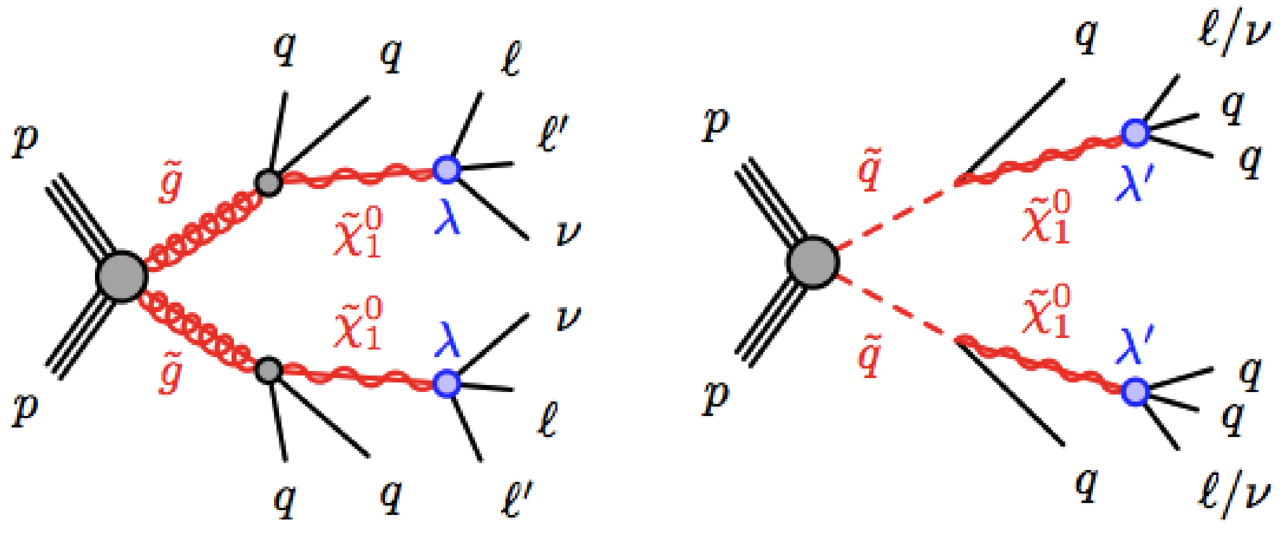
- D0:
  - hep-ex/0607028: displaced $\mu\mu$
  - 0906.1787: displaced $b\bar{b}$
  - (Non-pointing γ?)
- CDF:
  - hep-ex/9805017: displaced Z
- ALEPH
  - hep-ex/0203024: non-pointing γ
- Belle:
  - 1301.1105: $B \to D^{(*)}\ell\nu_h,\ \nu_h \to \ell\pi$

Displaced-vertex search at ATLAS

Considered scenarios - 1

- Decay suppressed by small coupling
  - E.g., SUSY with R-parity violation (RPV)

    → long-lived decaying $\tilde{\chi}^0$

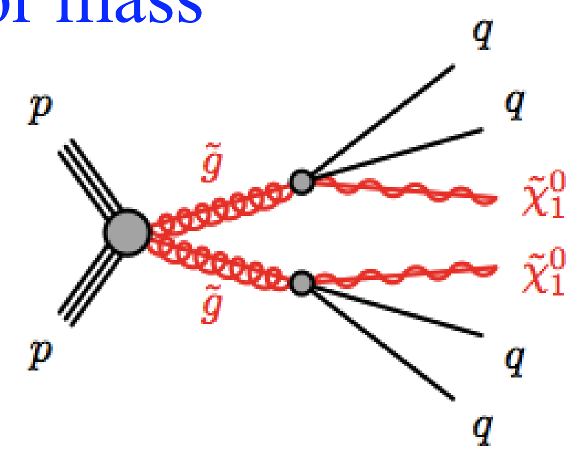


Considered scenarios - 2

- Decay suppressed by large propagator mass
  - E.g., "split SUSY":

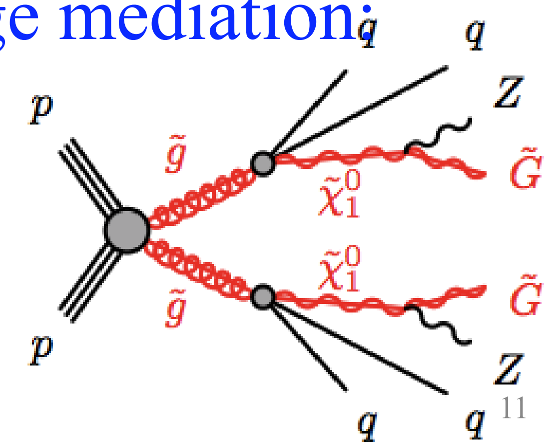
    $$\mathrm{m}_{\tilde{g}} \ll m_{\tilde{q}} \;\Rightarrow\; \Gamma_{\tilde{g}} \propto \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4}$$

    → long-lived decaying $\tilde{g}$



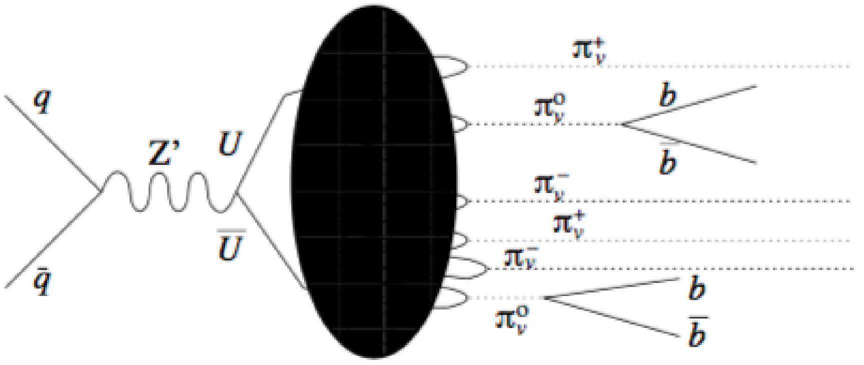
- Or by a high scale, e.g., general gauge mediation:
  - $\mathrm{m}_{\tilde{\chi}_1^0} \ll$ SUSY breaking scale $\sqrt{F}$

    → long-lived decaying $\tilde{\chi}_1^0$

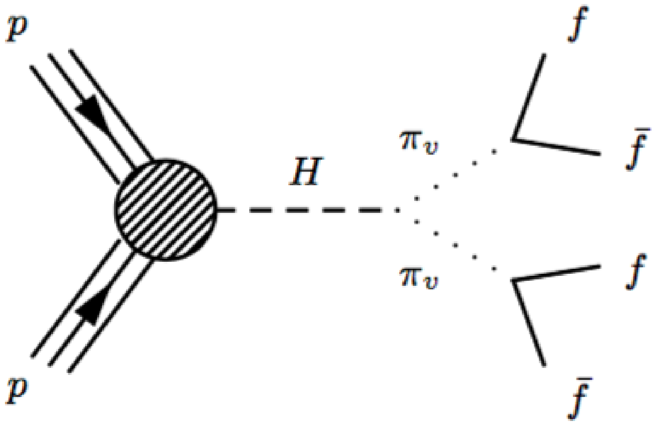


There are other scenarios

- Hidden valley
  - e.g., hep-ph/0604261 (Strassler, Zurek)



- Higgs → long-lived
  - 1508.01522 (Csaki Kuflik, Lombardo, Slone)



Analysis history

- 33 pb^{-1} of 7 TeV (2010) 1109.2242 (PLB)
  - DV+μ
- 4.4 fb^{-1} of 7 TeV (2011) 1210.7451 (PLB)
  - DV+μ improved (retracking, background estimate)
- 20.3 fb-1 of 8 TeV (2012) 1504.05162 (PRD)
  - More improvements (background estimate, material description)
  - DV+μ
  - DV+e
  - DV+jets
  - DV+E_{miss}^{T}
  - Dilepton DV

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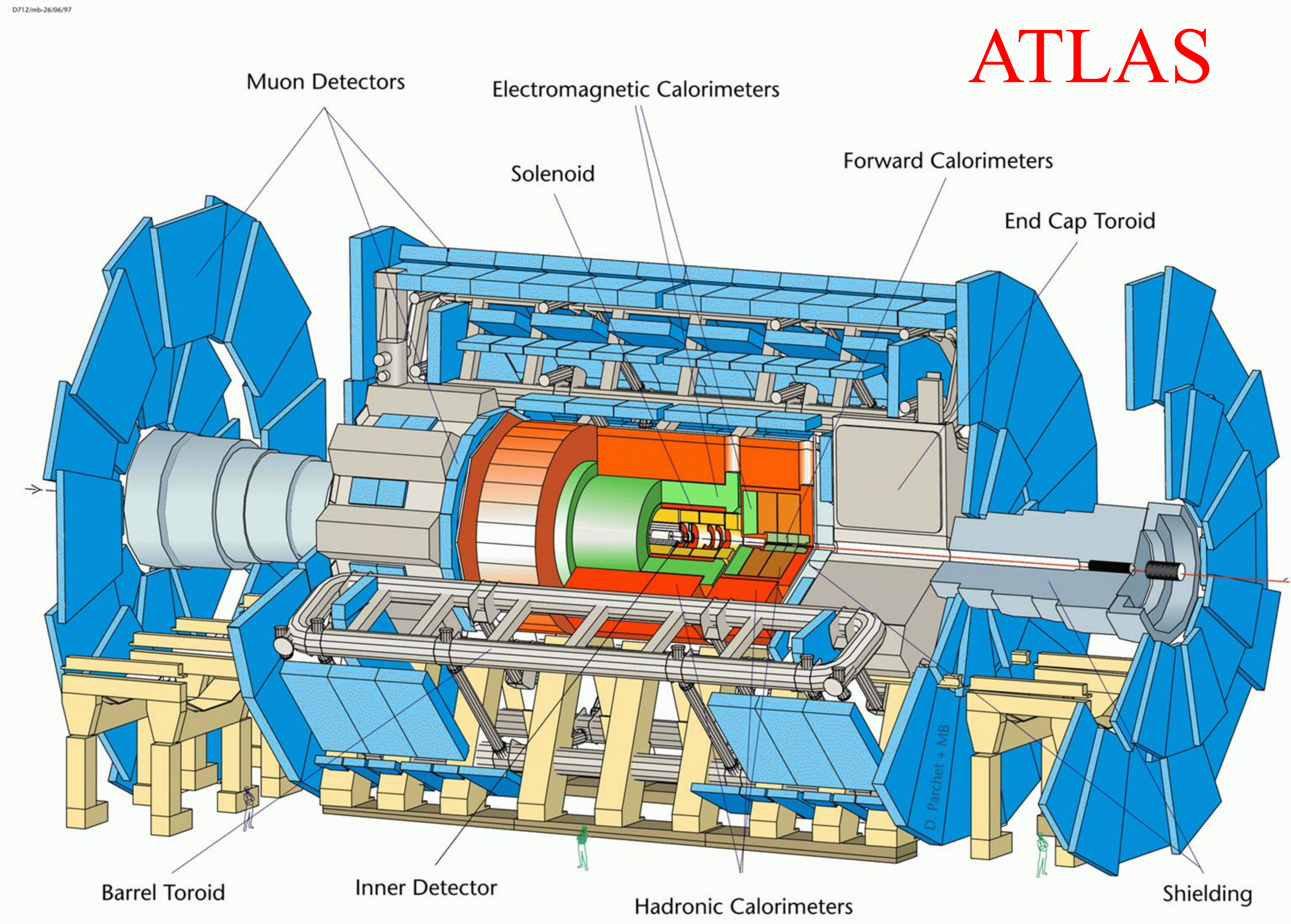
- N. Barlow (Cambridge)
- G. Cottin (Cambridge)
- M. Flowerdew (MPI)
- M. Goblirsch-Kolb (MPI)
- T.J. Khoo (Cambridge)
- O. Jinnouchi (Tokyo Tech)
- H. Otono (Kyushu)
- N. Pettersson (Tokyo Tech)
- A. Soffer (Tel Aviv)
- N. Taiblum (Tel Aviv)

From the previous analyses:

- F. Brochu (Cambridge)
- J. Ernst (Albany)
- K. Horn (SLAC)
- V. Jain (Albany)
- H.J. Kim (Stockholm)
- Kreisel (Tel Aviv)
- C.W. Loh (Indiana)
- N. Soni (Adelaide)

ATLAS

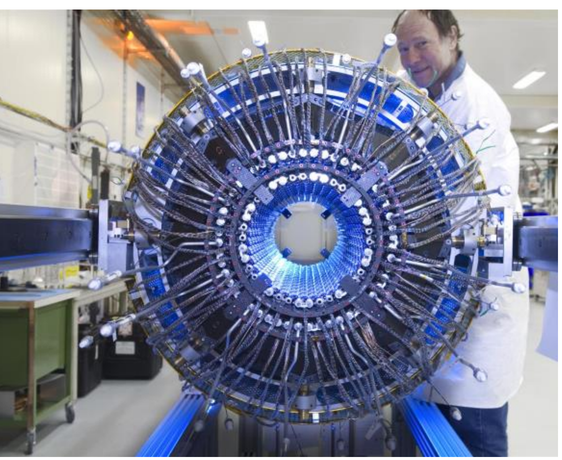

D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

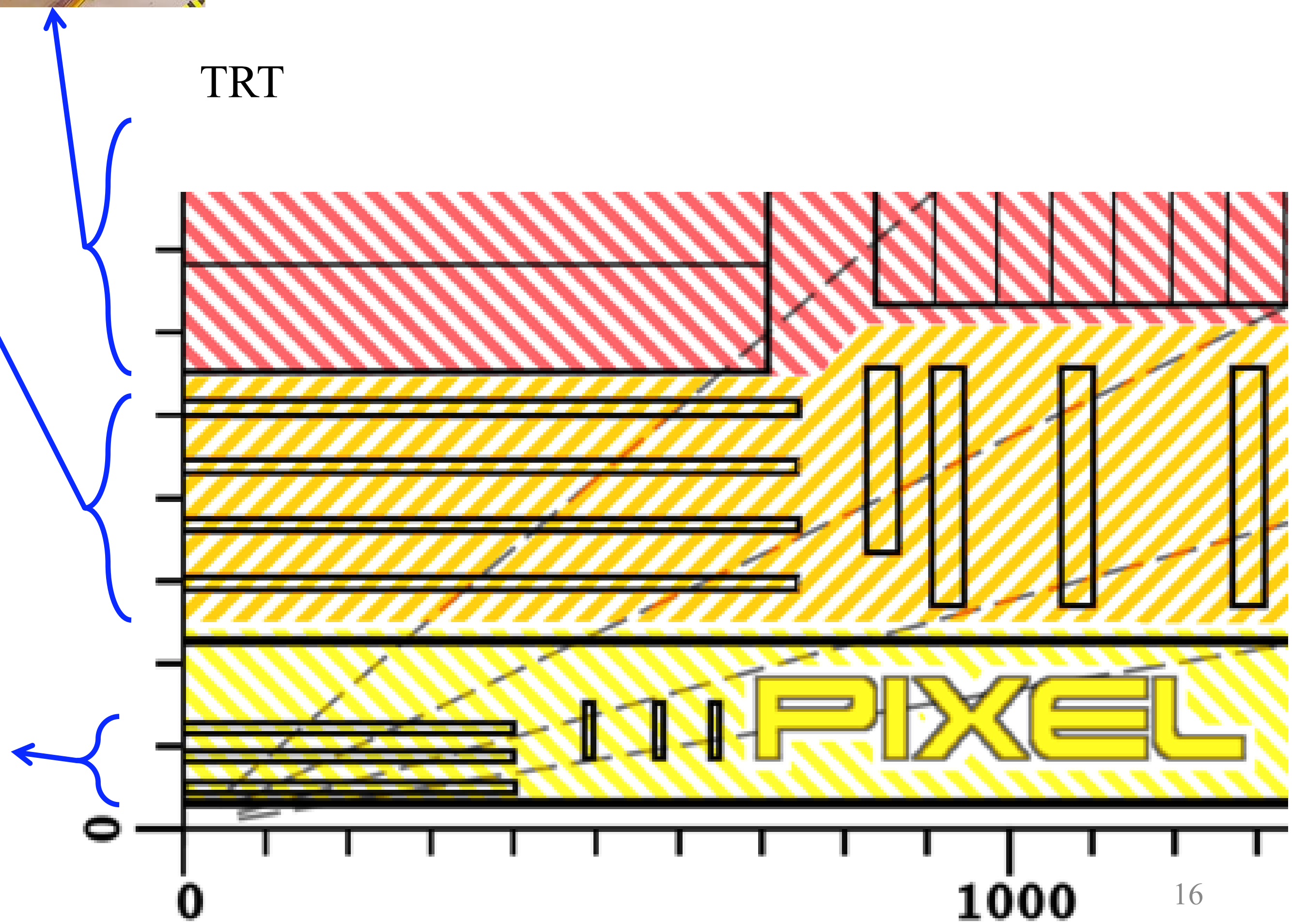
Track & vertex reco.

SCT

TRT

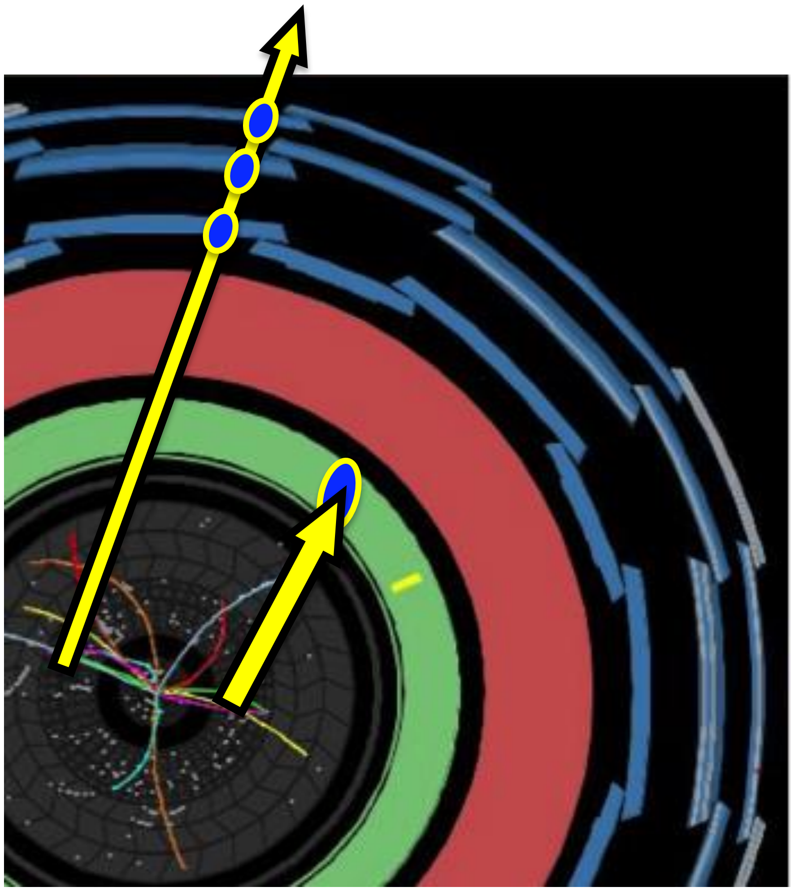
Pixel





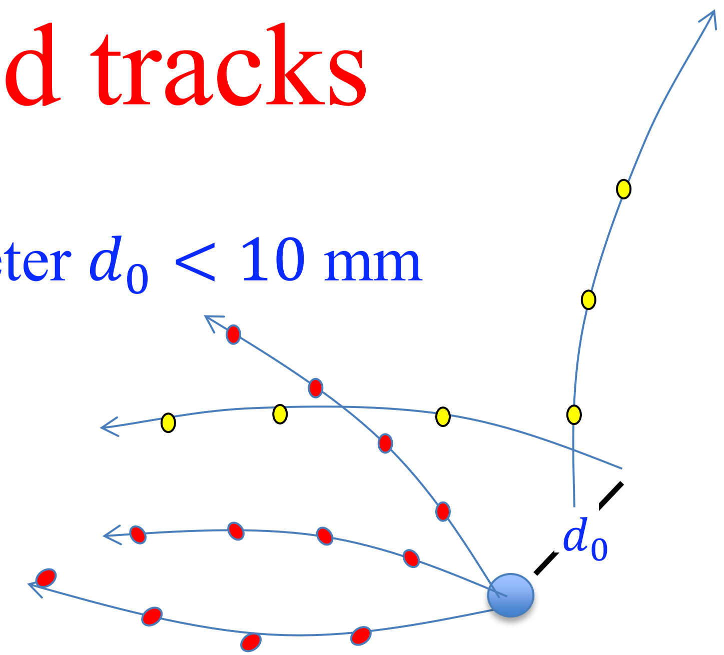
Trigger (might miss the DV tracks)

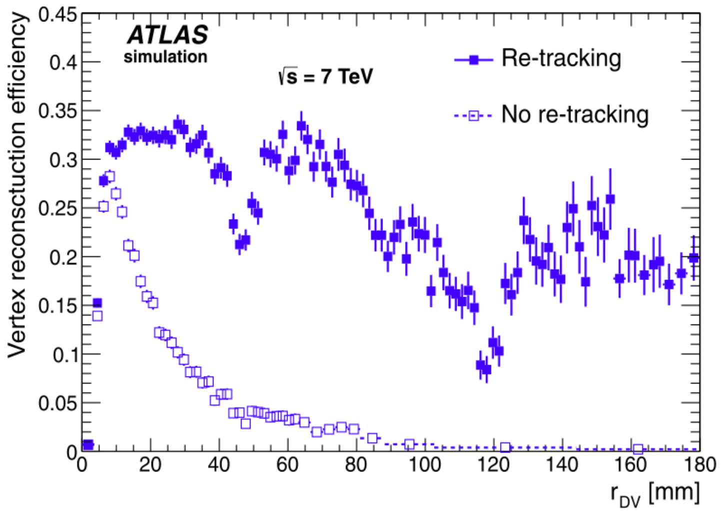
- DV+μ
  - Muon-spectrometer only, $p_T^{\mu} > 50$ GeV
- DV+e
  - Photon, $p_T^{\gamma} > 120$ GeV
- DV+jets
  - $4 \times 80 \parallel 5 \times 55 \parallel 6 \times 45$ GeV
- DV+E_T^{miss}
  - $E_{miss}^{T} > 80$ GeV
- Dilepton DV
  - $p_T^{\mu} > 50 \parallel p_T^{\gamma} > 120 \parallel 2\gamma \times 40$ GeV



Tracking displaced tracks

- ATLAS tracks must have impact parameter $d_0 < 10$ mm
  - Severely limits sensitivity for highly displaced vertices
- We perform offline "retracking":
  - Keep detailed information (DESD) for triggered events
  - Offline: retrack with unused hits and $d_0 < 300$ mm, $z_0 < 1500$ mm
  - Obtain significant efficiency improvement at large vertex distances:

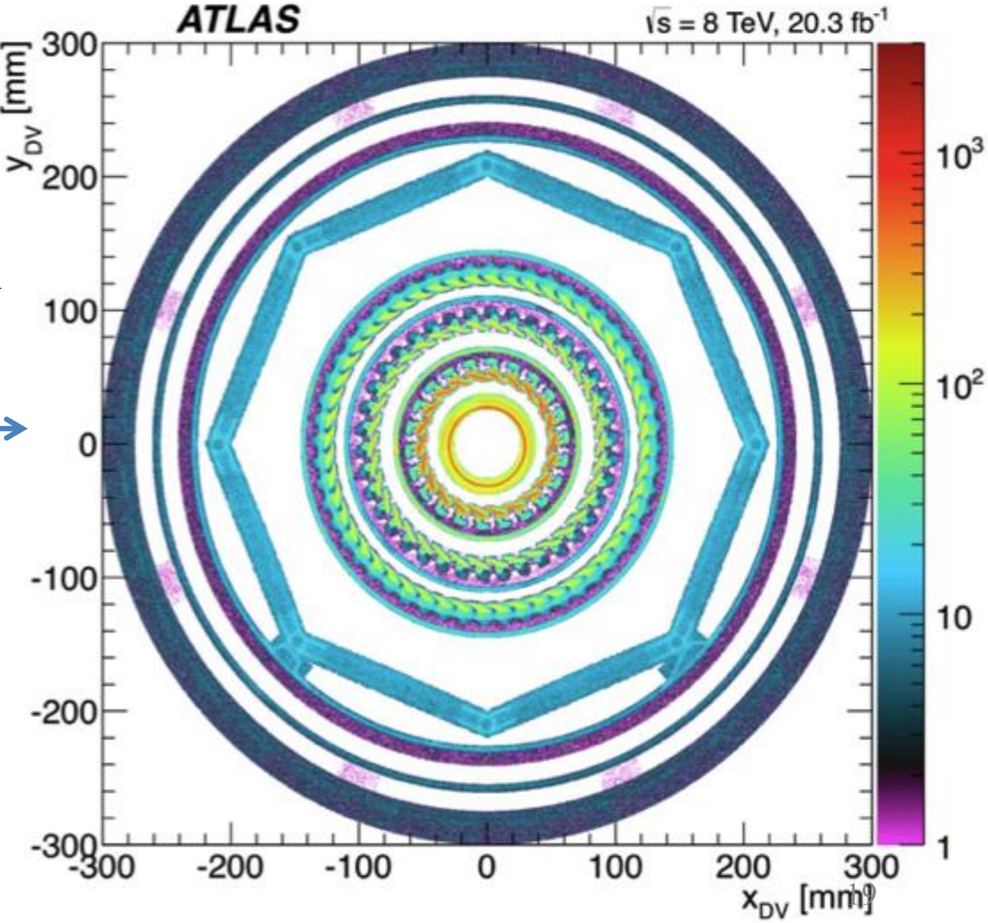




Vertex reconstruction efficiency (details later) before and after retracking

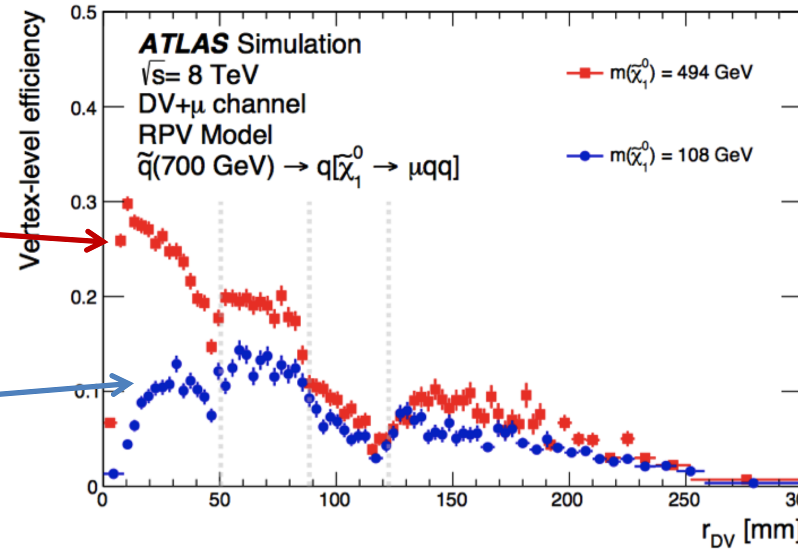
Vertex reconstruction

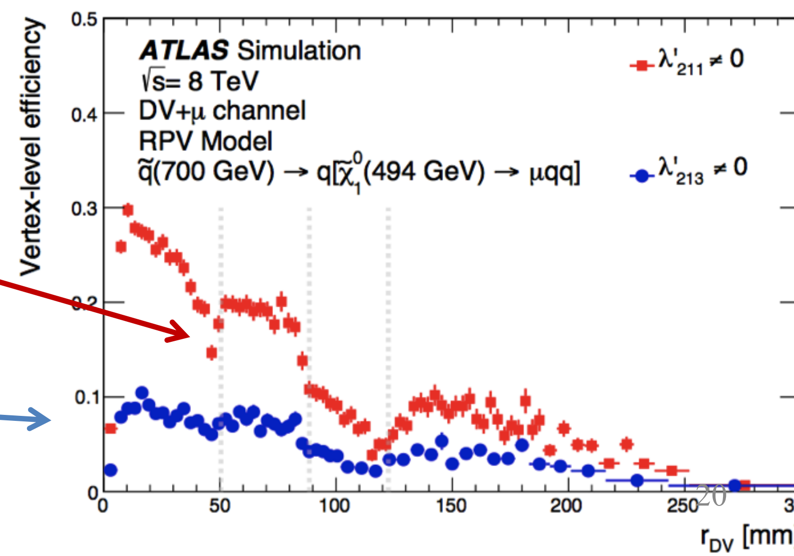
- Tracks:
  - $p_T \geq 1$ GeV, $d_0 > 2$ mm
- Displaced vertex (DV):
  - Vertex track pairs
  - Iterative process to associate 1 track → 1 DV, merge vertices within 3σ or 1 mm
  - $r > 4$ mm
  - Veto vertices in material →
- Multitrack final selection:
  - # tracks in DV: $N_t \geq 5$
  - DV mass: $m > 10$ GeV
- Dilepton final selection:
  - Lepton $p_T > 10$ GeV
  - $m > 10$ GeV



DV+μ efficiency (examples)

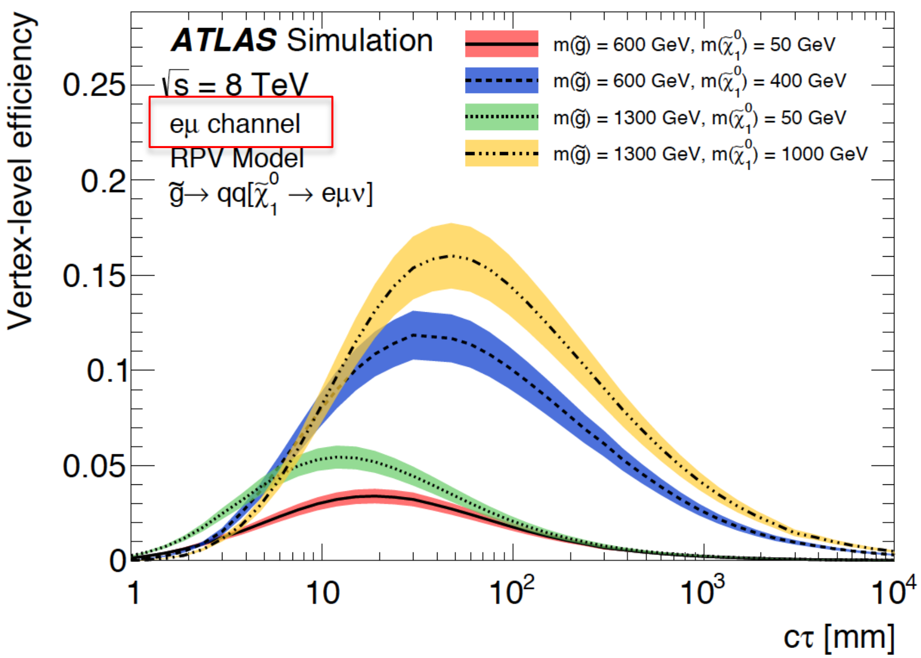
- Massive L (500 GeV): easy to find (many tracks)
- Boosted, light L (100 GeV): tracks fail $d_0 > 2$ mm @ small r
- Right before pixel layers: lose tracks due to shared hits
- $L \rightarrow c$ or b: tracks lost to tertiary vertex

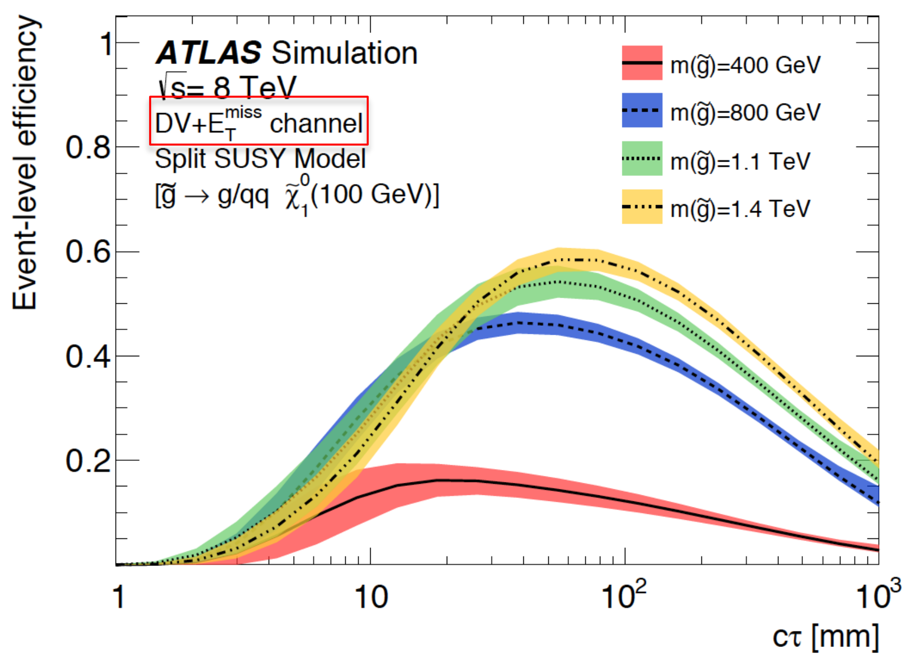




Efficiency vs. lifetime

- Optimal range of lifetimes
- Easier at high mass
  - Easier triggers
  - More tracks and mass in vertex



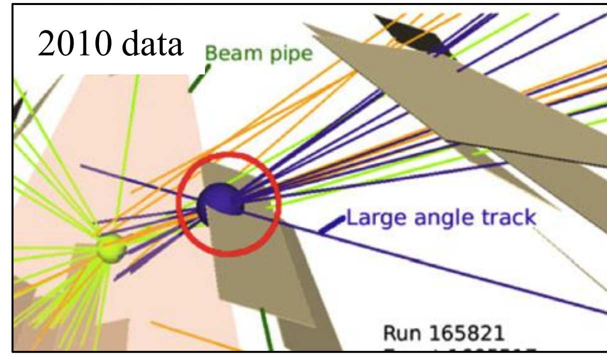


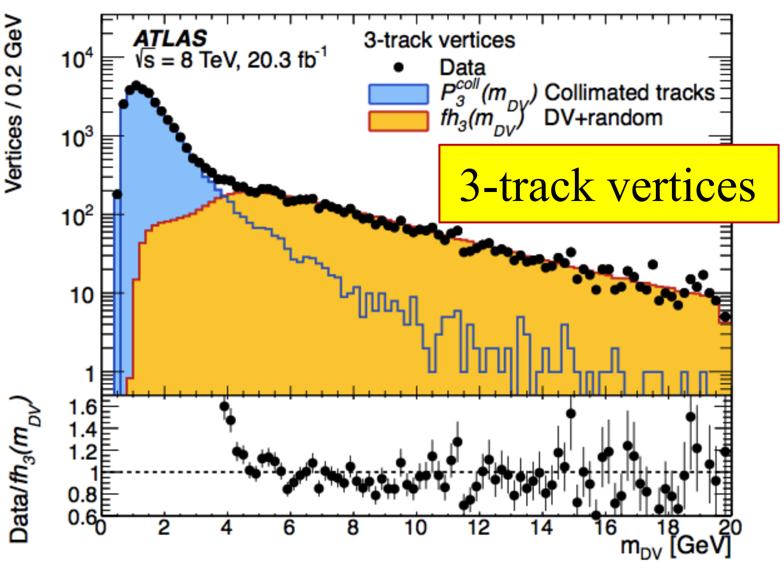
A selection of efficiency corrections/validations

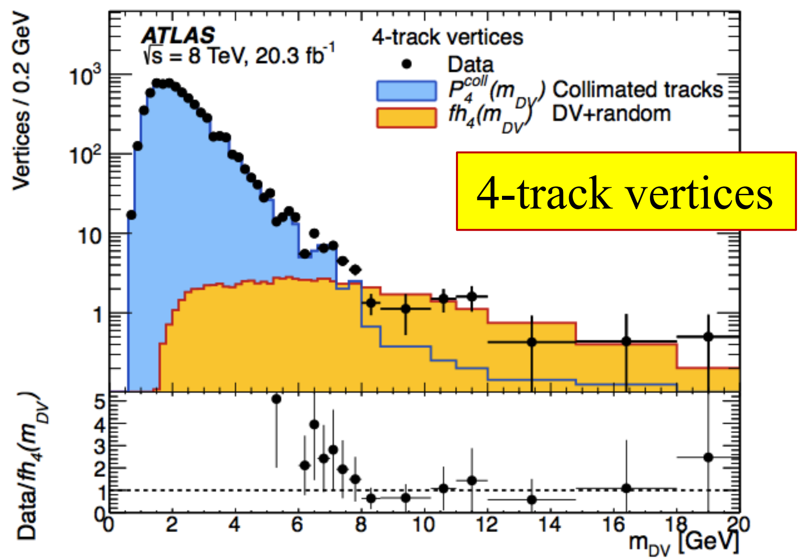
- Displaced track reconstruction efficiency:
  - K_S efficiency data-MC comparison
- Muon ID efficiency vs. d_0:
  - cosmic muons: select with ΔR, verify with Δp_T
- Electron ID efficiency vs. d_0:
  - No source of clearly identifiable displaced electrons
  - Use $Z \rightarrow e^+e^-$ data-MC comparison as a function of z_0
- Jet efficiency vs. displacement:
  - p_T variation in MC

Dominant background: multitrack

- Falls rapidly with #-of-tracks and mass
- Dominant source: low-mass material-interaction vertex accidentally crossed by high-p_T track
- Estimated by combining low-mass vertices with a track from another event, separately in 6 radial regions



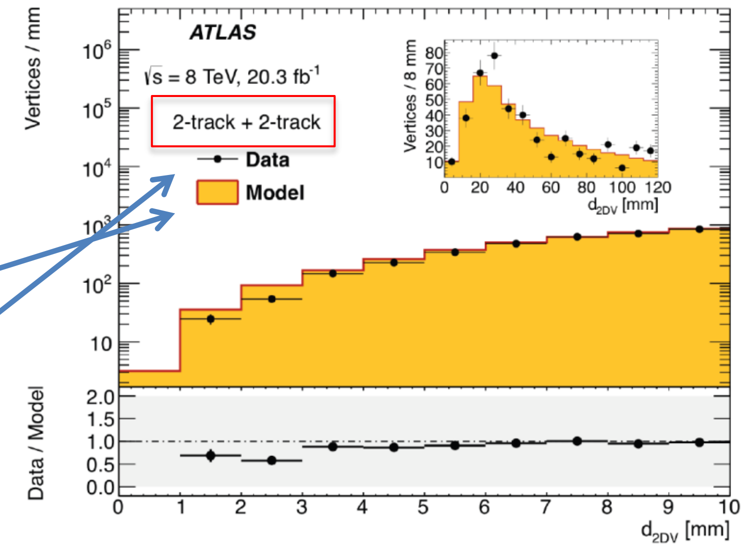




Channel	No. of background vertices ($\times 10^{-3}$)
DV+jet	$410 \pm 7 \pm 60$
DV+E_T^{miss}	$10.9 \pm 0.2 \pm 1.5$
DV+muon	$1.5 \pm 0.1 \pm 0.2$
DV+electron	$207 \pm 9 \pm 29$

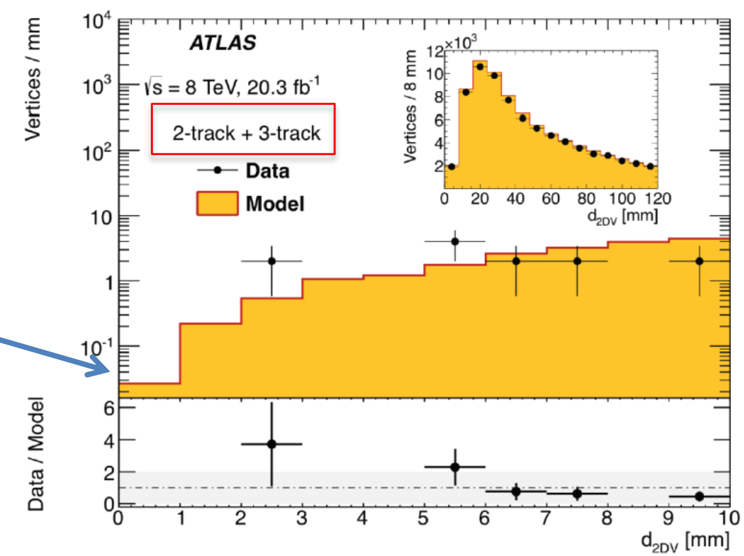
Minor background: multitrack

- Merged low-multiplicity vertices
- Studied from the distribution of the distance between vertices in different events (model) (after η weighting)
- Validated with vertices in same event (data)



(a)

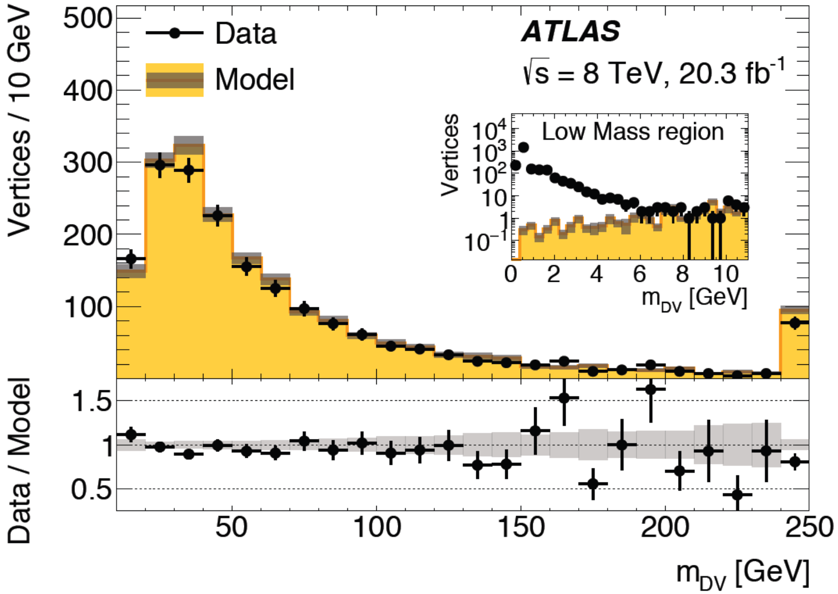
- Estimated background level:
  - 0.02 ± 0.02 events in DV+lepton
  - 0.03 ± 0.03 events in DV+jets/MET



(b)

Dominant background: dilepton

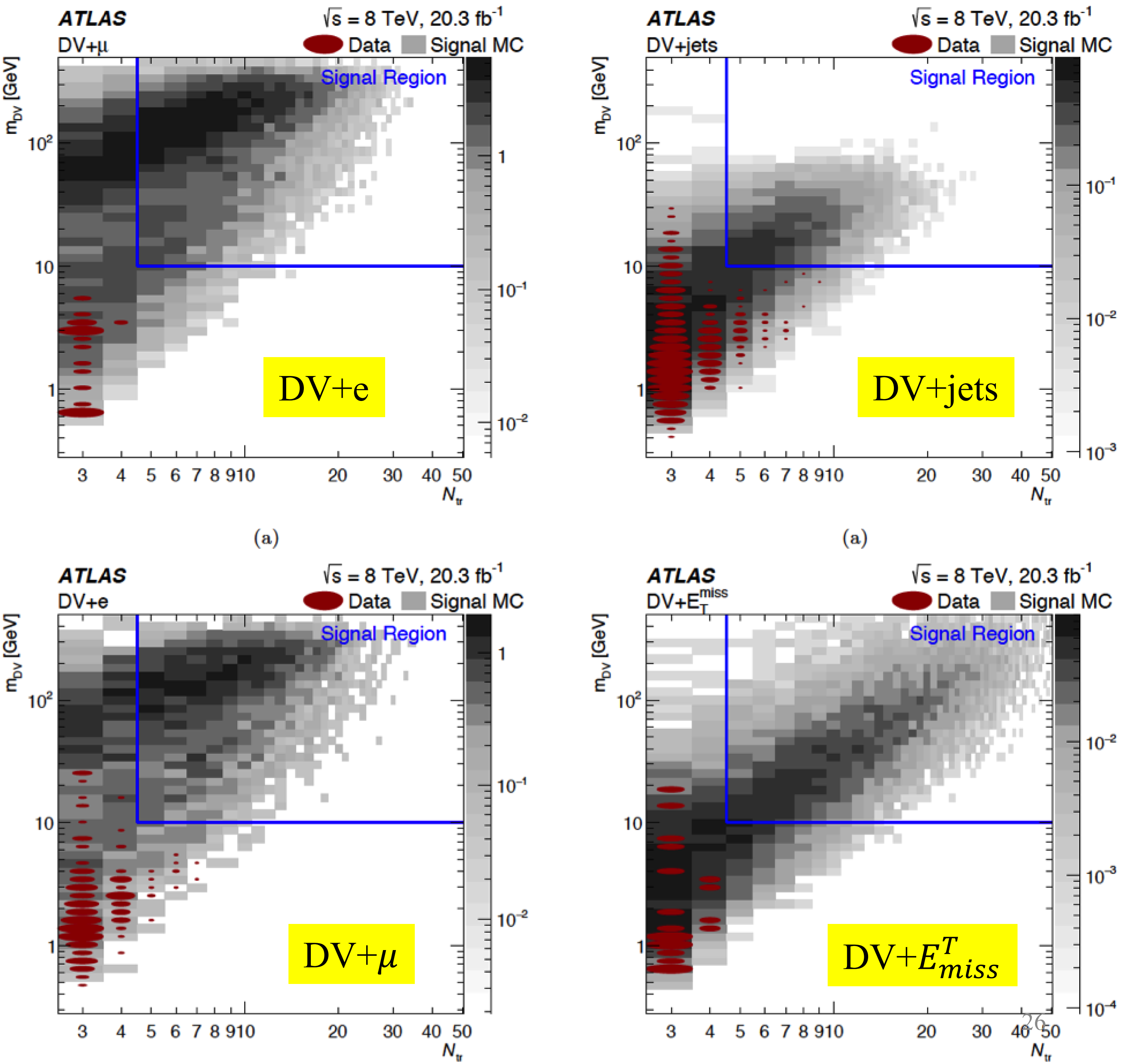
- Random crossings of leptons
- Studied by
  - Selecting 2 leptons from different events
  - Rotating one in steps of $\delta\phi < 0.03$
  - Vertex fitting at each step
  - If vertex passes cuts, assign weight $\delta\phi/2\pi$
  - $\sum$weights = random dilepton vertex prob.
- Validated using
  - MC
  - Non-leptonic tracks



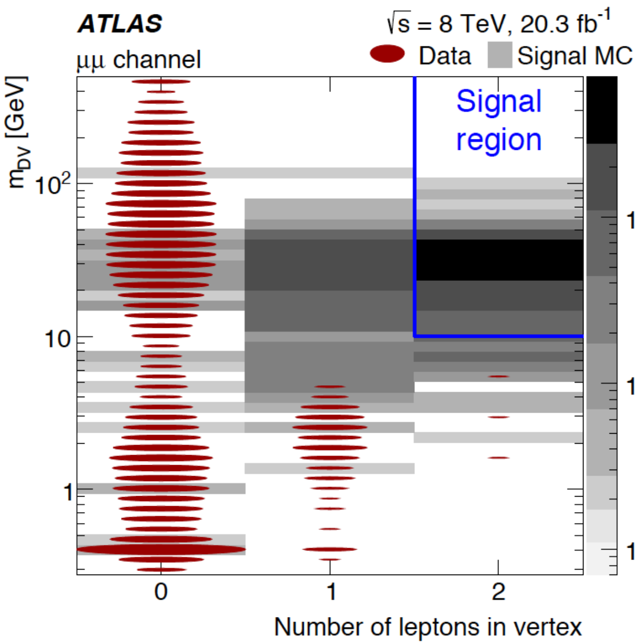
Channel	No. of background vertices ($\times 10^{-3}$)
e^+e^-	$1.0 \pm 0.2 \ ^{+0.3}_{-0.6}$
$e^\pm\mu^\mp$	$2.4 \pm 0.9 \ ^{+0.8}_{-1.5}$
$\mu^+\mu^-$	$2.0 \pm 0.5 \ ^{+0.3}_{-1.4}$

Multitrack Results

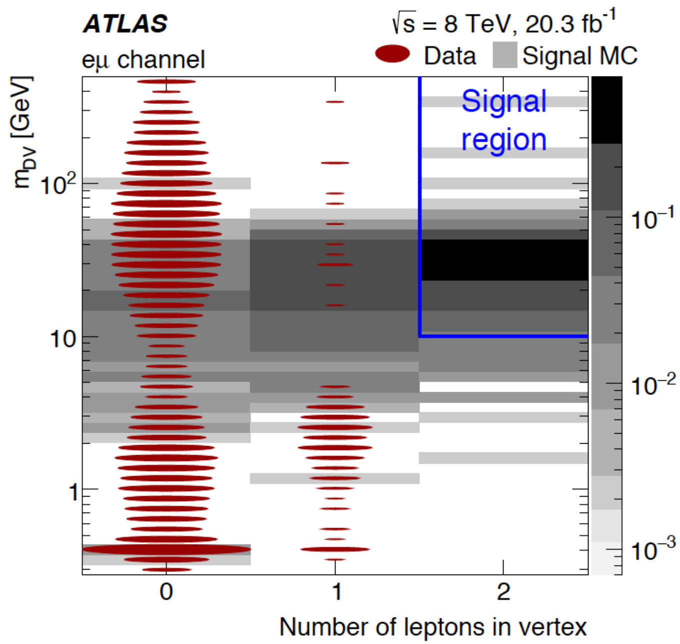
No events observed in the signal regions



Similar plots for dilepton channels

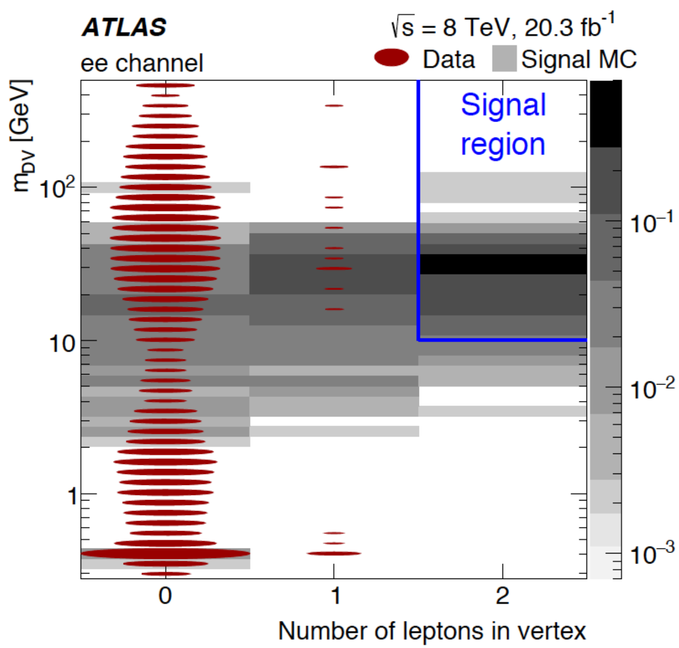


(a)



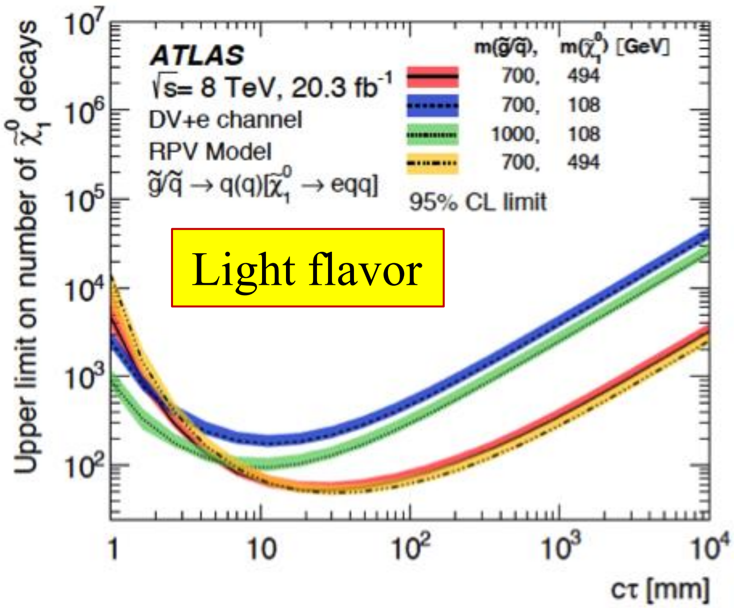
(b)

Dilepton results

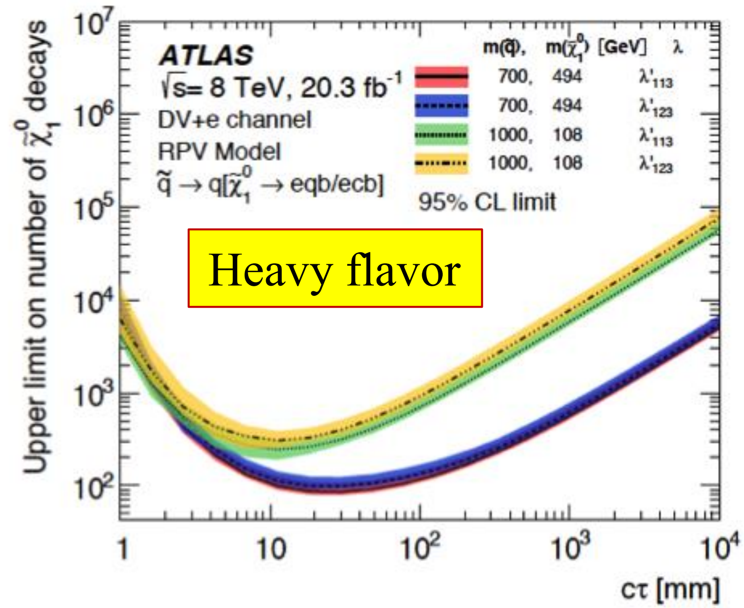


Example limits for RPV scenario

DV+e
Limits on
# of event

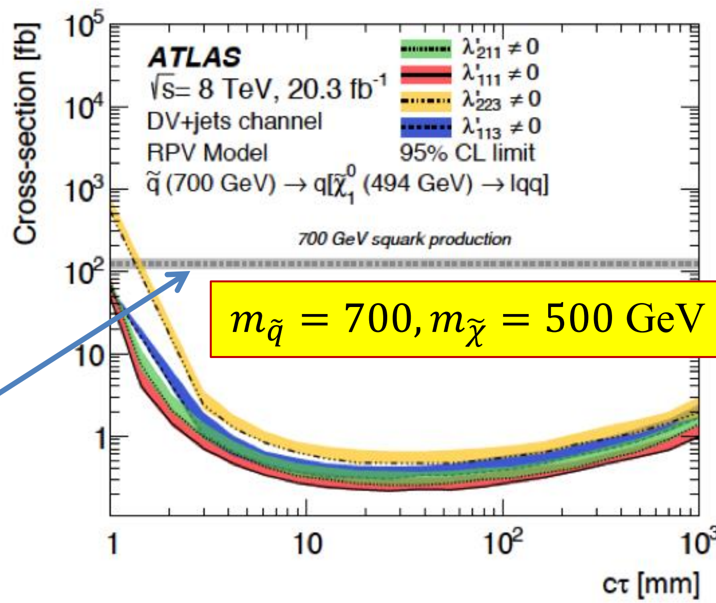


Light flavor

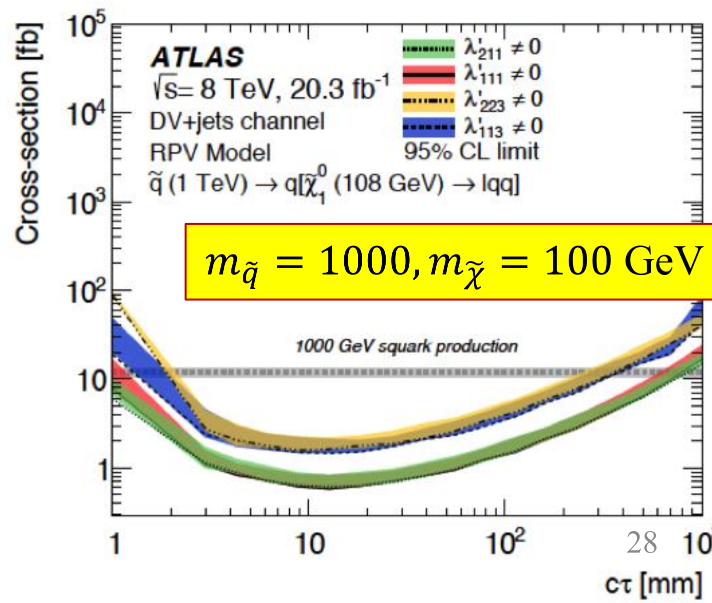


Heavy flavor

DV+jets
limits on
$\tilde{q}\tilde{q}$ cross section



$m_{\tilde{q}} = 700, m_{\tilde{\chi}} = 500$ GeV

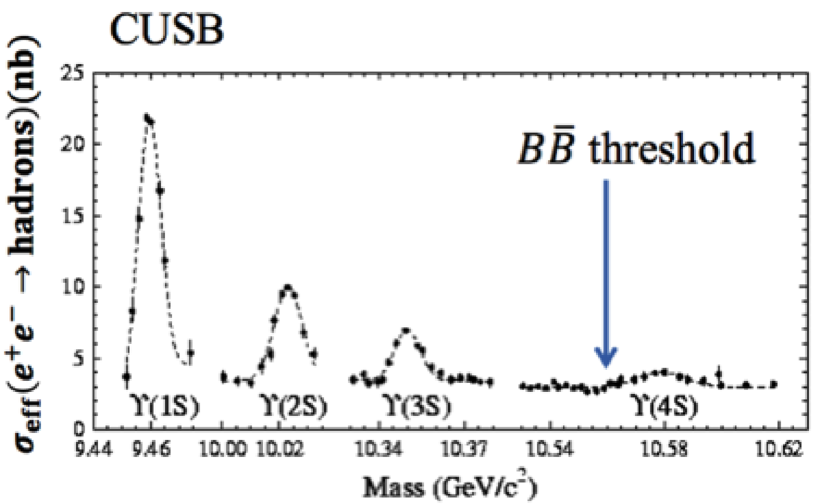


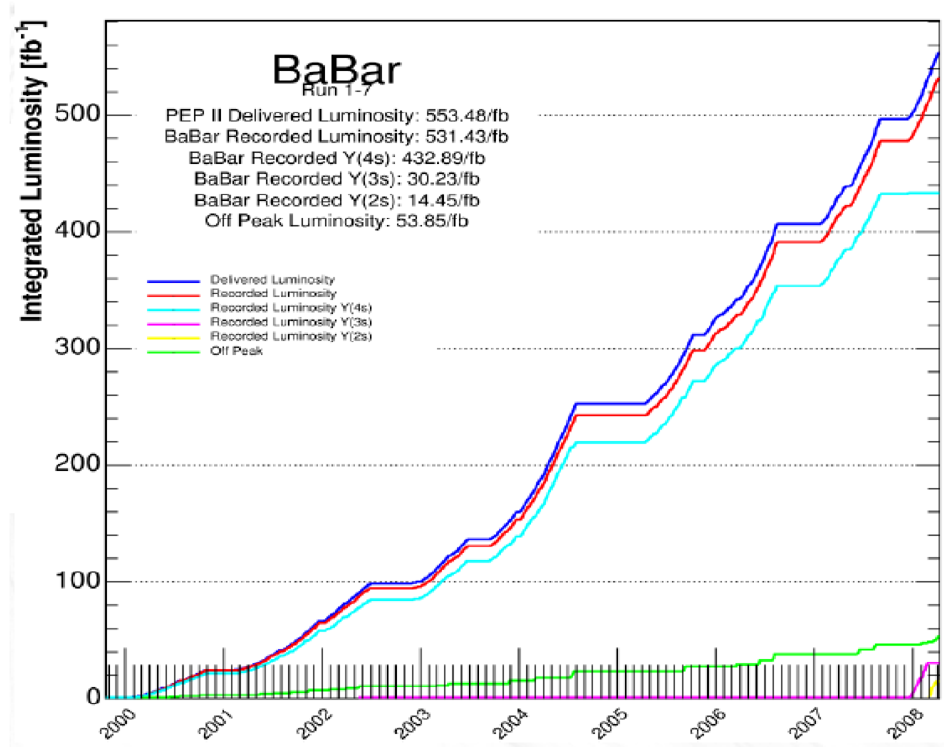
$m_{\tilde{q}} = 1000, m_{\tilde{\chi}} = 100$ GeV

Predictions

Displaced-vertex search at BABAR

BABAR Energy and data





L[Υ(4S)] = 424 fb^{-1} #[Υ(4S)] = 471×10^6

L[Υ(3S)] = 28 fb^{-1} #[Υ(3S)] = 121×10^6

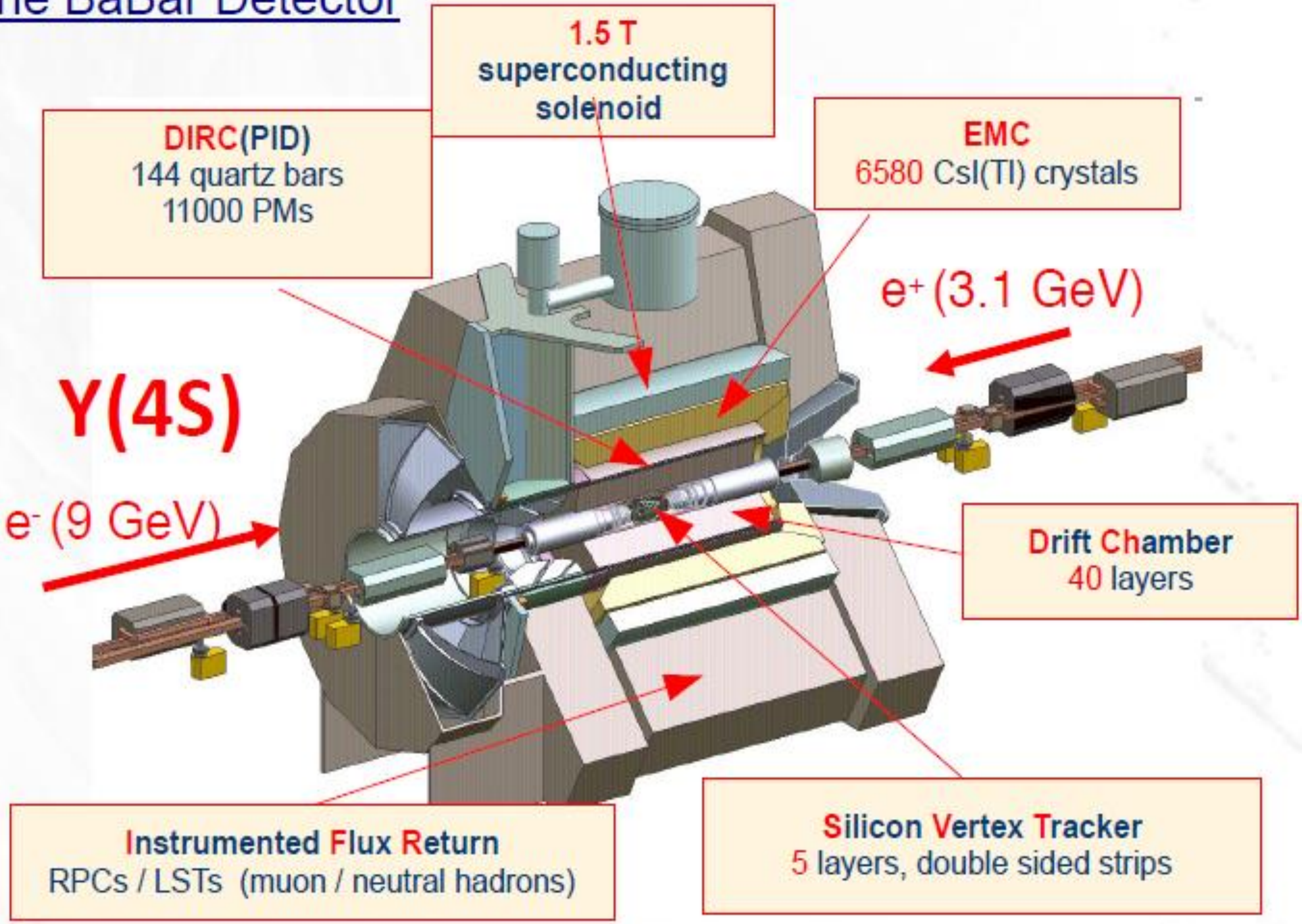
L[Υ(2S)] = 14 fb^{-1} #[Υ(2S)] = 99×10^6

$\sim 1.3 \times 10^9\ e^+e^- \to c\bar{c}$

$\sim 0.9 \times 10^9\ e^+e^- \to \tau^+\tau^-$

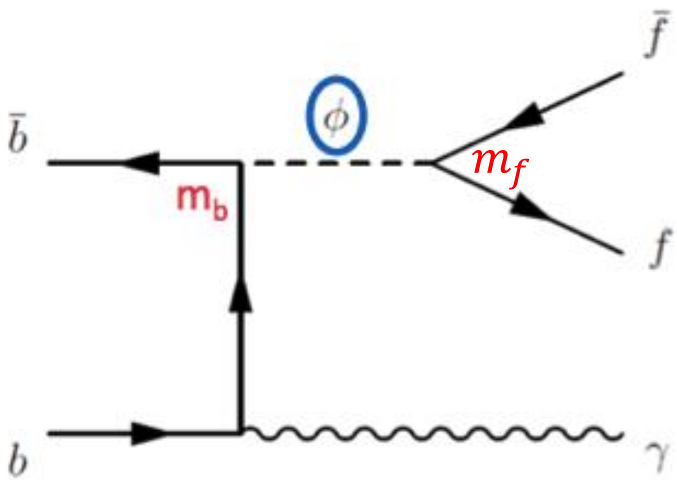
Belle data ended mid-2010,
L(4S) = 711 fb^{-1}, L(5S) = 121 fb^{-1}

The BaBar Detector

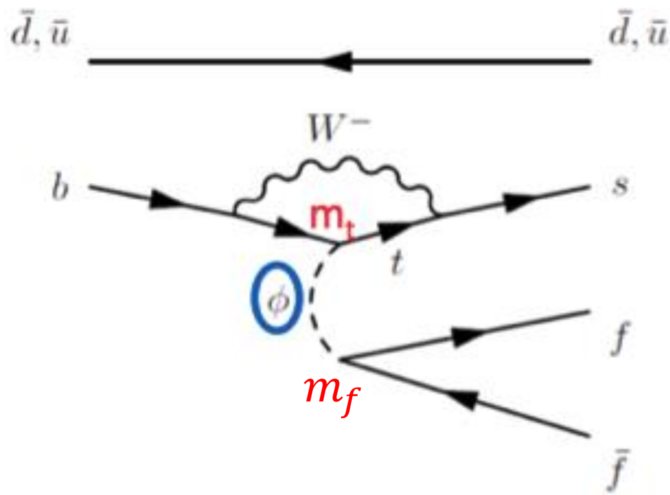


Scenarios - 1

- "Higgs portal": new scalar ϕ mixes with SM Higgs (e.g., 1310.8042)
  - ϕ produced with large coupling m_b or m_t
  - If $m_\phi < 2m_\mu$, the ϕ decays with small coupling m_μ, long-lived



$\Upsilon(2S/3S) \to \gamma\phi$



$b \to s\phi$

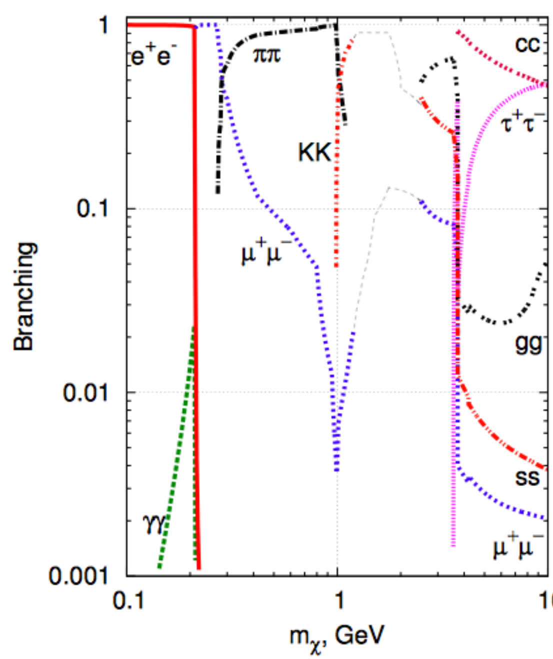
Scenarios – 1.5

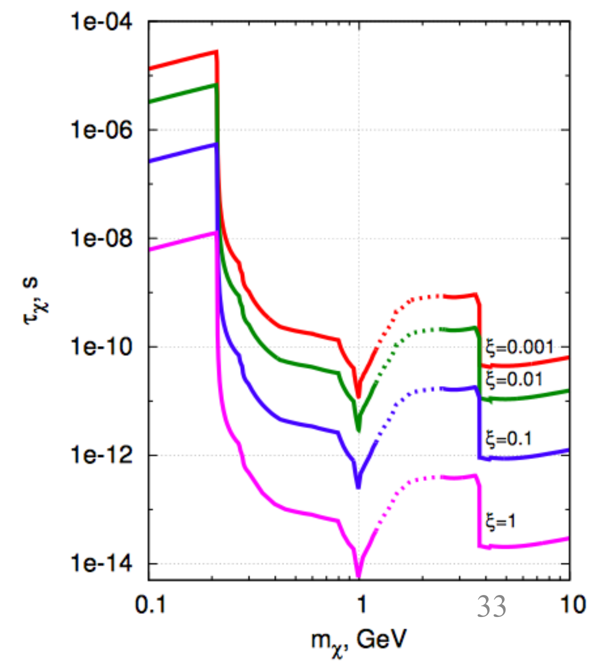
- E.g., inflaton mixes with the SM Higgs (1303.4395)

$$\mathcal{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}m_X^2 X^2 - \frac{\beta}{4}X^4 - \lambda\left(H^\dagger H - \frac{\alpha}{\lambda}X^2\right)^2$$

$$\mathcal{L}_{\rm grav} = -\frac{M_P^2 + \xi X^2}{2}R,$$

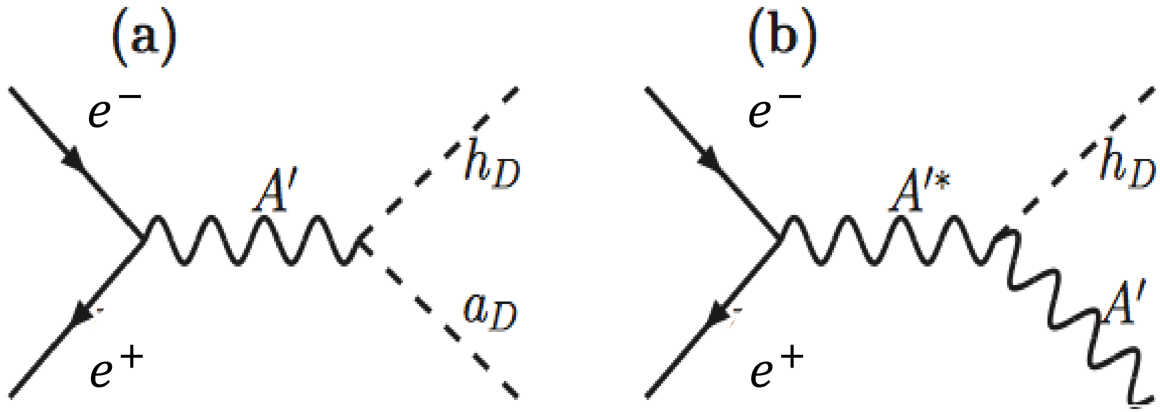
- Predicted parameters suitable for B-factory sensitivity:
  - $B(b \to sX) \sim 10^{-6}$
  - $B(\text{inflaton} \to 2\text{ tracks})$
  - Inflaton lifetime





Scenarios - 2

- Dark photon production (e.g., 0910.1602, 0903.3941)
  - A' decays promptly into hidden-sector scalars that decay as DV
  - A' is stable but undergoes dark-Higgsstrahlung with subsequent DV



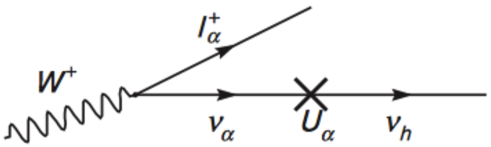
Analysis "history"

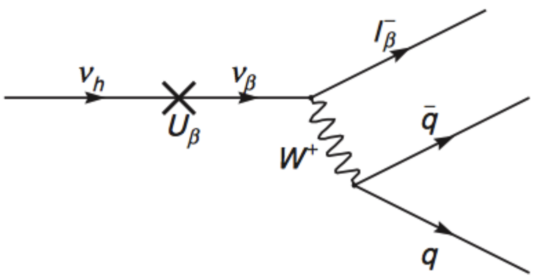
- Only one previous long-lived-particle search at a B factory: Belle search for

  $B \to D^{(*)} \ell \nu_h$

  $\quad\quad\quad\quad\quad \to \ell^- \pi^+$

  (1301.1105)

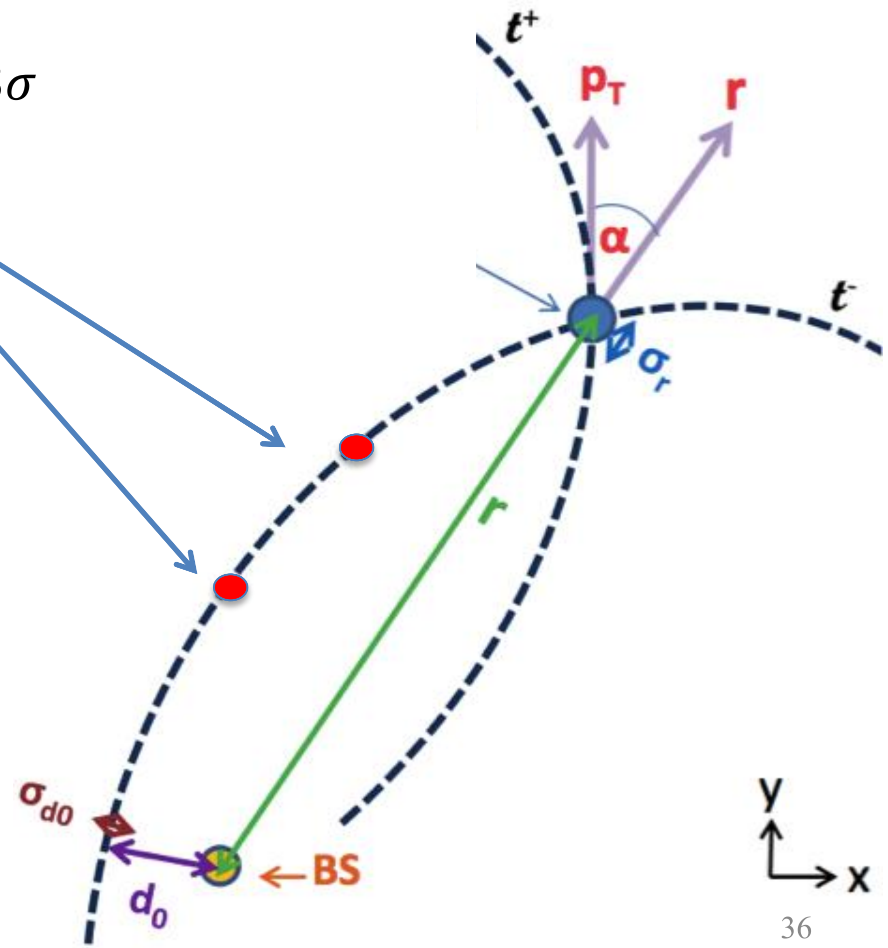




- Ours is the first search that is production-model independent, relying on 2-track DV as only signature
  - D. Peimer & A. Soffer

Event selection

- Vertex track pairs:
  - $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$
- Require
  - Track impact parameter $d_0 > 3\sigma$
  - No hits before the vertex
  - $1 < r < 50$ cm
  - $\alpha < 0.01$
  - Remove Bhabhas & cosmics with angle cuts
  - Crude veto of dense material regions

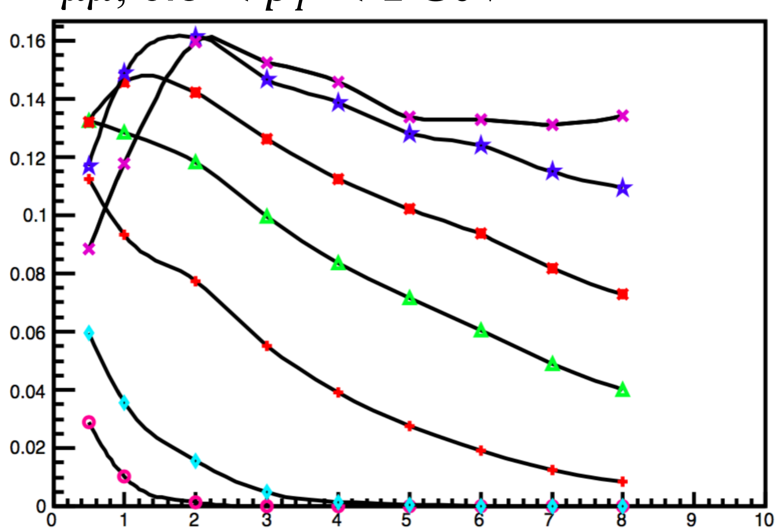


- Remaining background:
  - Mostly truly displaced tracks (K_S, material interactions)

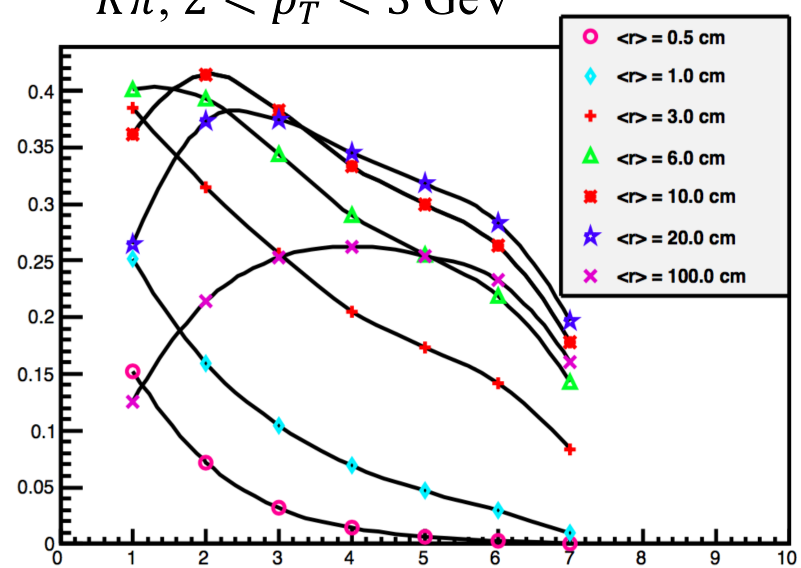
Efficiency parameterization

- Obtained efficiency for Higgs portal from $B \to X_s L$ – easy
  - Tune m_{X_s} distribution to match $B \to X_s \ell^+ \ell^-$ MC for given m_L
- For any model:
  - Simulate L production in various hadronic B and Υ decays
  - Tabulate efficiency for each channel vs. $m, p_T, c\tau$

$\mu\mu$, $0.6 < p_T < 1$ GeV



$K\pi$, $2 < p_T < 3$ GeV



Signal extraction

- Fit DV-mass distribution assuming background only – obtain background shape
  - Shape = spline, assuming only that the background doesn't peak sharply
  - Spline bin width is 15 × mass-dependent mass resolution
    - This 15 is the dominant source of systematic uncertainty, due to background modeling
- Scan for a signal peak on top of the background, in steps of 2 MeV
  - Must account for wide range of mass resolution vs. DV radius and mass
  - Shape = mass-resolution function from MC, $H\left(\frac{(m-m_0)}{\sigma_m}\right)$

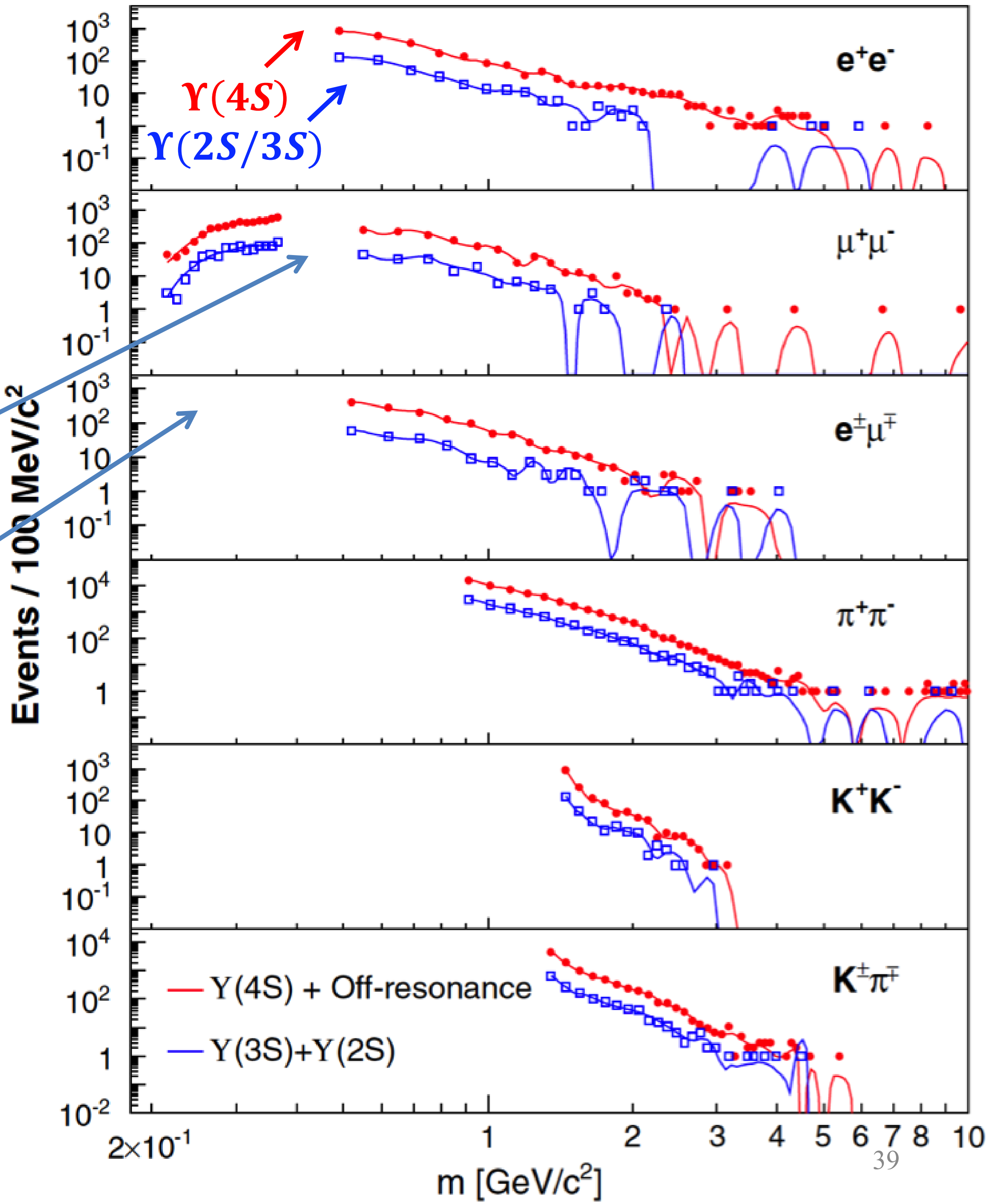
Mass hypothesis

Measured mass

Per-event mass resolution

- Search for points of high signal significance

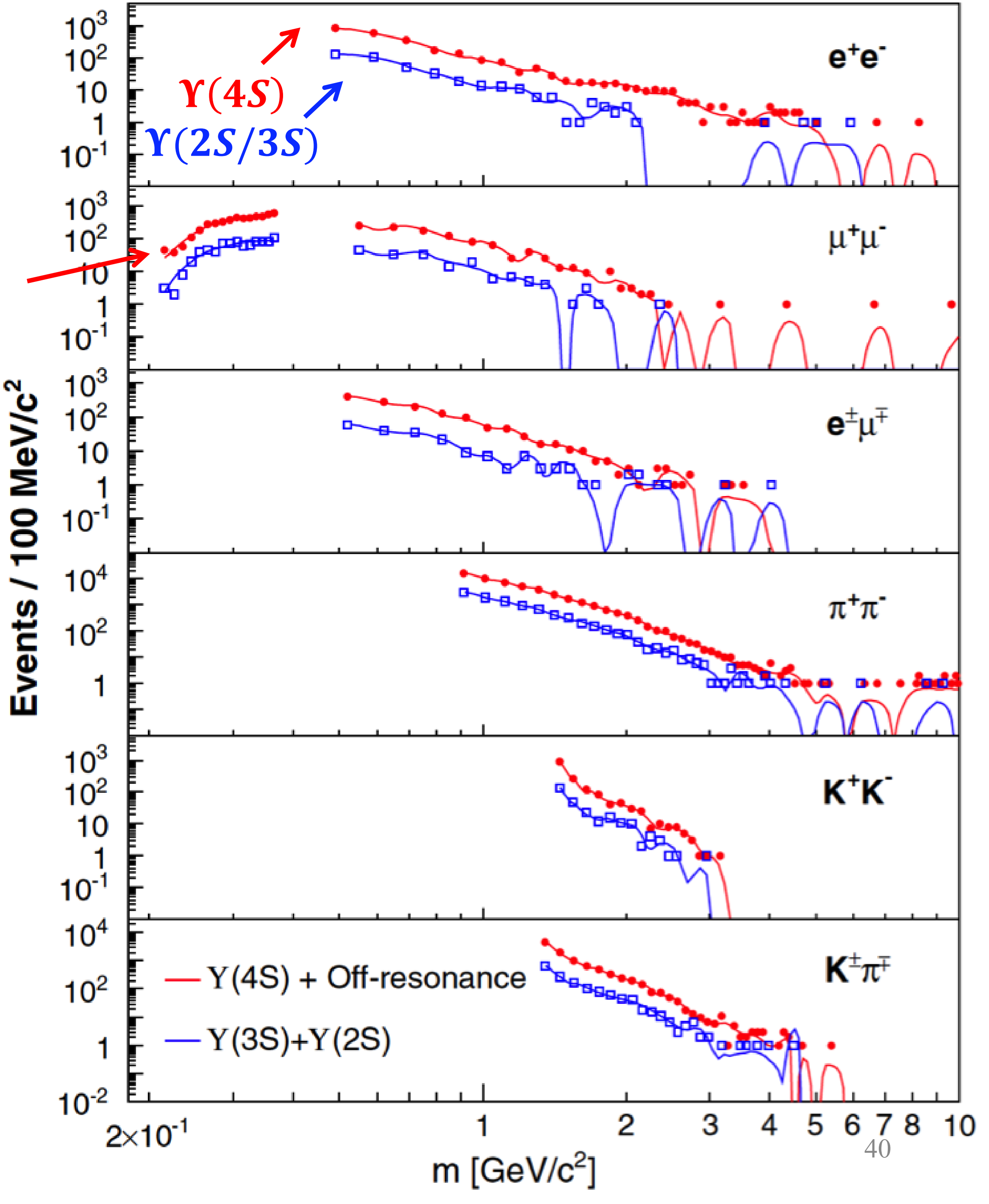
Results



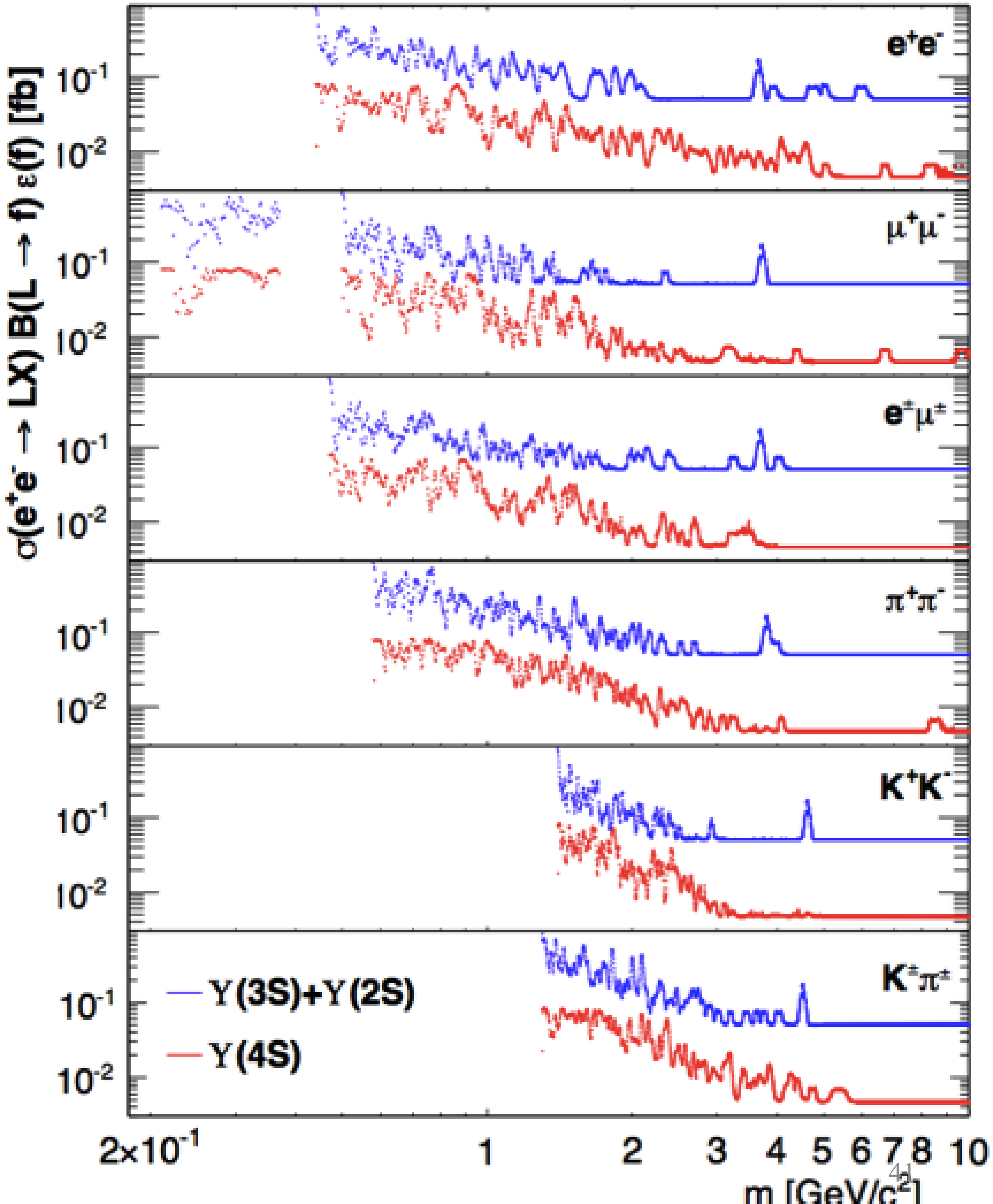
Exclude from search: K_S and low-mass regions incompatible with background fit method (determined using MC)

Results

- Maximum local signif. $= 4.7\ \sigma$ is at $\mu\mu$ threshold, $m = 0.212$ GeV, $n_{sig} = 13$
- Bgd. fluctuation prob. in low-mass $\mu\mu$ region $= 4 \times 10^{-4}$
- But consistent with material interactions:
- Of the 34 events with $m < 0.215$, most are in or near detector material.
- All low momentum tracks – poor particle identification.
- 10 events pass e^+e^- criteria
- 10 events pass $\pi^+\pi^-$ criteria



“Model-indep.” upper limits on $\sigma(L)\mathrm{B}(L \to f)\epsilon$



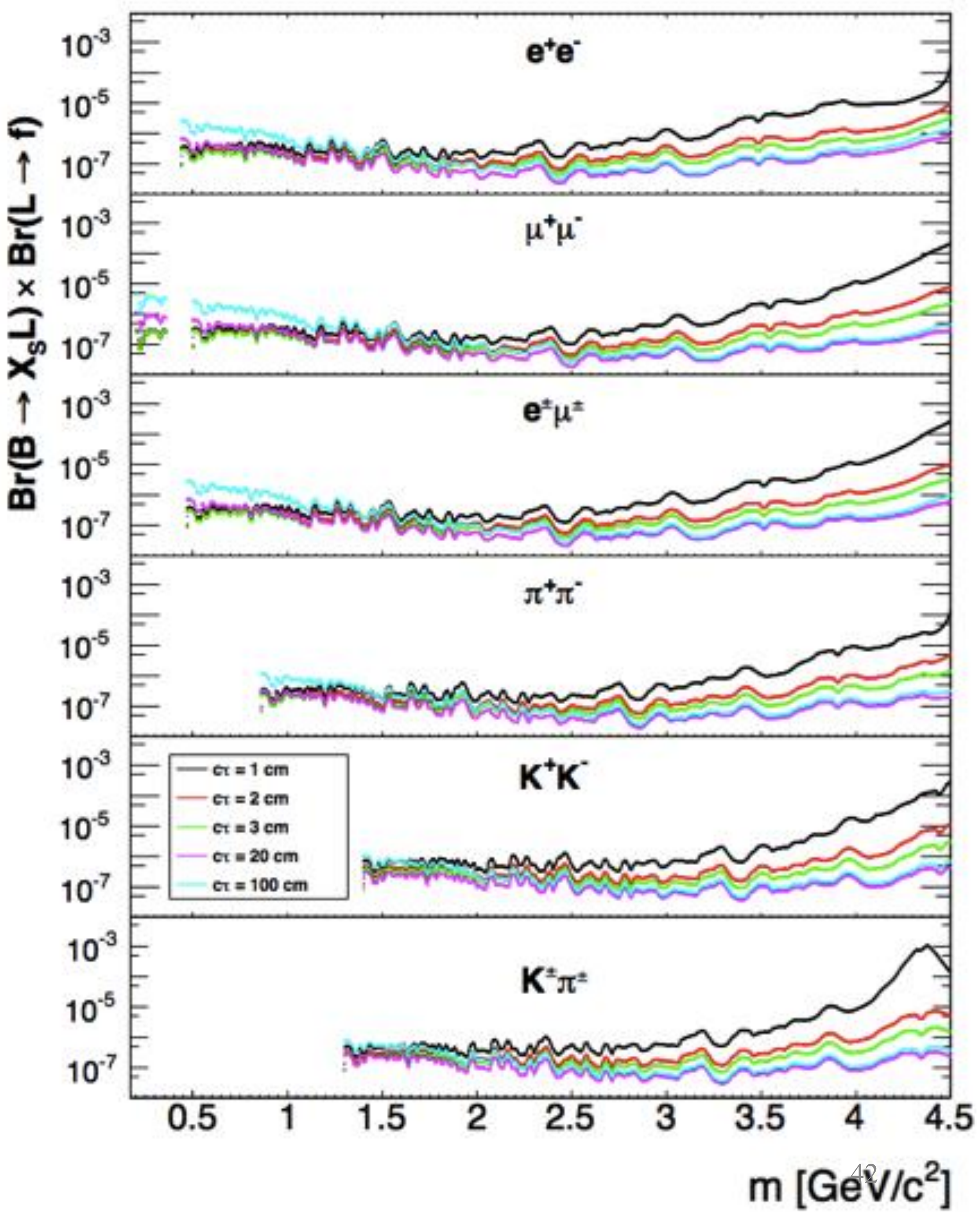
Provide efficiency table as a function of m, p_T, $c\tau$, so results can be applied to any specific model.

Efficiency dominated by $1 < r < 50$ cm cut

Higgs-portal "model-dep." upper limits on $\mathrm{B}(B \to X_S L)\mathrm{B}(L \to f)$

Exclude regions of inflaton-model parameter space (1303.4395)

In this model, LHCb later obtained much tighter limits for $B \to K^* L(\to \mu^+\mu^-)$ (1508.04094)



Summary and outlook

- Ongoing improvement in searches for high-mass DVs at LHC
- For Run-2:
  - Improving triggers, tracking and vertexing efficiency
  - Expanding cut envelope into nonzero-background regions
  - Testing additional models

- New DV search at a B factory
- In the future:
  - Possible signature expansion
  - 2018 – 2025: Belle-II could study this with × 100 luminosity, improved detector