university of groningen

faculty of science
and engineering

van swinderen institute for
particle physics and gravity

cLFV in Meson Decays

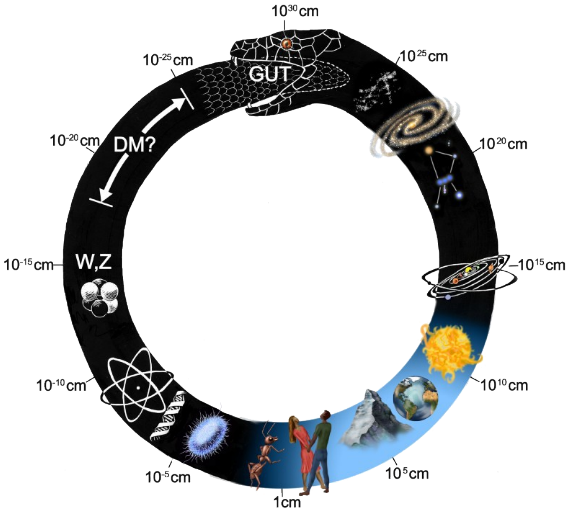
– at high energy colliders –

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Gerco Onderwater

International School on cLFV 2019 – IHEP Beijing

Who am I?



1993-1998 : VU/NIKHEF Amsterdam
Hadron group at the AmPS facility

1998-2004 : Univ. of Illinois at Urbana-Champaign
Precision Physics Group
Several low-energy “precision” experiments,
incl. muon g−2, EDM & lifetime @ BNL & PSI

2004-now : Univ. of Groningen
Van Swinderen Institute for Particle Physics & Gravity
Experimental Particle Physics Group

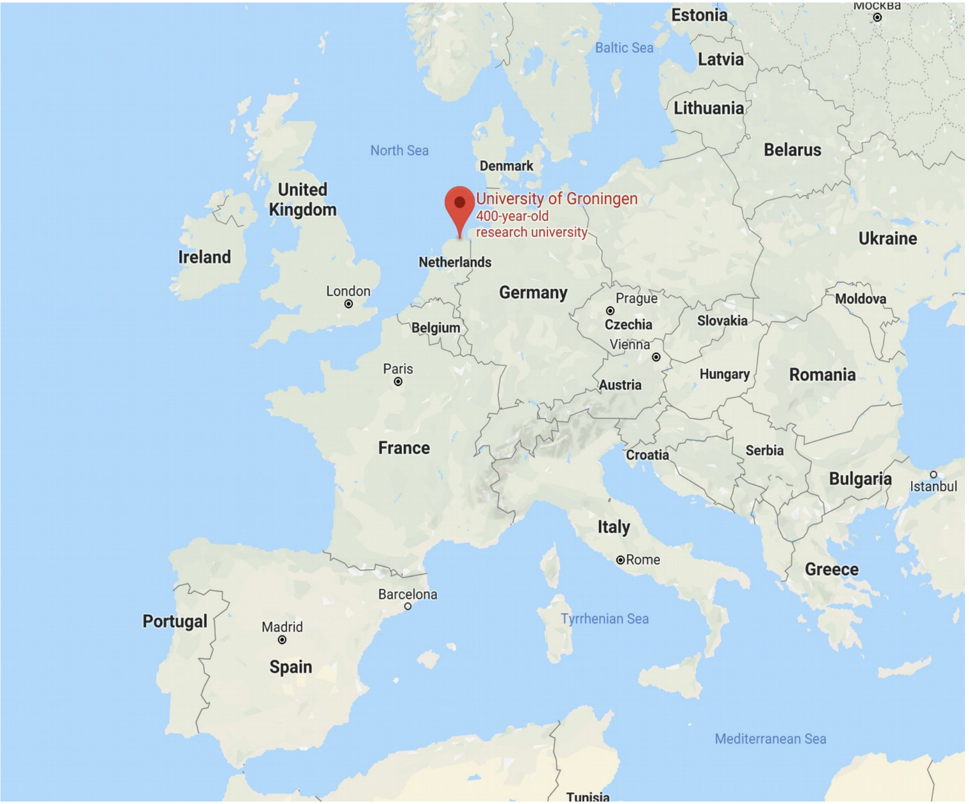
C, P, & T: EDM (μ,p,d,Ra,Xe), Ra$^+$APV, β-decay, SrF
LIV : ^{20}Na & Λ-decay, $d\tau/d\Omega$
LFV : $B_{(s)} \to e\mu$, $\Lambda_b \to \Lambda e\mu$
LU : Muon g−2

My research


inner detector
gradient magnet
μ orbit
electrodes
outer detector
upper ED
detector
lower
EDM
detect
return yoke
main coils
septum
inflector

University of Groningen

Groningen, the Netherlands



Outline

Goal

by the end of my lectures, you can formulate how cLFV appears in meson decays, what the essential steps are in the experimental searces, and how to interpret the result in relation to other cLFV searches

Topics to cover

cLFV in meson & baryon decay

Sensitivity & Selectivity

Hadron production

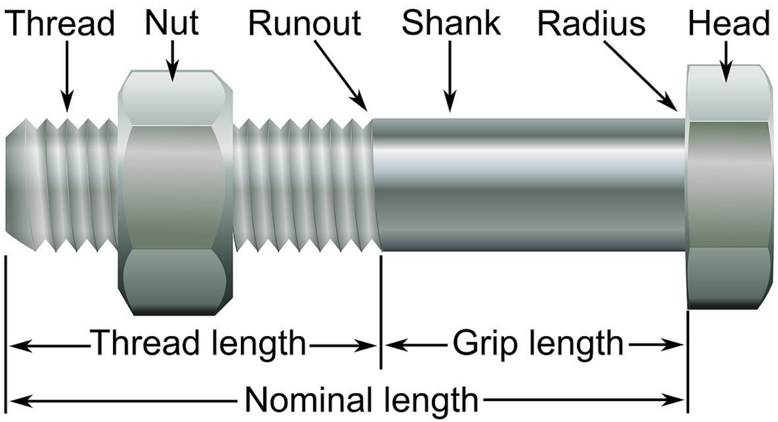
Particle identification

Signal & background: invariant mass spectrum

Normalisation

Efficiency

Interpretation



cLFV in hadron decay

Convention

e μ τ

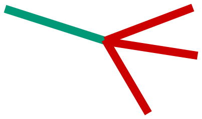
Towards studying (c)LFV

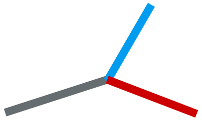
Angela Papa *Kiyoshi Hayasaka*

Decay	$\mu\to e\gamma$, $\mu\to eee$, $\tau\to\mu\mu\mu$, $\tau\to\mu hh$, …
Conversion	$\mu A\to eA$ *David Hitlin*
Production	$B_s\to e\mu$, $B\to Ke\mu$, $\Lambda_b\to\Lambda e\mu$, $h^0\to\mu\tau$, …
Oscillation	$\nu_e\leftrightarrow\nu_\mu\leftrightarrow\nu_\tau$, $M(\mu^+e^-)\leftrightarrow\overline{M}(\mu^-e^+)$
Number violation	$0\nu2\beta$, $B^-\to\pi^+\mu^-\mu^-$, …
Non-Universality	$\overline{B}^0\to D^{*+}\tau^-\overline{\nu}_\tau$ *vs* $\overline{B}^0\to D^{*+}\mu^-\overline{\nu}_\mu$, g_e vs g_μ , …

Lorenzo Calibbi

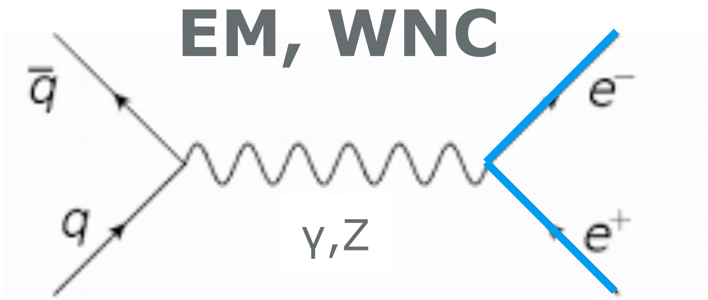
Sébastien Descotes-Genon *Tsutomu Mibe*

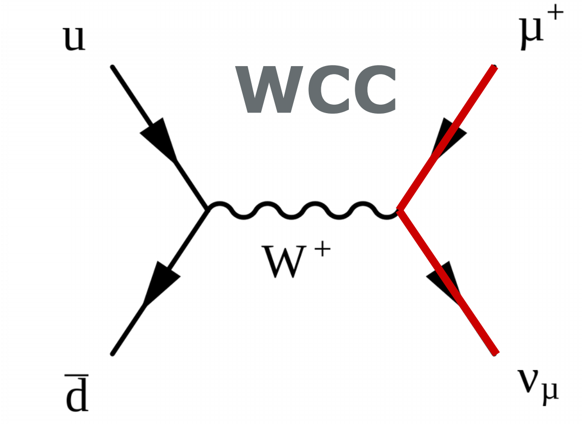


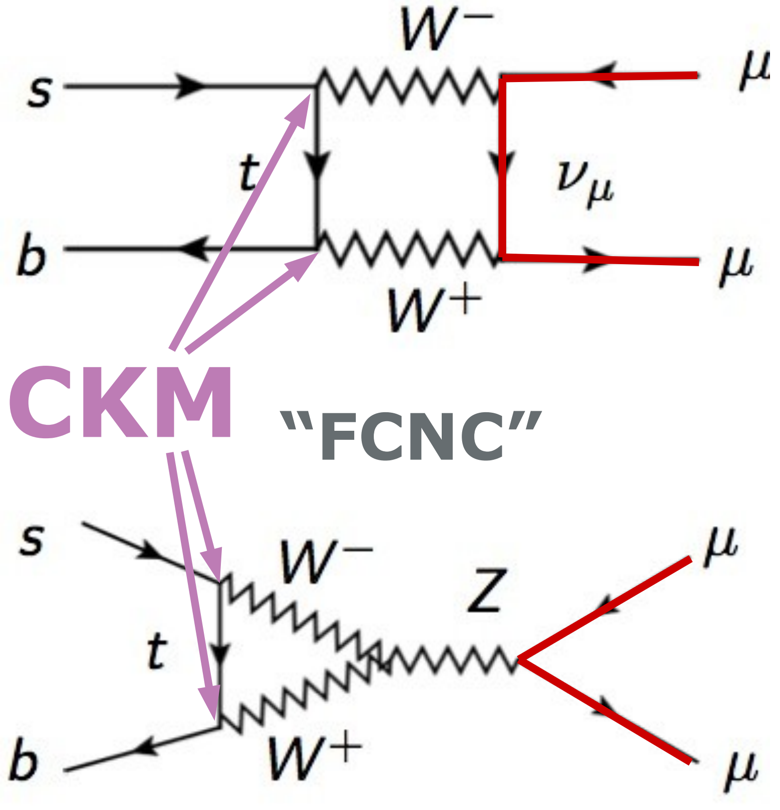


(charges dropped, unless relevant)

Leptonic meson decay in SM

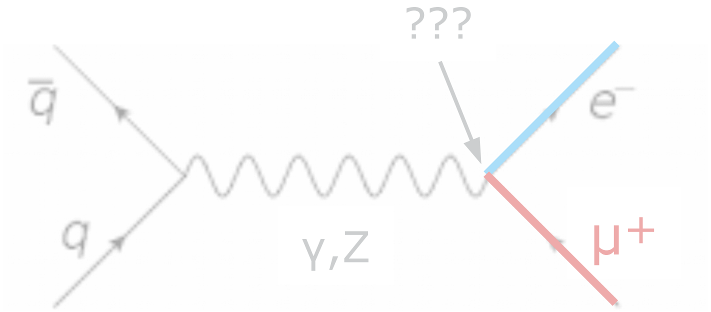

EM, WNC

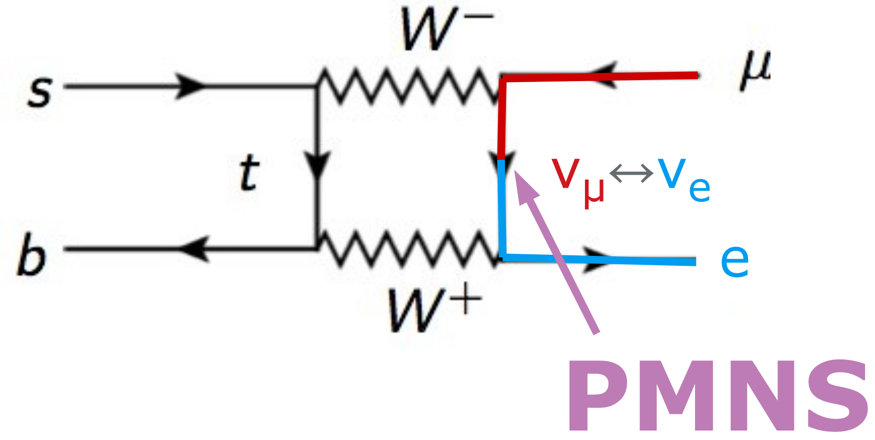

WCC

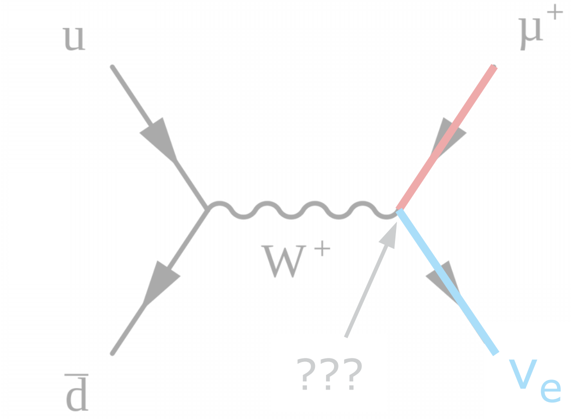

CKM

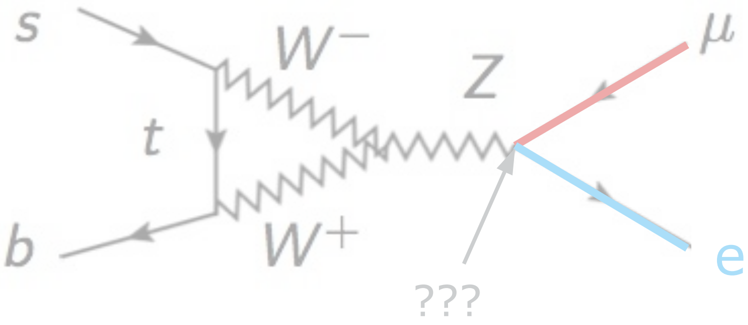
“FCNC”

Leptonic meson decay in SM





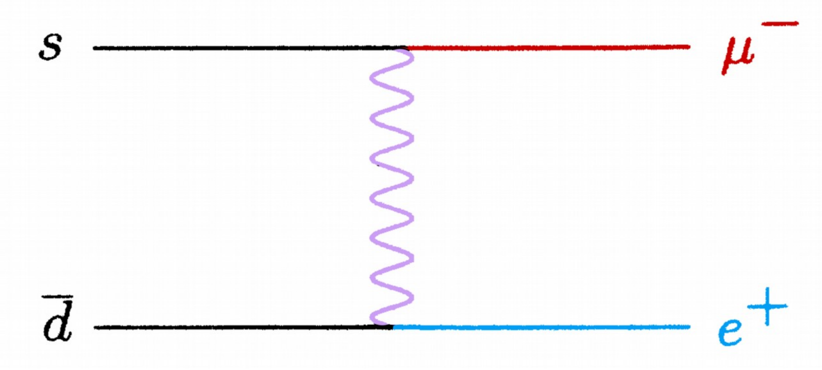


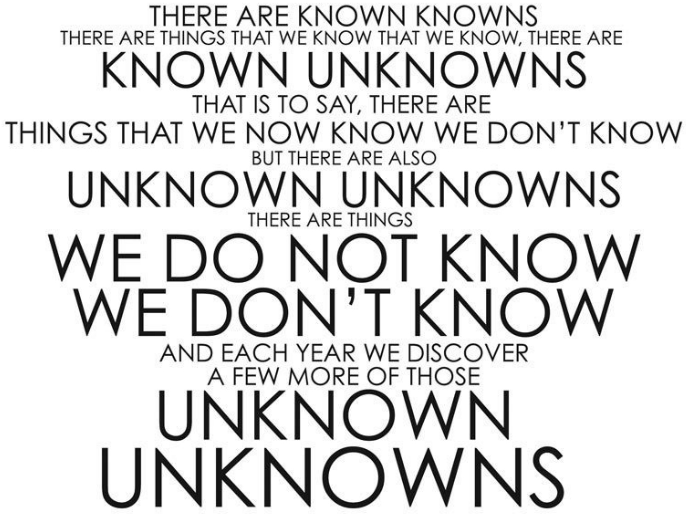


Leptonic meson decay post-SM

Standard Model cLFV
Only possible via neutrino oscillations
Unmeasureably small

Beyond Standard Model Physics
(Too) many well-motivated possibilities
Many produce results within reach of experiment
Experiments put stringents limits on them
E.g., **quark-lepton unification*** with lepto-quarks:





THERE ARE KNOWN KNOWNS
THERE ARE THINGS THAT WE KNOW THAT WE KNOW, THERE ARE
KNOWN UNKNOWNS
THAT IS TO SAY, THERE ARE
THINGS THAT WE NOW KNOW WE DON'T KNOW
BUT THERE ARE ALSO
UNKNOWN UNKNOWNS
THERE ARE THINGS
WE DO NOT KNOW
WE DON'T KNOW
AND EACH YEAR WE DISCOVER
A FEW MORE OF THOSE
UNKNOWN
UNKNOWNS

*https://doi.org/10.1103/PhysRevD.50.6843

Sensitivity & Selectivity

Some definitions

In designing an experiment two properties to be considered:

Sensitivity
Also known as *true positive rate*, *probability of detection*, or *efficiency*
“If the process occurs, what fraction of events do we actually see?”
In other words, your ability to identify and measure the signal

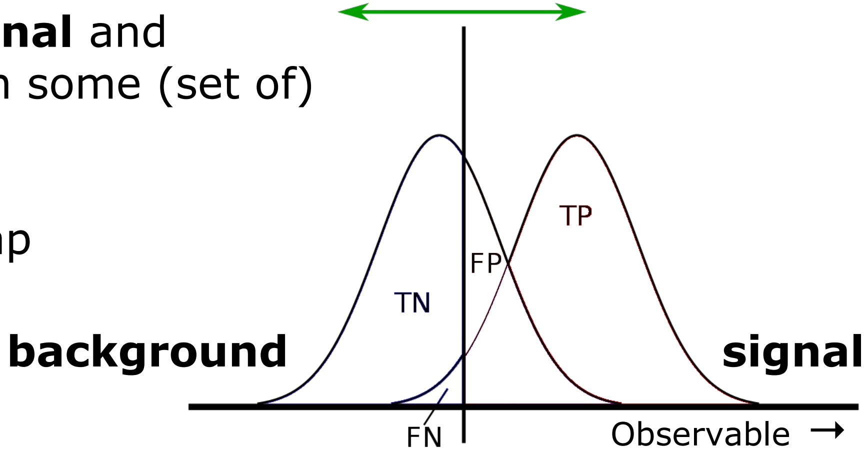
Selectivity
Also known as *specificity*, or *true negative rate*
“If another process occurs, what fractions of events are labeled as such?”
In other words, your ability to identify and eliminate background

Typically **sensitivity** and **selectivity** are mutually exclusive

Contingency table and ROC curve

Need to distinguish **signal** and **background**, based on some (set of) observable(s)

Signatures often overlap



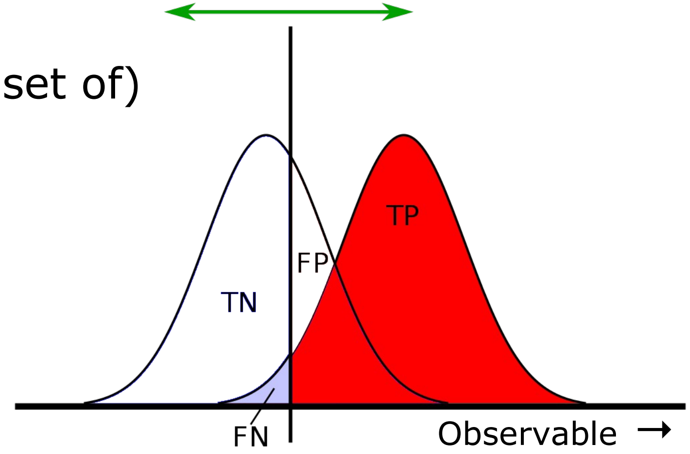
Contingency table and ROC curve

Need to distinguish **signal** and **background**, based on some (set of) observable(s)

Signatures often overlap

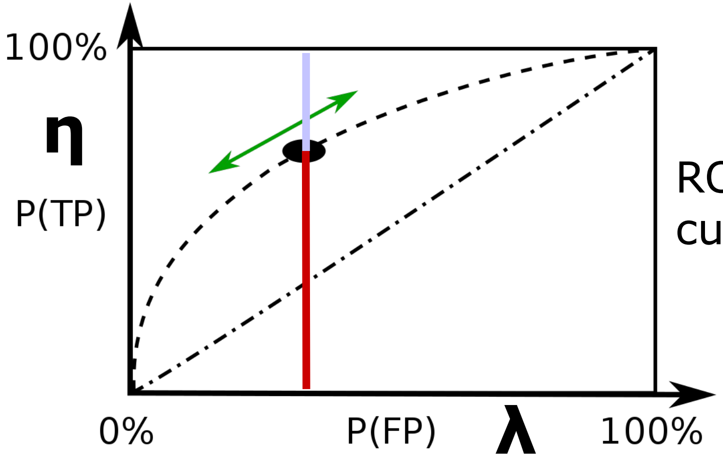
Goal
Maximize **TRUE POSITIVE η**

Side effect
Reduced efficiency (**FALSE NEGATIVE**)



TP	FP
FN	TN

contingency table



ROC curve

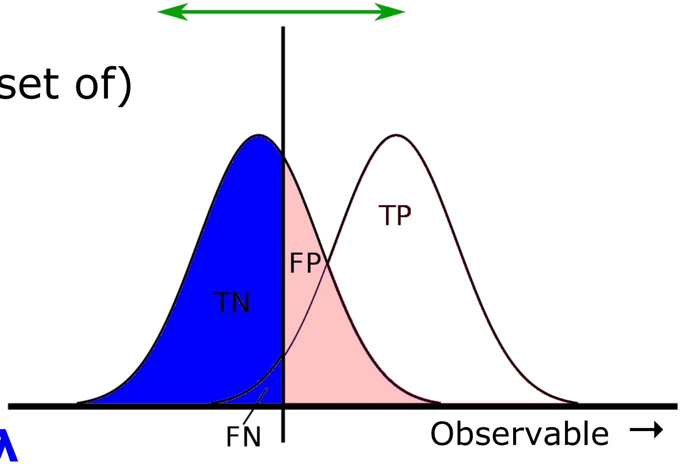
Contingency table and ROC curve

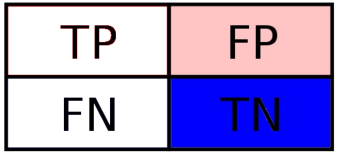
Need to distinguish **signal** and **background**, based on some (set of) observable(s)

Signatures often overlap

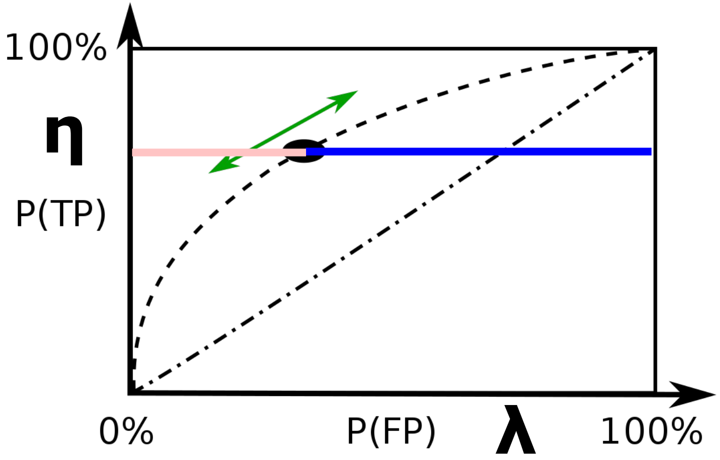
Goal
Maximize TRUE POSITIVE η
Maximize **TRUE NEGATIVE 1-λ**

Side effect
Reduced efficiency (FALSE NEGATIVE)
Noise leakage (**FALSE POSITIVE**)





TP	FP
FN	TN



Contingency table and ROC curve

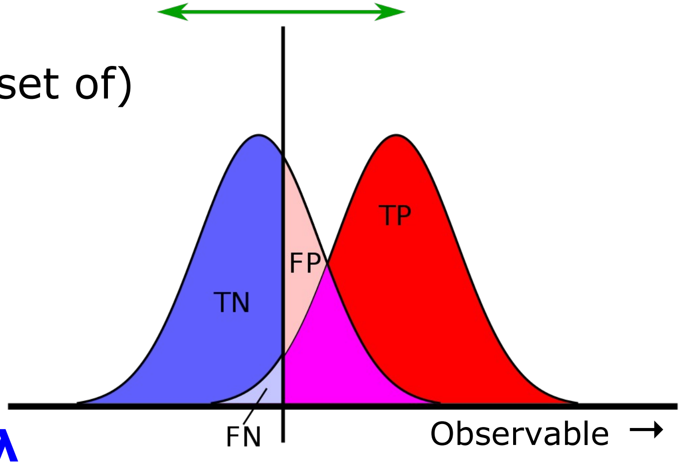
Need to distinguish **signal** and **background**, based on some (set of) observables

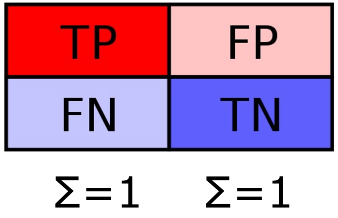
Signatures often overlap

Goal
Maximize **TRUE POSITIVE η**
Maximize **TRUE NEGATIVE 1-λ**

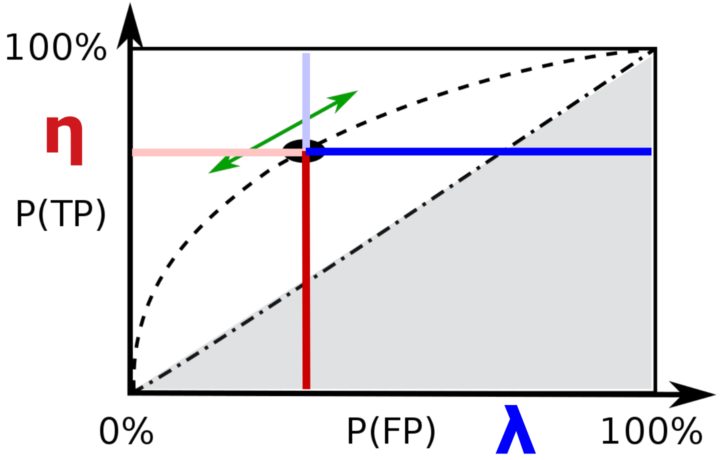
Side effect
Reduced efficiency (**FALSE NEGATIVE**)
Noise leakage (**FALSE POSITIVE**)

Need sophisticated optimization





TP	FP
FN	TN
Σ=1	Σ=1



Contingency table and ROC curve

Quiz 1
What does “ROC” stand for?

Answer: ROC = **R**eceiver **O**perating **C**haracteristic

Quiz 2
What does this have to do with cLFV? Where does this name come from?

Expected significance

Signal estimation : S

Within signal window number of counts is measured : $N_S = \eta\cdot S + \lambda\cdot B$
In an independent window the background is estimated : $N_B = \mathbf{k}\cdot\lambda\cdot B$
From these two together, the signal is estimated : $S = (N_S - N_B/\mathbf{k})/\eta$

Error estimation : σ

Uncertainty :

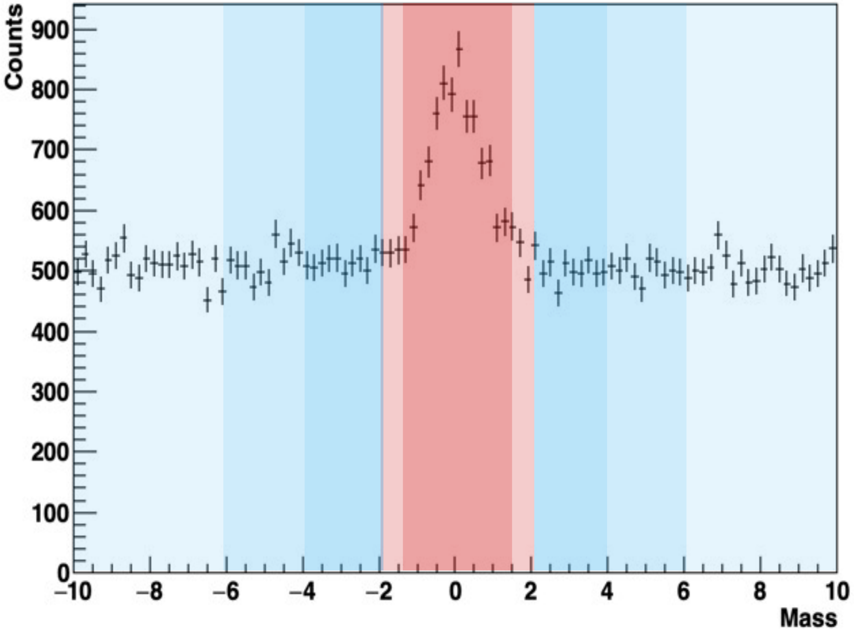
$$\begin{aligned}
\eta^2\sigma^2(S) &= \sigma^2(N_S) + \sigma^2(N_B)/\mathbf{k}^2 \\
&= N_S + N_B/\mathbf{k}^2 \\
&= (\eta\cdot S + \lambda\cdot B) + (\lambda\cdot B/\mathbf{k}) \\
&= \eta\cdot S + \mathbf{k}'\cdot\lambda\cdot B \qquad\qquad \mathbf{k}' = 1 + 1/\mathbf{k} \\
\sigma^2(S) &= S/\eta + \mathbf{k}'\cdot\lambda/\eta^2\cdot B
\end{aligned}$$

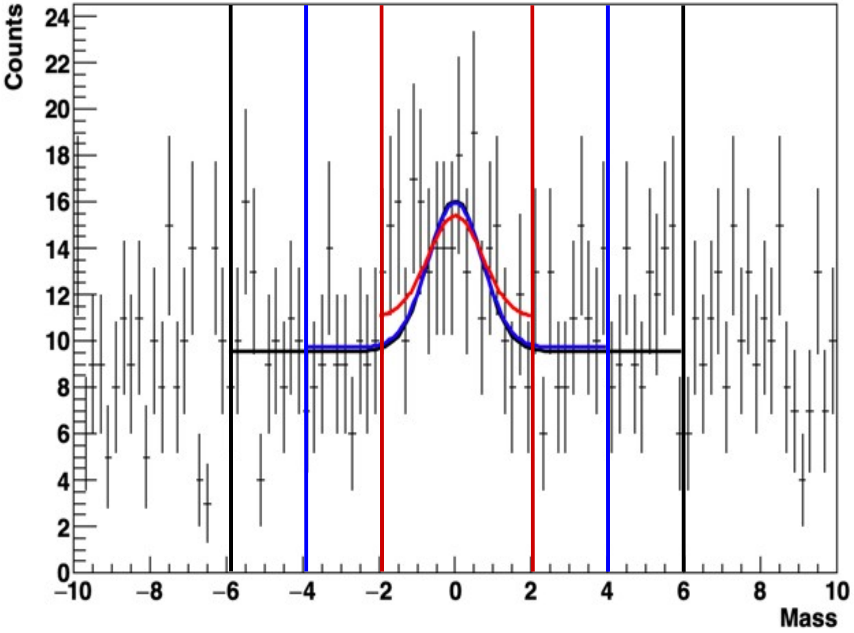
Significance : ρ

$$\rho \equiv S/\sigma(S) = \eta S/\sqrt{(\eta S+\mathbf{k}'\cdot\lambda\cdot B)} \overset{S \ll B}{\approx} \eta S/\sqrt{(\mathbf{k}'\cdot\lambda\cdot B)} \overset{S \leq 1}{\approx} \eta/\sqrt{(\mathbf{k}'\cdot\lambda\cdot B)}$$

So, need η large, λ small, k large, small B

Expected significance





Branching fractions *etc.*

Branching fraction $\mathcal{B}$ defined and measured as

$$\begin{aligned}\mathcal{B}(M\to X) &= \Gamma(M\to X)\ /\ \Gamma(M\to \text{anything}) \\ &= \int\Gamma(M\to X)\cdot dt\ /\ \int\Gamma(M\to \text{anything})\cdot dt \\ &= N(M\to X)\ /\ N(M\to \text{anything}) \\ &= N(M\to X)\ /\ N(M) \\ &= N(M\to X)\ /\ [\ N(\text{collisons})\cdot f(\text{collision}\to M)\ ] \\ &= N(M\to X)\ /\ [\ \int\mathcal{L}\cdot dt\cdot\sigma(\text{collision}\to M)\ ]\end{aligned}$$

Beware: could produce multiple M’s per collision!

$\mathcal{L}$: luminosity

σ : cross section

Also for other particles

$$\mathcal{B}(P\to Y) = N(P\to Y)\ /\ [\ \int\mathcal{L}\cdot dt\cdot\sigma(\text{collision}\to P)\ ]$$

Combining two reactions gives

$$\mathcal{B}(M\to X) = \mathcal{B}(P\to Y)\cdot N(M\to X)\ /\ N(P\to Y)\cdot\sigma(\text{collision}\to P)/\sigma(\text{collision}\to M)$$

Need high $\int L\cdot dt$, large $\sigma(\text{collision}\to M,P)$, known $\mathcal{B}(P\to Y)$ & $f(P)/f(M)$

Hadron production

High Energy Machines (2000–)

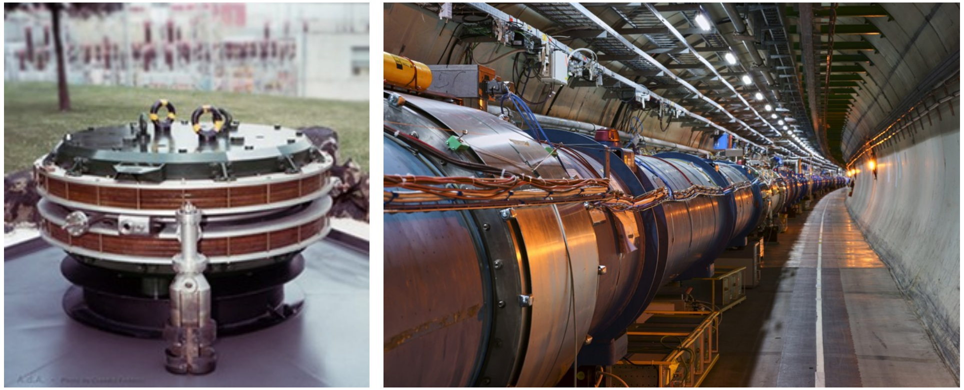
Electron-positron colliders
LEP, BEPC (II), CESR(-c), VEPP(-4M,5, 2000), DAΦNE, *PEP-II*, (*Super*)*KEKB*
$\mathcal{E}$= 104 4.63 6 6 0.7 9+3.1 7+4 GeV

Electron-Proton colliders
HERA (27.5+920GeV)

Proton-Antiproton colliders
Tevatron (980GeV)

Proton-Proton colliders
RHIC (255GeV), LHC (6.5TeV)

Fixed target machines
LANL, PSI, AGS, J-PARC

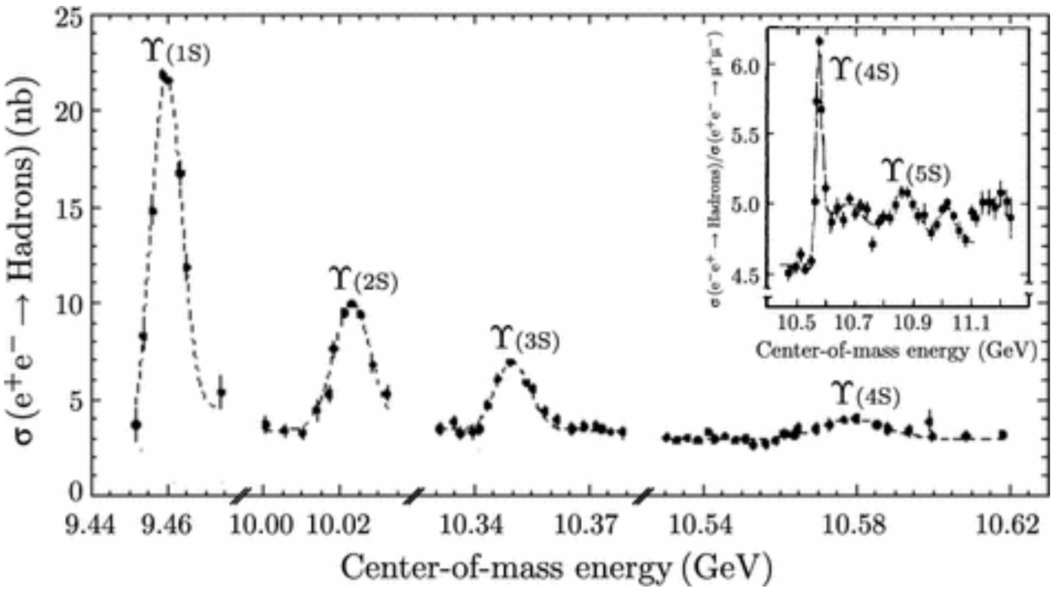


Electron-Positron Colliders

Some scan their energy, but mostly fixed
Resonant production, *e.g.* via $e^+e^- \to J/\Psi \to M\bar{M}$

Only Y(4S) decays into $B\bar{B}$ ($\mathcal{B}>96\%$)

Most are symmetric, so J/Ψ($c\bar{c}$) or Y($b\bar{b}$) is at rest
Ofter referred to as **B-factories**, or **tau-charm factories**
(depending on most abundant production channel)



$\sigma(e^+e^- \to Y(4S)) \sim 5$ nb
$= 5\cdot10^{-33}$ cm²

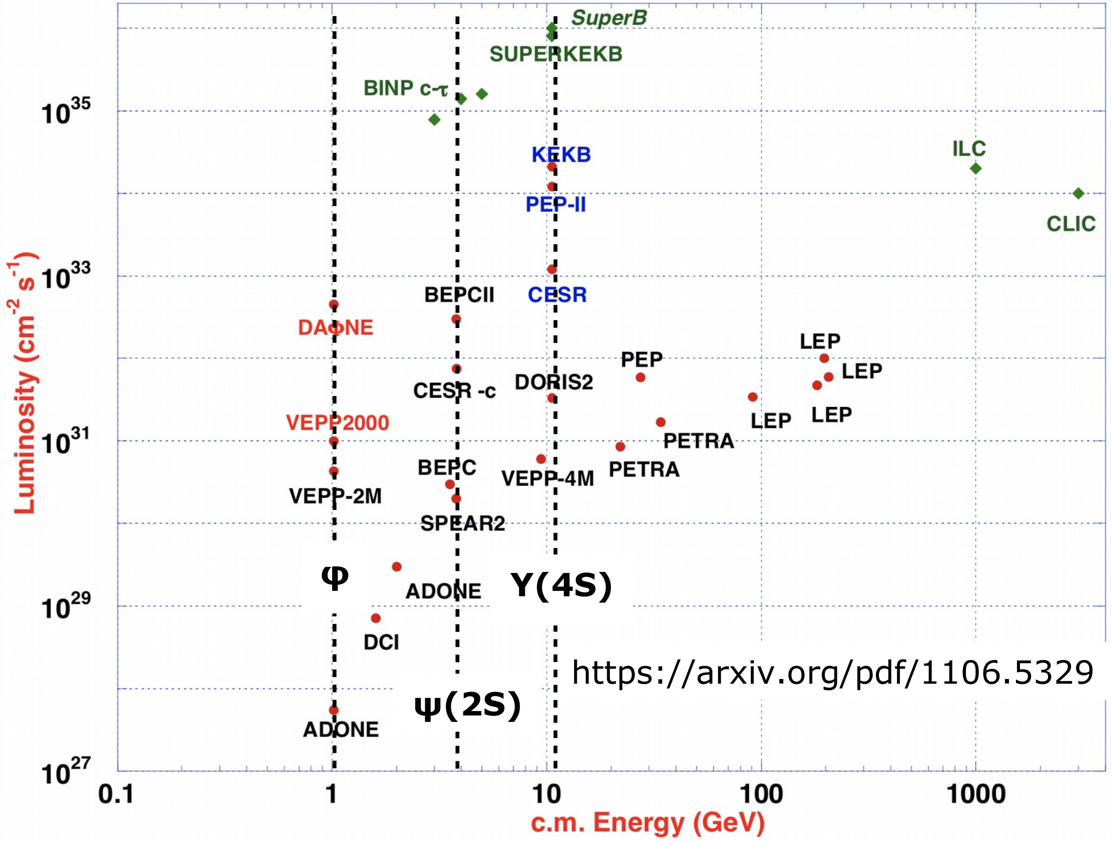
Electron-Positron Colliders

KEKB
Luminosity of 10^{34} cm$^{-2}\cdot$s^{-1}
Production rate of ~50 $\Upsilon\cdot$s^{-1}
Annually ~5·10^8 $B\bar{B}$

SuperKEKB
Annually ~5·10^9 $B\bar{B}$

BEPC
Annually ~3·10^9 Ψ(2S)

DOI:10.1063/PT.6.1.20180516a



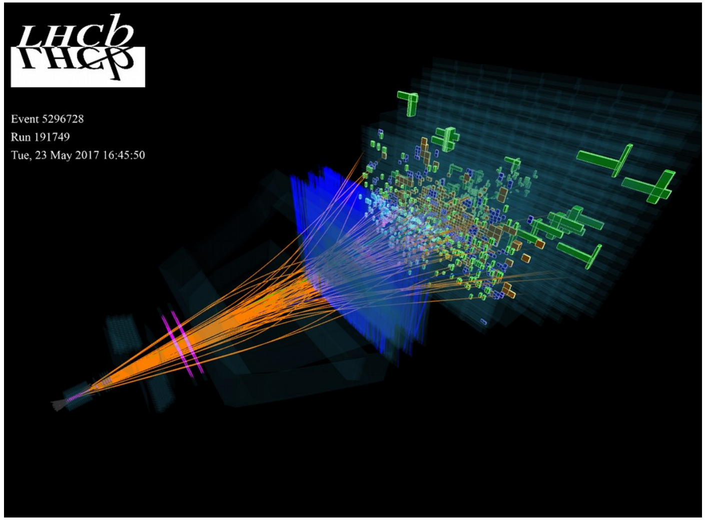
https://arxiv.org/pdf/1106.5329

Figure 1. Peak luminosity and energy of the past, present and future (diamonds) electron-positron colliders.

Large Hadron Collider

Proton on proton collision
Enormous energy: 6.5 TeV + 6.5 TeV
Single collision produces many particles (100’s)

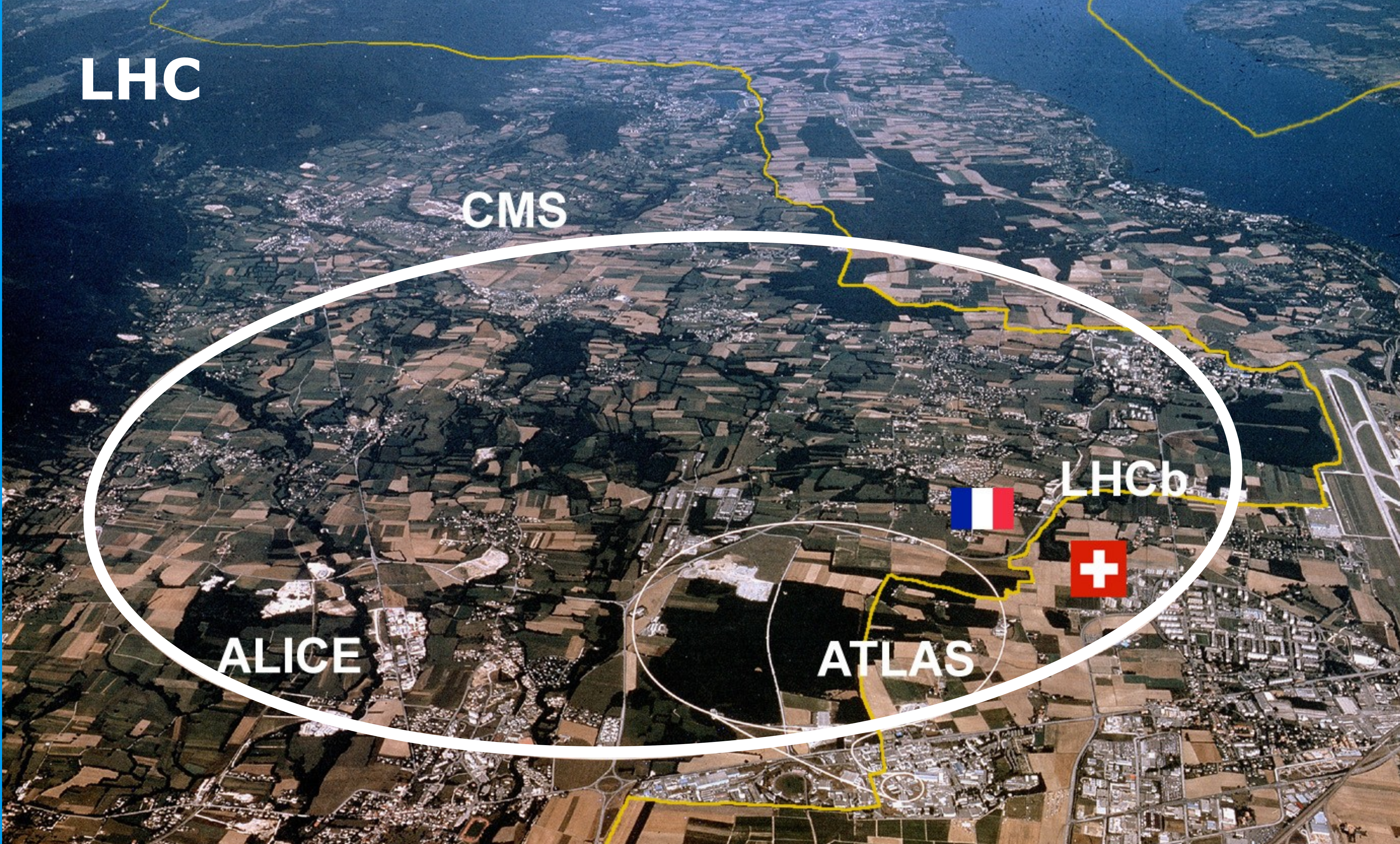
LHCb (2015-2018)
Average luminosity <L> ~ 50 $\mu b^{-1} \cdot s^{-1}$
$B\bar{B}$ production in acceptance $\sigma(pp \rightarrow b\bar{b}X)$ ~ 150 μb
Production rate $B\bar{B}$ ~ 7500 s^{-1}
Integrated luminosity: 6 fb^{-1}
Total production: ~ 10^{12} $B\bar{B}$



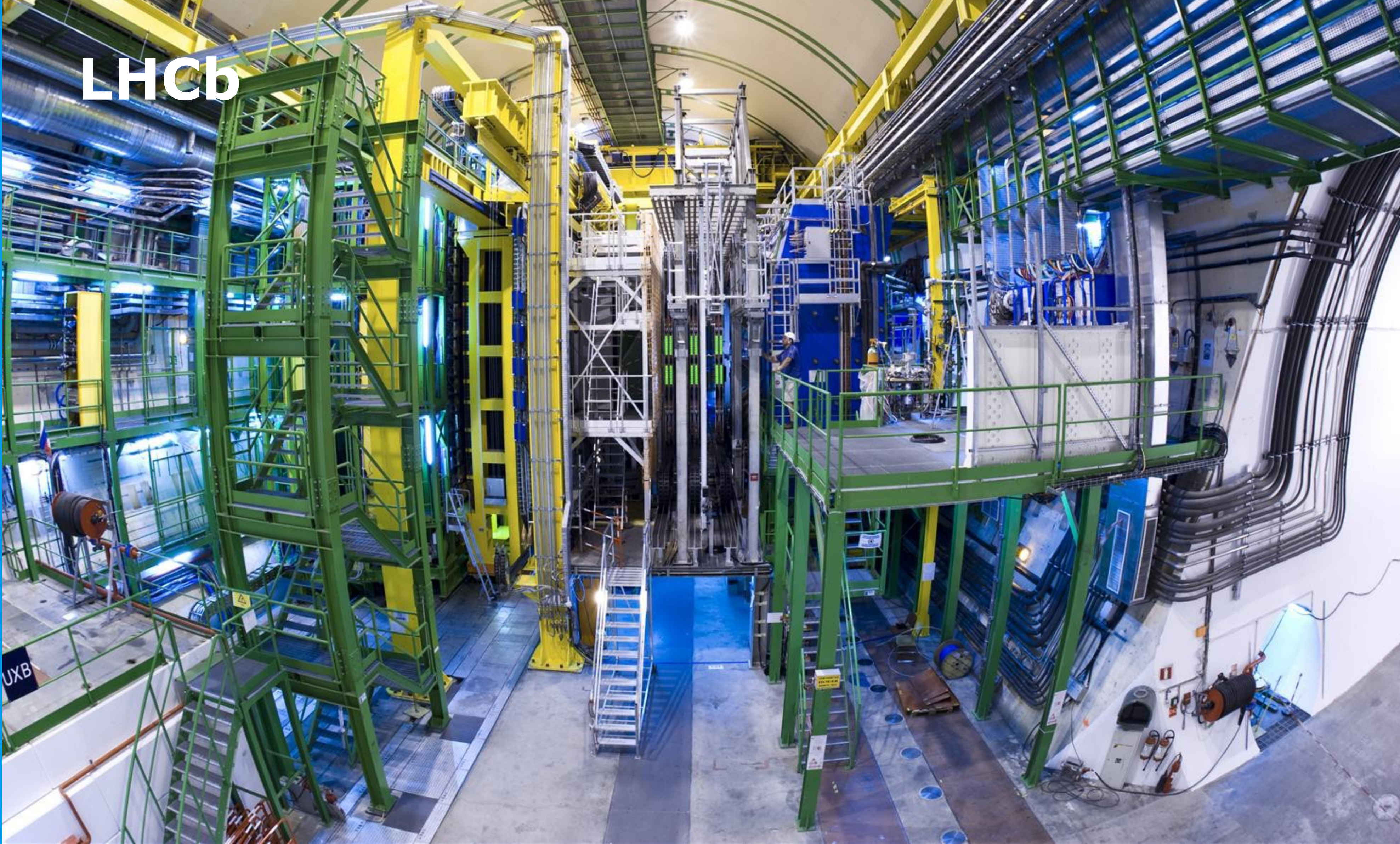
ATLAS (2015-2018)
Integrated luminosity: 160 fb^{-1}
$B\bar{B}$ production in acceptance $\sigma(pp \rightarrow b\bar{b}X)$ ~ 500 μb
Total production: ~ 10^{14} $B\bar{B}$

Particle identification

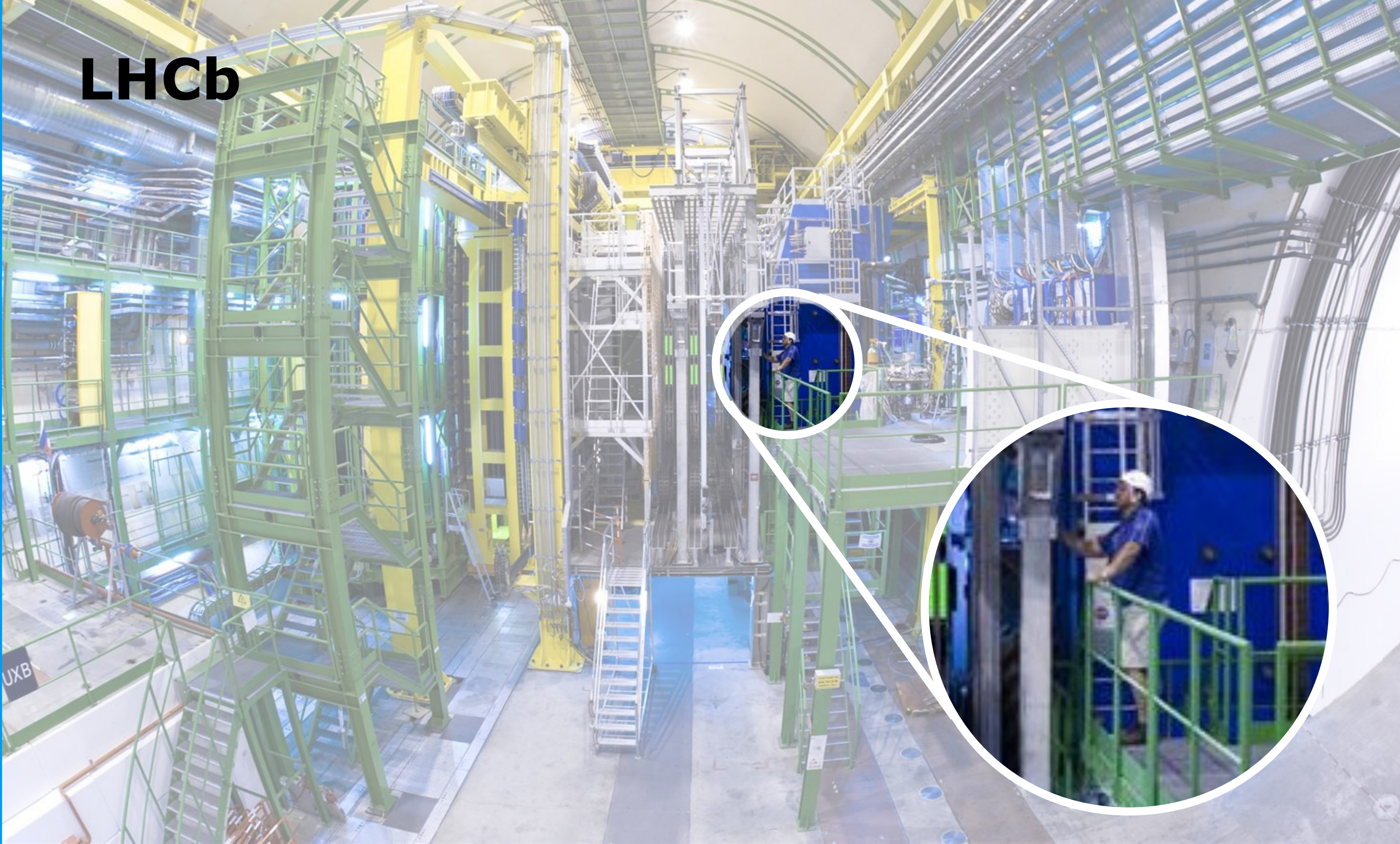
LHC



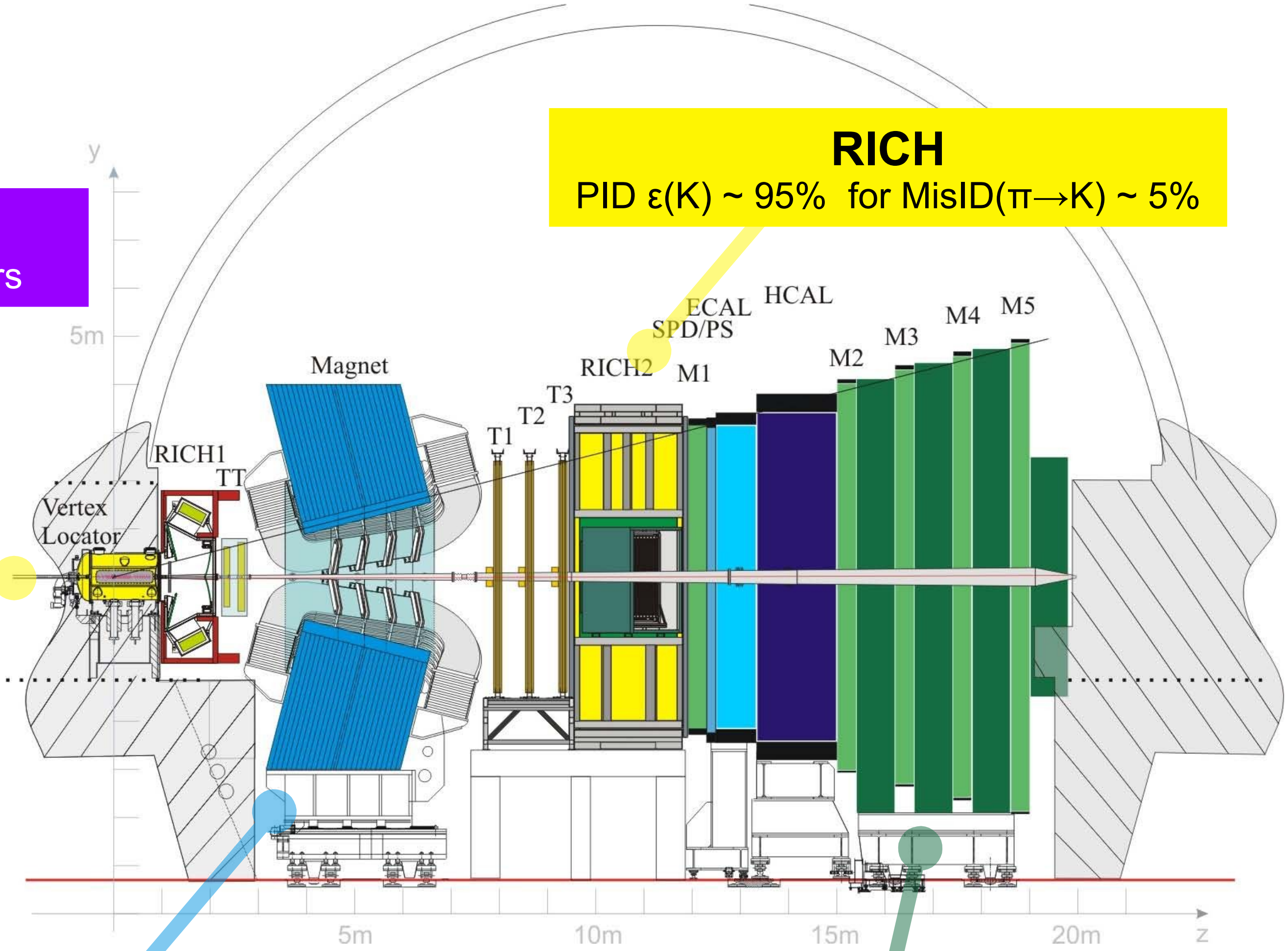
LHCb



LHCb



LHCb



Trigger
high efficiency *esp.* muon triggers

RICH
PID $\varepsilon(K) \sim 95\%$ for MisID($\pi \to K$) ~ 5%

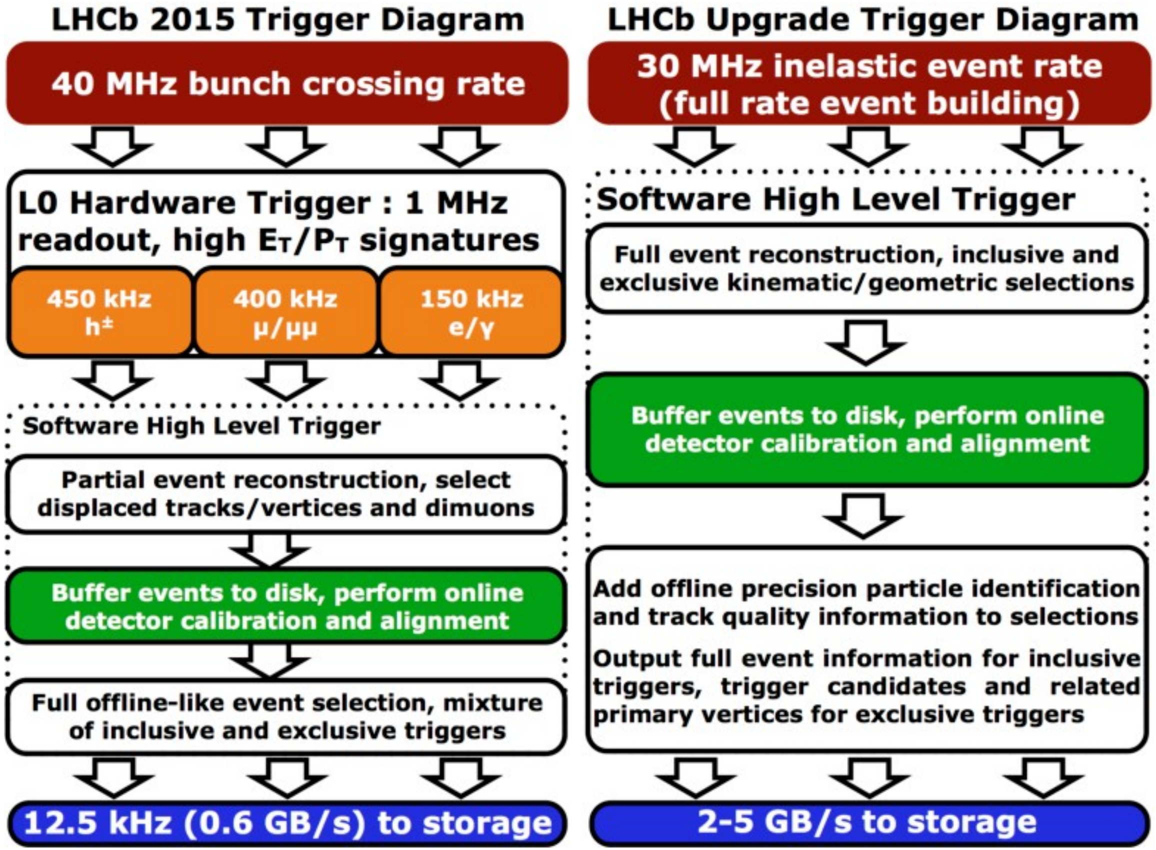
VELO
IP resolution $15+29/(p_T/\mathrm{GeV})$ μm

Tracking Δp/p
0.4% @ 5 GeV/*c* – 1.0% @ 200 GeV/*c*

Muon ID
identification ε ~ 97% misID ~ 2%

Triggering

Most collison events are un-interesting → event selection / triggering



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

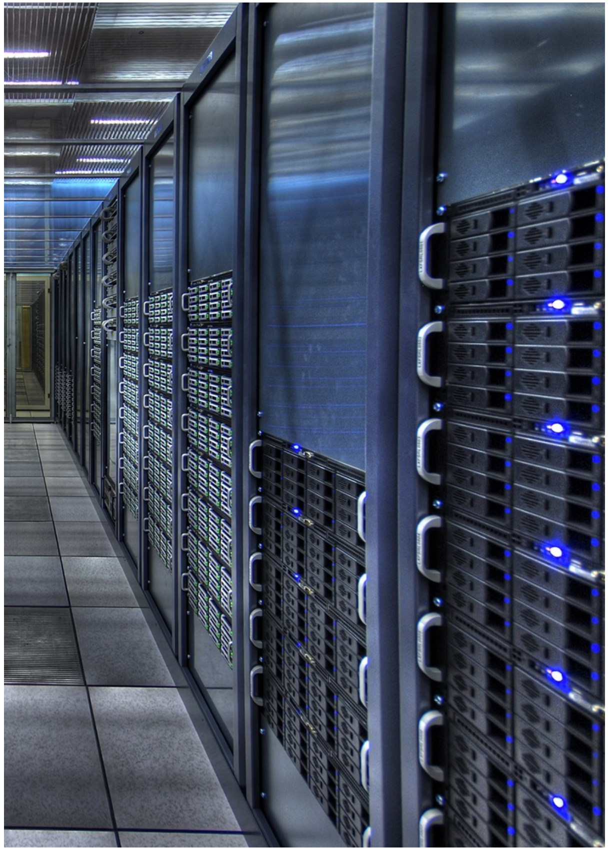
Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

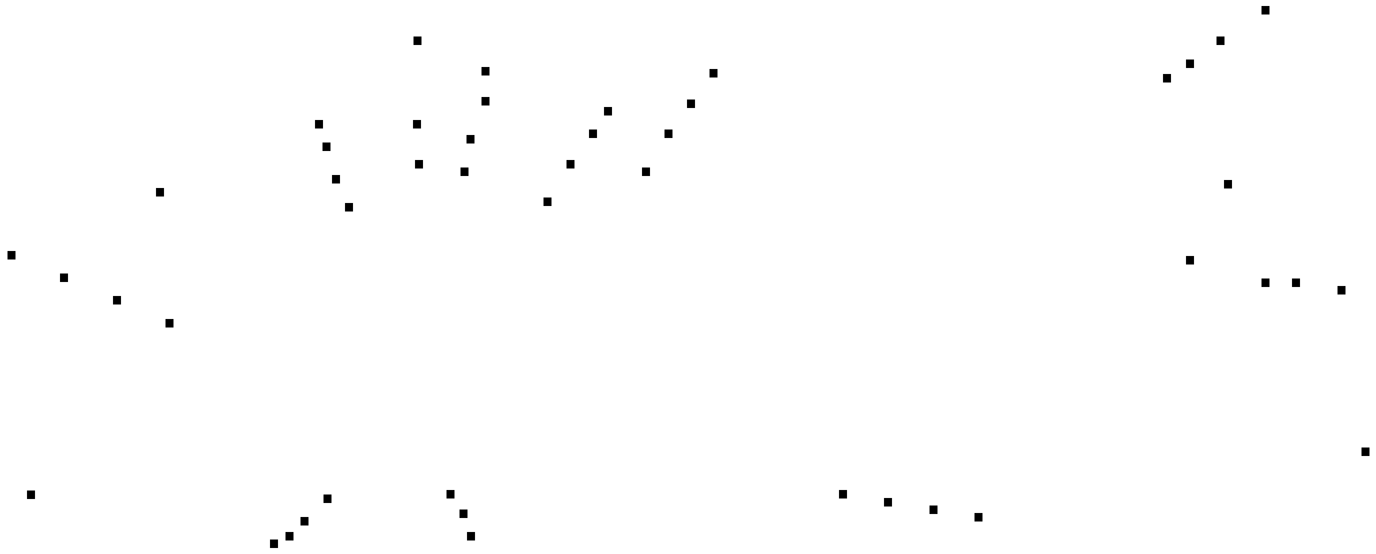
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage



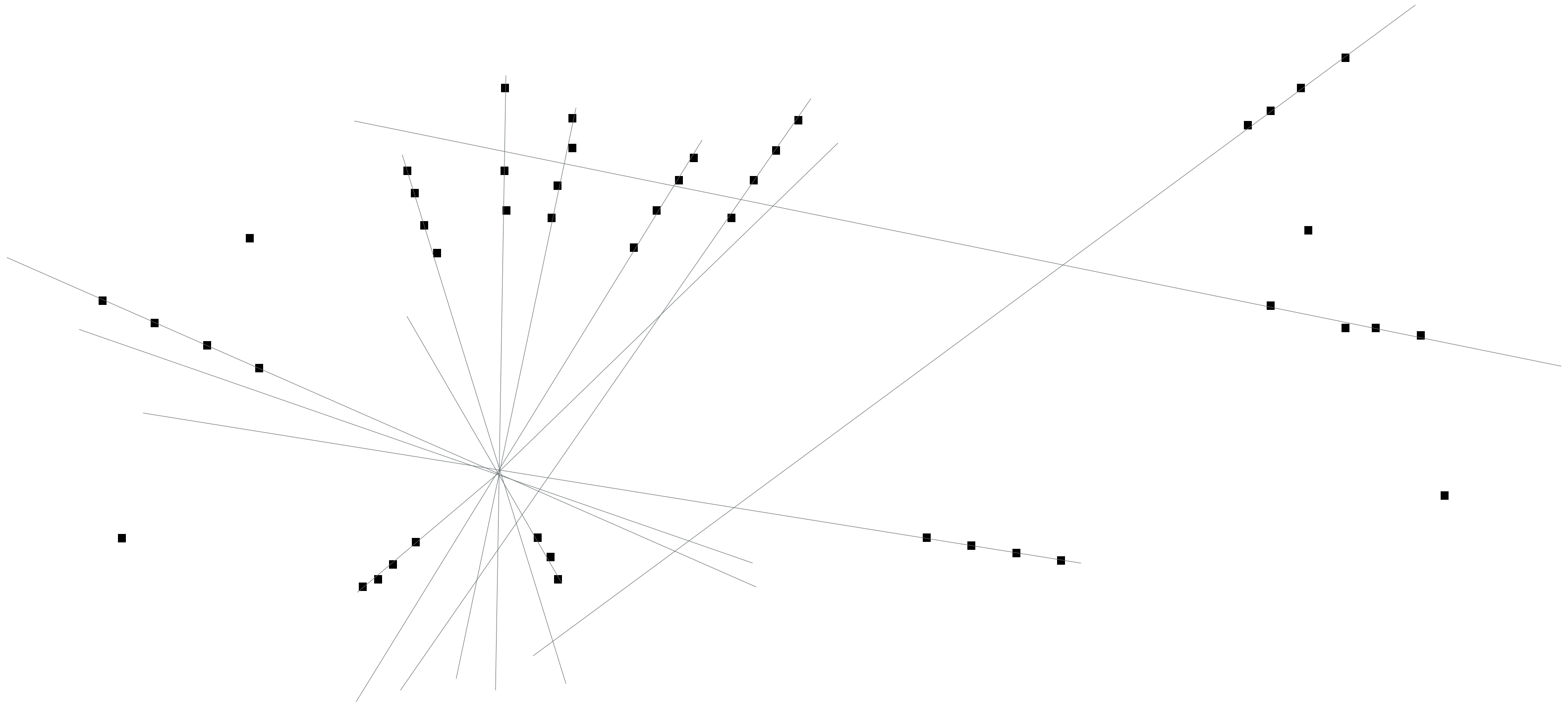
Reconstruction

Tracking : connecting hits



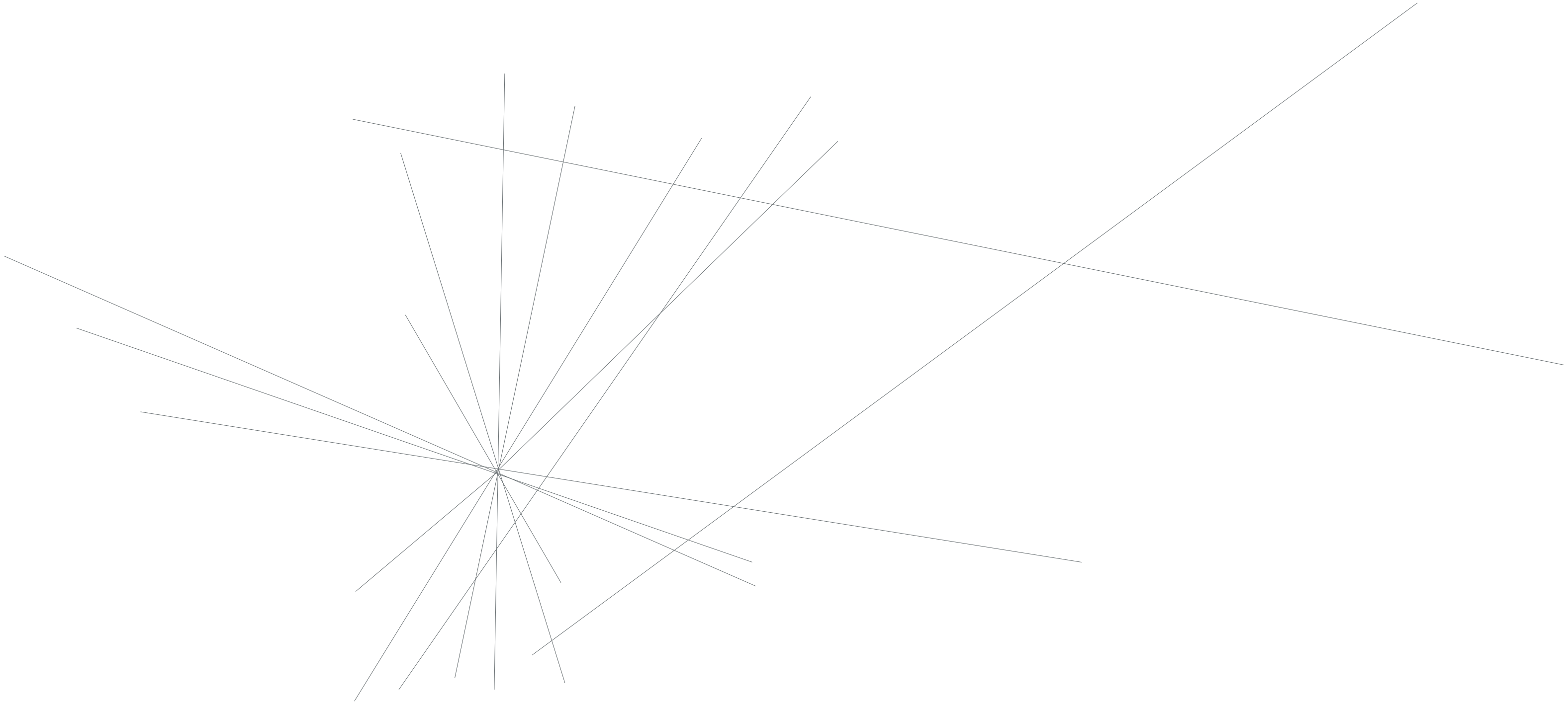
Reconstruction

Tracking : connecting hits to form tracks



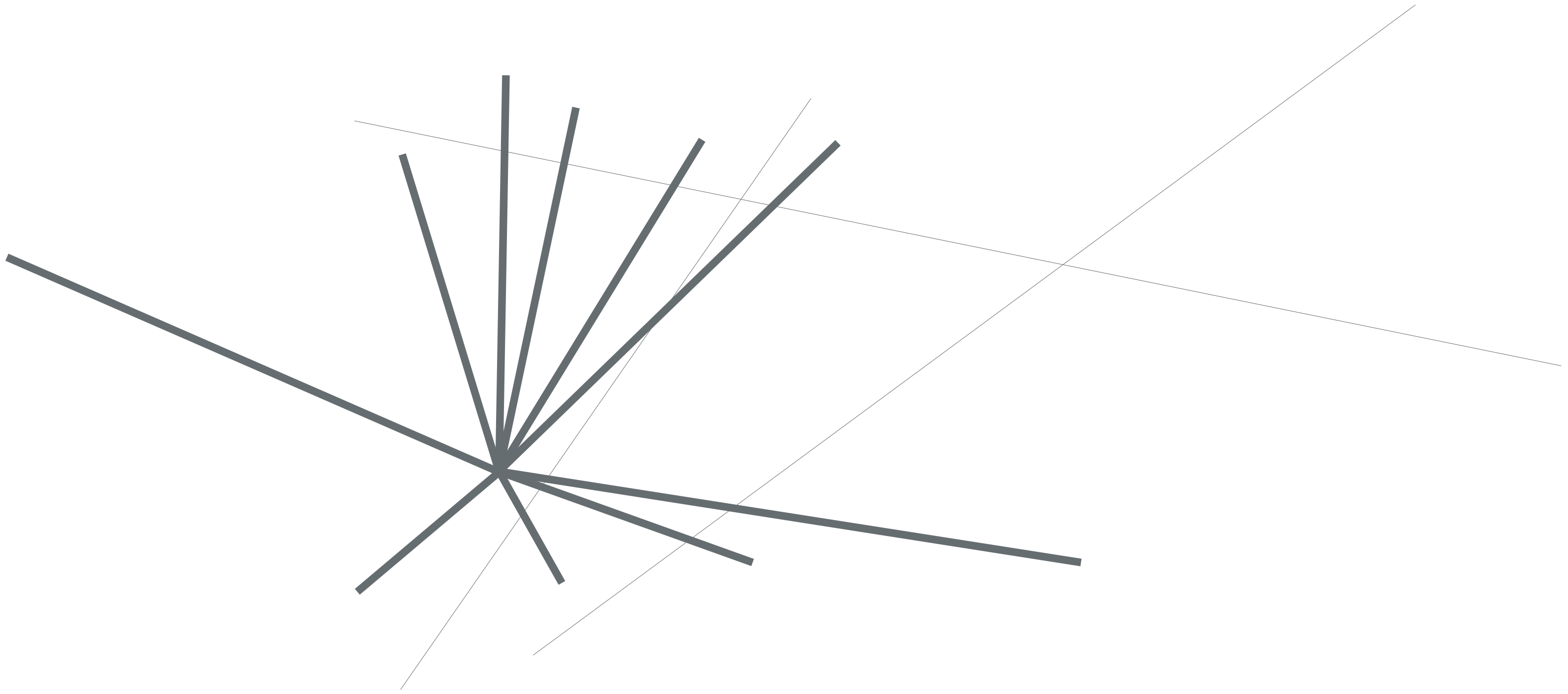
Reconstruction

Tracking : connecting hits to form tracks
and determine *charge* and *momentum* from bending in magnetic field



Reconstruction

Find the primary vertex = collision point of two protons
Many tracks will originate from a common location close to the beam

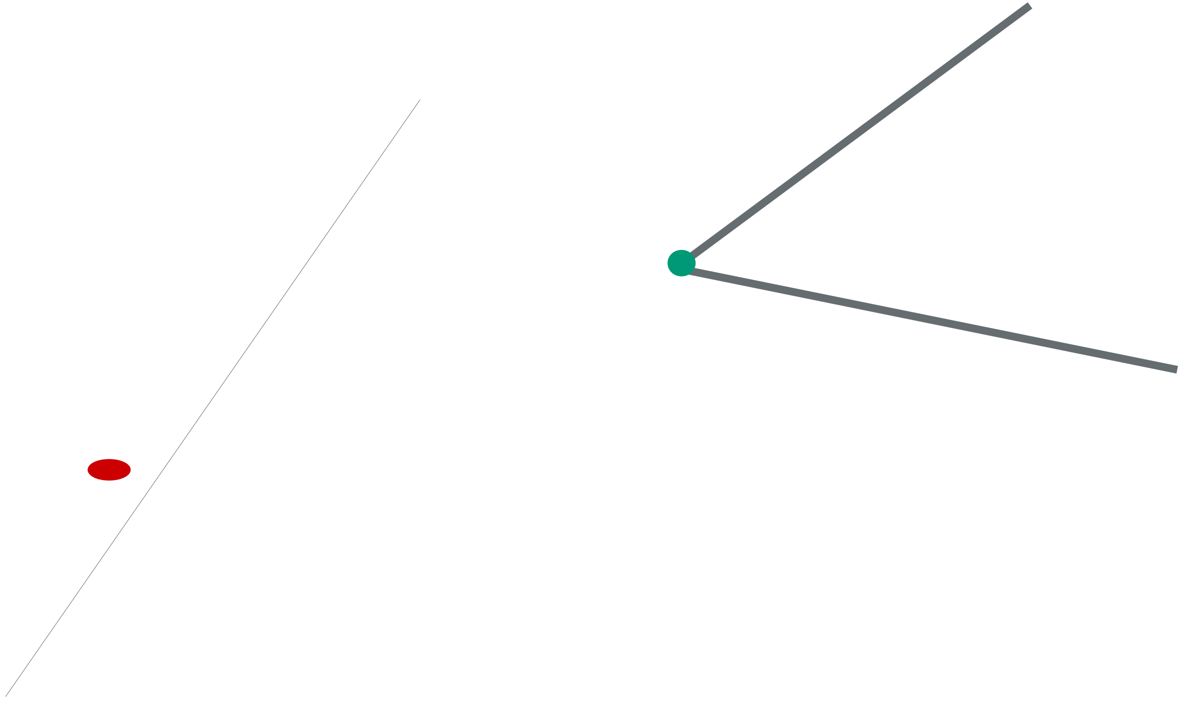


Reconstruction

Find the primary vertex

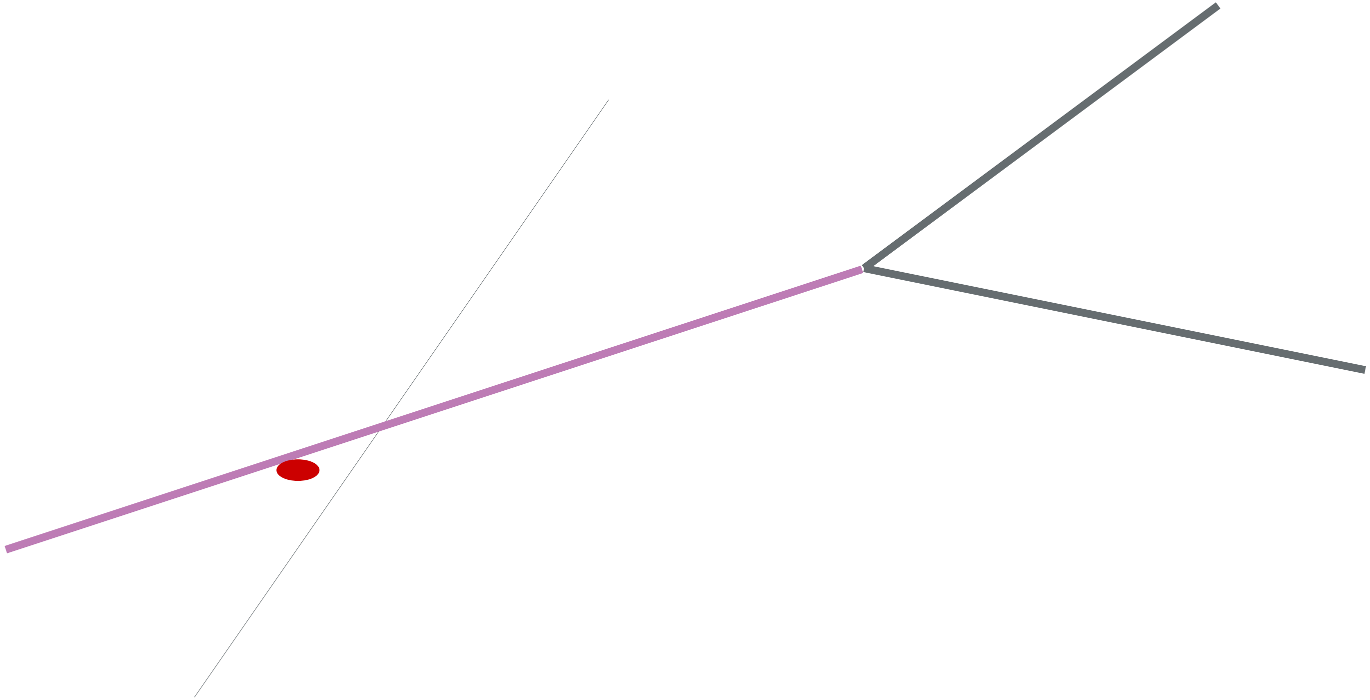
Reconstruction

Find secondary vertex
= location in space where two (or more tracks) converge
WARNING: probability that 2 lines in 3D space cross = zero, so use “best” point



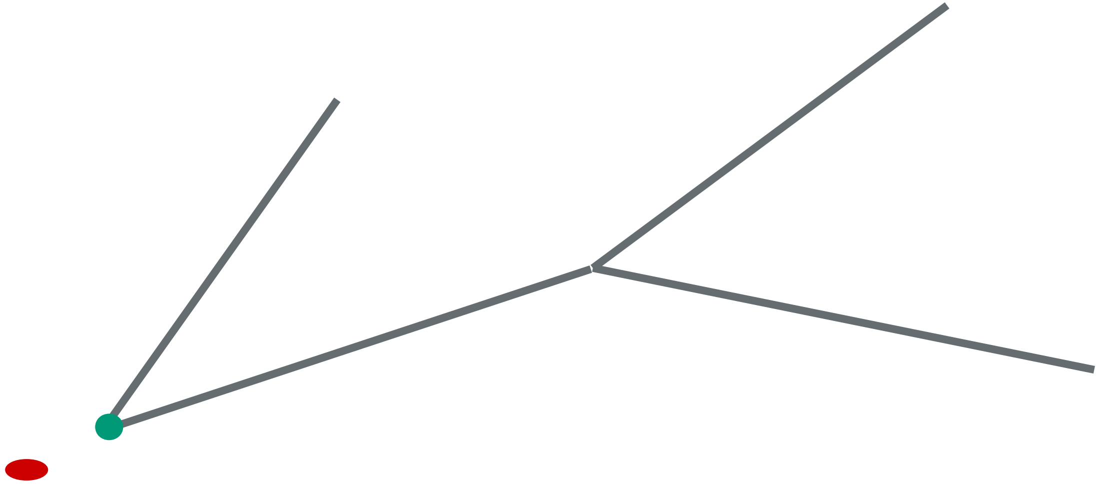
Reconstruction

Find secondary vertex, reconstuct parent track
Combing 3-momenta gives parent 3-momentum, and direction of track
POSSIBLE IMPROVEMENT: refit tracks with perfect secondary vertex



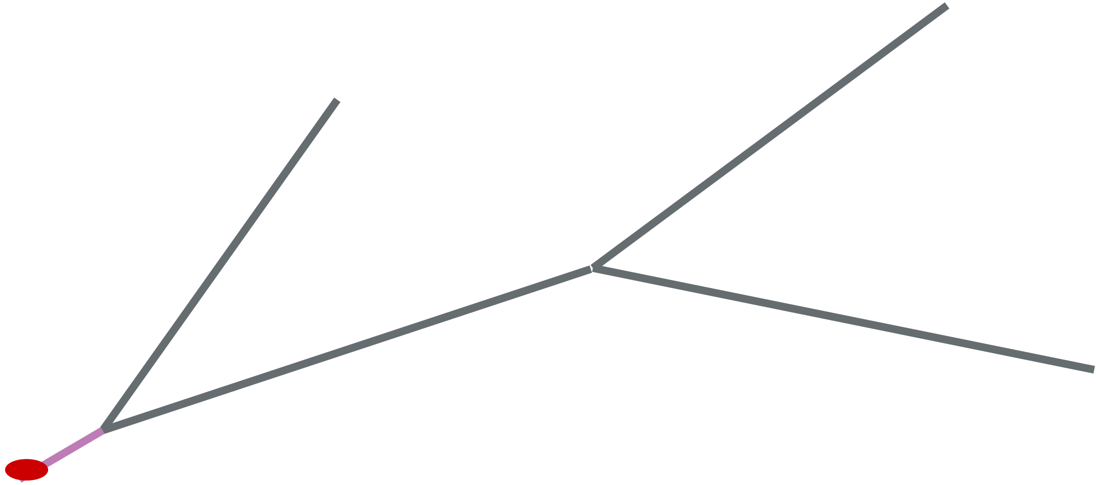
Reconstruction

Find secondary vertex, reconstuct parent track, and repeat



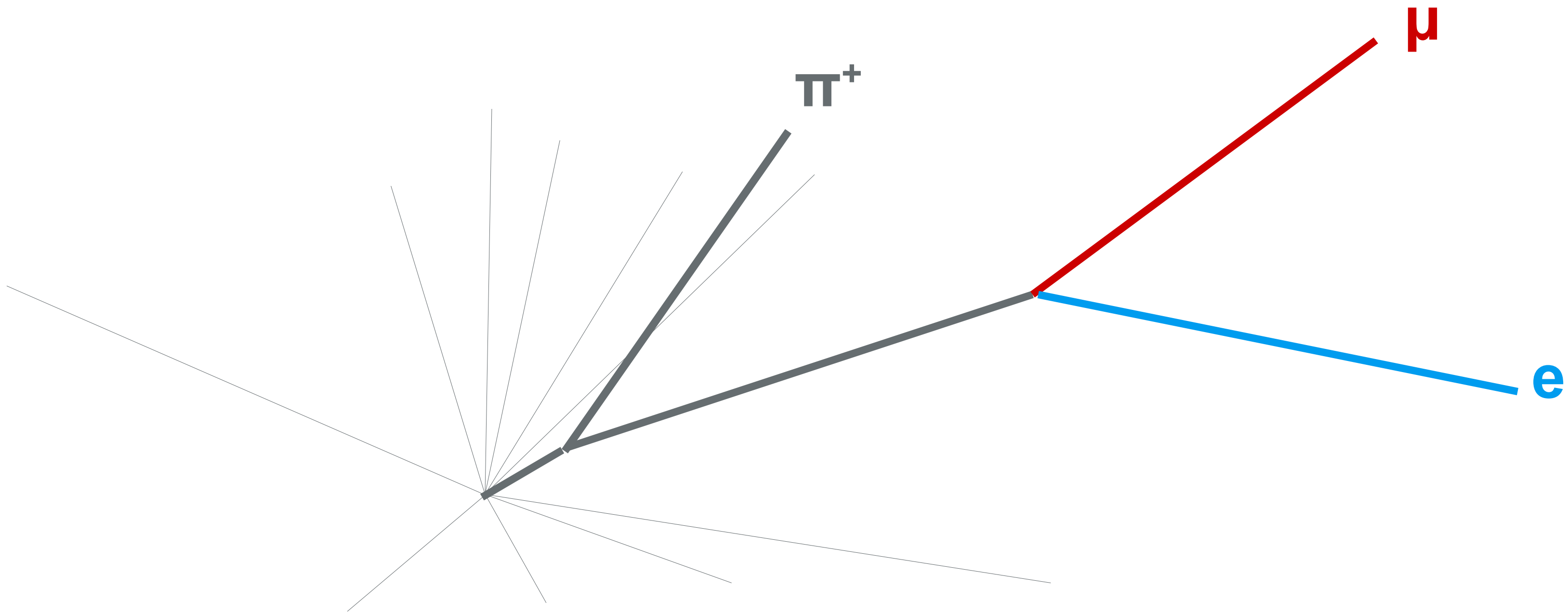
Reconstruction

Find secondary vertex, reconstuct parent track, and repeat
until last parent tracks comes from primary vertex



Reconstruction

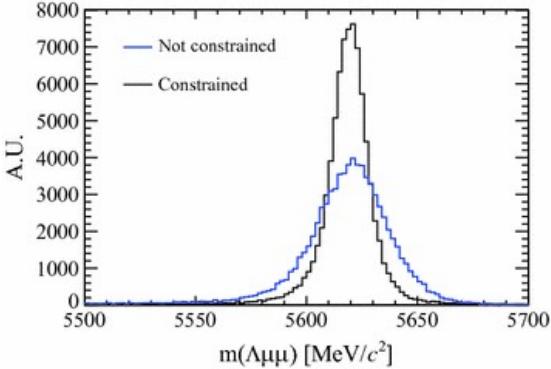
Identify detected particles
WARNING: cannot be done uniquely, assume *most likely* identity

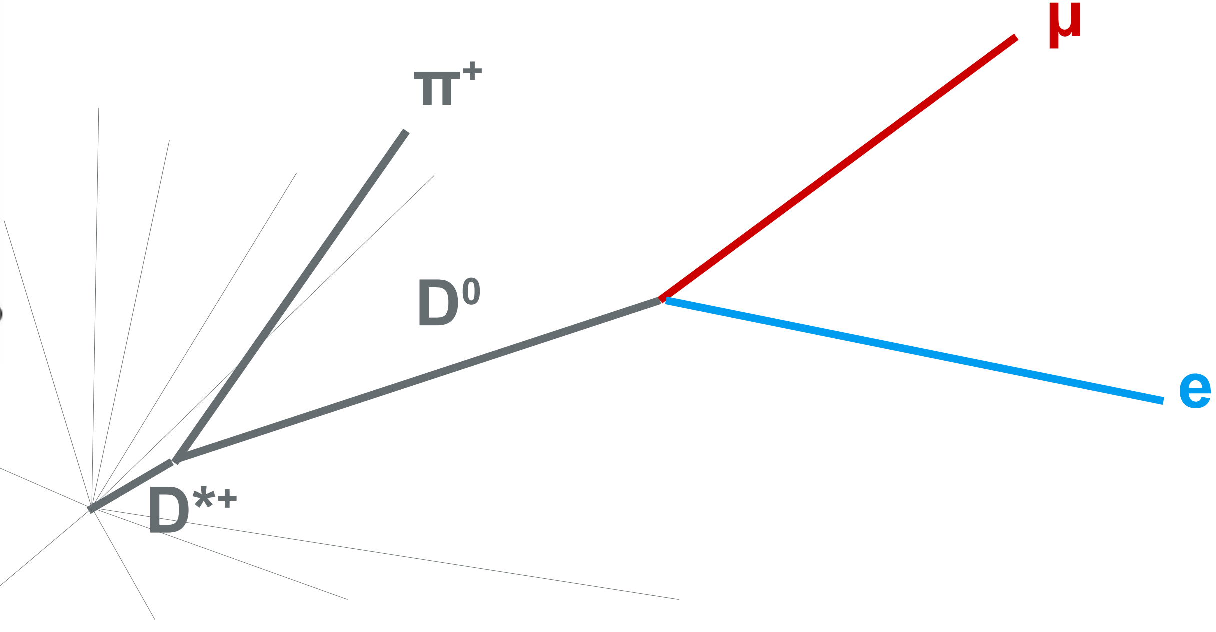


Reconstruction

Identify invisible particles

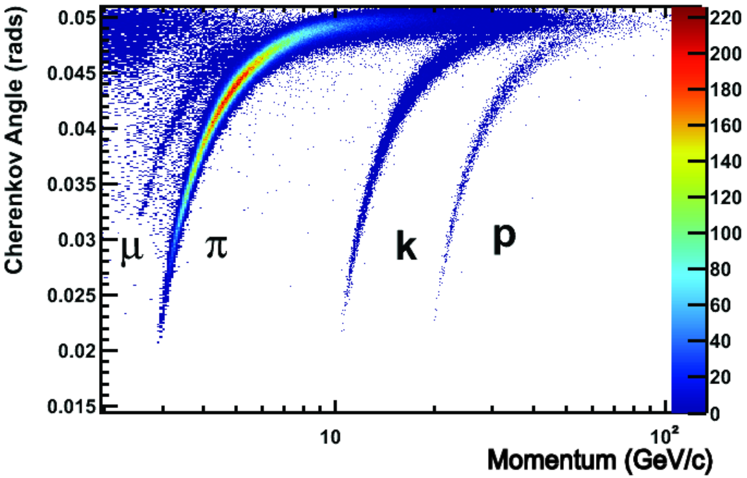
Construct four-momenta of parents, calculate invariant mass, and identify
POSSIBLE IMPROVEMENT: refit tracks with perfect vertices and/or parent mass

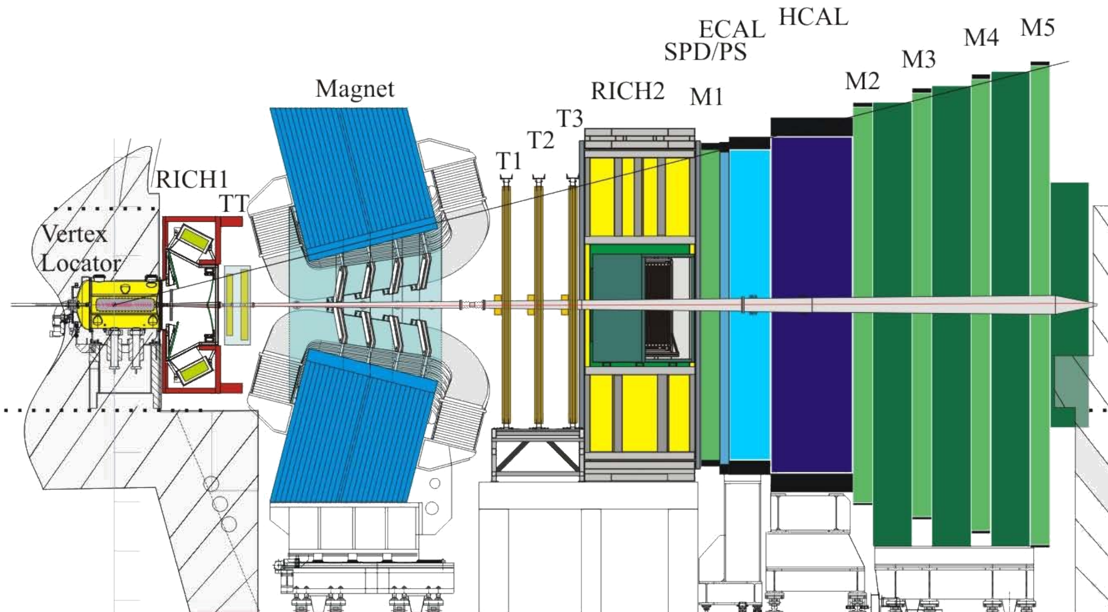




Challenge #1 : Particle (mis-)ID

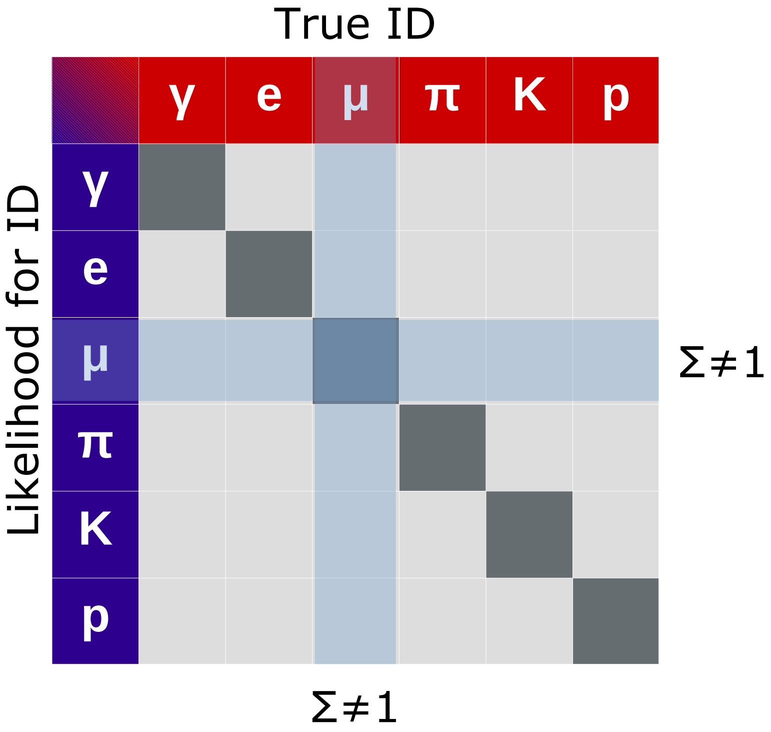
At LHCb all light particles (γ,e,μ,π,K,p) ultra-relativistic, p ≤ 200GeV/*c*
Photons and electron cause similar shower (mostly) in EM calorimeter (**ECAL**)
Photons leave no/little signal in pre-shower detector (**PS**) and trackers (**TT**–**T3**)
(Essentially) only muons make it to the muon chambers (**M1**–**M5**)
Hadrons (mostly) stop in hadronic calorimeter (**HCAL**)
Ring-imaging Cherenkov Detector (**RICH**) distinguishes velocity
All rather energy dependent





Challenge #1 : Particle (mis-)ID

Particle not uniquely ID’ed
Likelihood per species



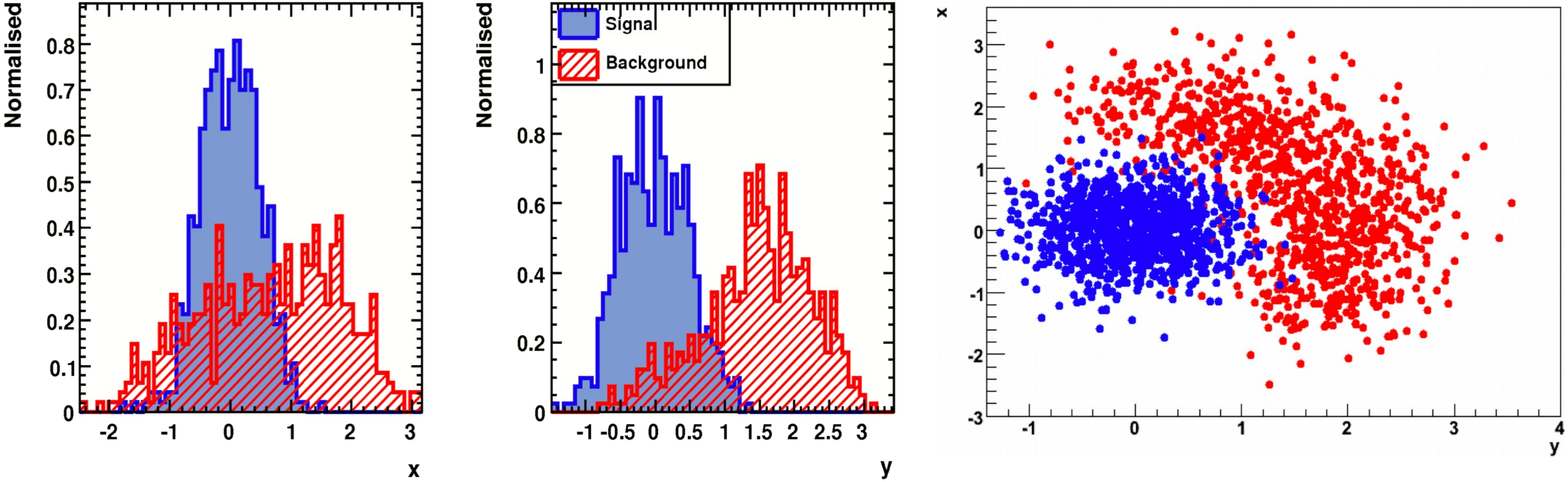
True ID

Likelihood for ID

	γ	e	μ	π	K	p	
γ	■		▨				
e		■	▨				
μ	▨	▨	■	▨	▨	▨	Σ≠1
π			▨	■			
K			▨		■		
p			▨			■	
			Σ≠1				

(Boosted) decision trees

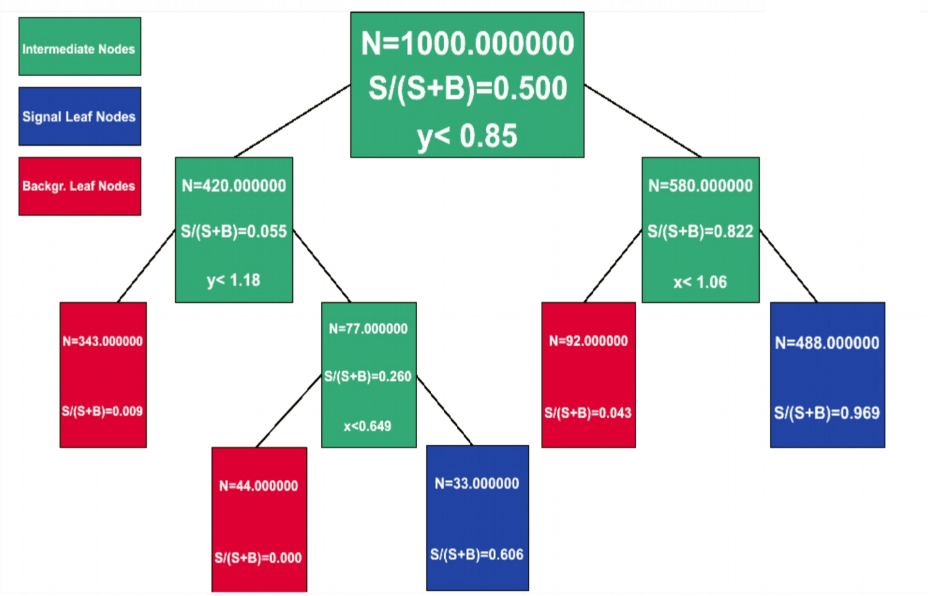
Example: **signal** and **background** measured in 2 detectors **X** and **Y**

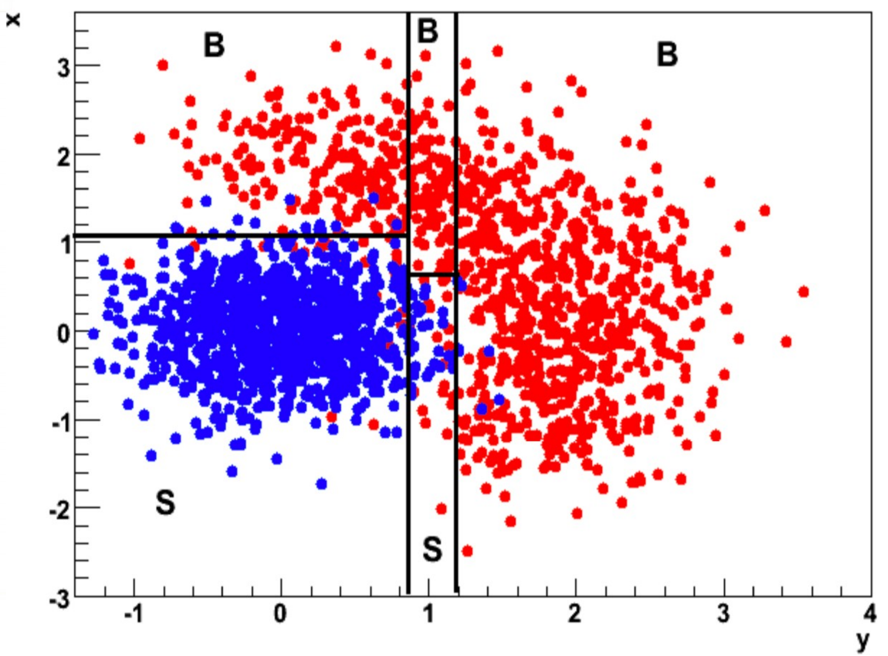


Signal windows has lots of background→ (automatically) optimize selection?

(Boosted) decision trees

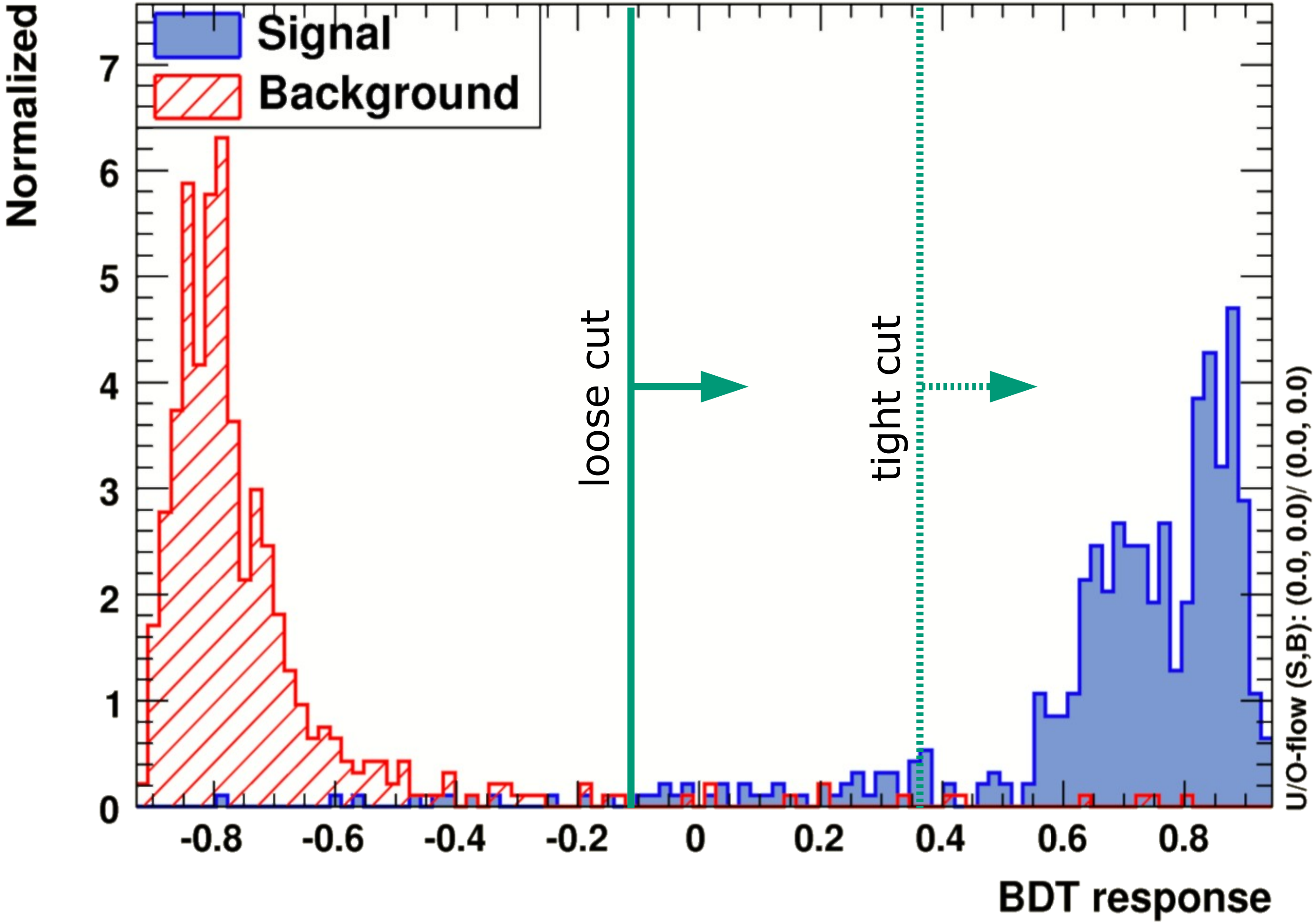
Repeatedly split data in **X** or **Y** to optimize **signal-significance**





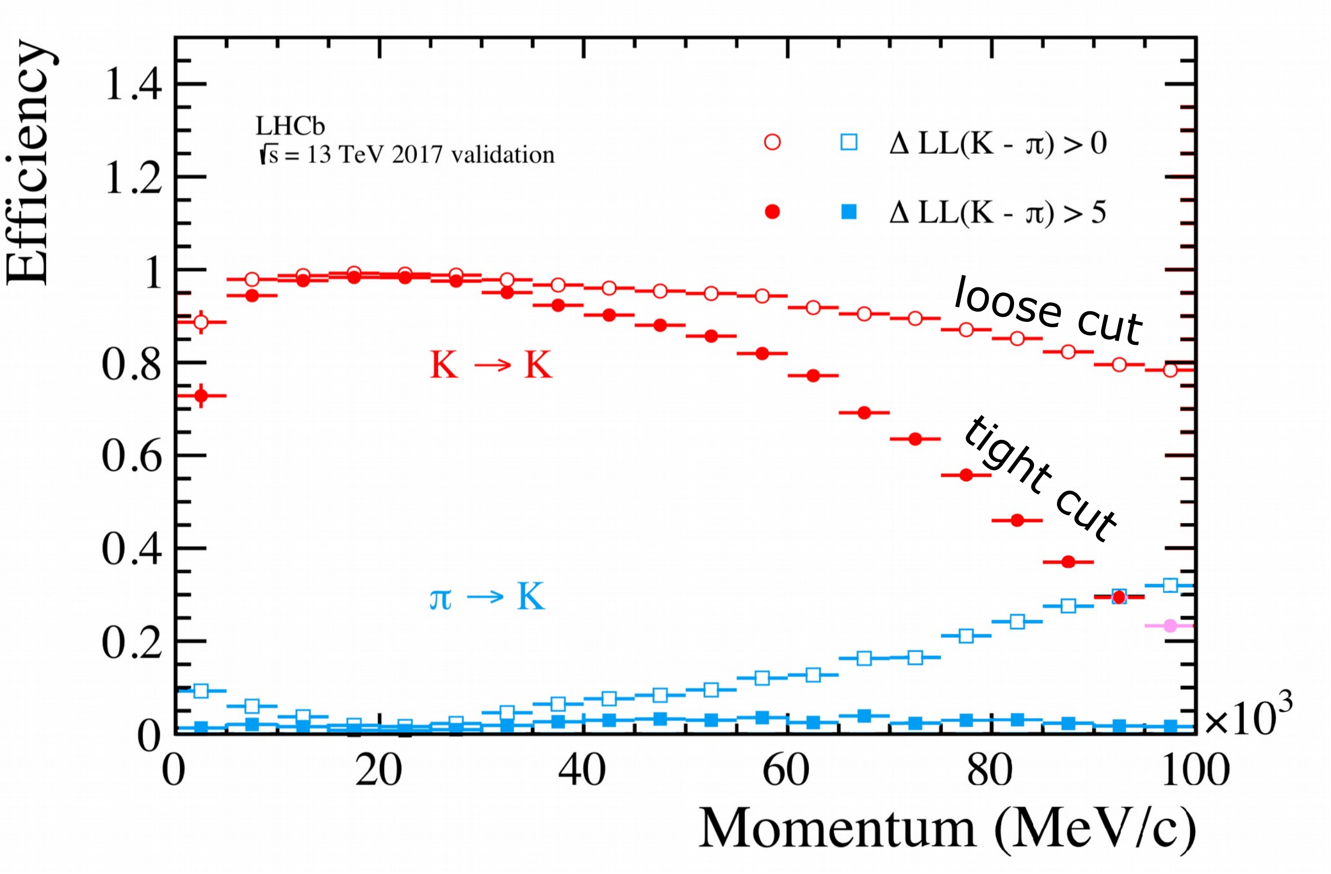
Boosting: take output of DT and re-weight training data for next DT

(Boosted) decision trees



Particle (mis-)ID

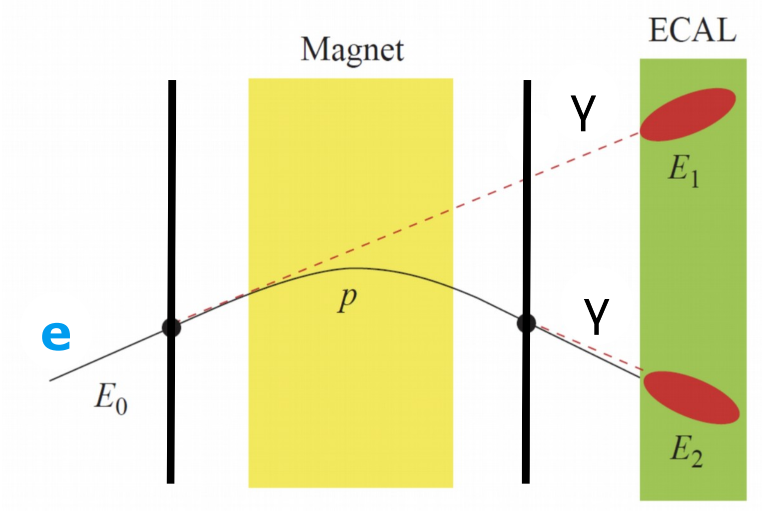
Incorrect inclusion/rejection of event for further analysis
Leads to mis-reconstruction of parent mass



Challenge #2 : Bremsstrahlung

Charged particles deflected by other particles (nuclei) emit radiation
Bremsstrahlung is proportional to γ^6.
Especially important for **electrons**
Photons emitted predominantly along direction of motion
Main effect : change in *magnitude* of momentum, less so in *direction*

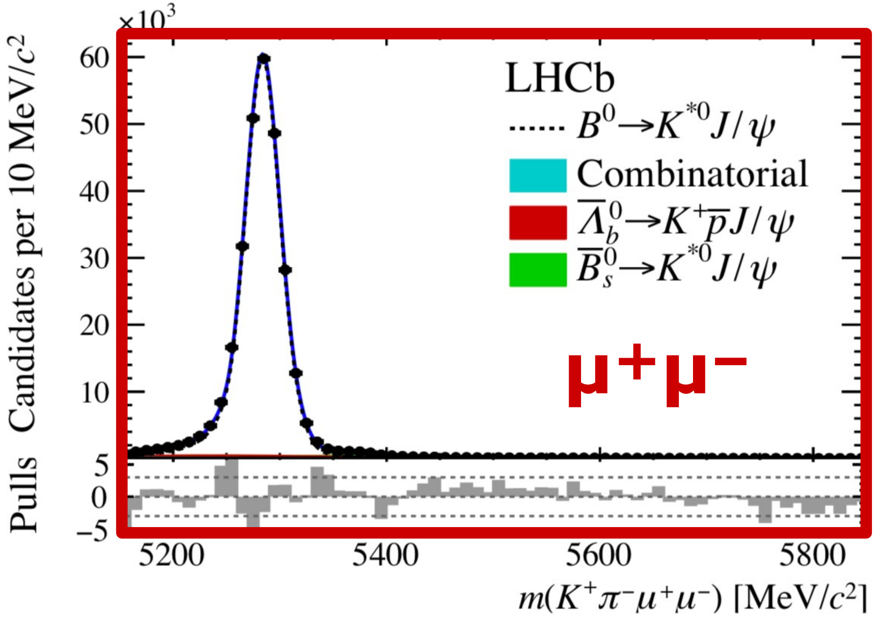
In part automatically recovered, in part to be done by-hand

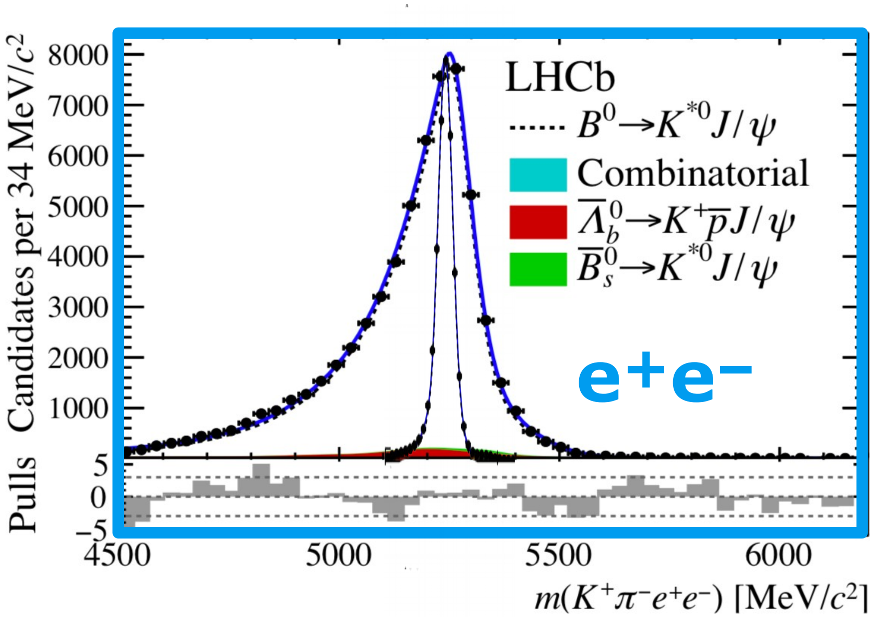


Challenge #2 : Bremsstrahlung

Reconstructed parent mass less precise
→ wider signal region
→ more background
→ lower signal significance
→ weaker limit

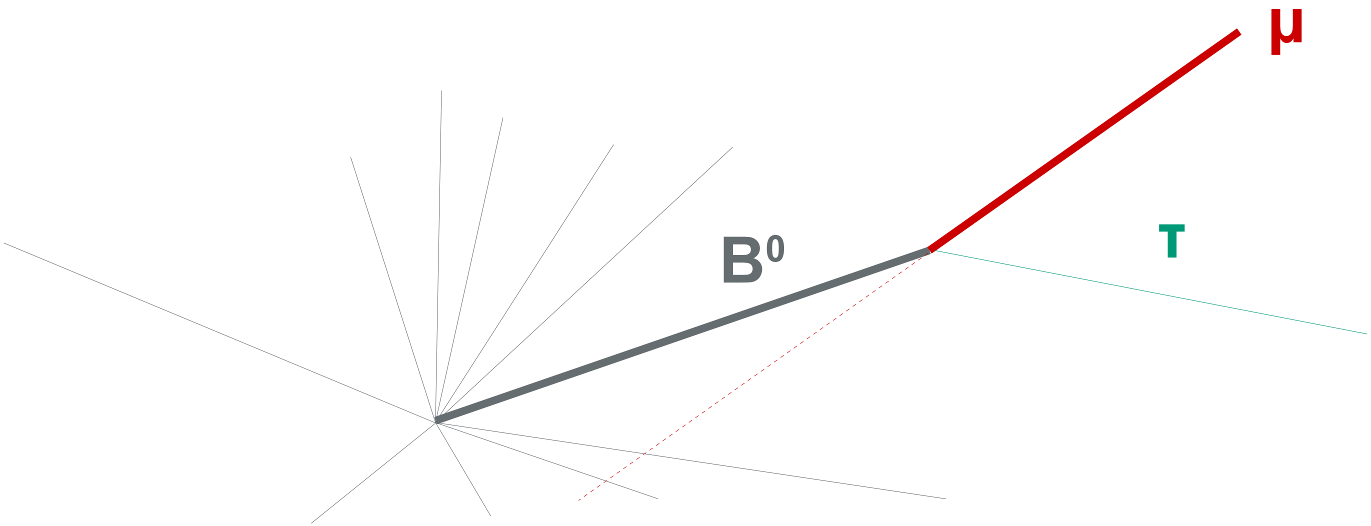
$B^0 \to K^{*0}(K^+\pi^-)\ J/\psi(\ell^+\ell^-)$





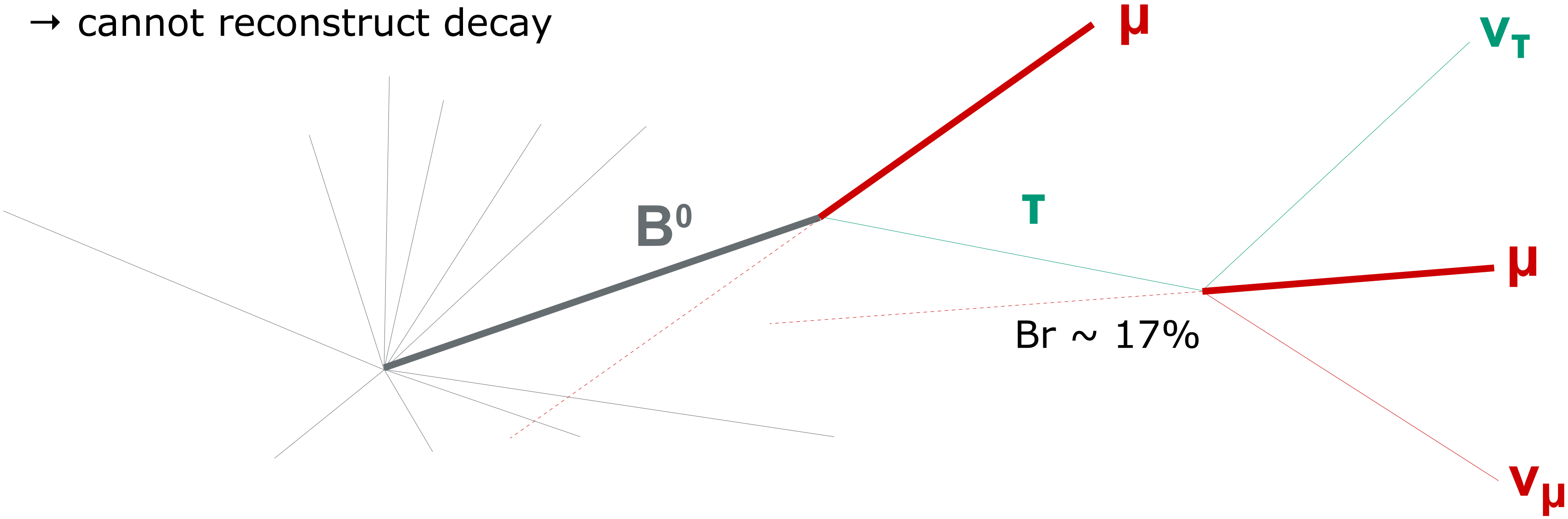
Challenge #3 : Tau-decay

Tau lifetime is 0.29 ps (cτ = 87 µm)
So **tau** cannot be detected itself



Challenge #3 : Tau-decay

Can only detect charged decay products, not neutrinos
→ always missing tau-neutrino, if leptonic decay also second one
→ missing p and E
→ cannot find secondary vertex
→ cannot reconstruct decay



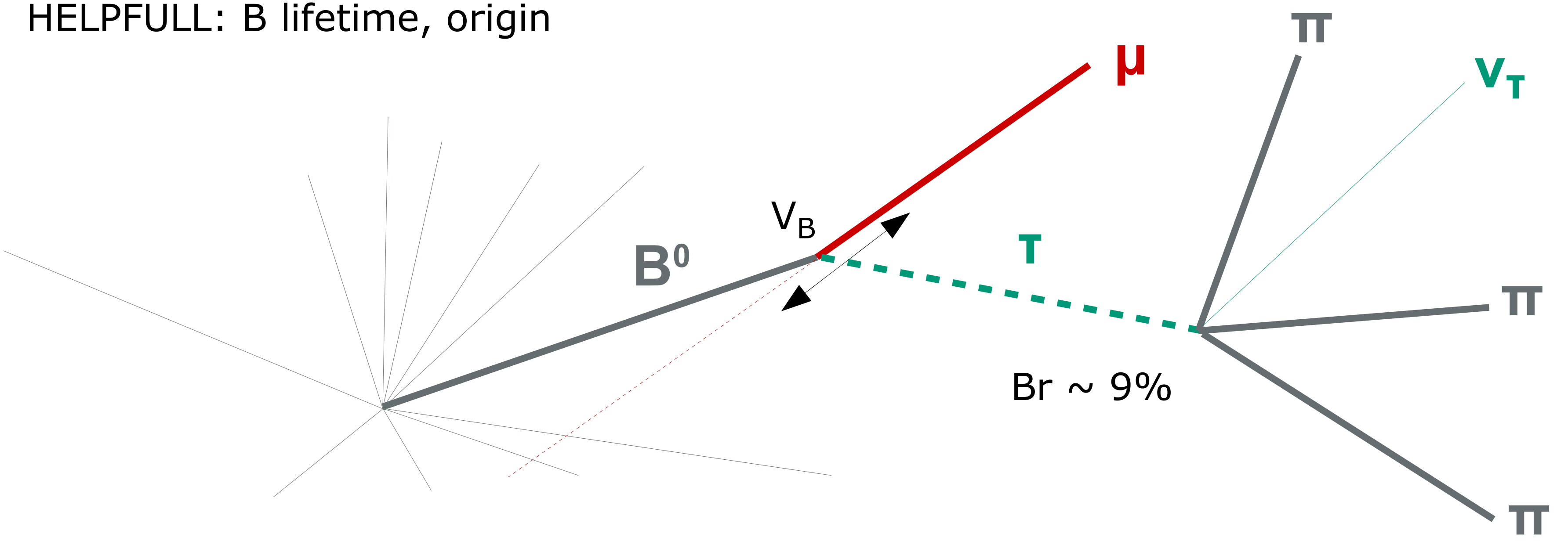
Challenge #3 : Tau-decay

$p_{\perp}(\nu)$ along $\mathbf{p_{\mu}} \times \mathbf{p_{\tau}}$

$p_{\parallel}(\nu)$ along $\mathbf{p_{\tau}}$

$p_{\llcorner}(\nu)$ 3rd term $\perp \mathbf{p_{\tau}}$

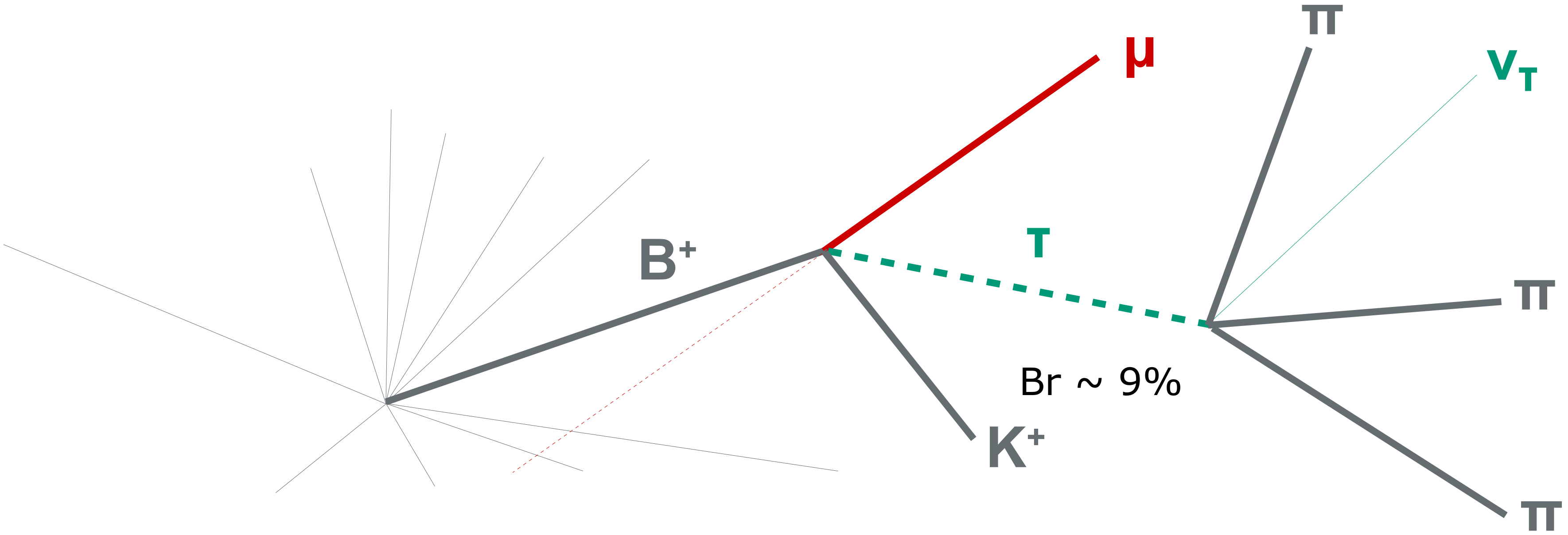
Hadronic decay : only a single missing neutrino
Several charged pions : can reconstruct **tau** decay vertex
PROBLEM: B decay vertex along **μ** track unknown
HELPFULL: B lifetime, origin



Can reconstruct B decay vertex if **tau** & B0 mass/origin assumed
always: $p_{\perp}(\nu) = -p_{\perp}(\mathbf{3\pi})$, for given V_B: $p_{\llcorner}(\nu) = -p_{\llcorner}(\mathbf{3\pi})$, $p_{\parallel}(\nu)$ fixed by masses

Challenge #3 : Tau-decay

Adding an extra charged meson fixes B decay vertex
“Tags” the presence of the parent meson
CHALLENGE: need to detect 5 particles



$p_\perp(\boldsymbol{\nu})$ and $p_\llcorner(\boldsymbol{\nu})$ determined by $p(\mathbf{3\pi})$, but still need to find $p_\parallel(\boldsymbol{\nu})$

SOLUTION: could fix **tau** mass and check B mass or v.v.