university of groningen / faculty of science and engineering / van swinderen institute for particle physics and gravity

cLFV in Meson Decays

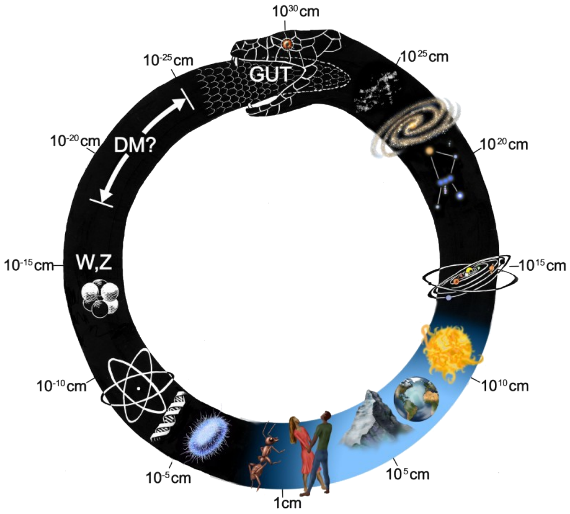
– at high energy colliders –

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

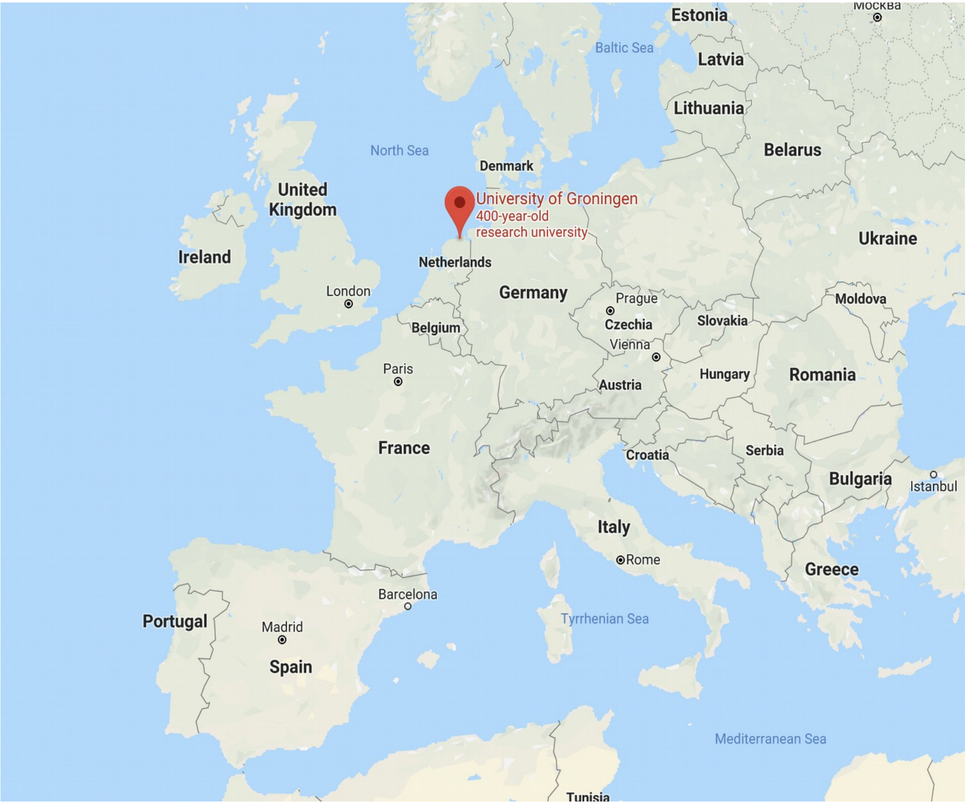
C, P, & T: EDM (μ,p,d,Ra,Xe), Ra^+APV, β-decay, SrF
LIV : ^{20}Na & Λ-decay, dτ/dΩ
LFV : $B_{(s)} \rightarrow e\mu$, $\Lambda_b \rightarrow \Lambda e\mu$
LU : Muon g−2

My research


inner detector
gradient magnet
μ orbit
electrodes
outer detector
upper EDI 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

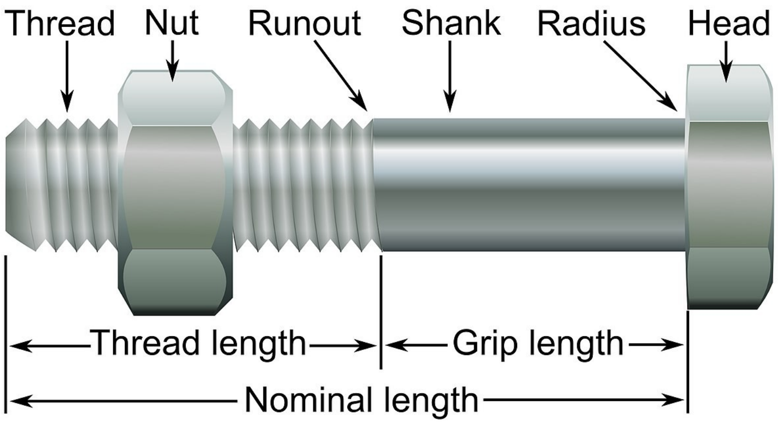
Particle identification

Signal & background: invariant mass spectrum

Normalisation

Efficiency

Interpretation



cLFV in hadron decay

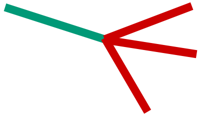
Convention

e **μ** **τ**

Towards studying (c)LFV

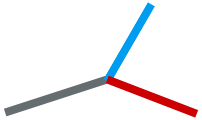
Angela Papa *Kiyoshi Hayasaka*

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 $0\nu2\beta$, $B^-\to\pi^+\mu^-\mu^-$, …

Lorenzo Calibbi

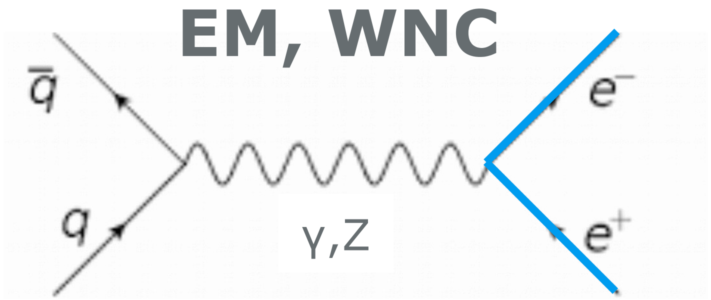
Non-Universality $\overline{B}^0\to D^{*+}\tau^-\overline{\nu}_\tau$ *vs* $\overline{B}^0\to D^{*+}\mu^-\overline{\nu}_\mu$, g_e vs g_μ , …

Sébastien Descotes-Genon *Tsutomu Mibe*

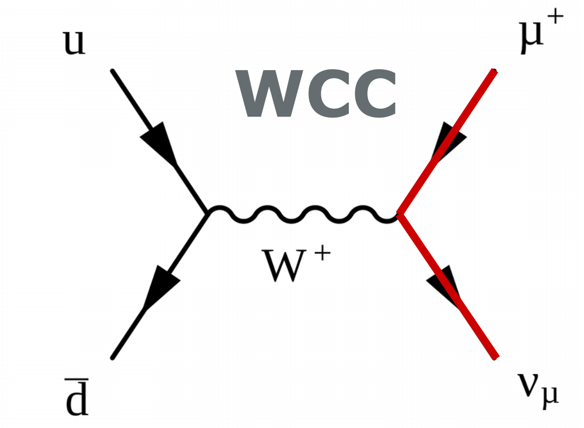
(charges dropped, unless relevant)

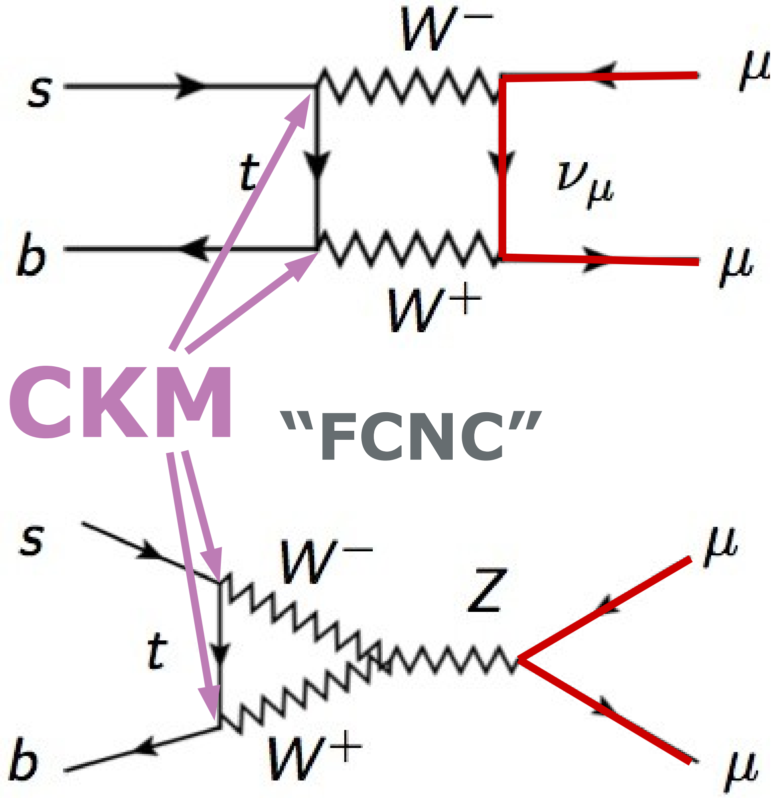
Leptonic meson decay in SM

EM, WNC



WCC

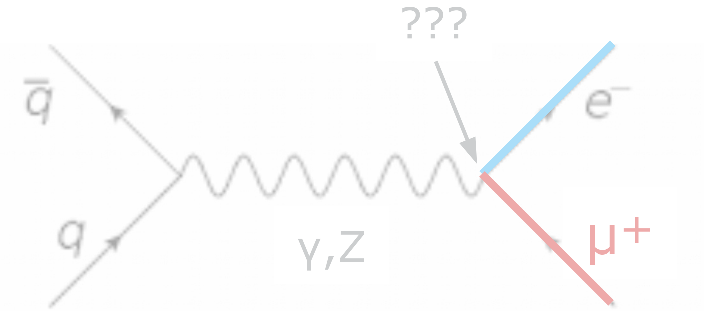


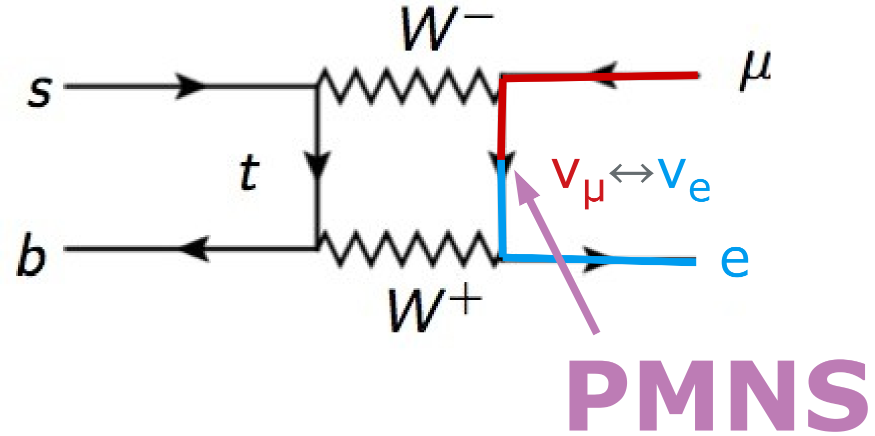


CKM

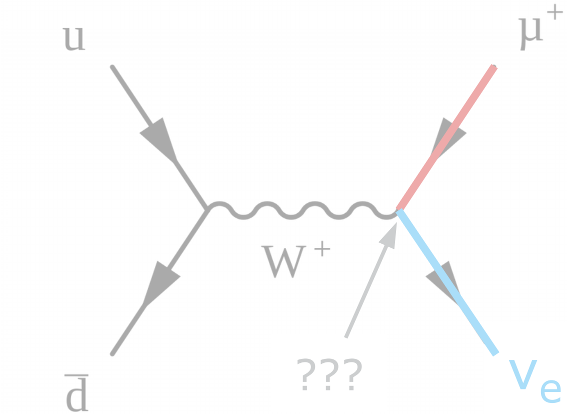
“FCNC”

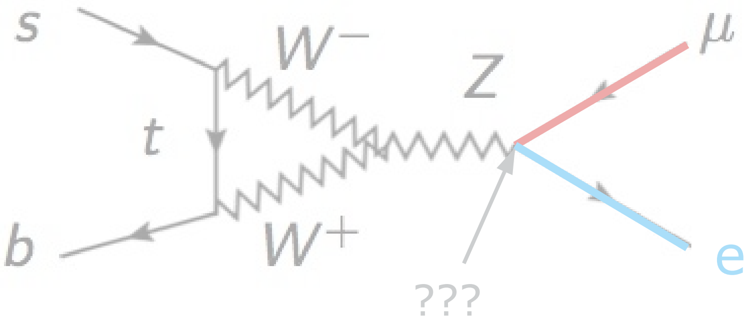
Leptonic meson decay in SM





PMNS

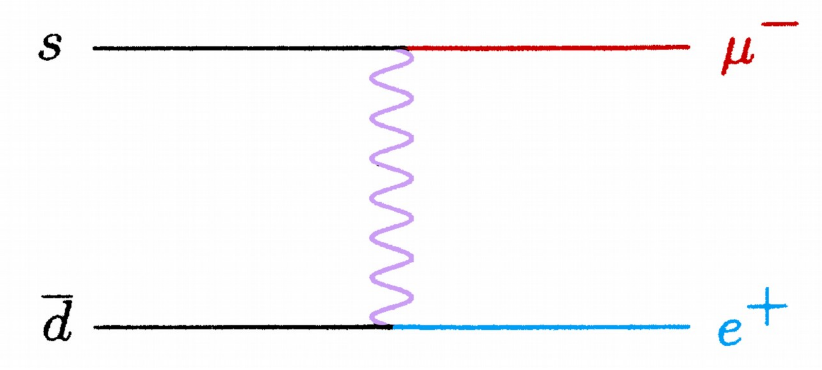


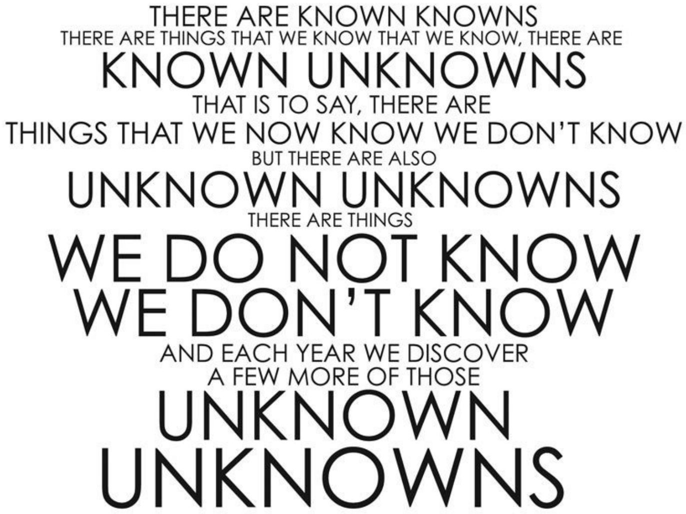


Leptonic meson decay post-SM

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

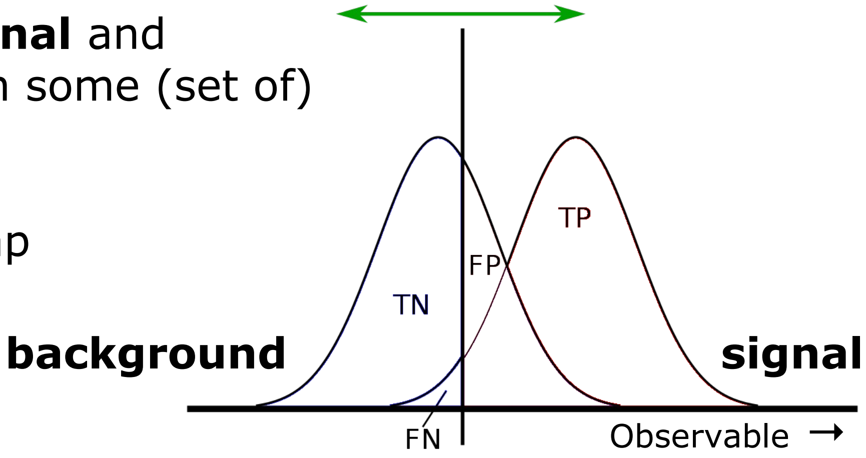
Selectivity
Also known as *specificity*, or *true negative rate*
"If another process occurs, what fractions of events are labeled as such?"
In other words, your ability to identify and eliminate background

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



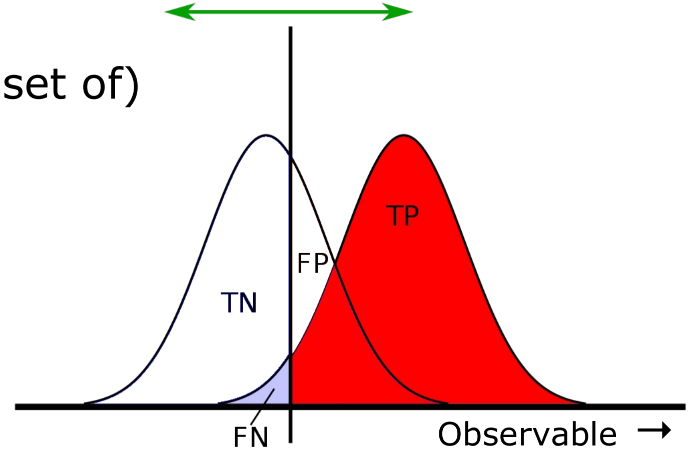
Contingency table and ROC curve

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

Signatures often overlap

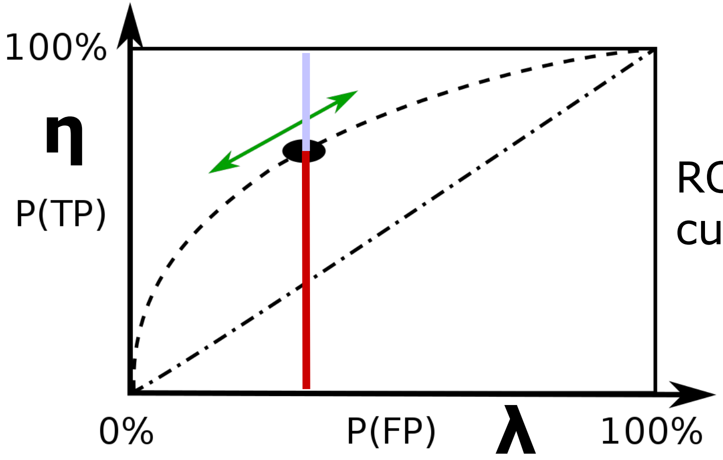
Goal
Maximize **TRUE POSITIVE η**

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

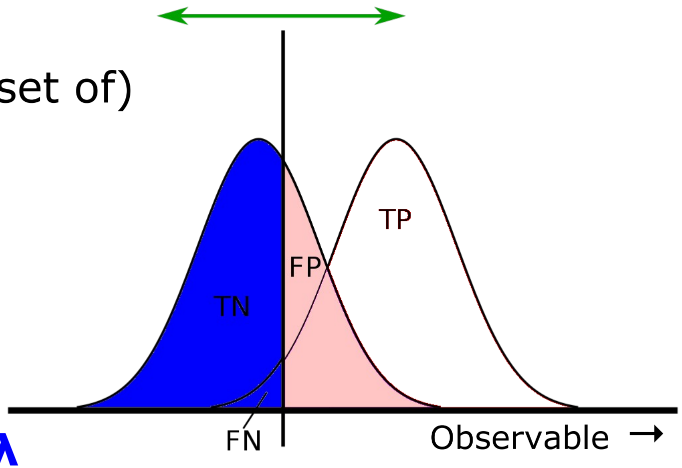
Maximize **TRUE POSITIVE η**

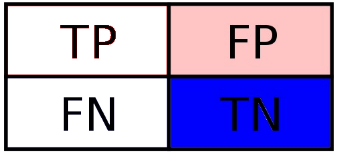
Maximize **TRUE NEGATIVE 1-λ**

Side effect

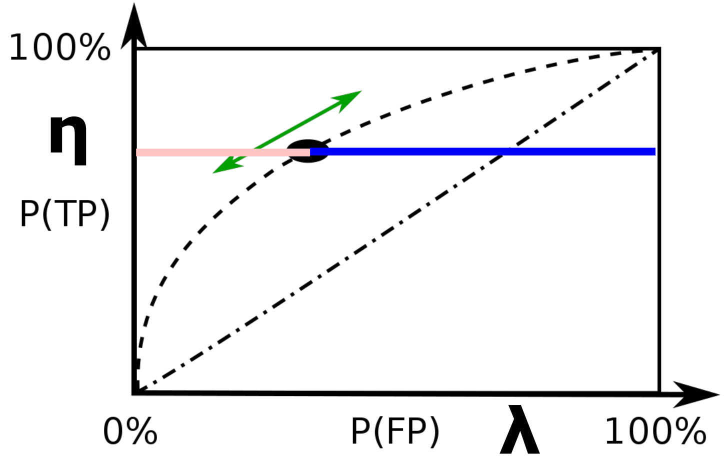
Reduced efficiency (**FALSE NEGATIVE**)

Noise leakage (**FALSE POSITIVE**)





TP	FP
FN	TN



Contingency table and ROC curve

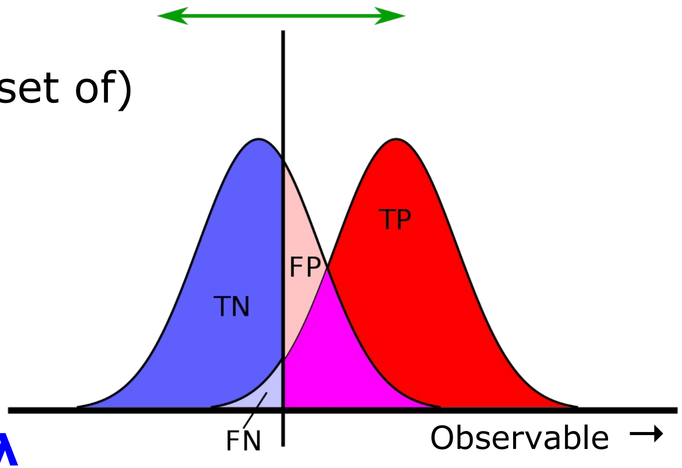
Need to distinguish **signal** and **background**, based on some (set of) observables

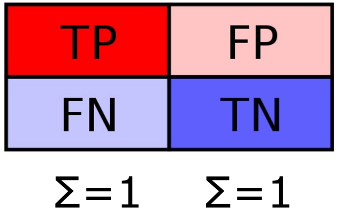
Signatures often overlap

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

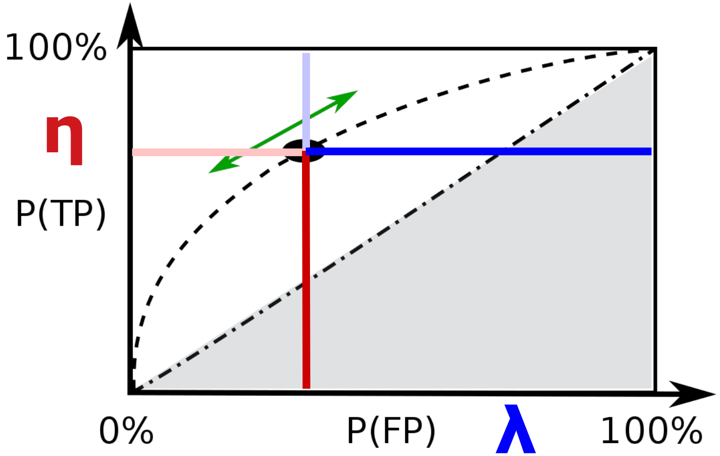
Side effect
Reduced efficiency (**FALSE NEGATIVE**)
Noise leakage (**FALSE POSITIVE**)

Need sophisticated optimization





TP	FP
FN	TN
Σ=1	Σ=1

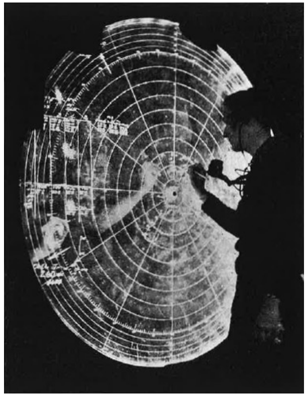


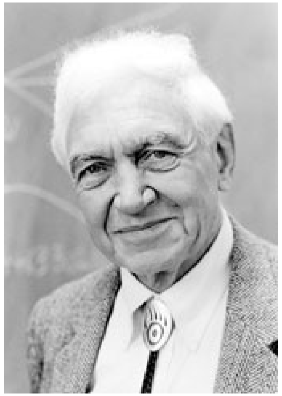
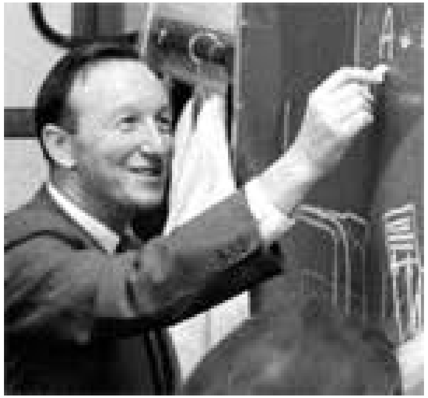
Contingency table and ROC curve

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 : $N_S = \eta\cdot S + \boldsymbol{\lambda}\cdot B$

In an independent window the background is estimated : $N_B = \mathbf{k}\cdot\boldsymbol{\lambda}\cdot B$

From these two together, the signal is estimated : $S = (N_S - N_B/\mathbf{k})/\boldsymbol{\eta}$

Error estimation : σ

Uncertainty :

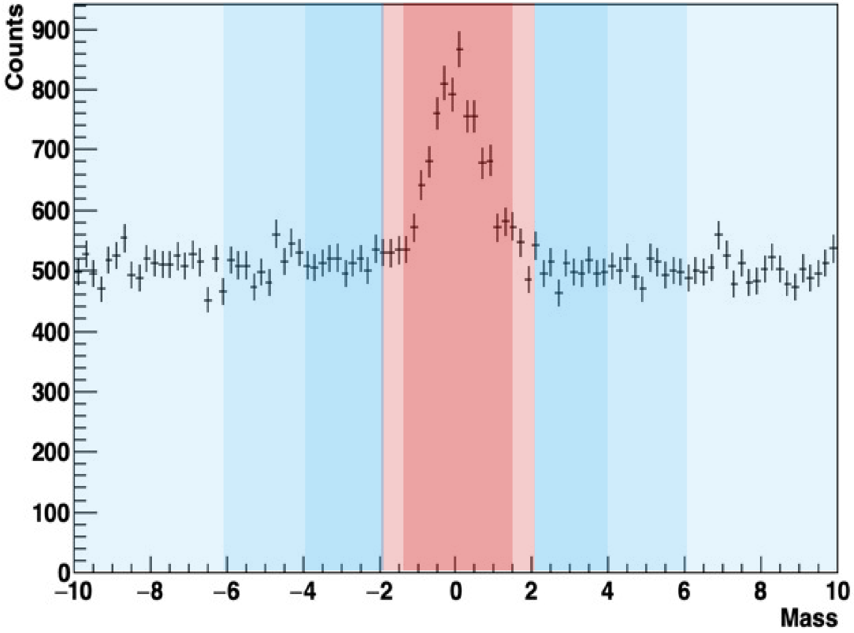
$$\begin{aligned} \boldsymbol{\eta}^2\sigma^2(S) &= \sigma^2(N_S) + \sigma^2(N_B)/\mathbf{k}^2 \\ &= N_S + N_B/\mathbf{k}^2 \\ &= (\boldsymbol{\eta}\cdot S + \boldsymbol{\lambda}\cdot B) + (\boldsymbol{\lambda}\cdot B/\mathbf{k}) \\ &= \boldsymbol{\eta}\cdot S + \mathbf{k}'\cdot\boldsymbol{\lambda}\cdot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

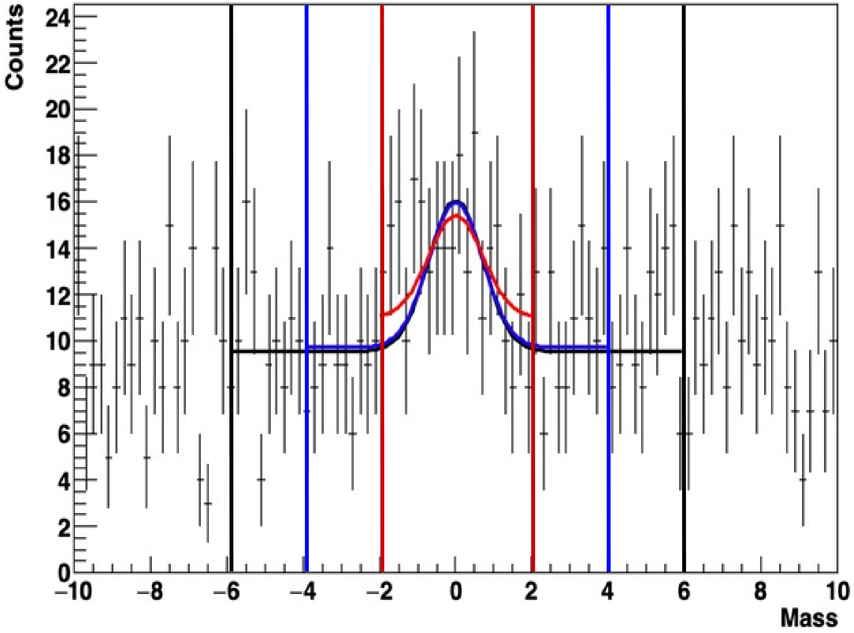
Significance : ρ

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

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

Expected significance





Branching fractions *etc.*

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

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

Beware: could produce multiple M's per collision!

$\mathcal{L}$: luminosity

σ : cross section

Also for other particles

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

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

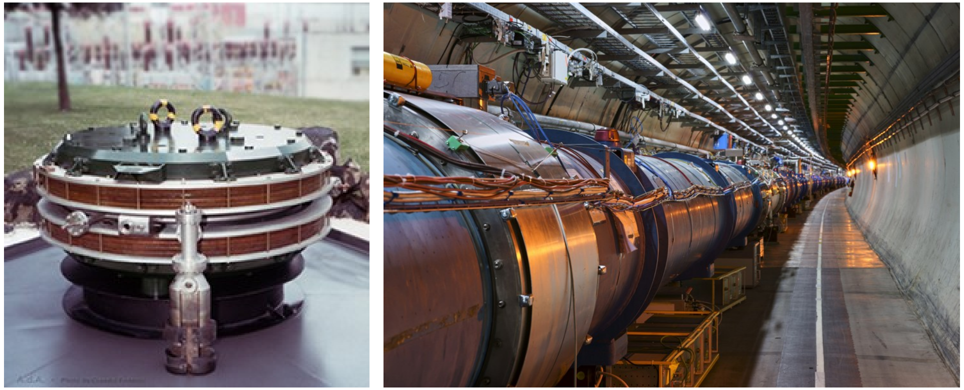
	LEP	BEPC (II)	CESR(-c)	VEPP(-4M,5, 2000)	DAΦNE	*PEP-II*	*(Super)KEKB*
$\mathcal{E}$=	104	4.63	6	6	0.7	9+3.1	7+4 GeV

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, BNL, J-PARC

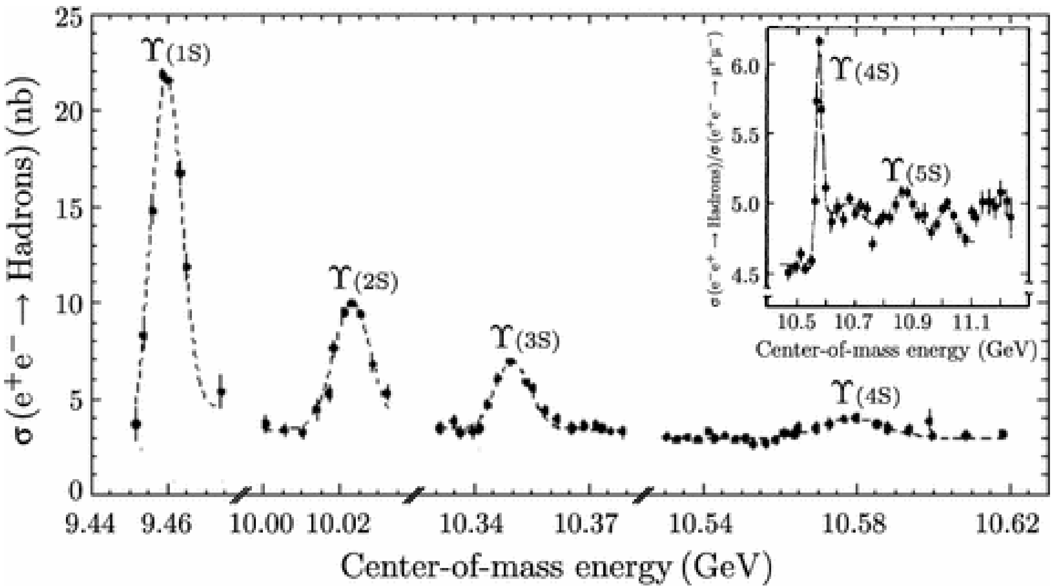


Electron-Positron Colliders

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

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

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



At Ecm = m(Y(4S)):
$\sigma(e^+e^- \rightarrow \text{hadron}) \sim 5$ nb
$= 5 \cdot 10^{-33}$ cm²

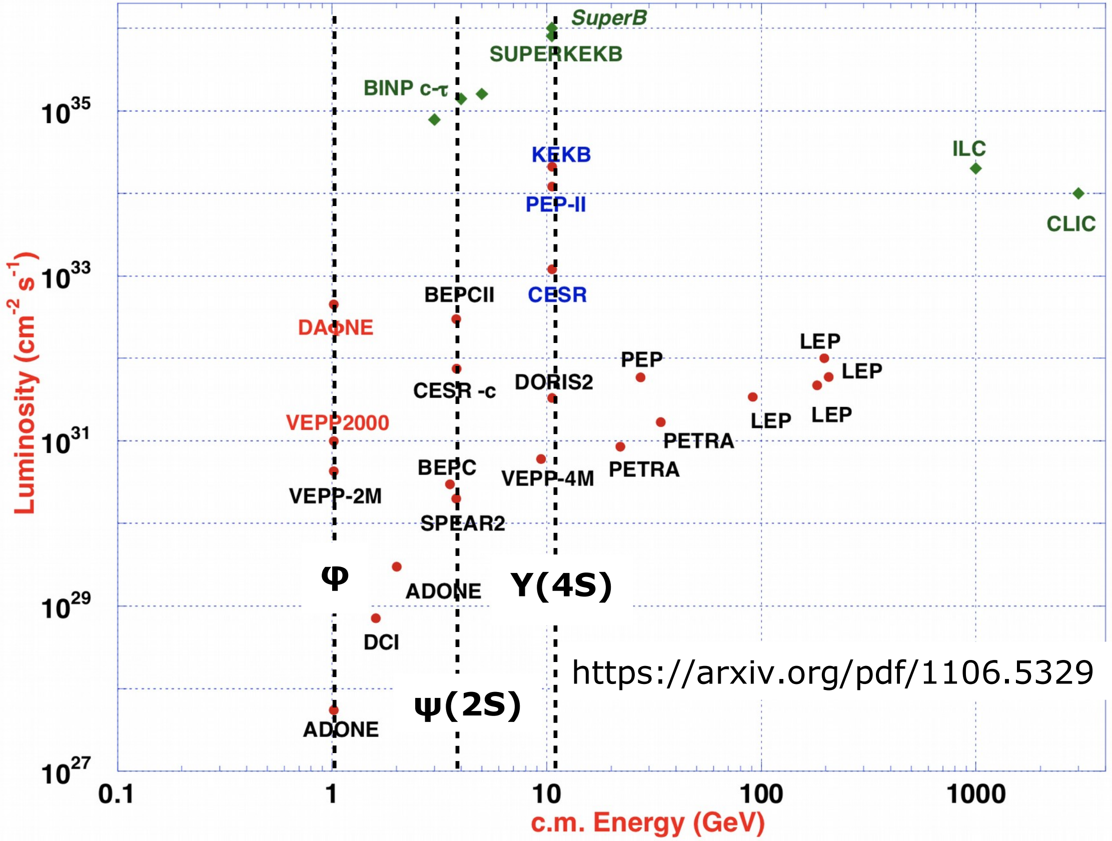
Electron-Positron Colliders

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

SuperKEKB
Annually ~5·10^{9} $B\bar{B}$

BEPC
Annually ~3·10^{9} $\Psi(2S)$

DOI:10.1063/PT.6.1.20180516a



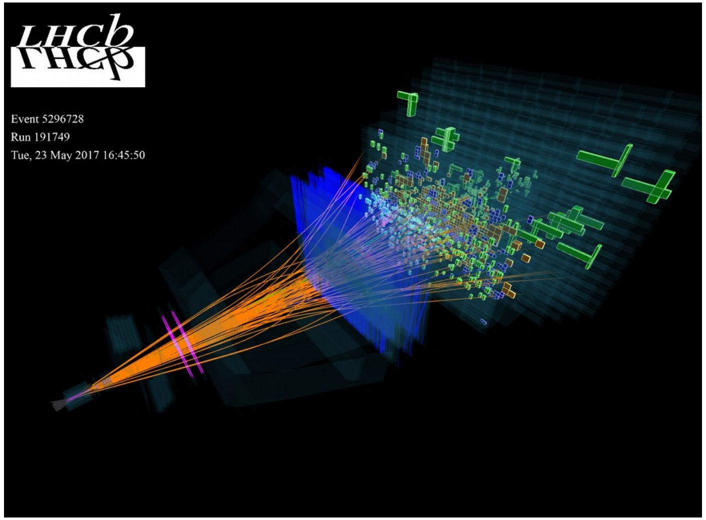
https://arxiv.org/pdf/1106.5329

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)

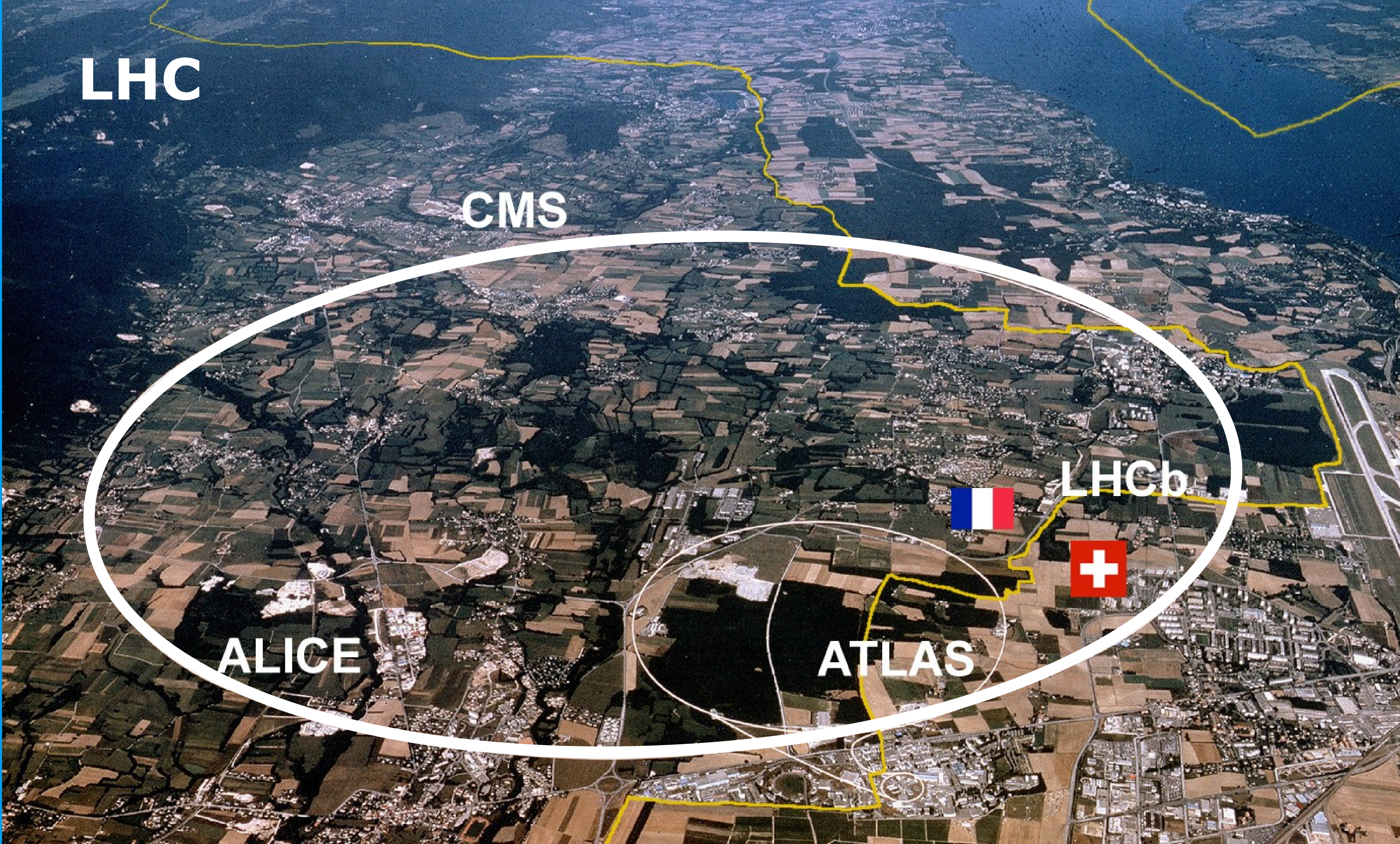
LHCb (2015-2018)
Average luminosity <L> ~ 50 $\mu b^{-1}\cdot s^{-1}$
$B\bar{B}$ production in acceptance $\sigma(pp\rightarrow b\bar{b}X)$ ~ 150 μb
Production rate $B\bar{B}$ ~ 7500 s^{-1}
Integrated luminosity: 6 fb^{-1}
Total production: ~ 10^{12} $B\bar{B}$



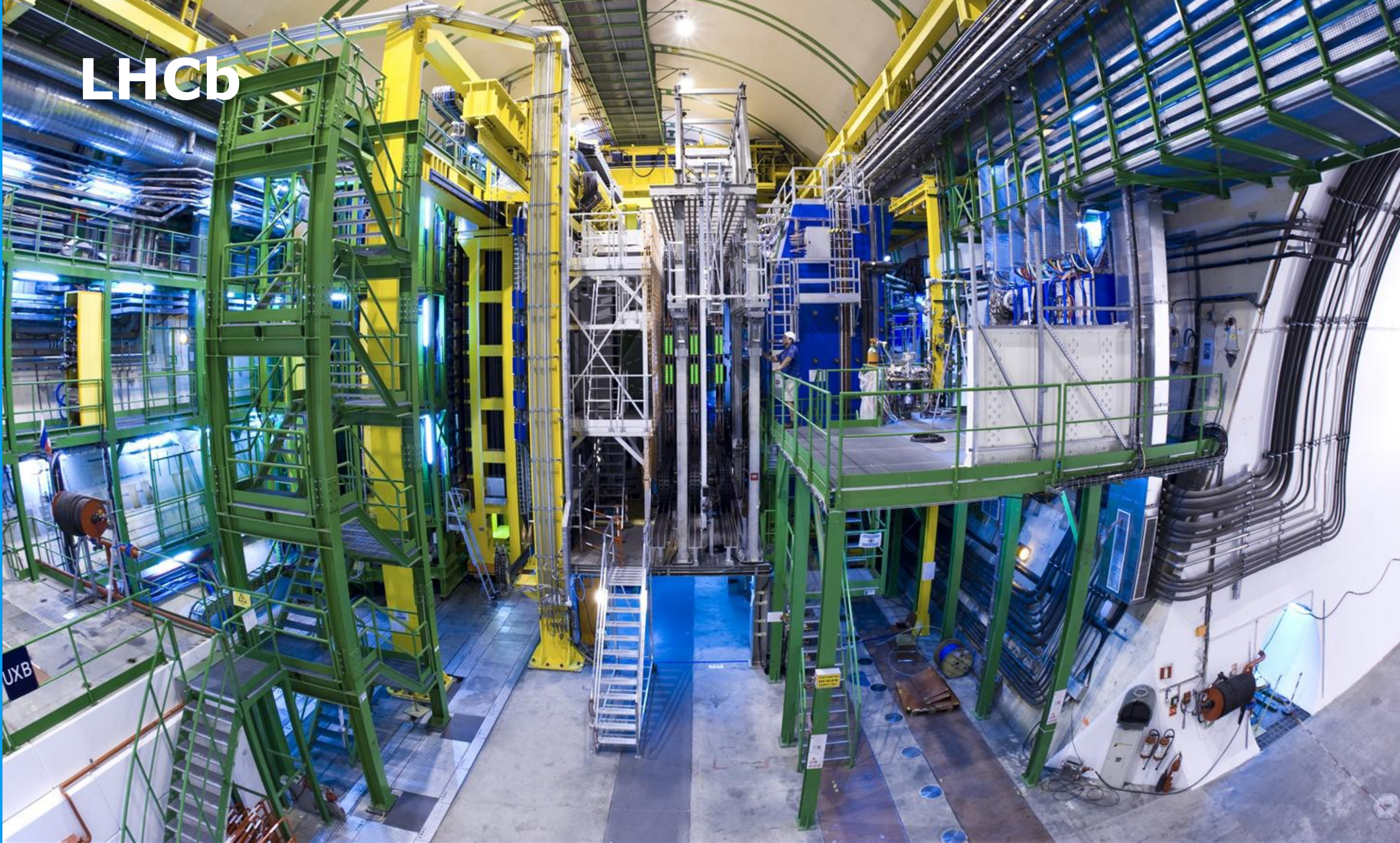
ATLAS (2015-2018)
Integrated luminosity: 160 fb^{-1}
$B\bar{B}$ production in acceptance $\sigma(pp\rightarrow b\bar{b}X)$ ~ 500 μb
Total production: ~ 10^{14} $B\bar{B}$

Particle identification

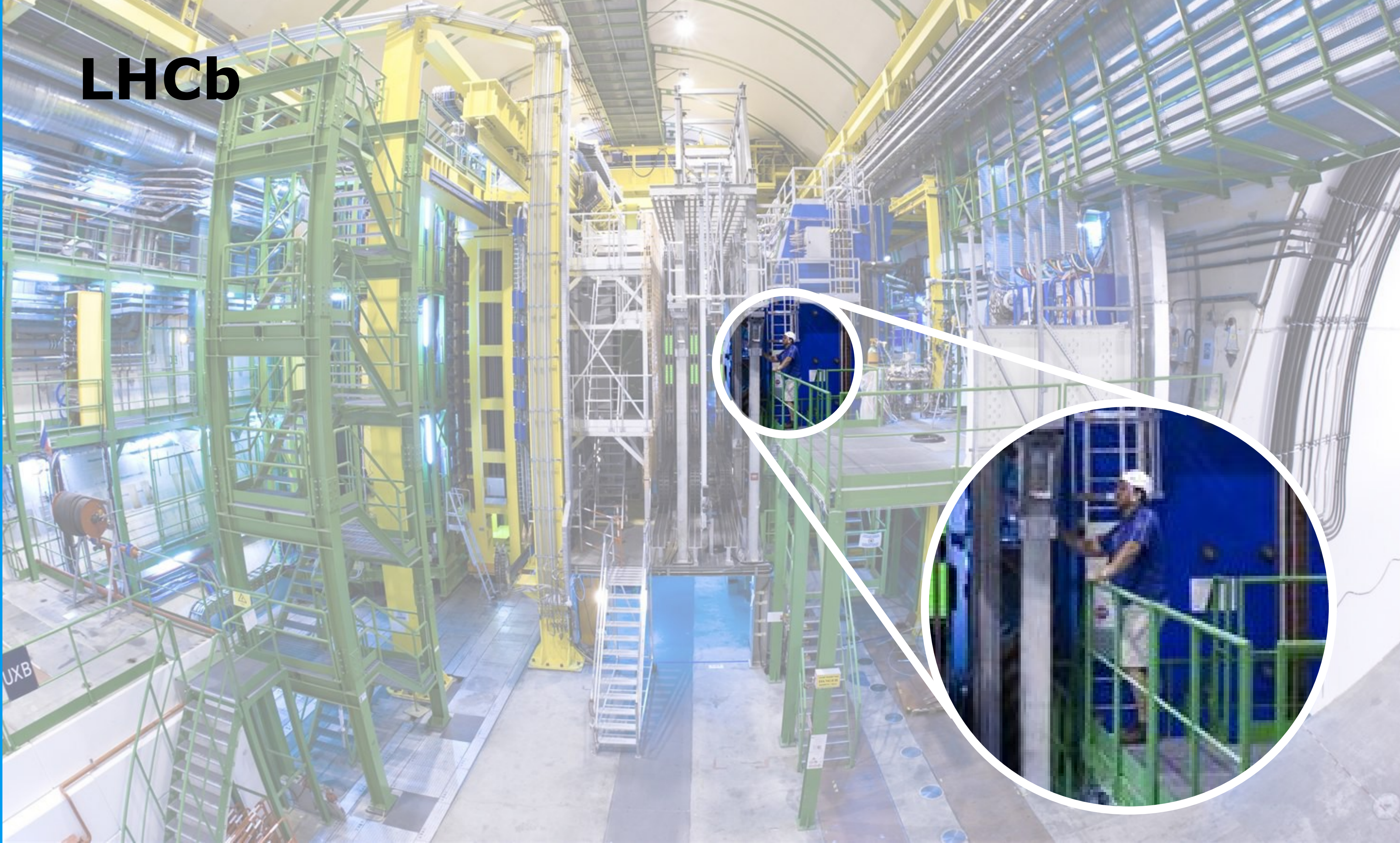
LHC



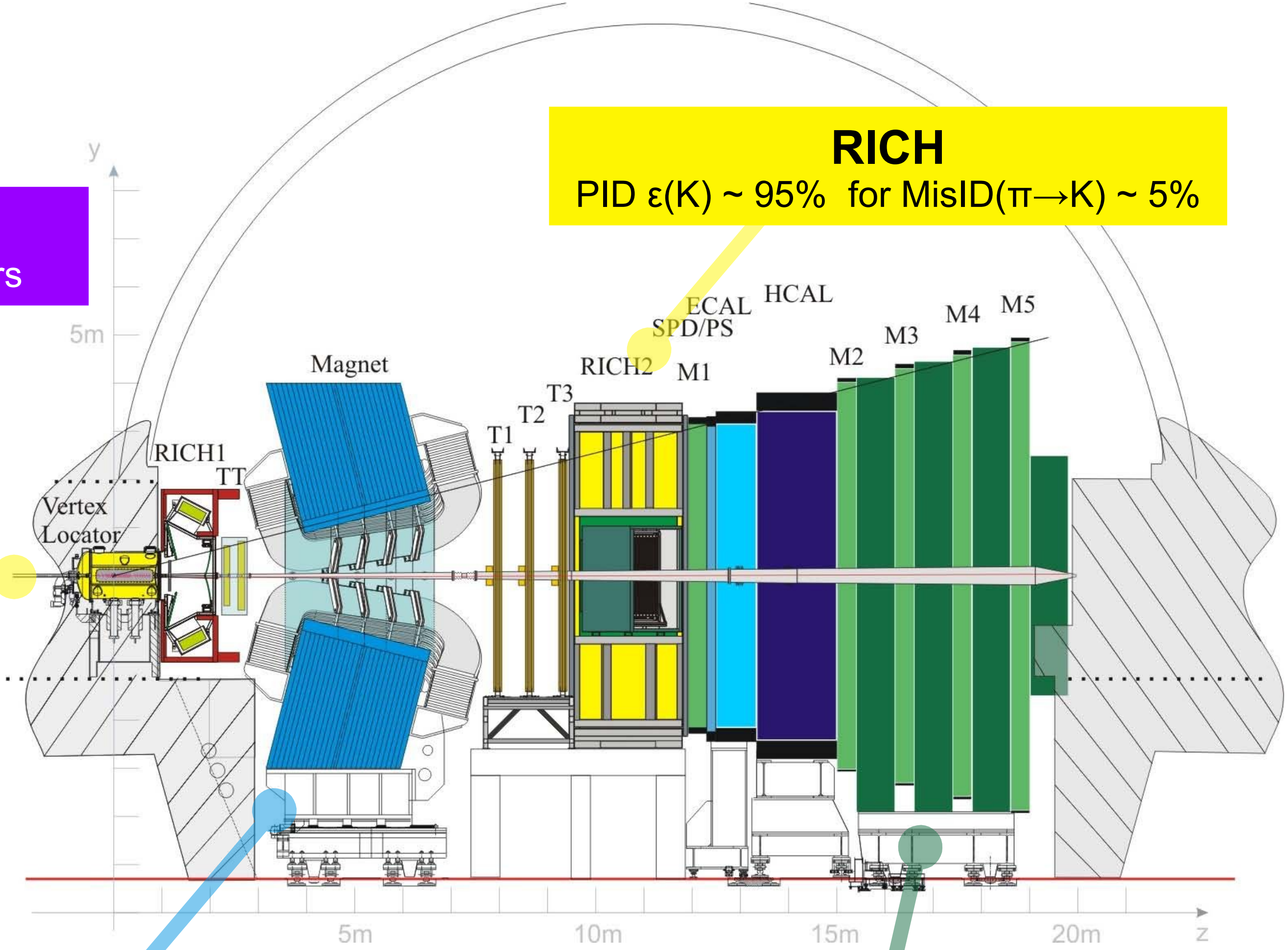
LHCb



LHCb



LHCb



Trigger
high efficiency *esp.* muon triggers

RICH
PID ε(K) ~ 95% for MisID(π→K) ~ 5%

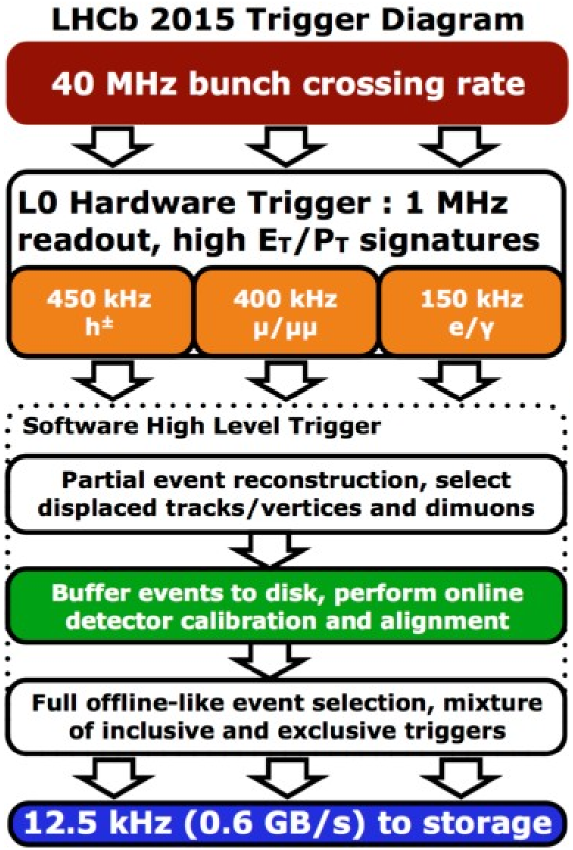
VELO
IP resolution 15+29/(p_T/GeV) μm

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

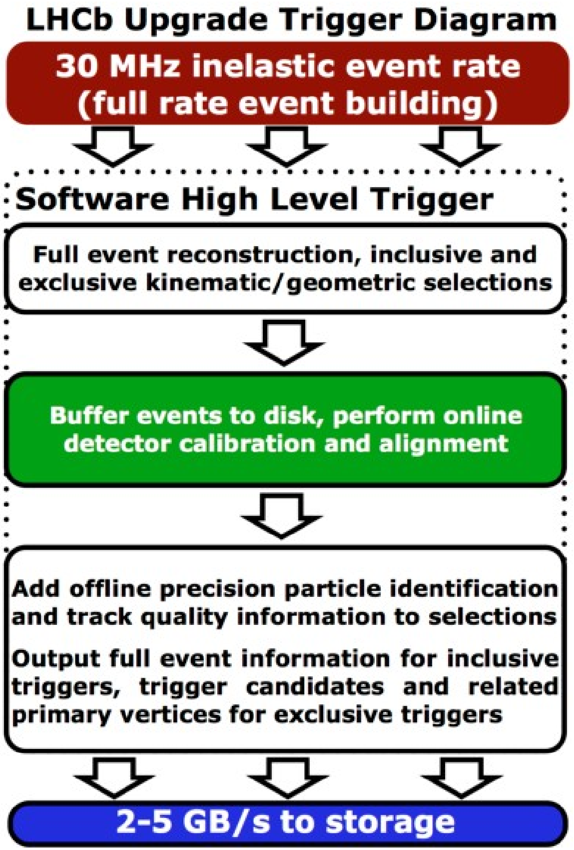
Software High Level Trigger

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

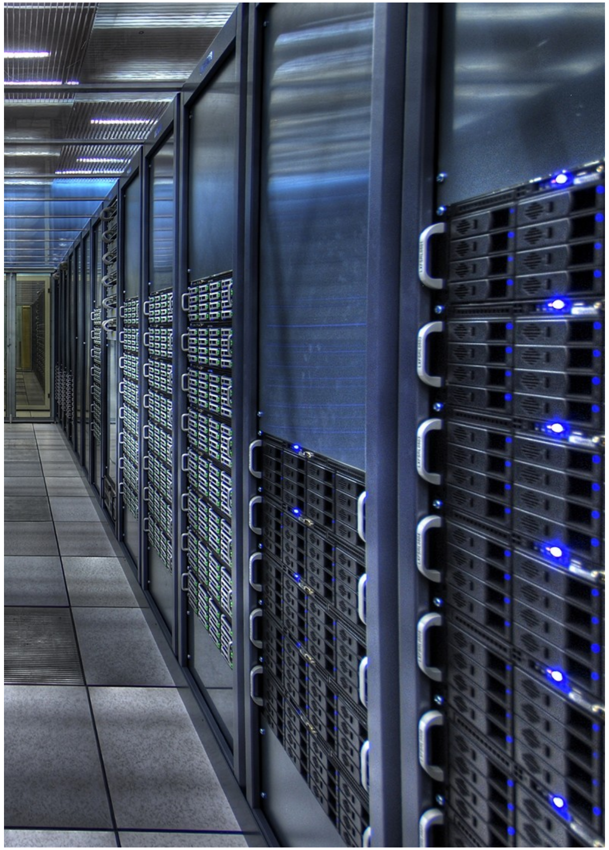
Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

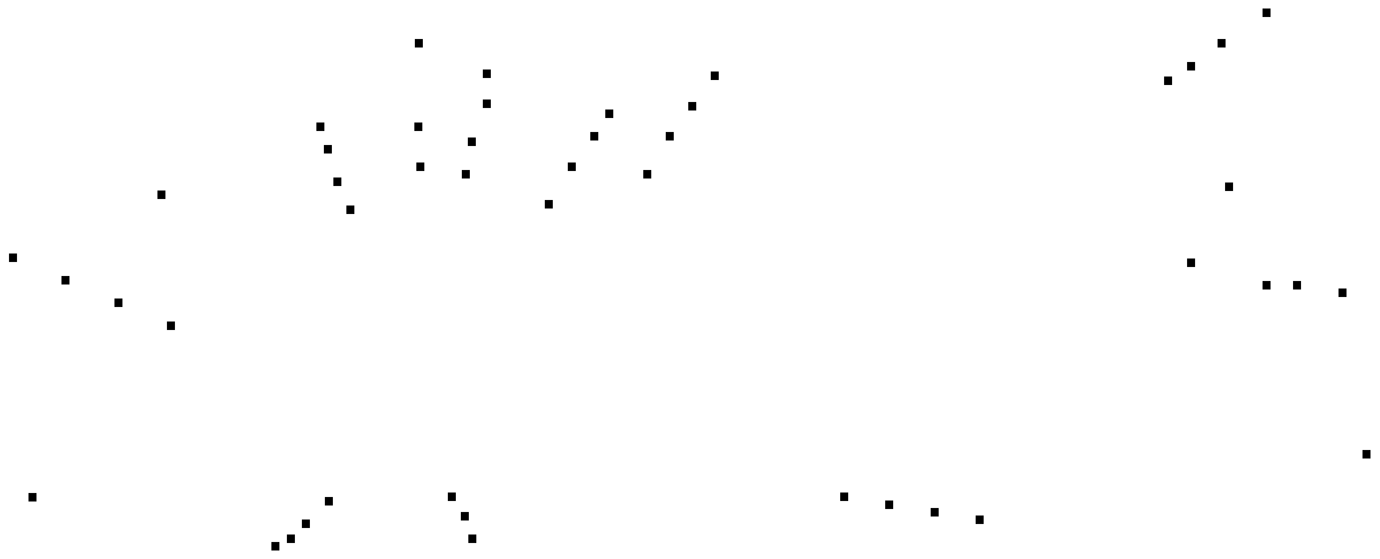
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage



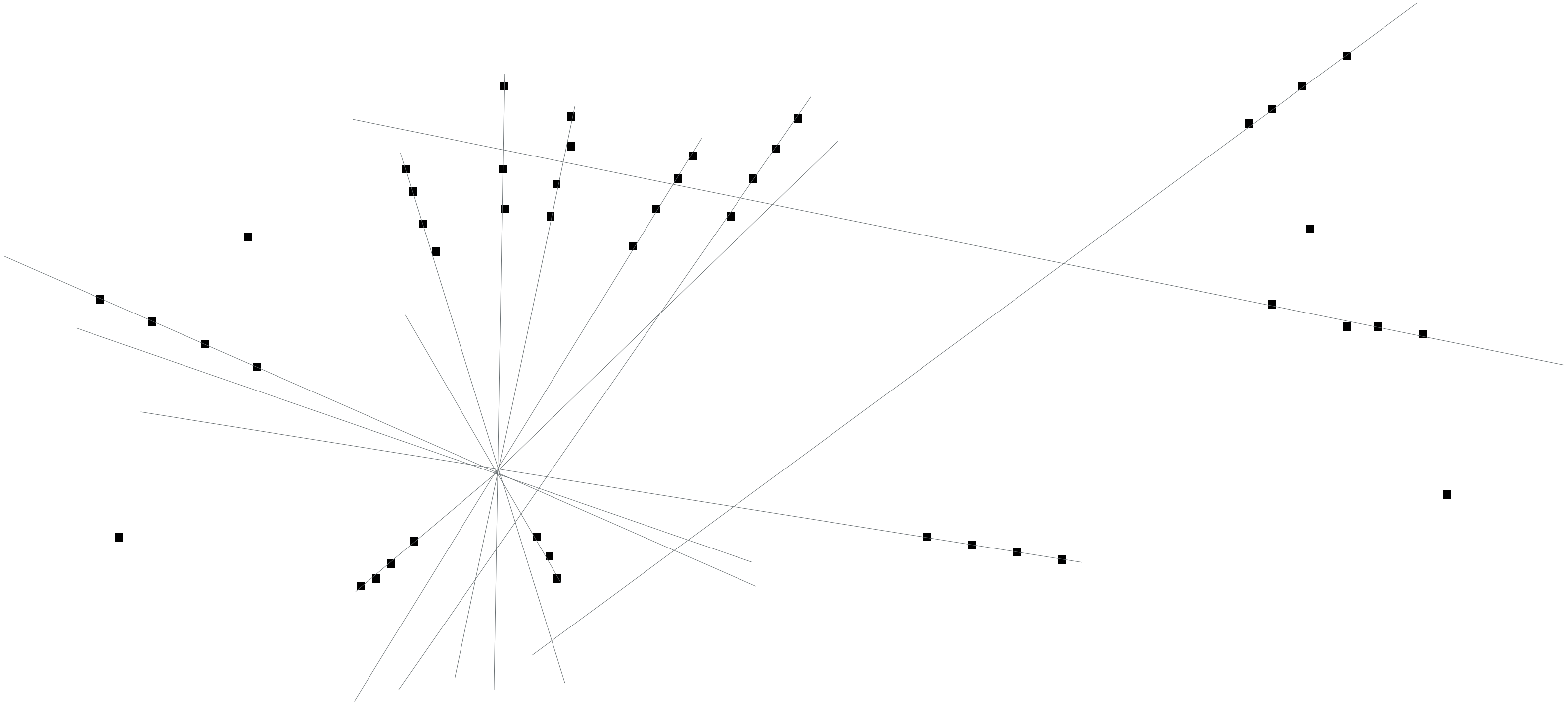
Reconstruction

Tracking : connecting hits



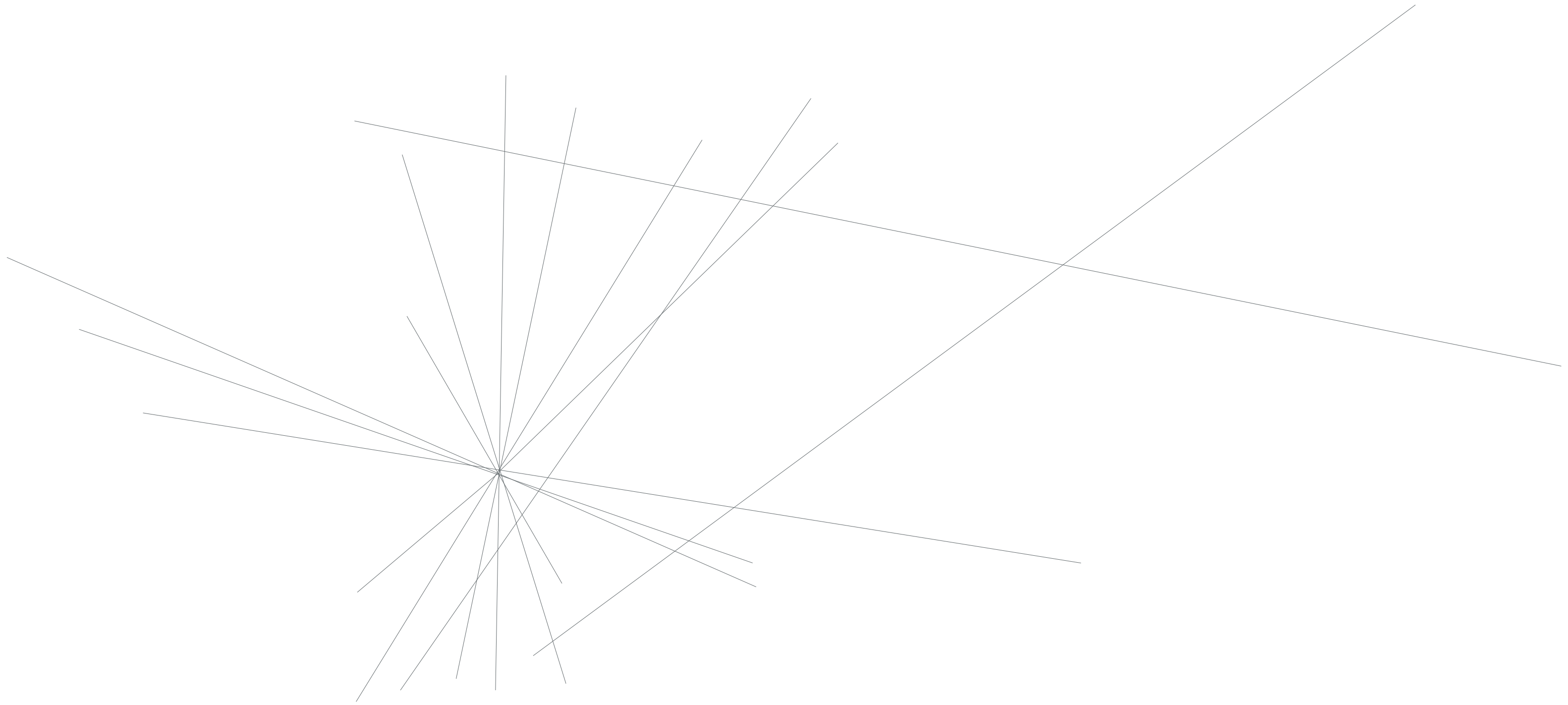
Reconstruction

Tracking : connecting hits to form tracks



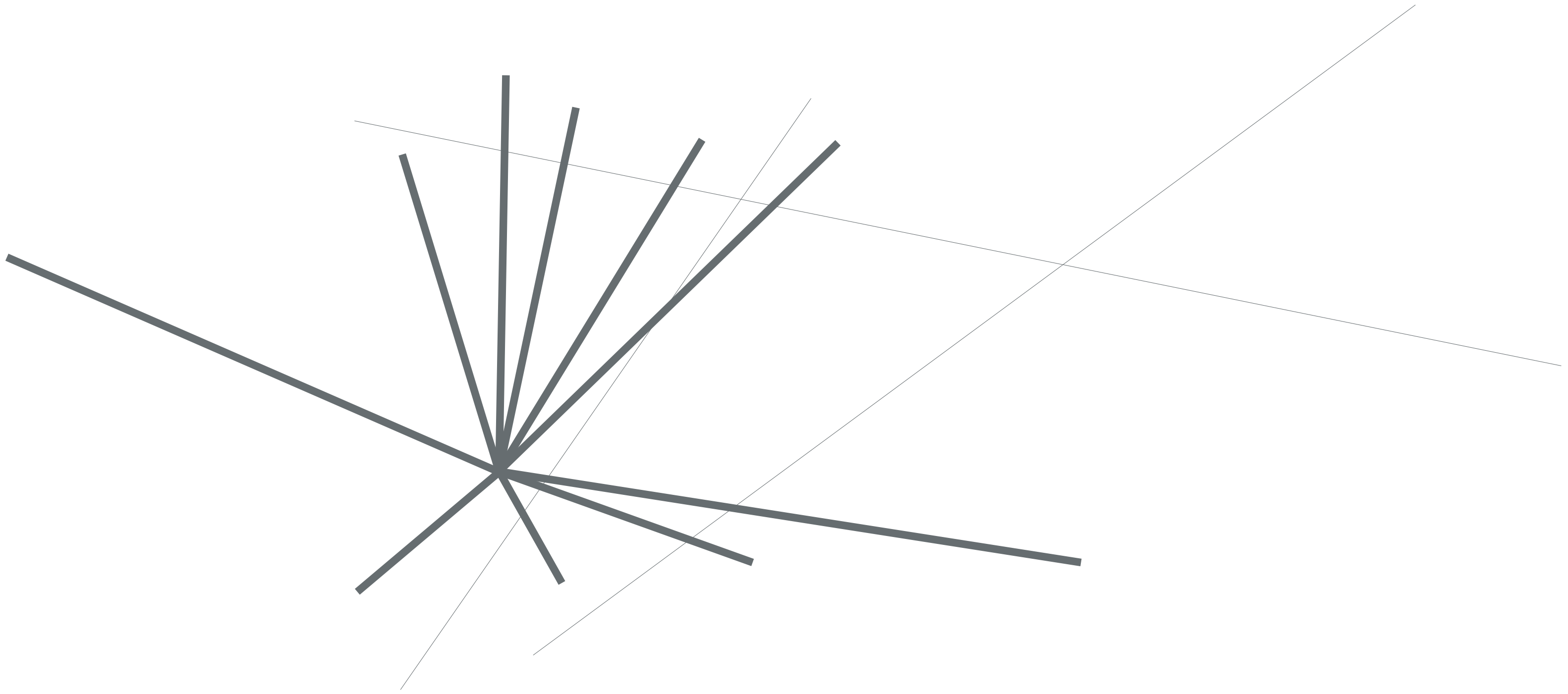
Reconstruction

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

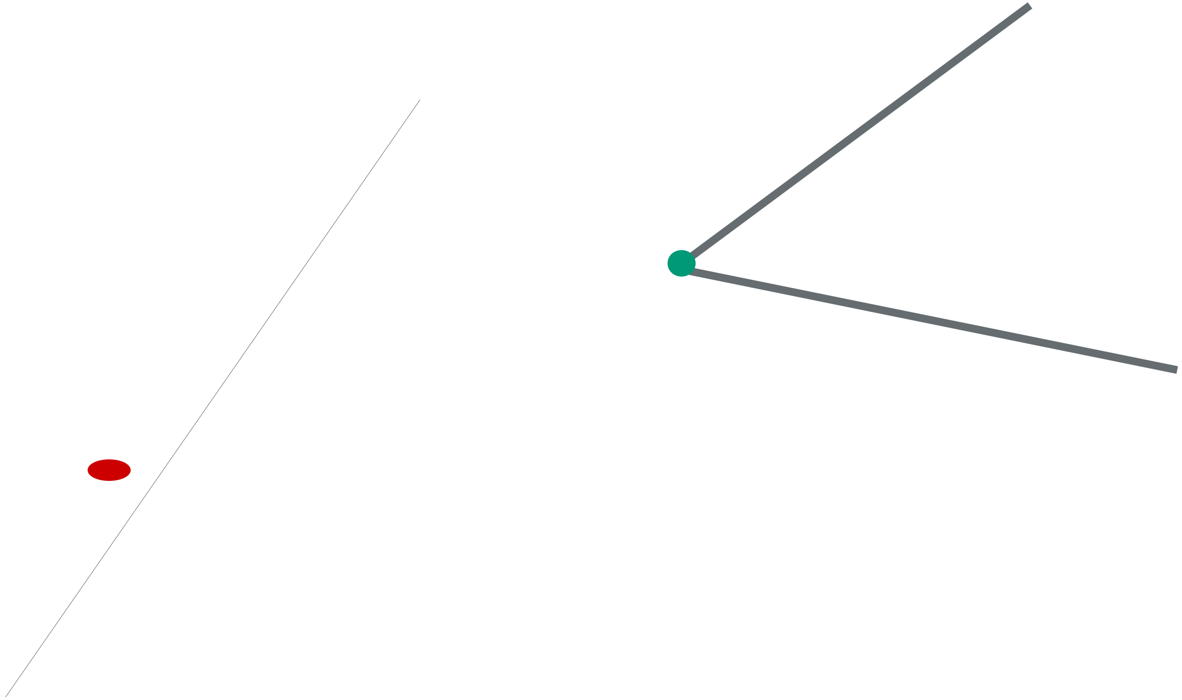


Reconstruction

Find the primary vertex

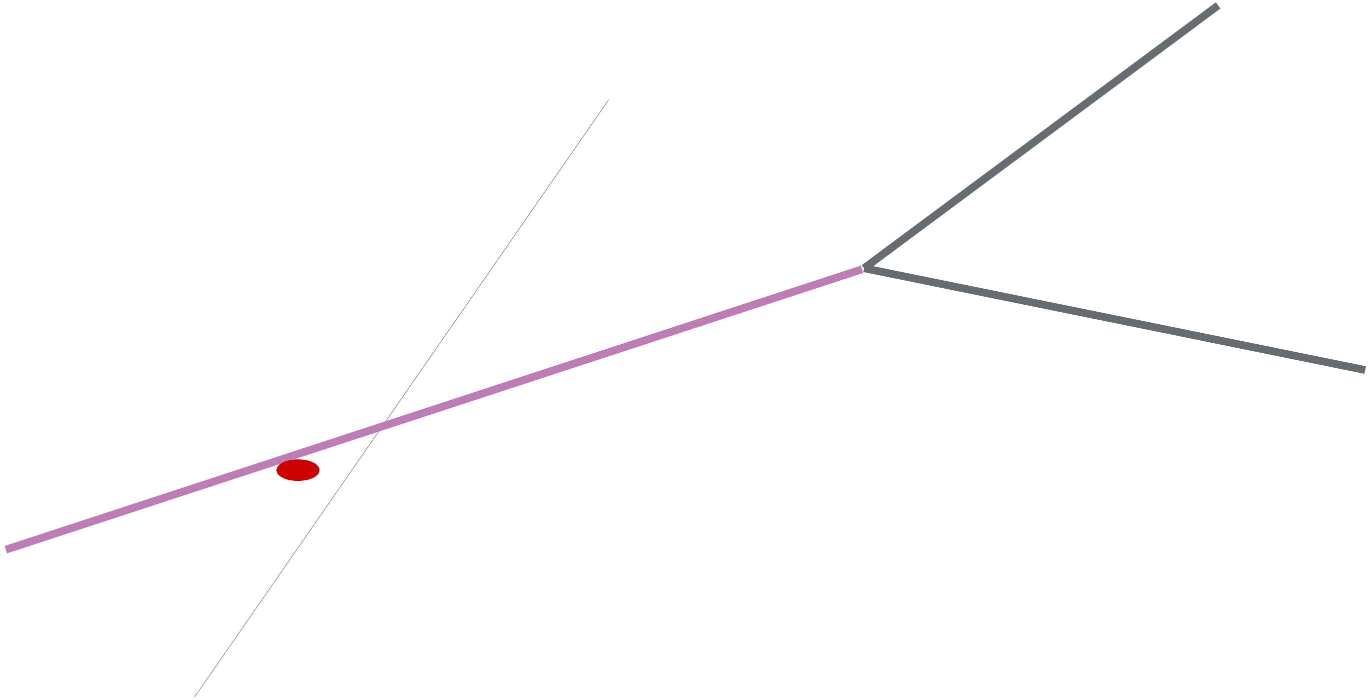
Reconstruction

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



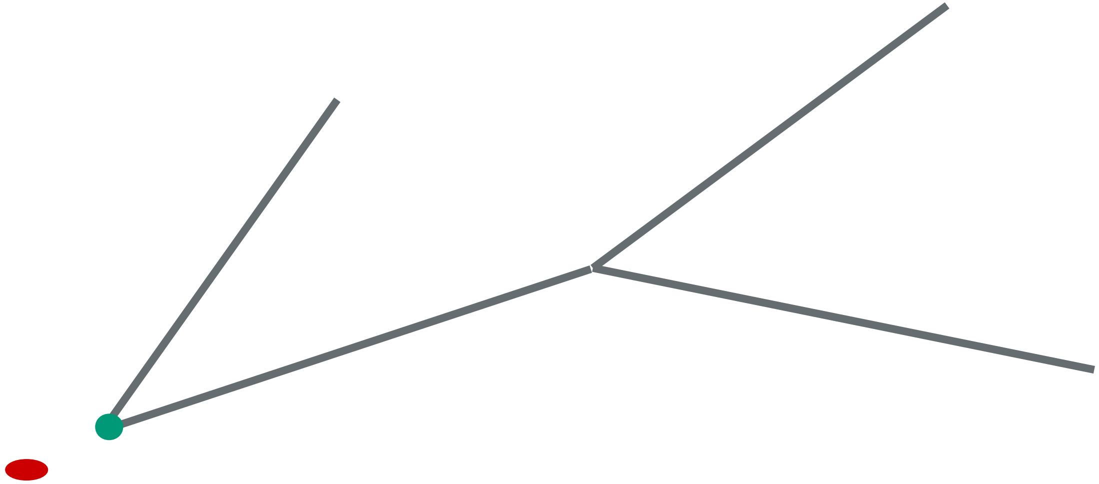
Reconstruction

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



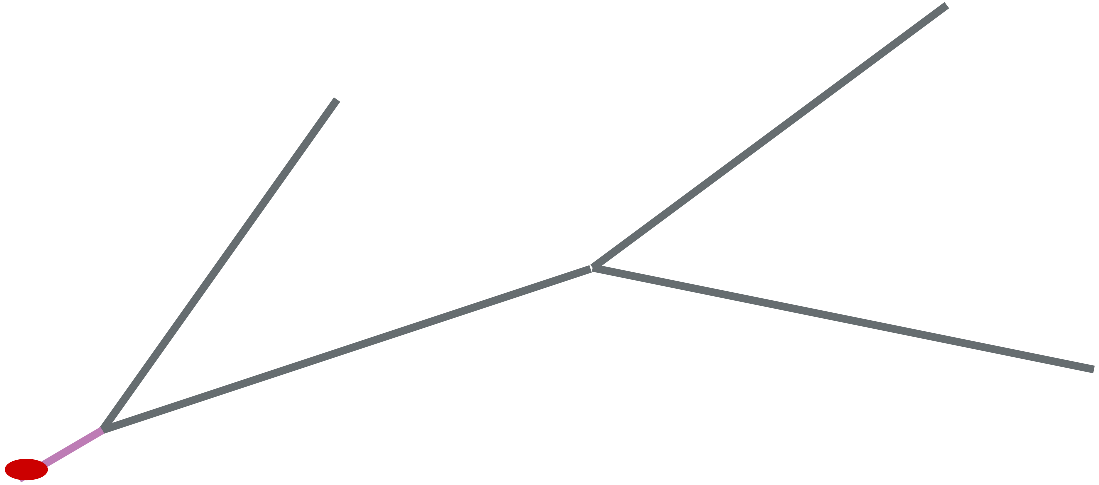
Reconstruction

Find secondary vertex, reconstuct parent track, and repeat



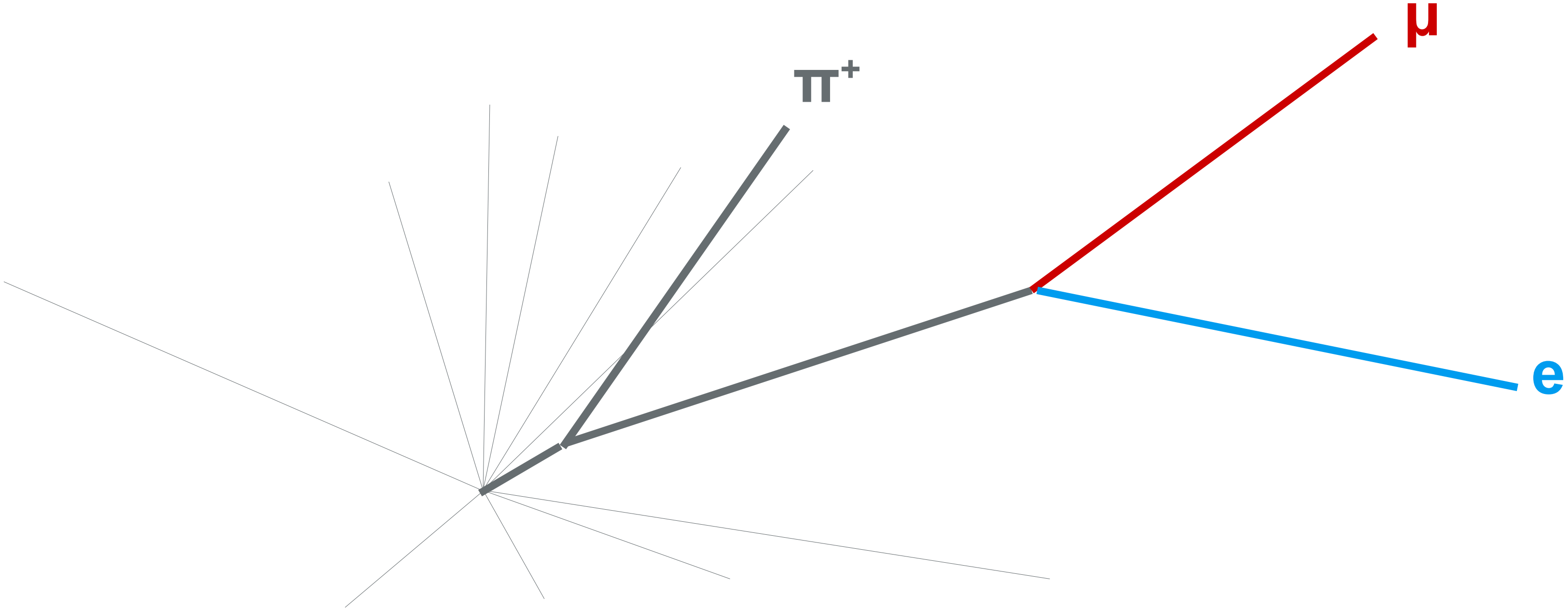
Reconstruction

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

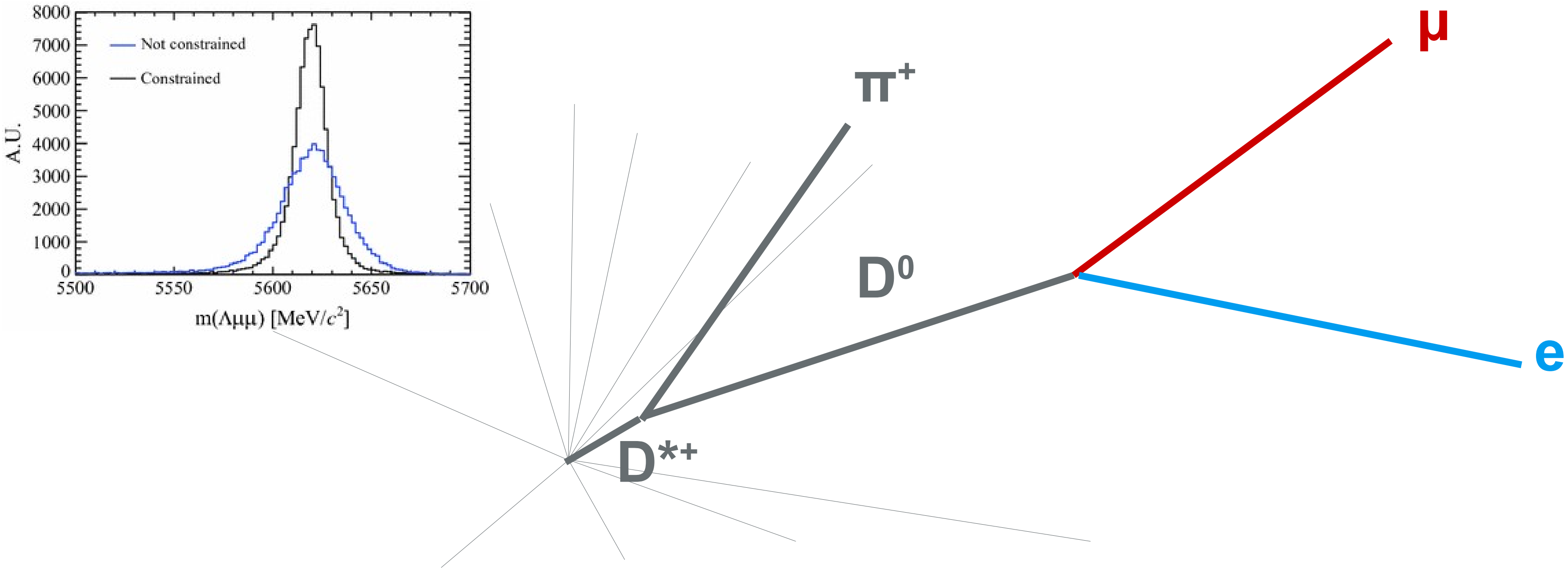


Reconstruction

Identify invisible particles

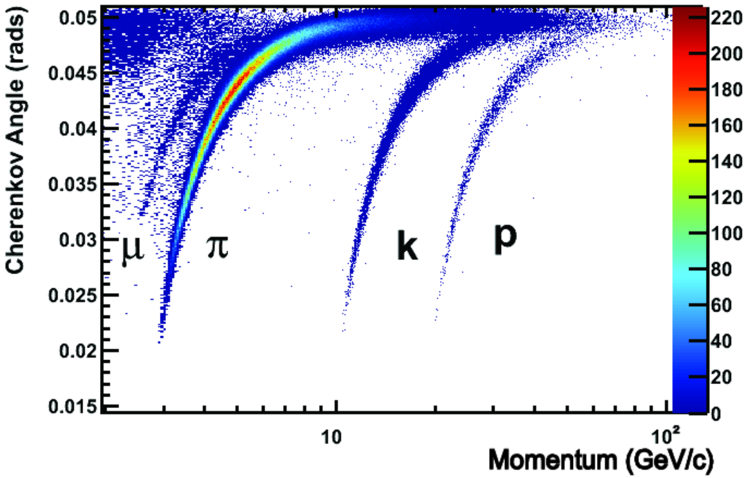
Construct four-momenta of parents, calculate invariant mass, and identify

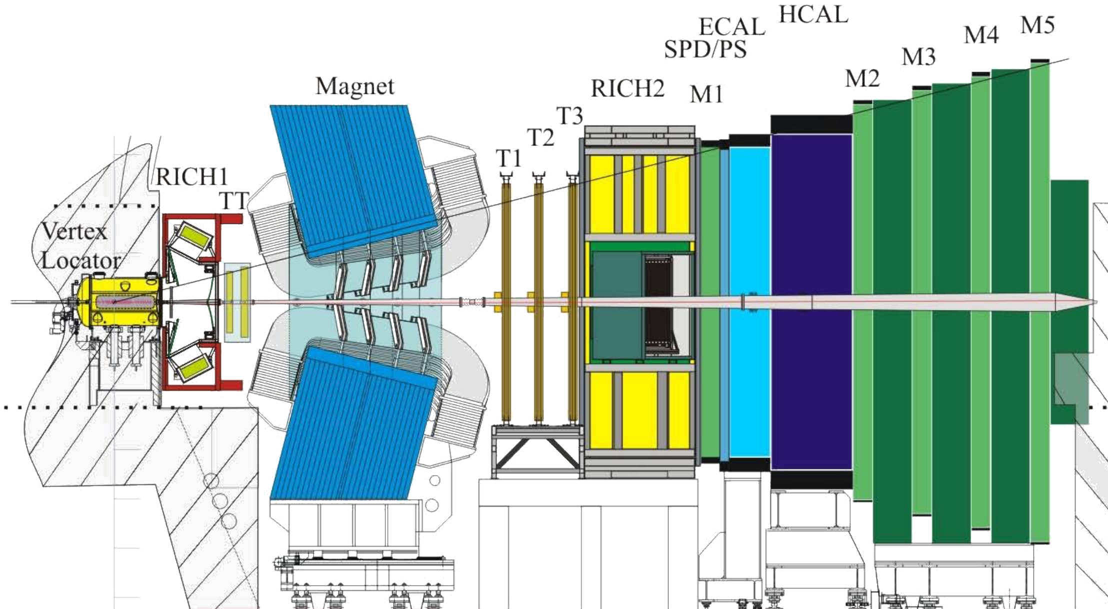
POSSIBLE IMPROVEMENT: refit tracks with perfect vertices and/or parent mass



Challenge #1 : Particle (mis-)ID

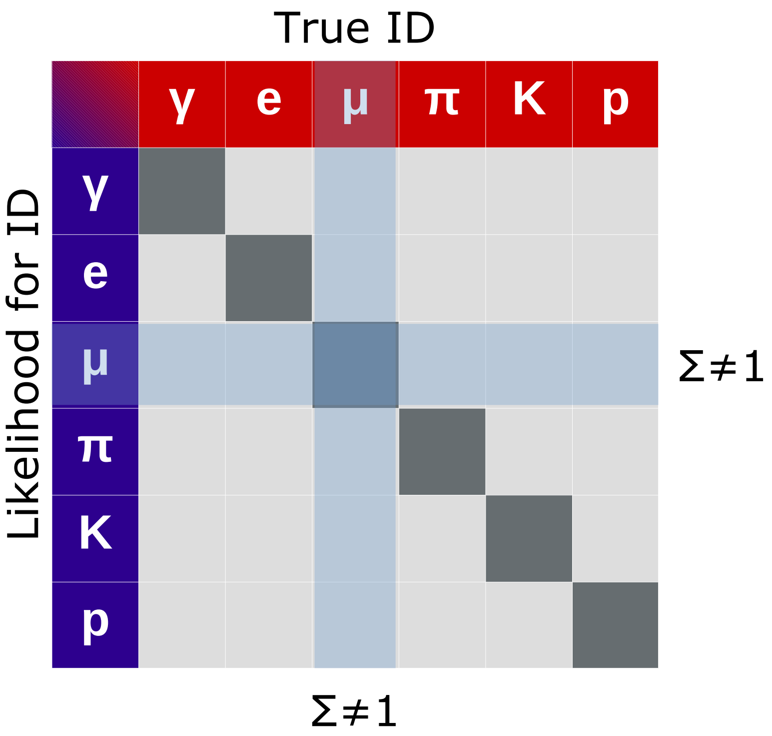
At LHCb all light particles (γ,e,μ,π,K,p) ultra-relativistic, p ≤ 200GeV/*c*
Photons and electron cause similar shower (mostly) in EM calorimeter (**ECAL**)
Photons leave no/little signal in pre-shower detector (**PS**) and trackers (**TT–T3**)
(Essentially) only muons make it to the muon chambers (**M1–M5**)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





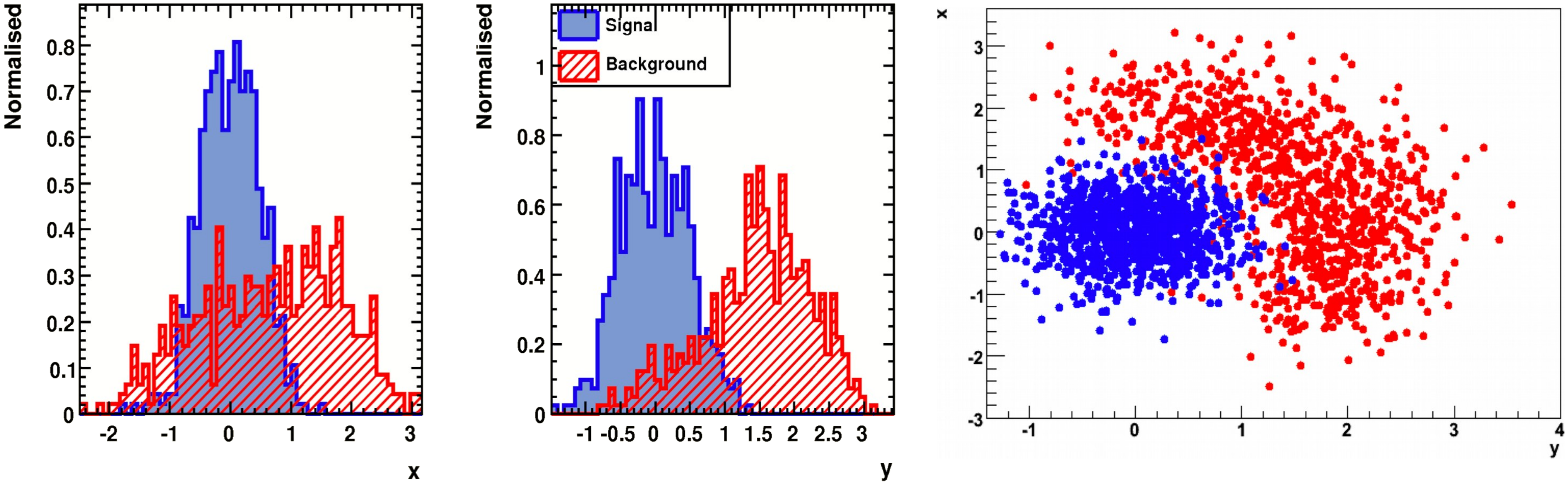
Challenge #1 : Particle (mis-)ID

Particle not uniquely ID'ed
Likelihood per species



(Boosted) decision trees

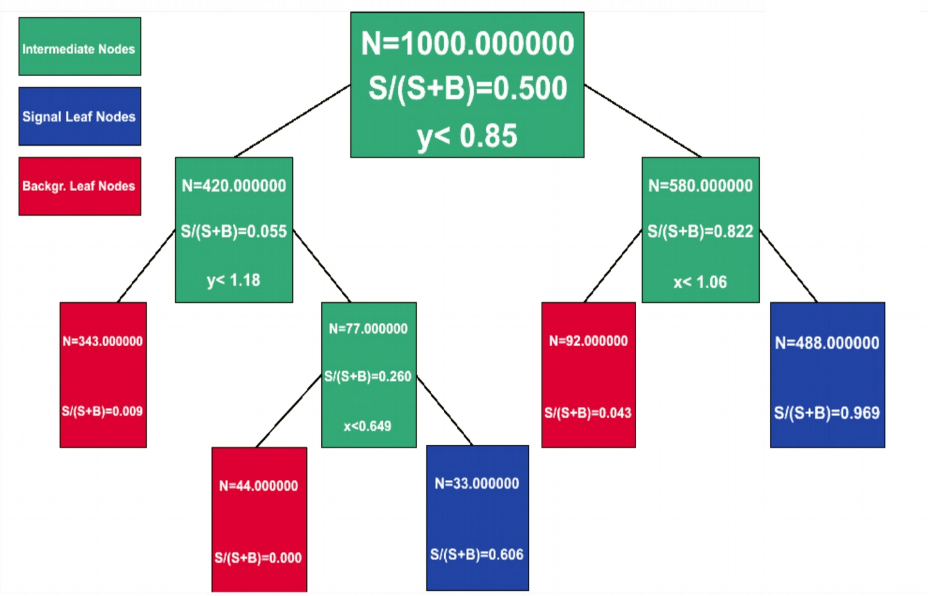
Example: **signal** and **background** measured in 2 detectors **X** and **Y**

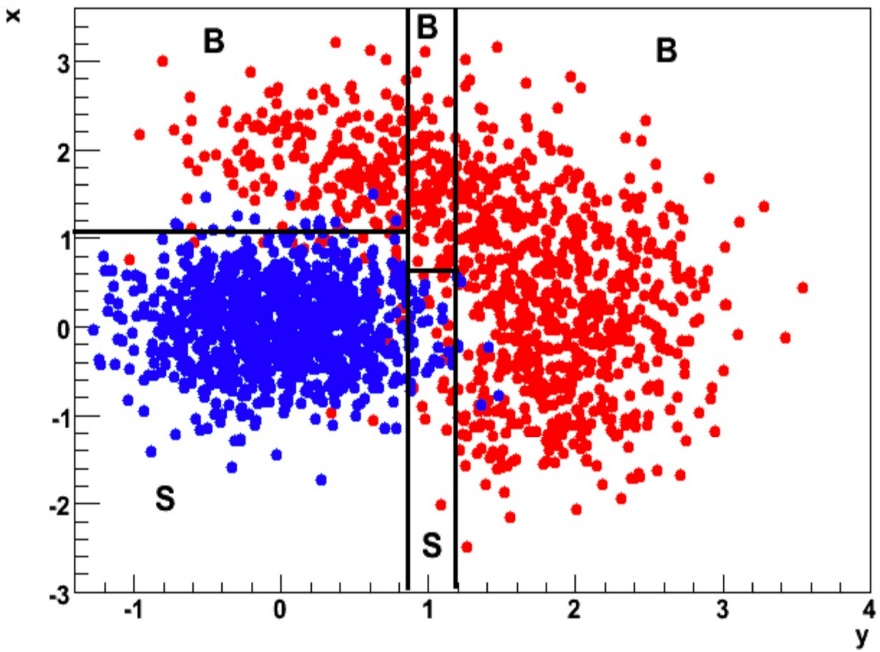


Signal windows has lots of background→ (automatically) optimize selection?

(Boosted) decision trees

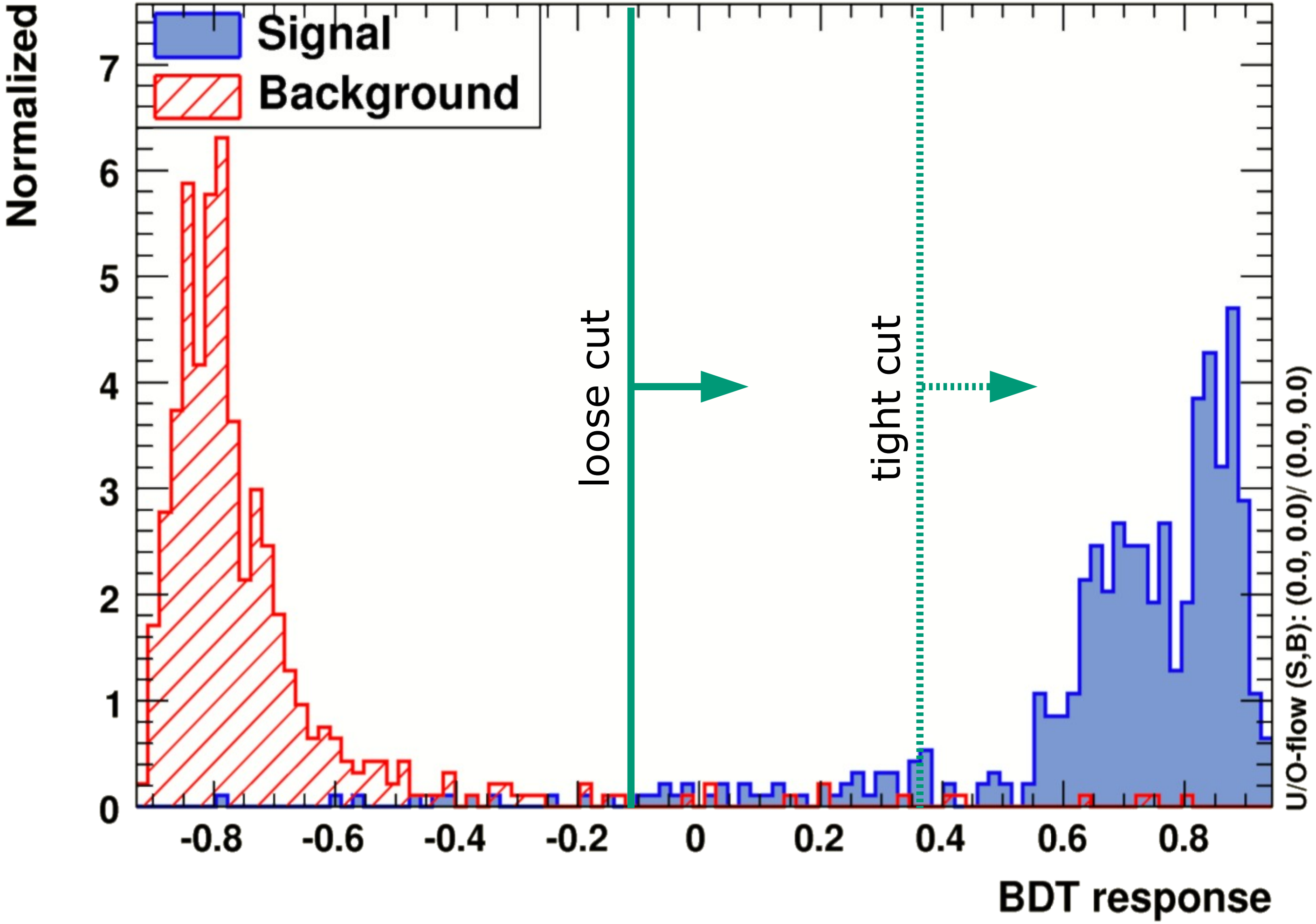
Repeatedly split data in **X** or **Y** to optimize **signal-significance**





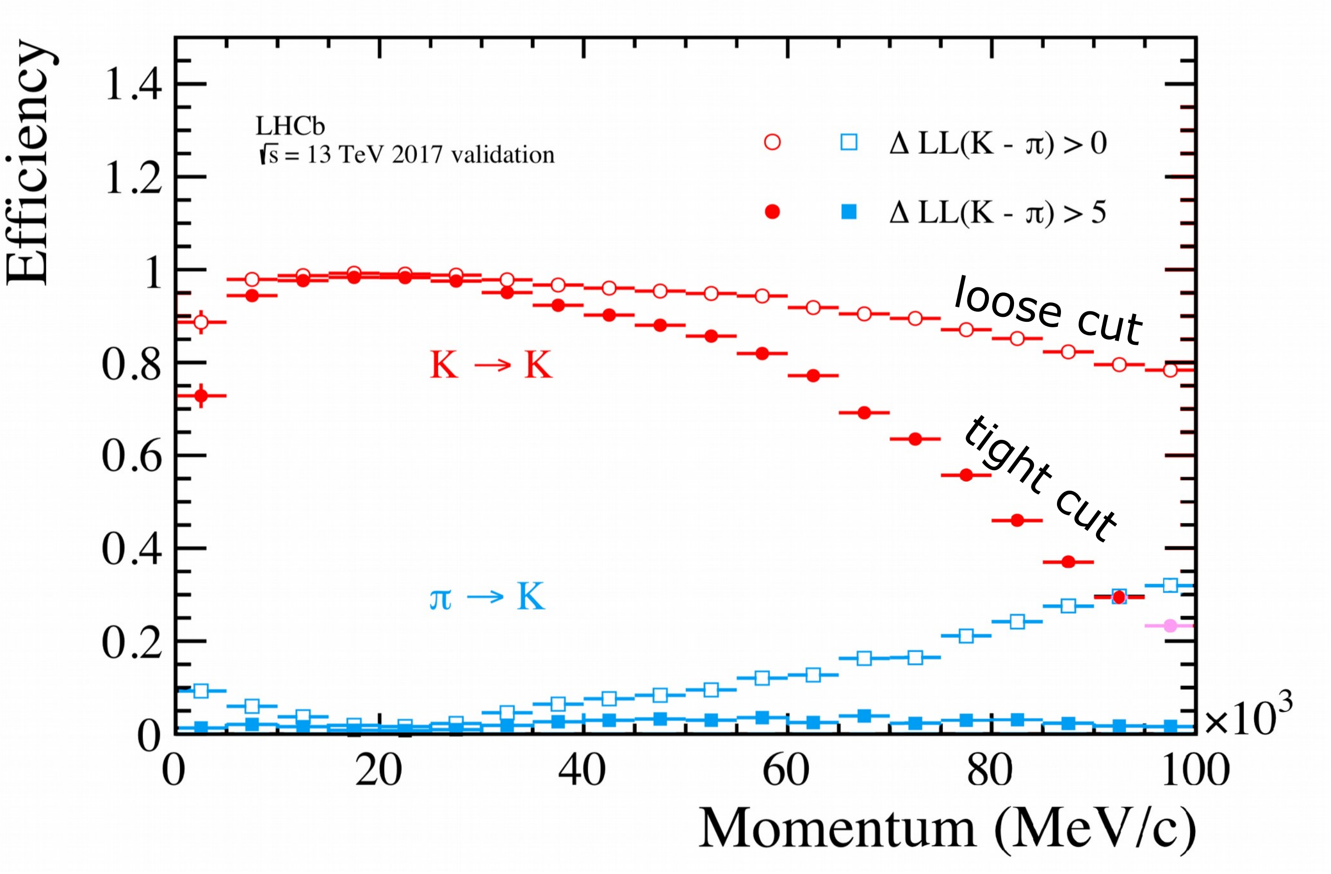
Boosting: take output of DT and re-weight training data for next DT

(Boosted) decision trees



Particle (mis-)ID

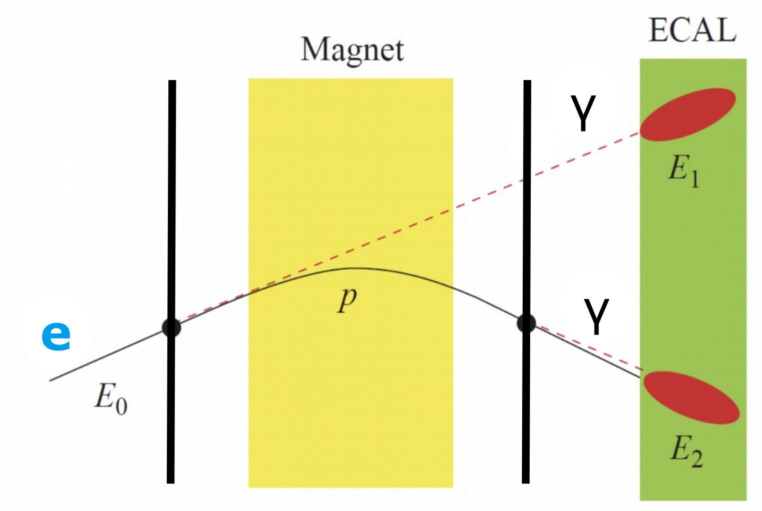
Incorrect inclusion/rejection of event for further analysis → η, λ
Leads to mis-reconstruction of parent mass



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*

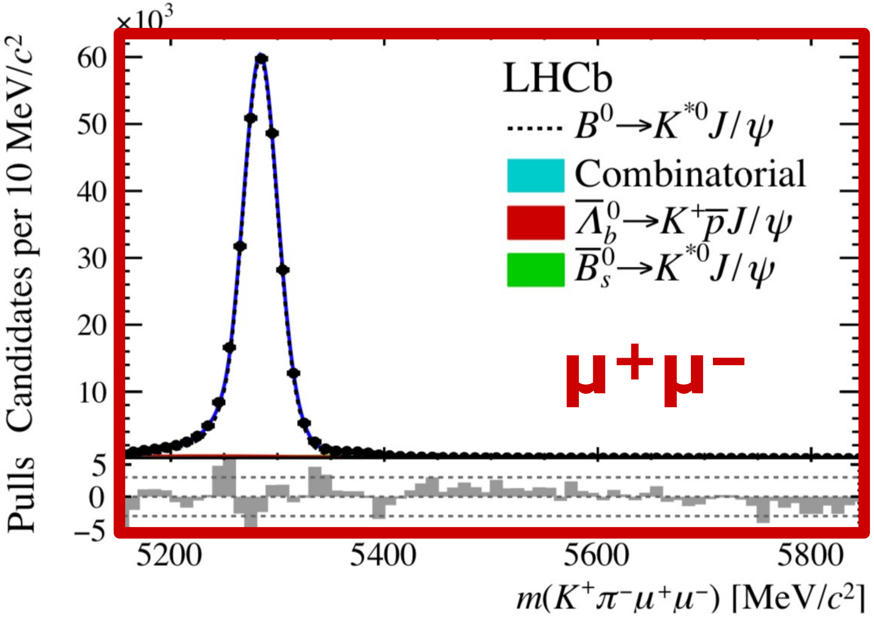
In part automatically recovered, in part to be done by-hand

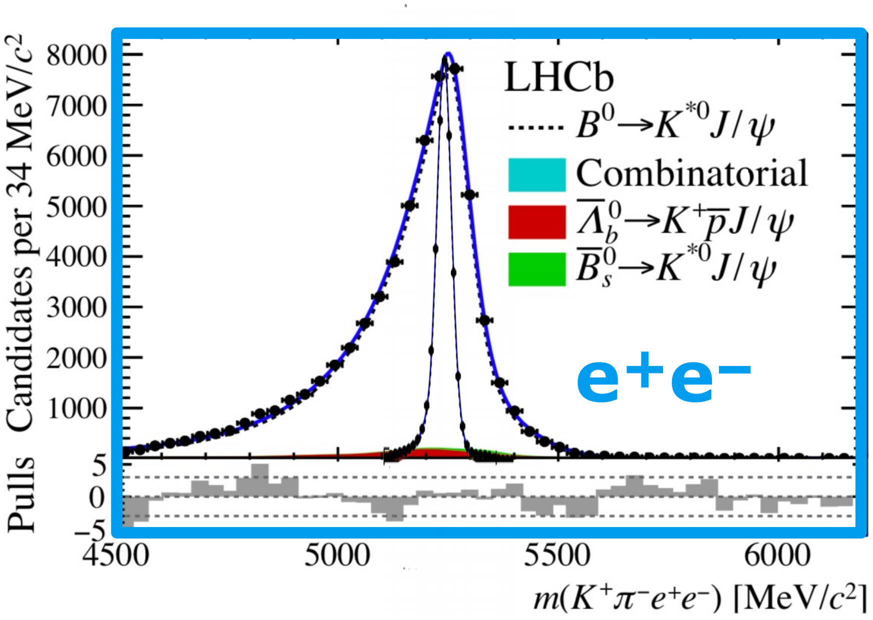


Challenge #2 : Bremsstrahlung

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

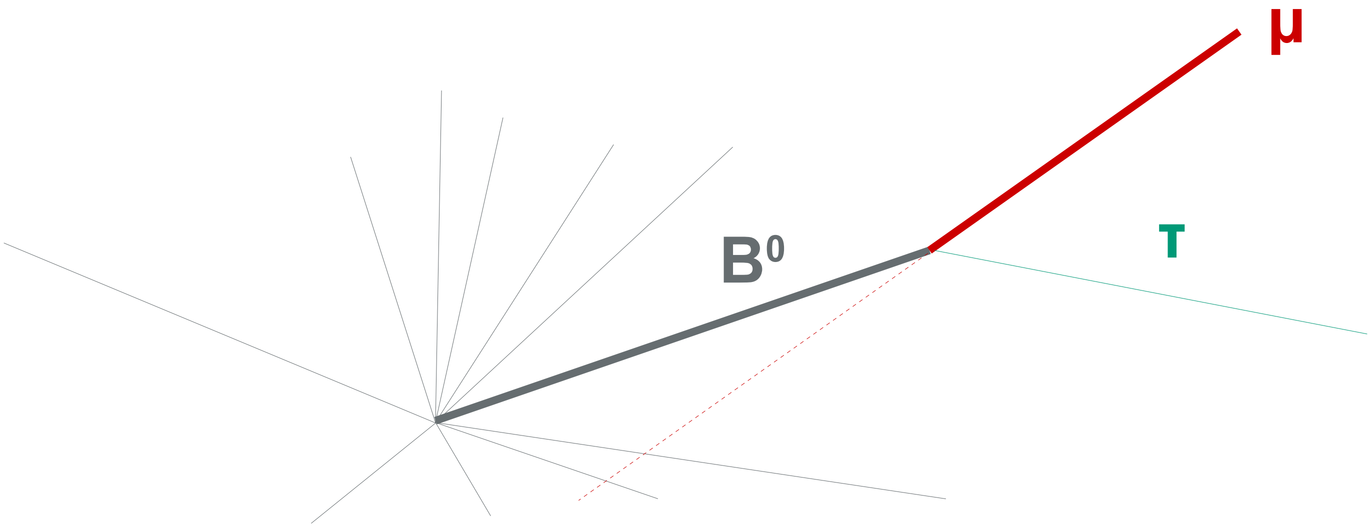
$B^0 \to K^{*0}(K^+\pi^-)\, J/\psi(\ell^+\ell^-)$





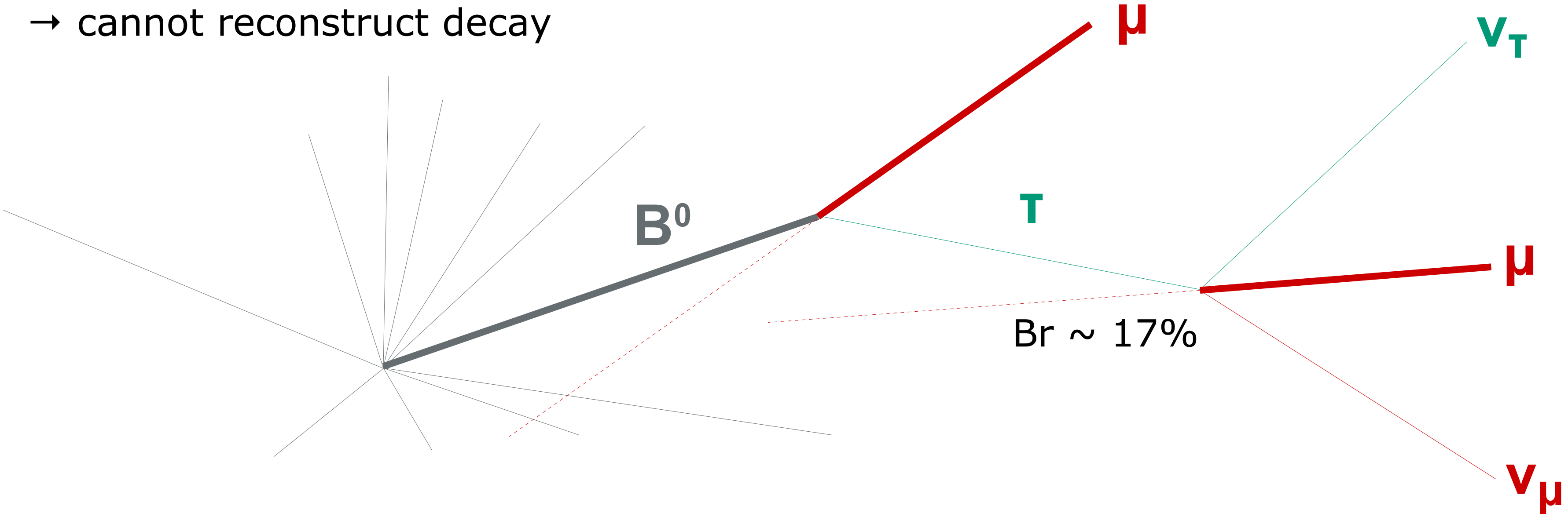
Challenge #3 : Tau-decay

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



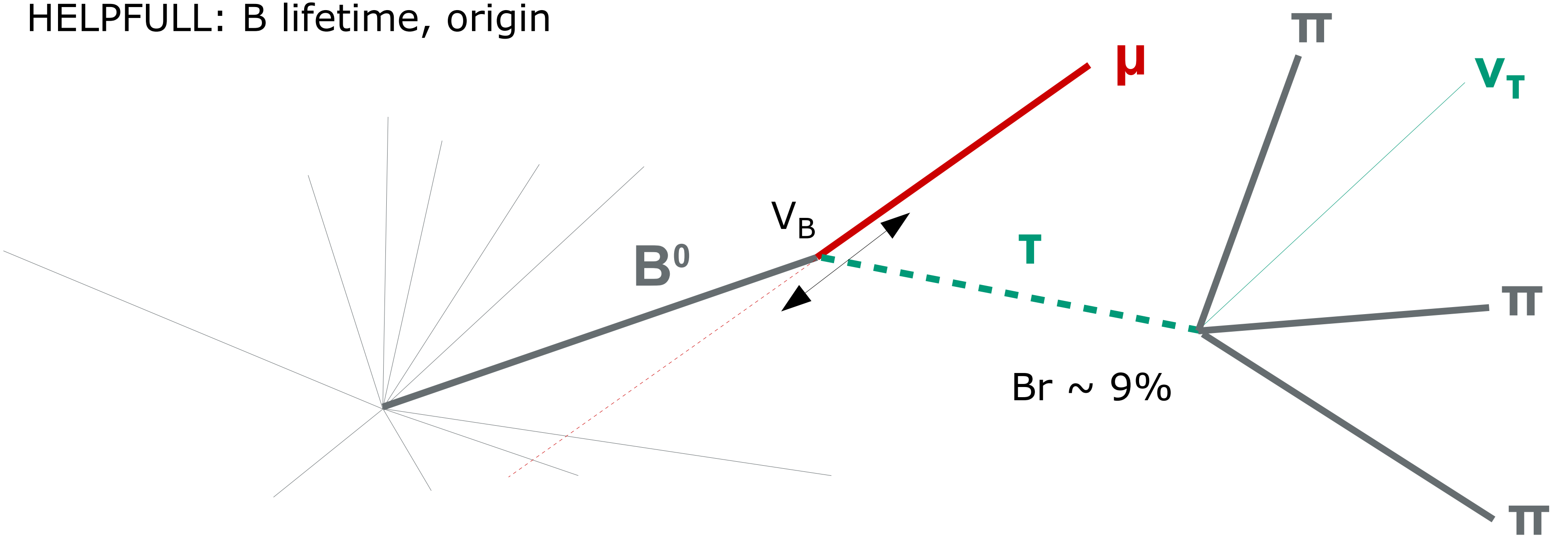
Challenge #3 : Tau-decay

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

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

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

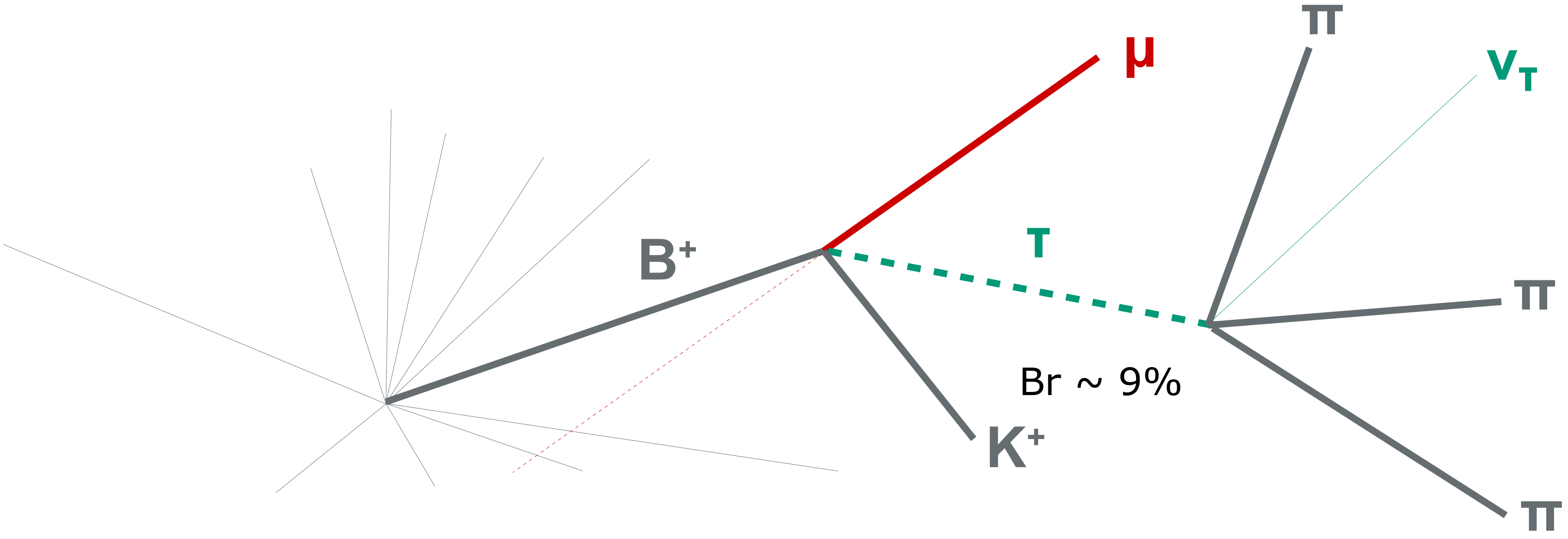
Hadronic decay : only a single missing neutrino
Several charged pions : can reconstruct **tau** decay vertex
PROBLEM: B decay vertex along **μ** track unknown
HELPFULL: B lifetime, origin



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

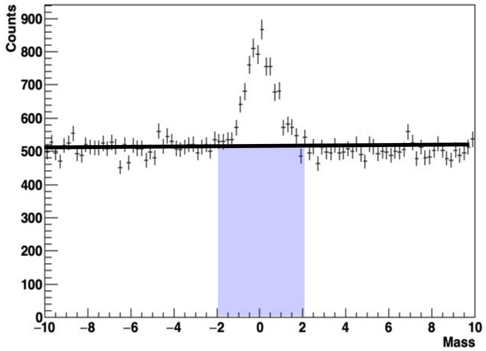


$p_\perp(\mathbf{v})$ and $p_\llcorner(\mathbf{v})$ determined by $p(\mathbf{3\pi})$, but still need to find $p_\parallel(\mathbf{v})$
SOLUTION: could fix **tau** mass and check B mass or v.v.

Signal & Background

Signal

Important S vs B selection criterium : Invariant Mass of Parent
Reconstructed from directly detected particles

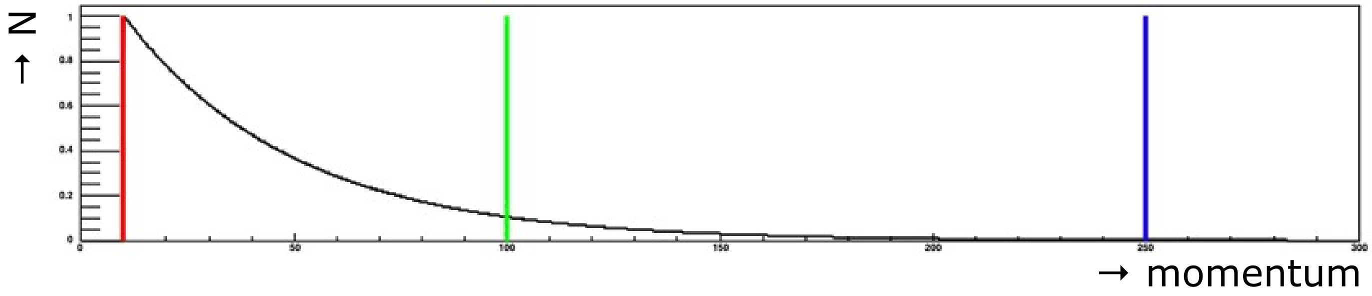


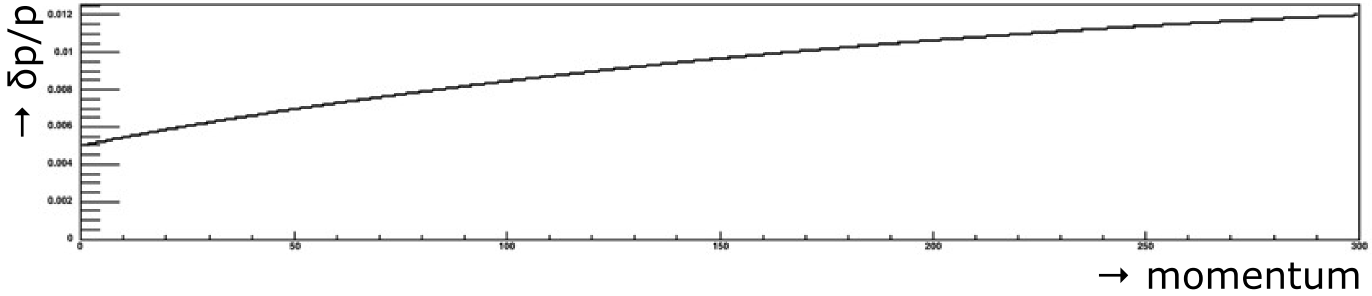
Reminder: signal significance
$\rho \equiv S/\sigma(S) = \eta S/\sqrt{(\eta S+\mathbf{k}'\cdot\boldsymbol{\lambda}\cdot B)} \approx \eta S/\sqrt{(\mathbf{k}'\cdot\boldsymbol{\lambda}\cdot B)} \approx \eta/\sqrt{(\mathbf{k}'\cdot\boldsymbol{\lambda}\cdot B)}$

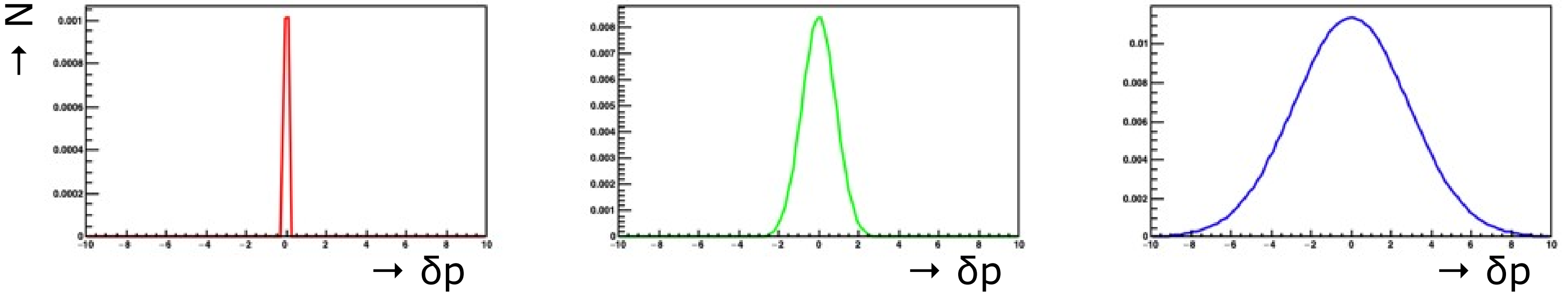
Some observations
Narrower window has less background B
→ work hard to get best possible resolution
Signal window or fitting range depends on *peak shape*
Shape not trivial, *i.e.* not Gaussian
→ *relative* momentum resolution is mostly constant
cLFV has no visible peak that can be fit
→ need to determine shape beforehand

Fix signal shape and fit amplitude to set limit

Signal Peak Shape

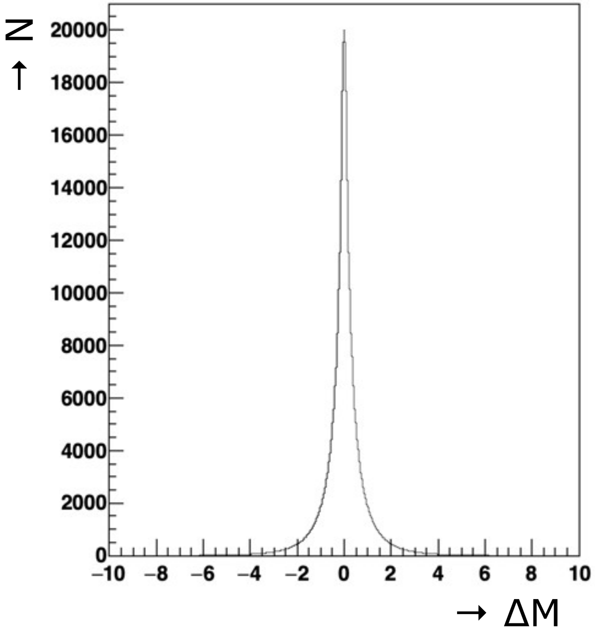


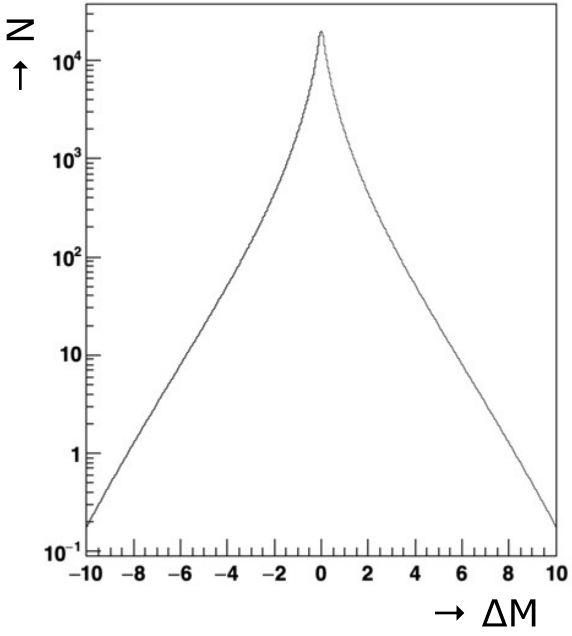




Signal Peak Shape

Resulting invariant mass distribution = sum of Gaussians
Shape depends on (distribution of) momenta of child-particles
Shape depends on (distribution of) angles between momenta
Shape depends on (illuminated part of) detector acceptance

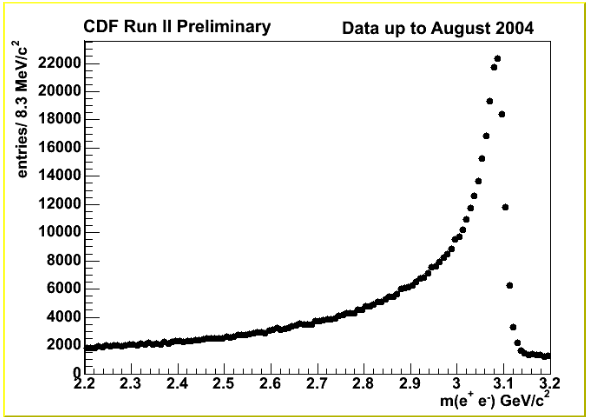




Signal Peak Shape

Dealing with Bremsstrahlung
Incorporate energy lost via photon
Requires photon energy distribution
→ material traversed by electron
→ physics behind bremsstrahlung
→ via modelling or calibration channel

Crystal Ball function
Parametrizes lossy processes
Nasty to fit



The Crystal Ball function is given by:

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \leqslant -\alpha \end{cases}$$

where

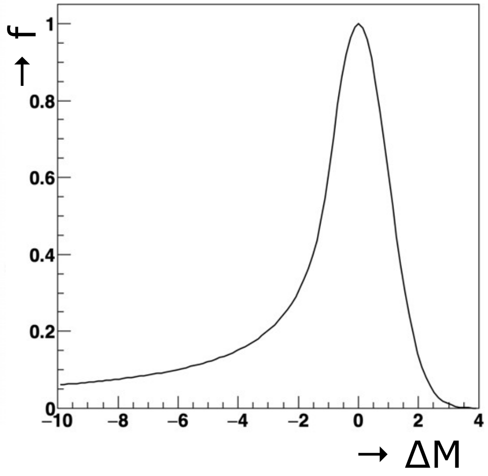
$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

$$N = \frac{1}{\sigma(C+D)},$$

$$C = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

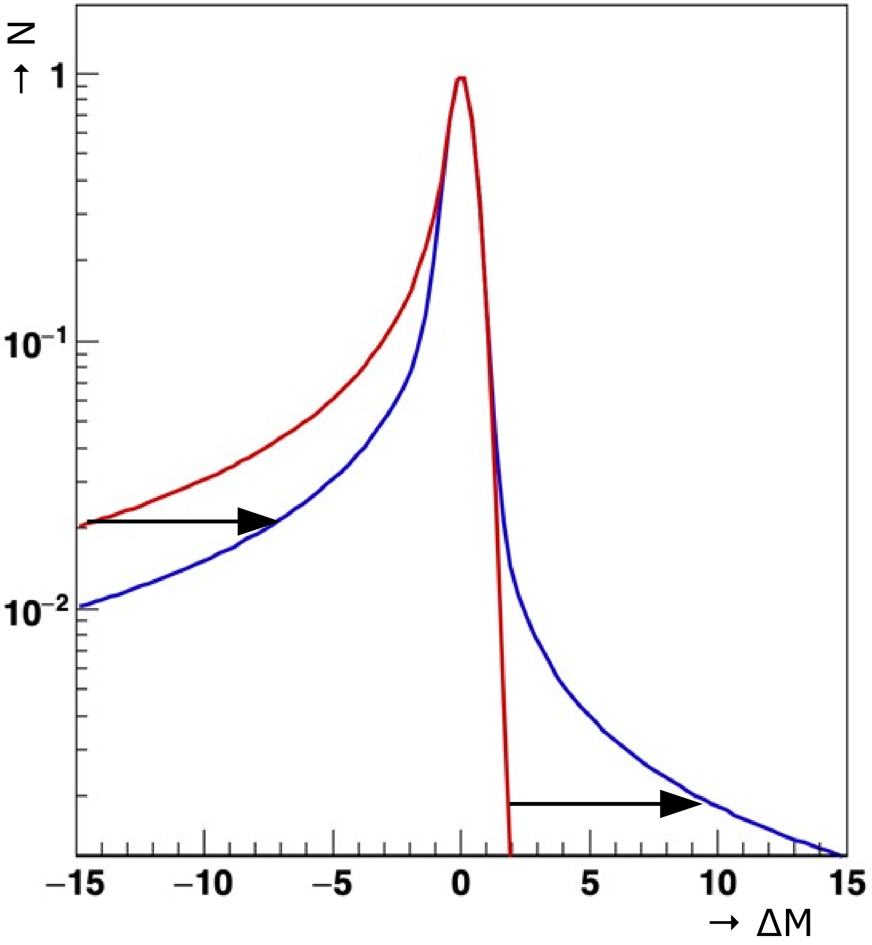
$$D = \sqrt{\frac{\pi}{2}}\left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right).$$



Signal Peak Shape

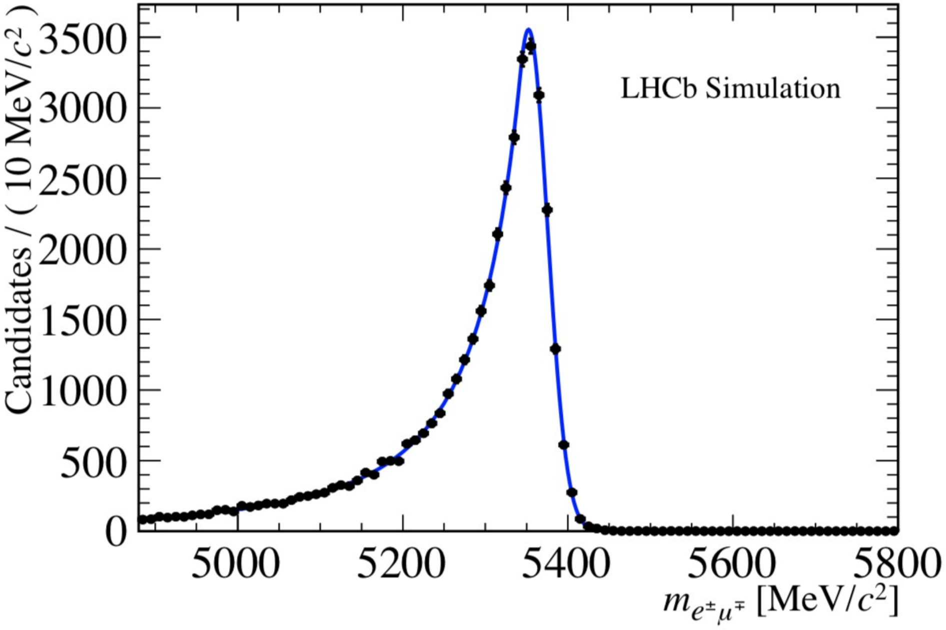
Photon recovery
Reduces low-end tail
→ when photon correctly added
Introduces high-end tail
→ when photon incorrectly added

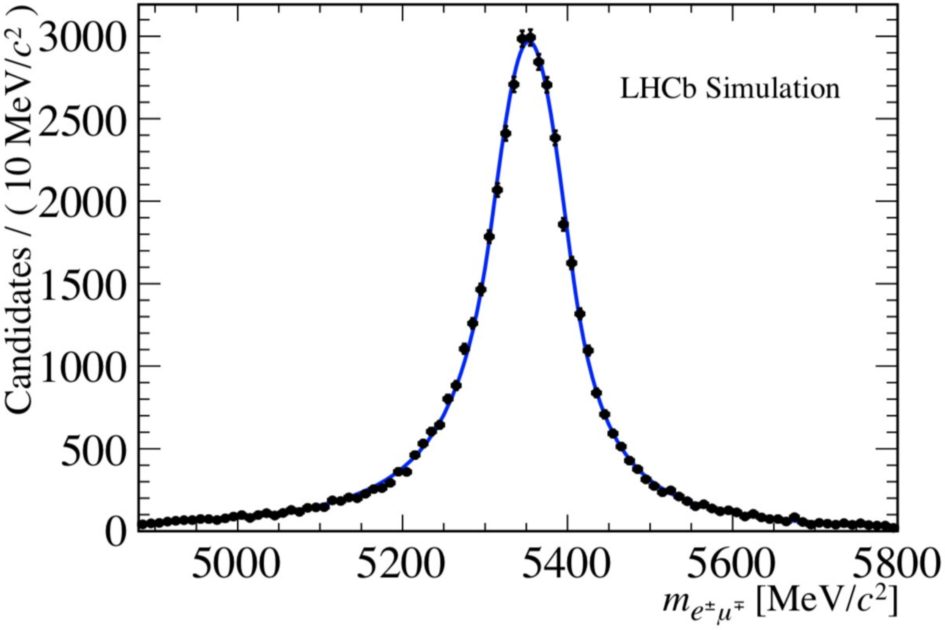
Overal width decreases



Signal Peak Shape

Simulation of $B_s \to e\mu$





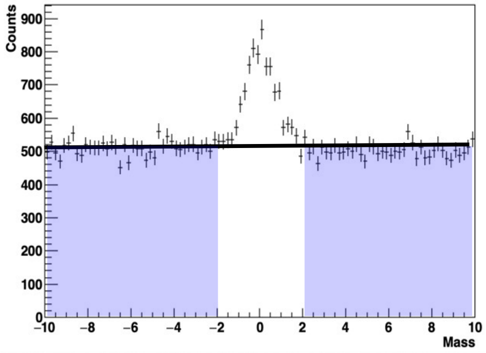
Background

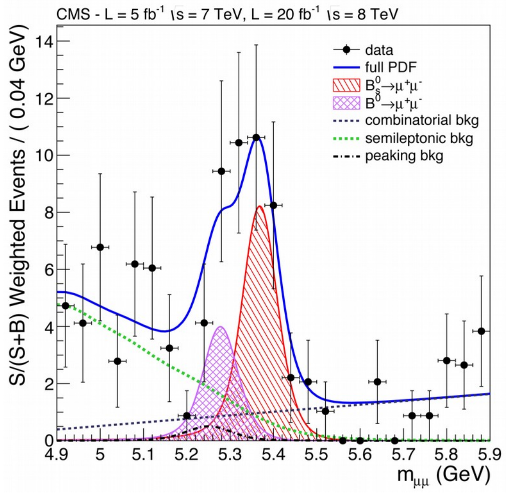
Important S vs B selection criterium : Invariant Mass of Parent
Reconstructed from directly detected particles

Reminder: signal significance
$\rho \equiv S/\sigma(S) = \eta S/\sqrt{(\eta S+\mathbf{k'}\cdot\boldsymbol{\lambda}\cdot B)} \approx \eta S/\sqrt{(\mathbf{k'}\cdot\boldsymbol{\lambda}\cdot B)} \approx \eta/\sqrt{(\mathbf{k'}\cdot\boldsymbol{\lambda}\cdot B)}$

Some observations
Independent determination of B requires “room in tails”
→ need to understand background shape

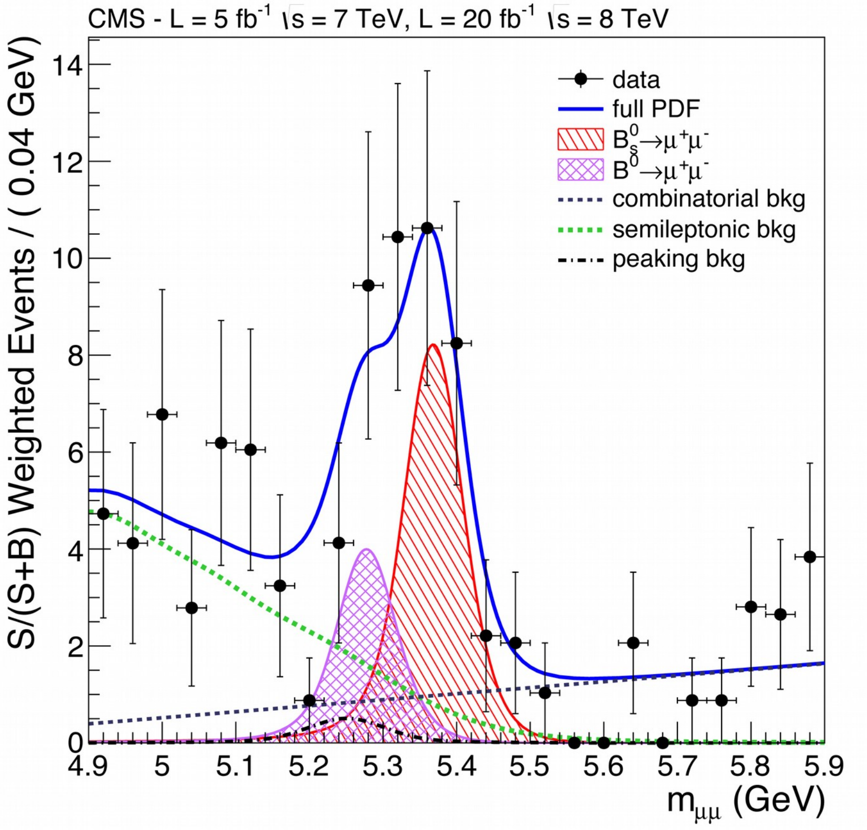
Types of background
- ▸ Peaking
- ▸ Semi-peaking
- ▸ Smooth





Peaking Background

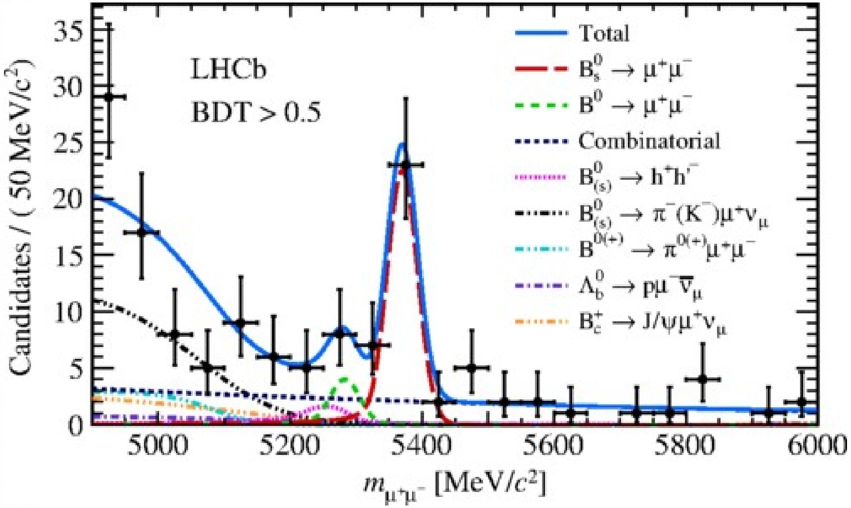
Due to another parent with similar mass



Example:

B^0 → $\mu\mu$ m(B^0)=5280 MeV

B_s^0 → $\mu\mu$ m(B_s^0)=5367 MeV



Peaking Background

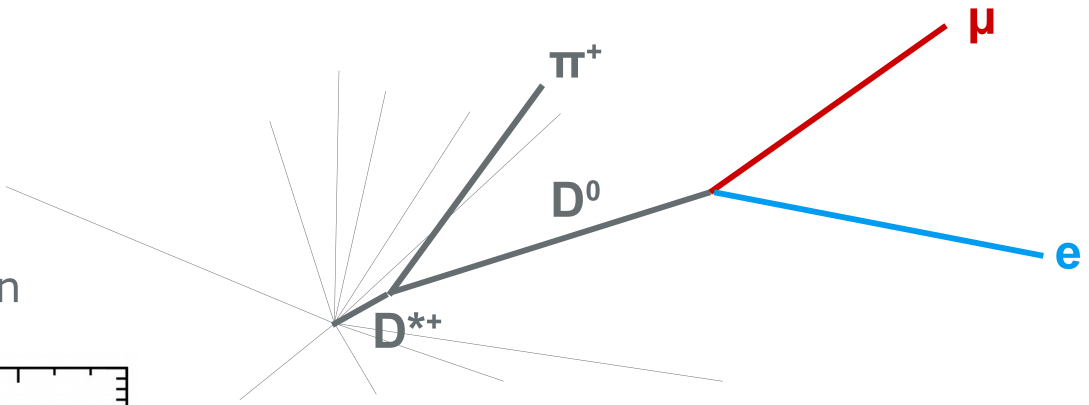
Due to mis-ID

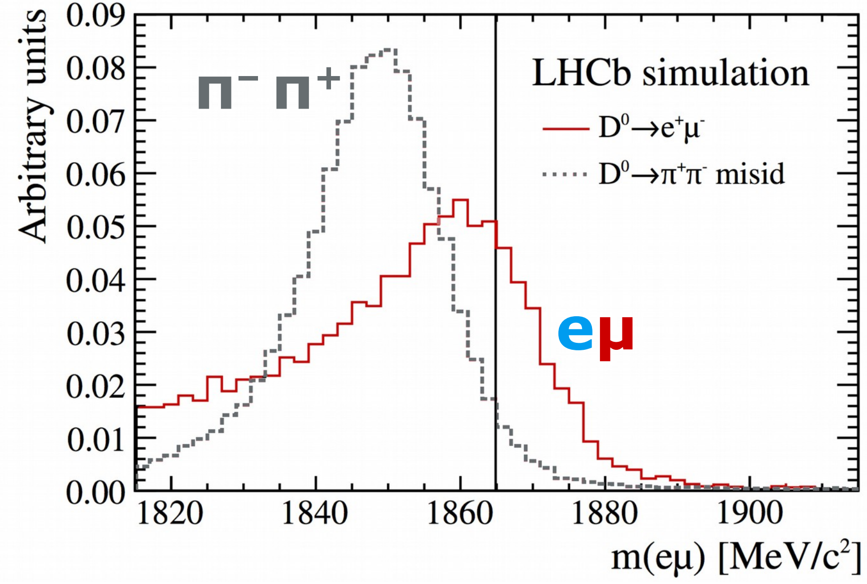
Example

$D^{*+} \rightarrow D^0 \pi^+$

↳ $D^0 \rightarrow e\mu$ Signal

↳ $D^0 \rightarrow K^- \pi^+$ Normalization

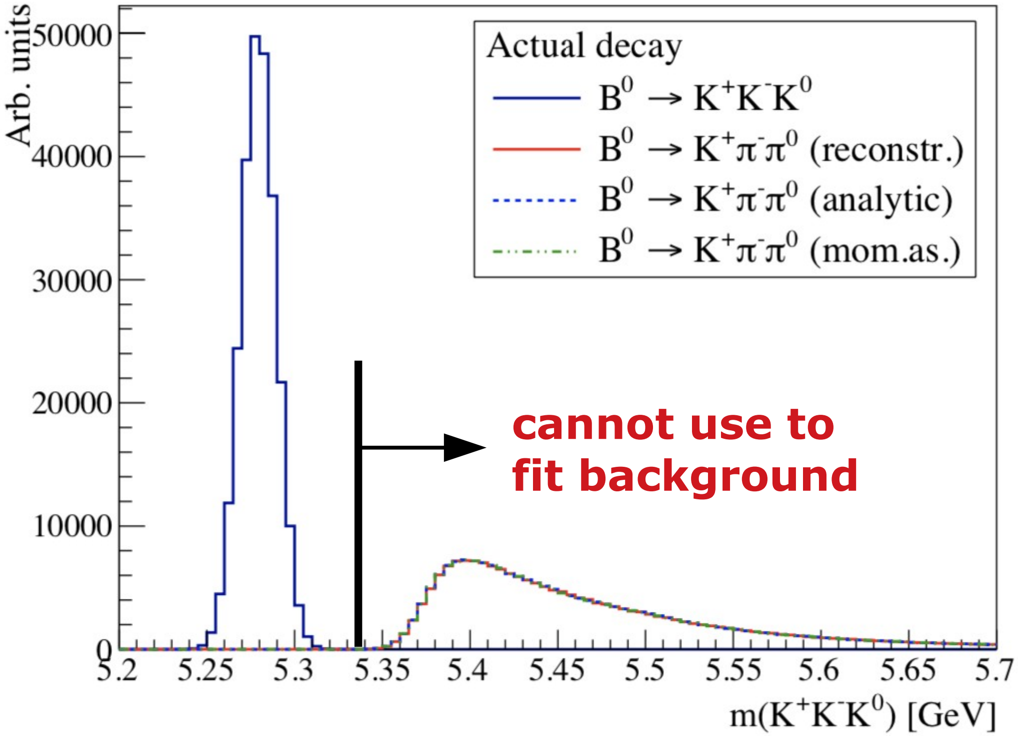




Probability for
$\pi^+\pi^- \rightarrow e\mu$ mis-ID
$\sim (1\text{–}2)\times10^{-8}$

(Semi-)Peaking Background

Mis-ID events mostly shift away from peak
Cannot use high-mass side for background determination
i.e. without knowing/fitting the shape



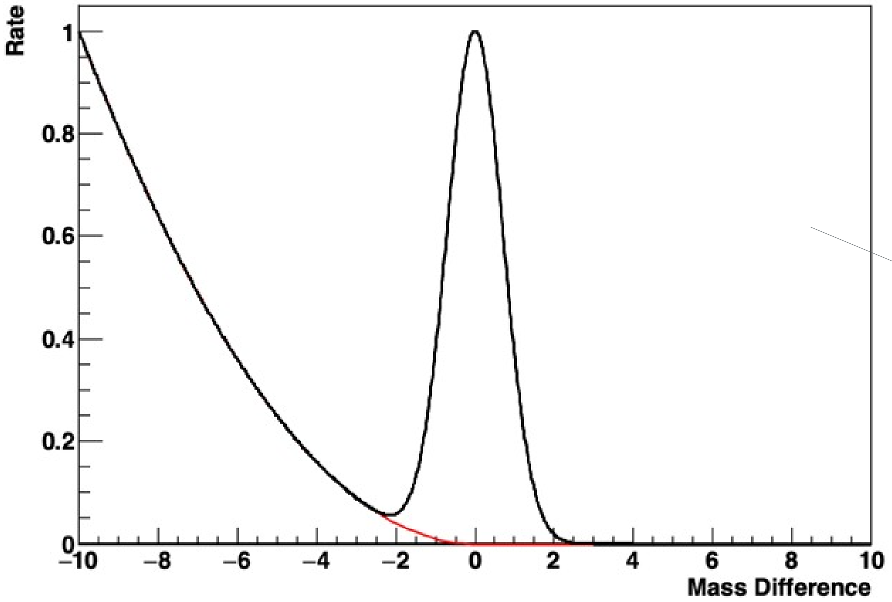
cannot use to fit background

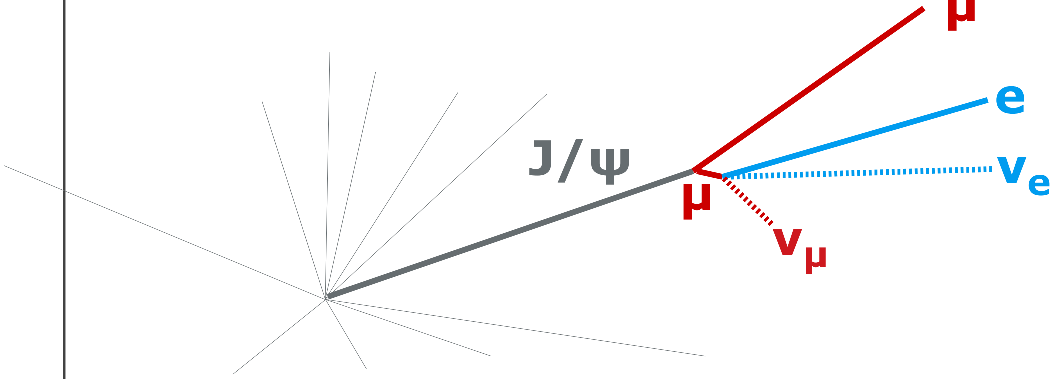
Semi-Peaking Background

Typically due to reaction with one or more missing particles

Example

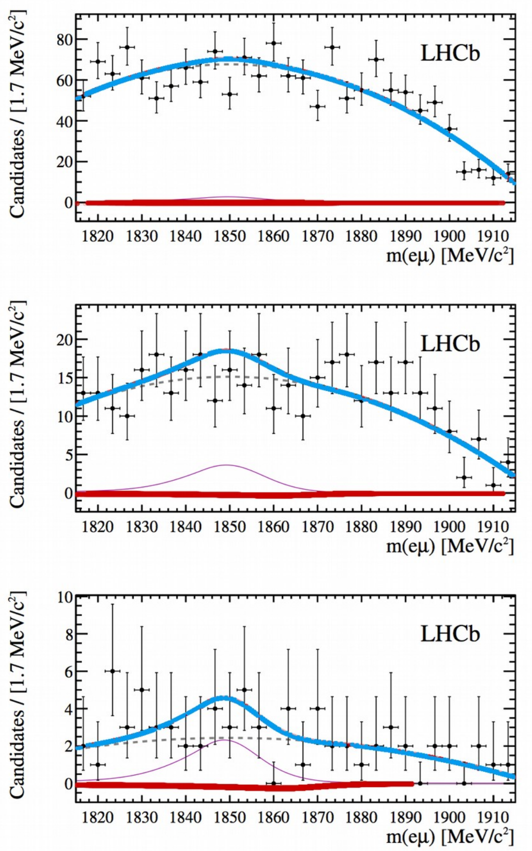
$J/\psi \rightarrow \mu^+\mu^-(\rightarrow e^-\bar{\nu}\nu)$ vs $J/\psi \rightarrow \mu^+e^-$)



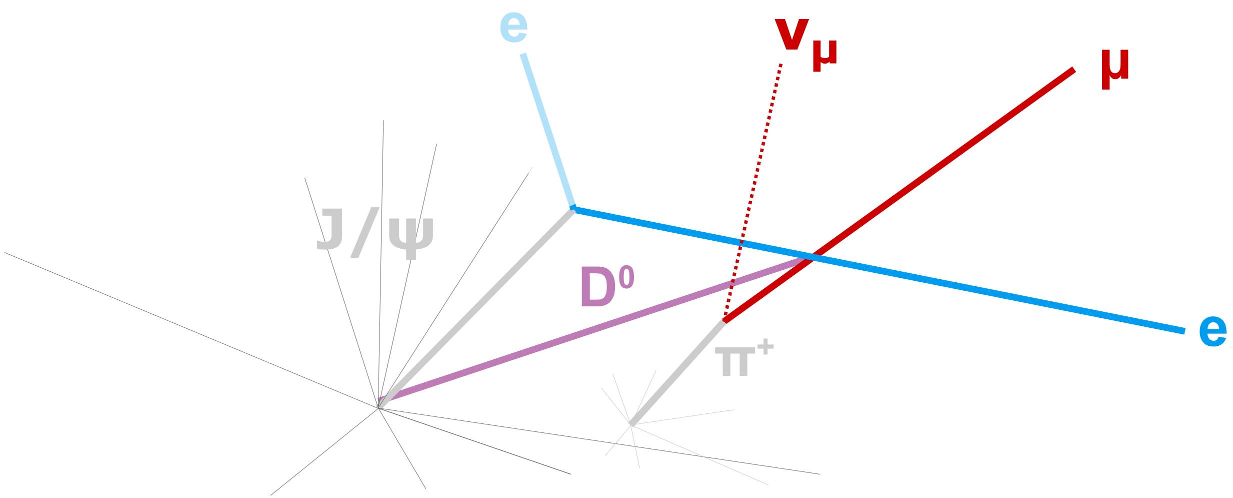


Smooth Background

Mainly due to combinatorial background



Particles have no kinematics relation
and happen to cross "by accident"
Resulting invariant mass distribution featureless
More probable in crowded environment
Challenging @ LHC, much better @ e^+e^-



Normalisation

Efficiency

Interpretation

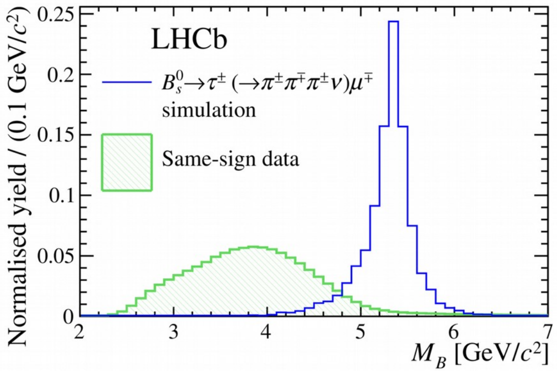
LFV Results (2009-2019)

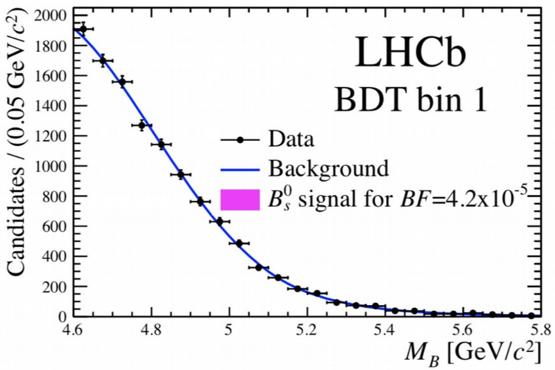
LHCb		
$\tau \to \mu\mu\mu$	4.6×10^{-8}	JHEP 02 (2015) 121
$D^0 \to e\mu$	1.3×10^{-8}	PLB 754 (2016) 167
$B^0{}_{(s)} \to e\mu$	$1.0/5.4 \times 10^{-9}$	JHEP 03 (2018) 078
$B^0{}_{(s)} \to \mu\tau$	$1.2/3.4 \times 10^{-5}$	arXiv:1905.06614
$h^0 \to \mu\tau$		EPJ C78 (2018) 1008
ATLAS / CMS		
$Z^0 \to \mu\tau$	1.7×10^{-5}	Eur. Phys. J. C 77 (2017) 70
$H \to e/\mu\tau$	$6/3 \times 10^{-3}$	JHEP 06 (2018) 001
BES		
$J/\psi \to e\mu$	1.6×10^{-7}	PRD 87 (2013) 112007
BaBar		
$\Upsilon(nS) \to e/\mu\tau$	$\sim 3 \times 10^{-6}$	PRL 104 (2010) 151802
VEPP		
$\varphi \to e\mu$	2×10^{-6}	PRD 81 (2010) 057102

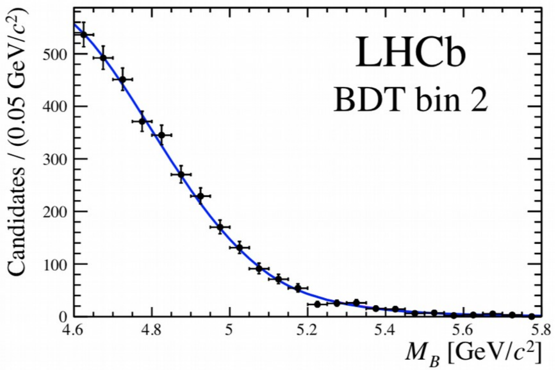
Latest LFV Result (LHCb)

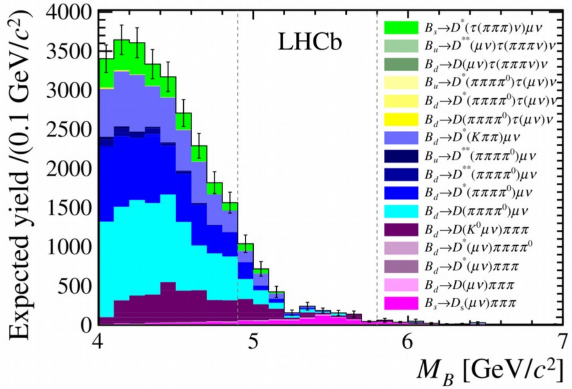
$B^0_{(s)} \to \mu\tau$

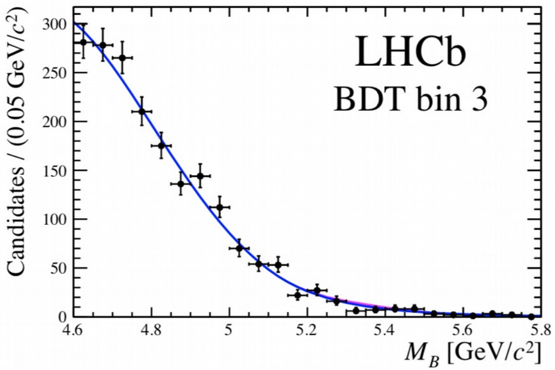
ArXiv:1905.06614
Br($B^0_{(s)} \to \mu\tau$) < 1.4/4.2 x 10^{-5} (95% C.L.)
Previous : Br($B^0 \to \mu\tau$) < 3.8 x 10^{-5} (90% C.L.) @ CLEO

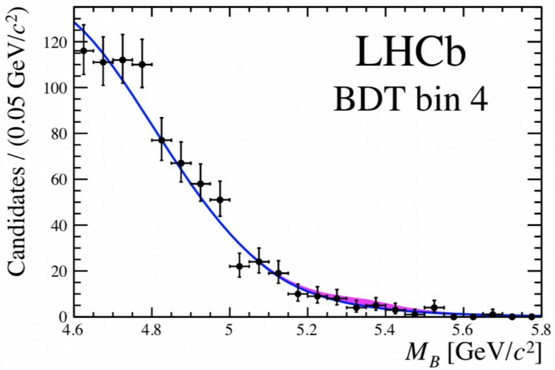




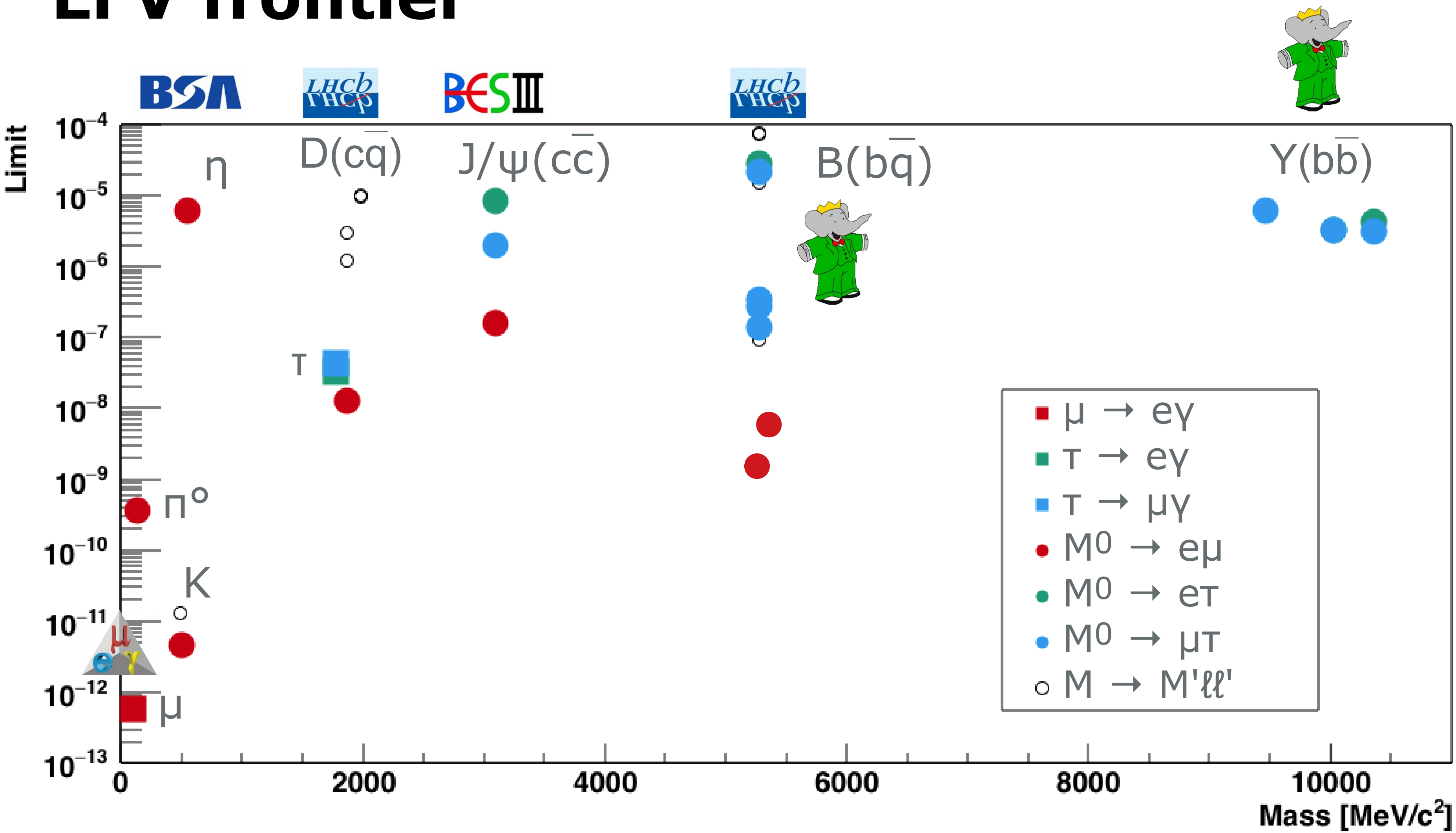




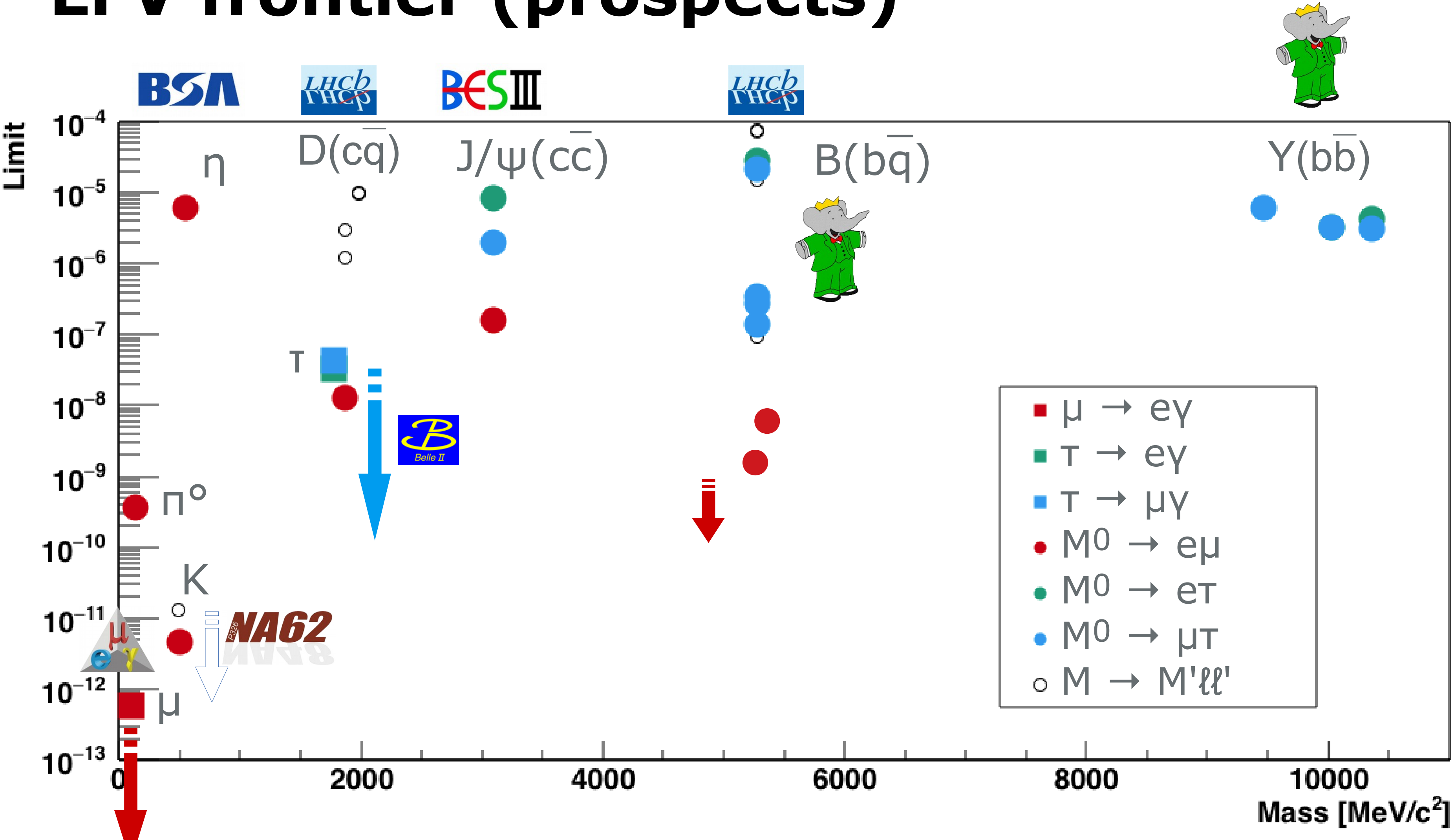




LFV frontier



LFV frontier (prospects)



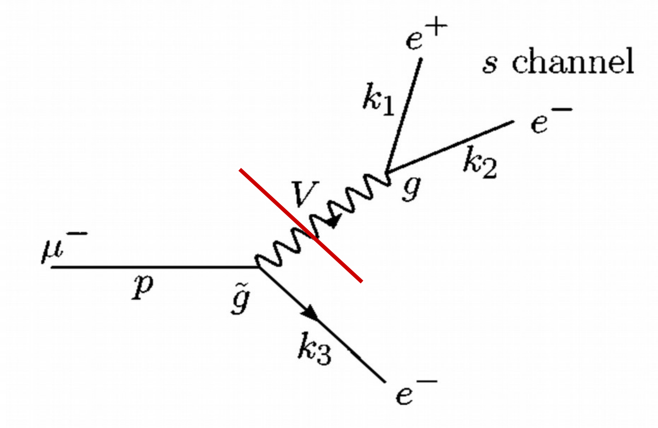
LFV frontier (intermezzo)

Constraints on two-body LFV decay processes
S. Nussinov, R. D. Peccei, and X. M. Zhang
Phys. Rev. D 63 (2000) 016003

Unitarity puts rather strong constraints on two-body LFV processes

For example: Br[$\tau \to e\mu\mu$] > Br[$\tau \to e\varphi$] · Br[$\varphi \to \mu\mu$] ≈ $3 \cdot 10^{-4}$ · Br[$\tau \to e\varphi$]

Thus (stringent) bound on Br[$\tau \to e\mu\mu$] produces a limit on Br[$\tau \to e\varphi$]

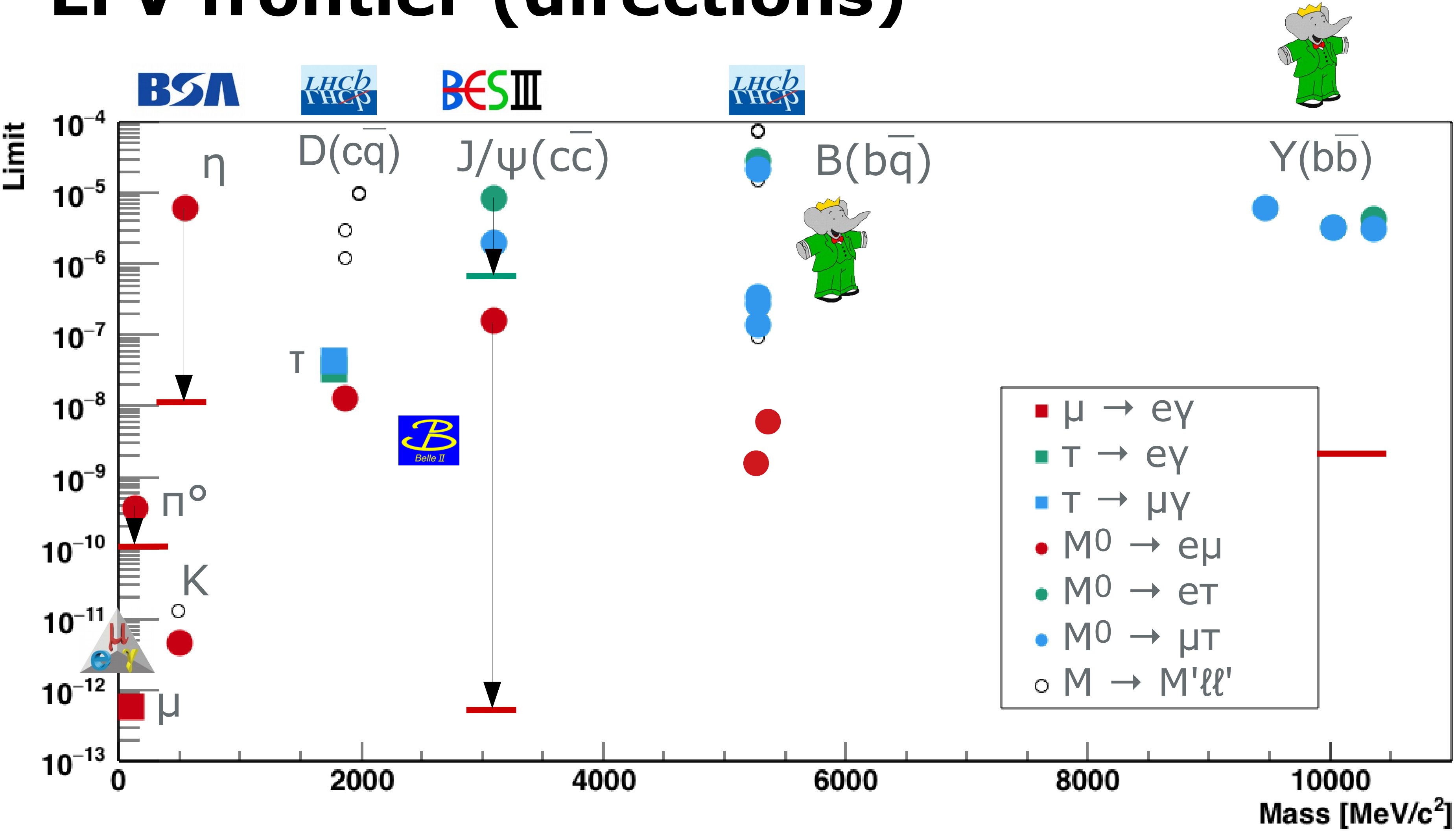


Br[$\mu \to eee$] < 10^{-12}
- ▶ Br[$\varphi \to e\mu$] < $4 \cdot 10^{-17}$
- ▶ Br[$J/\psi \to e\mu$] < $4 \cdot 10^{-13}$
- ▶ Br[$\Upsilon \to e\mu$] < $2 \cdot 10^{-9}$

Br[$\mu \to e\gamma\gamma$] < 10^{-10}
- ▶ Br[$\pi^0 \to e\mu$] < 10^{-10}
- ▶ Br[$\eta \to e\mu$] < 10^{-8}

CAVEAT: indirect bounds (somewhat) model dependent; also other relations

LFV frontier (directions)



LHC & low energy

Ten different gauge invariant operators with 2 quarks and 2 leptons
Quote limits in terms of cutoff scale Λ of effective operators

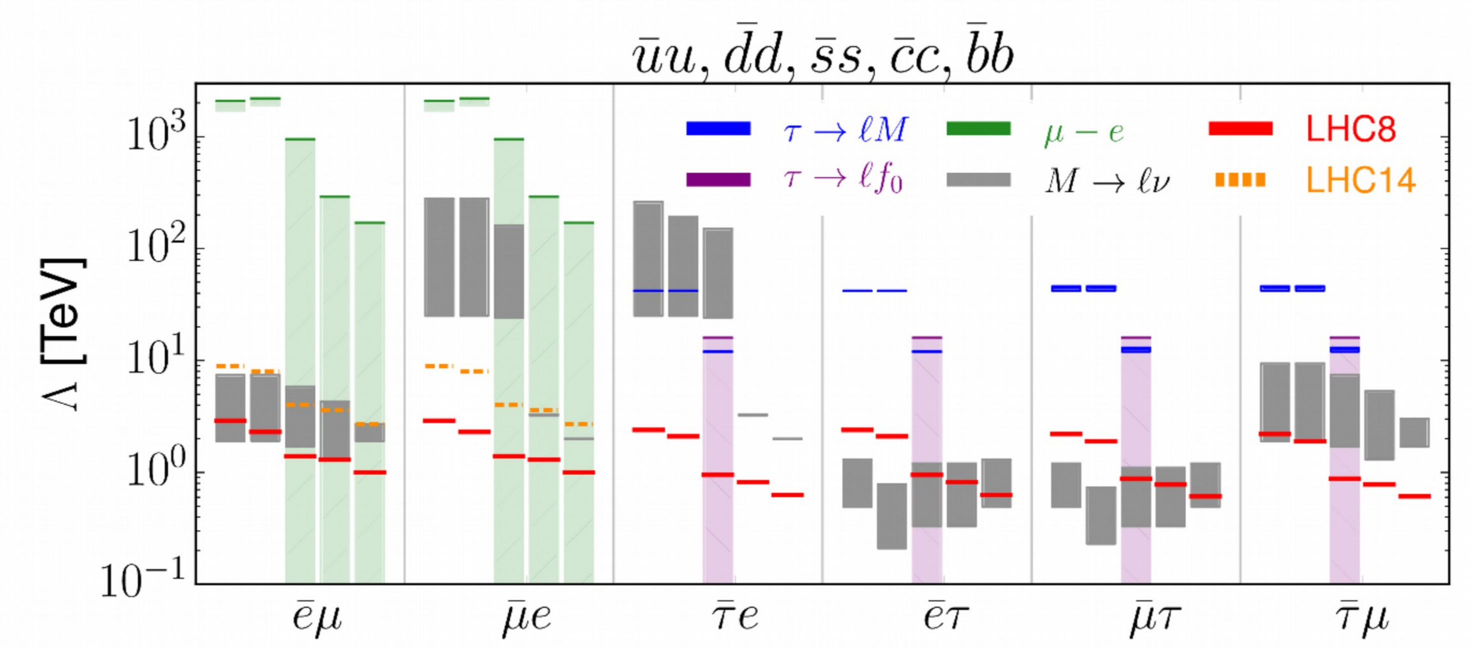


Figure 5. Summary plots of most stringent limits from precision experiments and the LHC. See the text for a detailed explanation.

"A Case Study of the Sensitivity to LFV Operators with Precision Measurements and the LHC", Cai & Schmidt, JHEP02(2016)176

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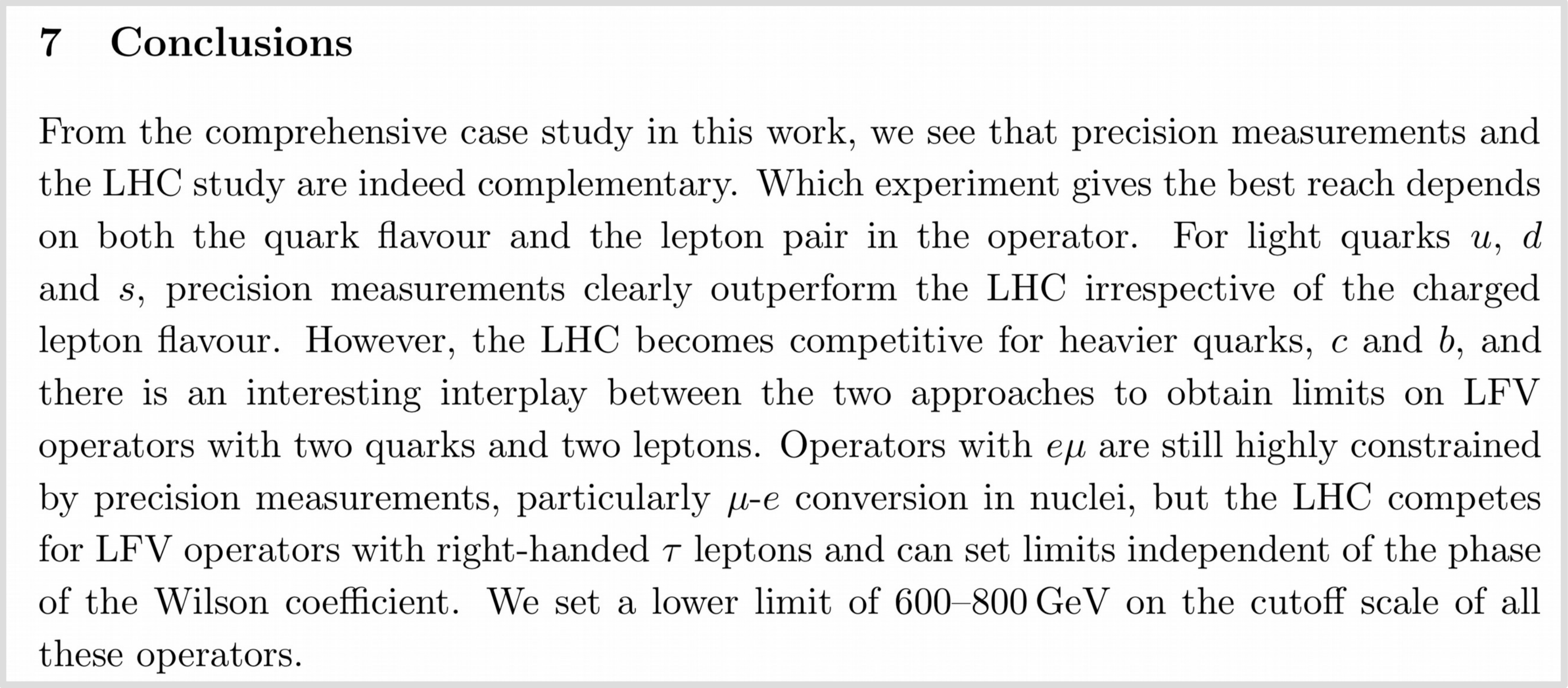

7 Conclusions

From the comprehensive case study in this work, we see that precision measurements and the LHC study are indeed complementary. Which experiment gives the best reach depends on both the quark flavour and the lepton pair in the operator. For light quarks u, d and s, precision measurements clearly outperform the LHC irrespective of the charged lepton flavour. However, the LHC becomes competitive for heavier quarks, c and b, and there is an interesting interplay between the two approaches to obtain limits on LFV operators with two quarks and two leptons. Operators with $e\mu$ are still highly constrained by precision measurements, particularly μ-e conversion in nuclei, but the LHC competes for LFV operators with right-handed τ leptons and can set limits independent of the phase of the Wilson coefficient. We set a lower limit of 600–800 GeV on the cutoff scale of all these operators.

“A Case Study of the Sensitivity to LFV Operators with Precision Measurements and the LHC”, Cai & Schmidt, JHEP02(2016)176

Personal outlook

Charm

$D_{(s)} \to e\mu$	will improve 10-100x @ LHCb
$D_{(s)} \to e\mu\gamma$	lifts helicity suppression, costs α, need Eγ threshold
$D^+ \to K^+ e\mu$	lower efficiency, tighter mass-peak?

Bottom

$B_{(s)} \to e\mu$	will improve 10-100x @ LHCb
$B_{(s)} \to \mu\tau$	will improve 10x @ LHCb
$B_{(s)} \to e\mu\gamma$	lifts helicity suppression, costs α, need Eγ threshold
$B_{(s)} \to K^{*0}(K^+\pi^-)\ e/\mu/\tau(3\pi)$	for least unconstrained tau decay
$B_{(c)}^+ \to (K/D)^+\ e/\mu/\tau$	heaviest open-flavour meson

Baryons

$\Lambda_b \to \Lambda(p\pi)\ e\mu$	production cross secion σ(Λb)/σ(B) ~ 0.1 – 1

Final words

Search for cLFV @ colliders is certainly possible

Experiment design an art, with many subtleties to take into account

Can benefit from developments in hadronic + SM research

Relation between low-E and high-E cLFV results exist

Such relations are model-dependent

Just do it!