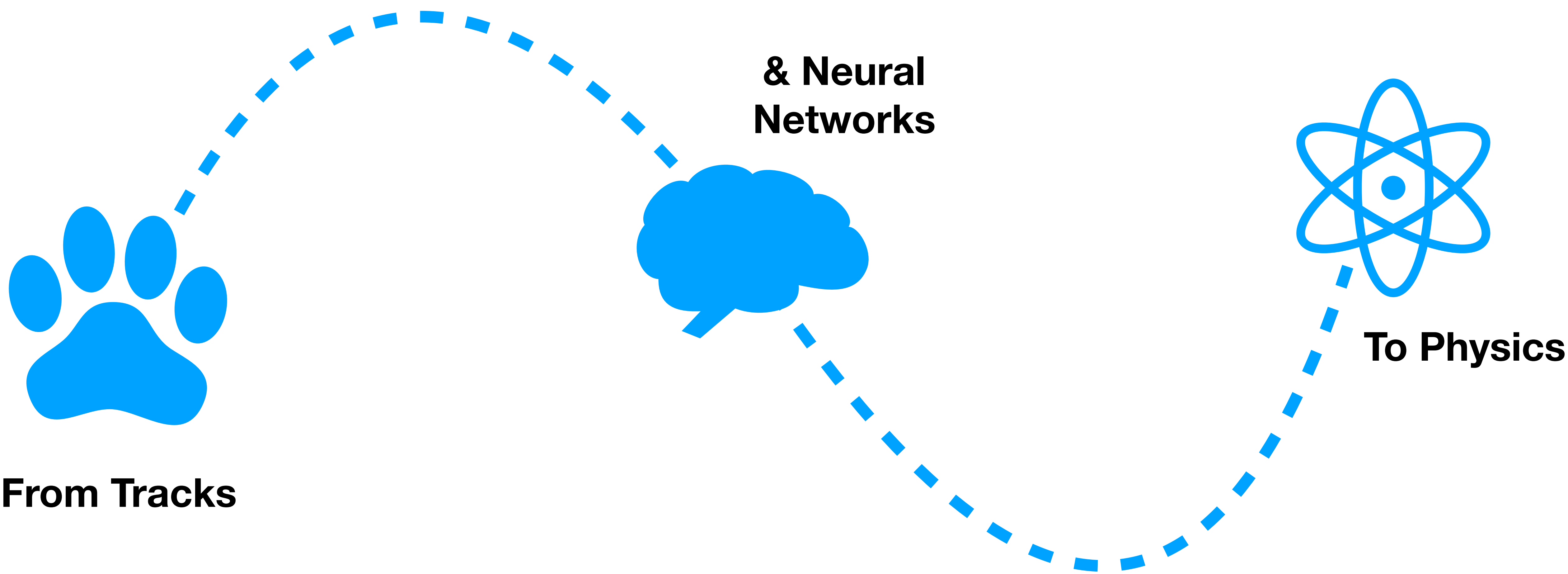
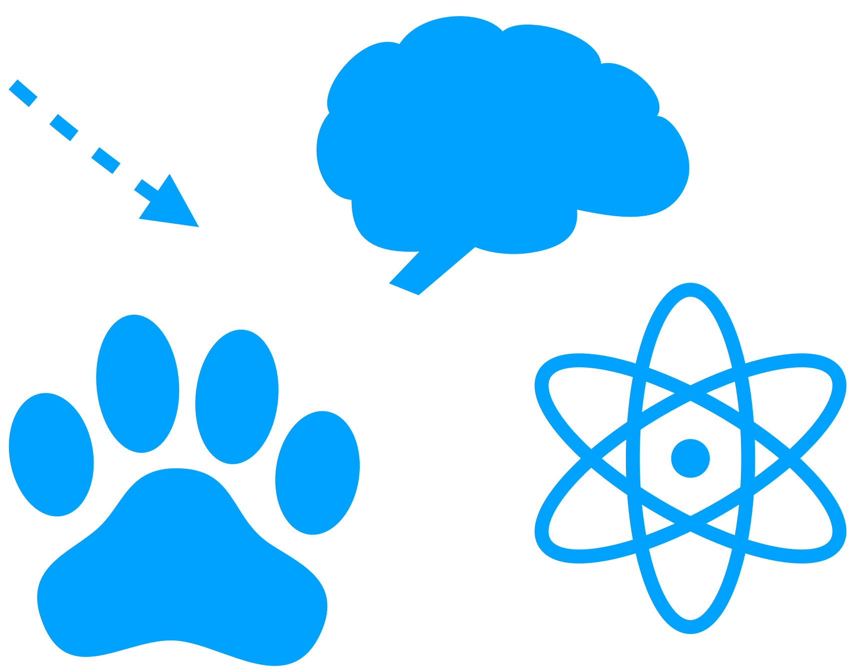
Many thanks to Martin Heck

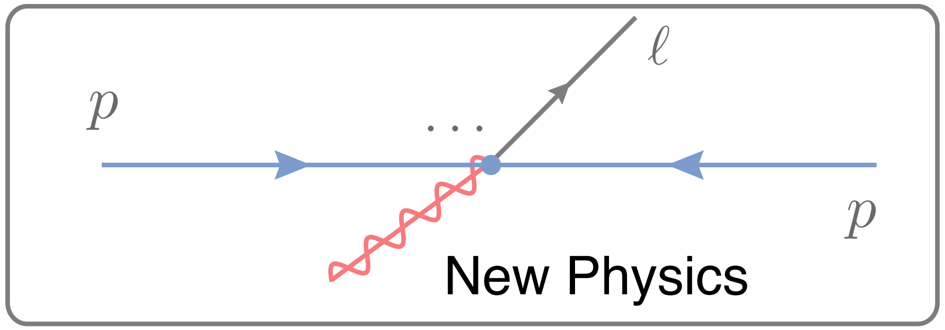


Florian Bernlochner
florian.bernlochner@cern.ch

Setting the Scene

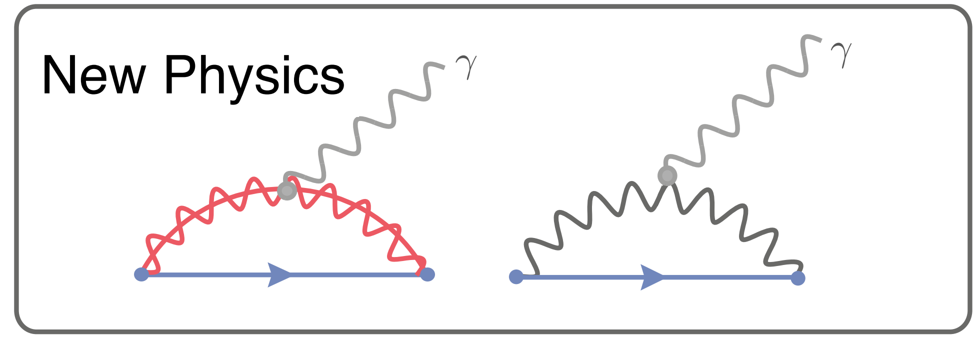


The Precision Frontier of Particle Physics



Energy Frontier Ansatz

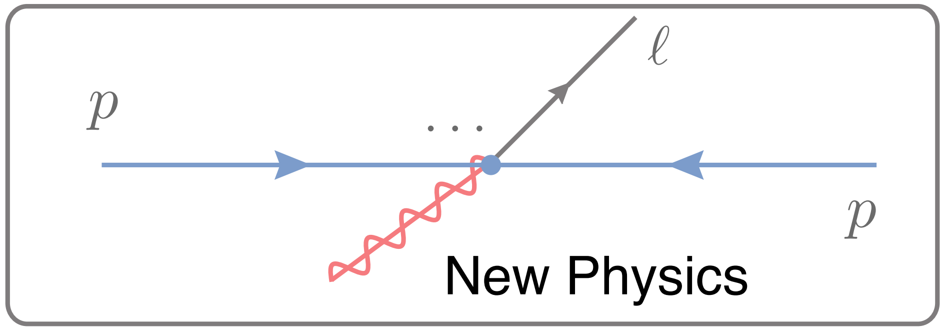
e.g. LHC, Tevatron



Intensity Frontier Ansatz

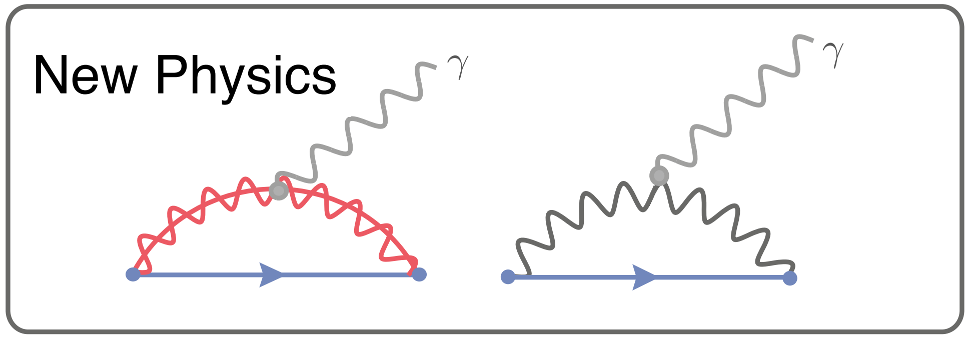
e.g. BaBar, CLEO, Belle

The Precision Frontier of Particle Physics



Energy Frontier Ansatz

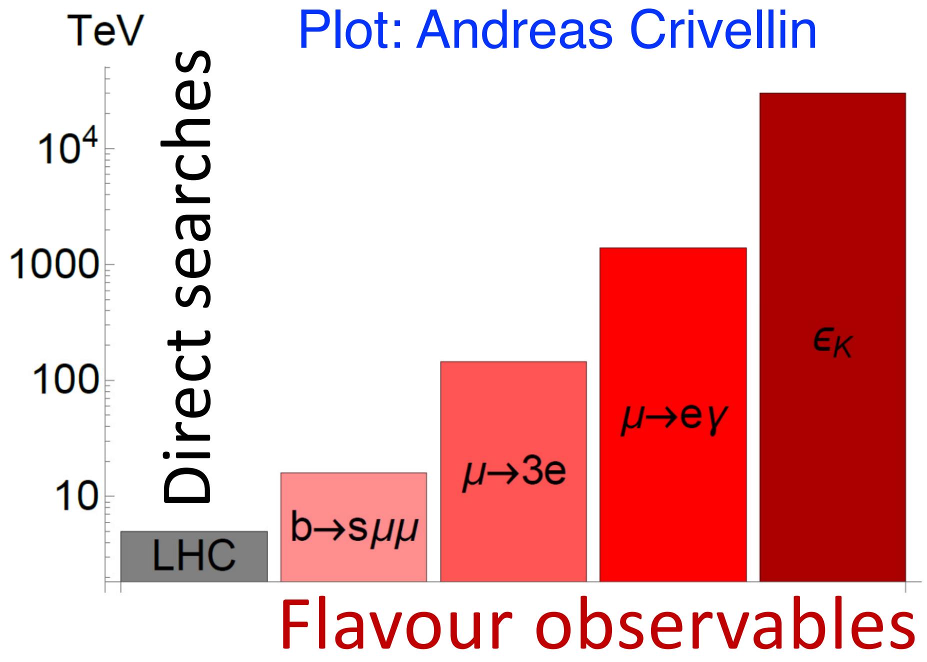
e.g. LHC, Tevatron



Intensity Frontier Ansatz

e.g. BaBar, CLEO, Belle

Large degree of complementarity



Belle II

At B-Factories with B-Mesons

The Belle II Experiment

‘→ el le ←’

‘B’ breaks the symmetry
In elle, hence Belle :-)

$$\sqrt{s} = 10.58\,\mathrm{GeV}$$

$$e^+ \longrightarrow \Upsilon(4S) \longleftarrow e^-$$

$\langle b\bar{b}\rangle$

$\Upsilon(1S) = \langle b\bar{b}\rangle$

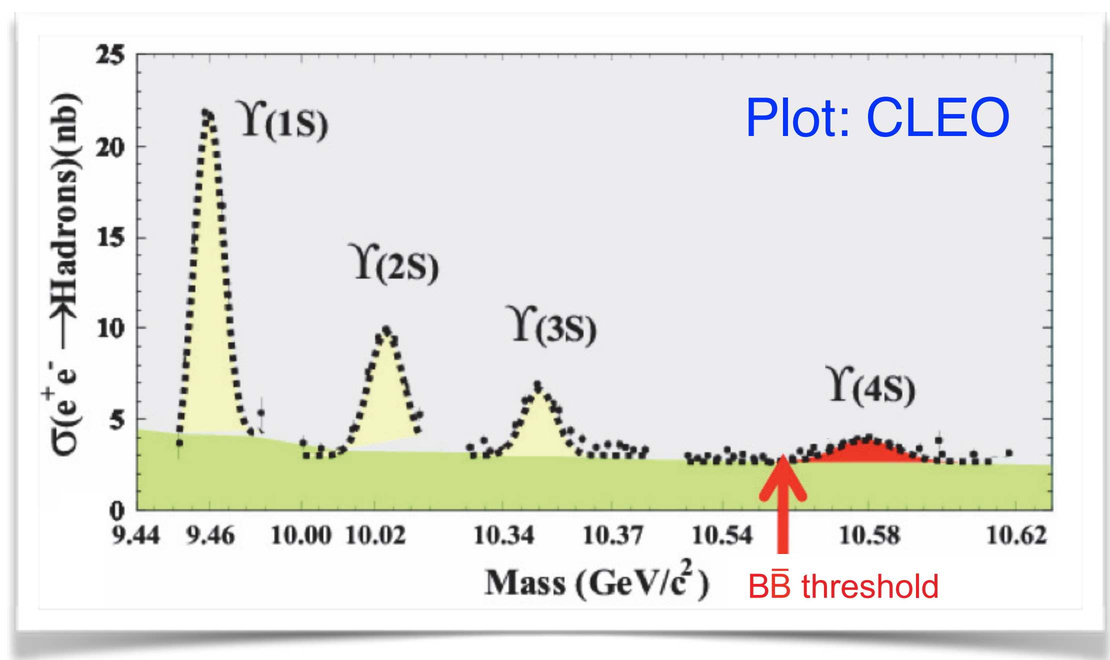
$\Upsilon(4S) = \langle b\bar{b}\rangle$

$\bar{q} \leftarrow \star \rightarrow q$

$\langle b\bar{q}\rangle$ $\langle \bar{b}q\rangle$

quark-antiquark-pair produced from vacuum

Fragmentation into two bound states: B-Mesons

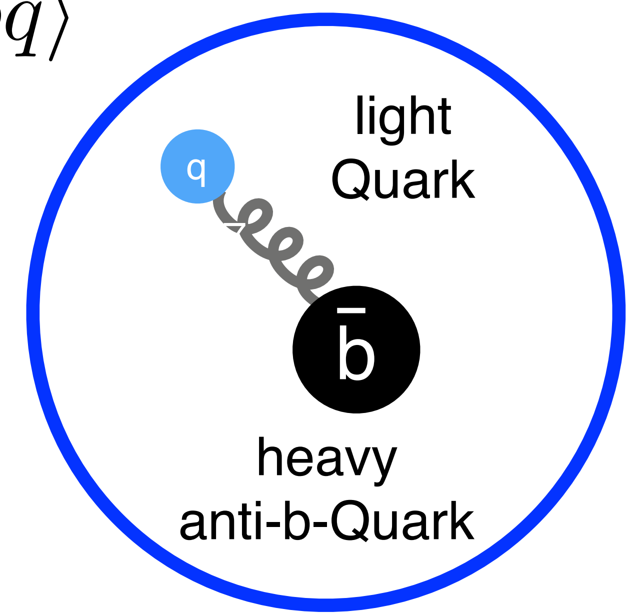


The Belle II Experiment: B-Meson Decays

...

$\langle \bar{b} q \rangle$

B-Meson



$\tau_B \approx 1.5 \times 10^{-12}\,\mathrm{s}$

inclusive charged particle multiplicity: **~5.4 per B-Meson**

or ~ **11** per B-Meson pair

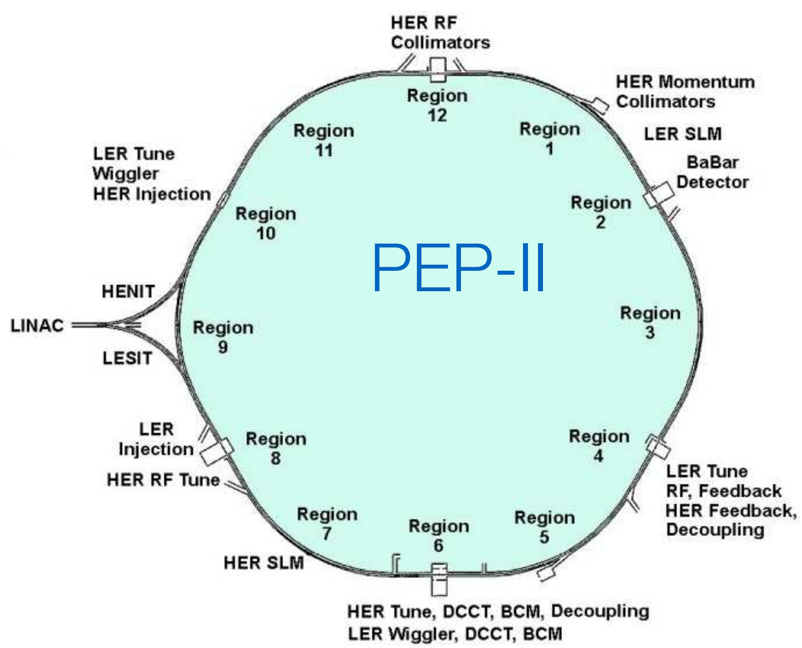
Murphy's Law of Flavour Physics

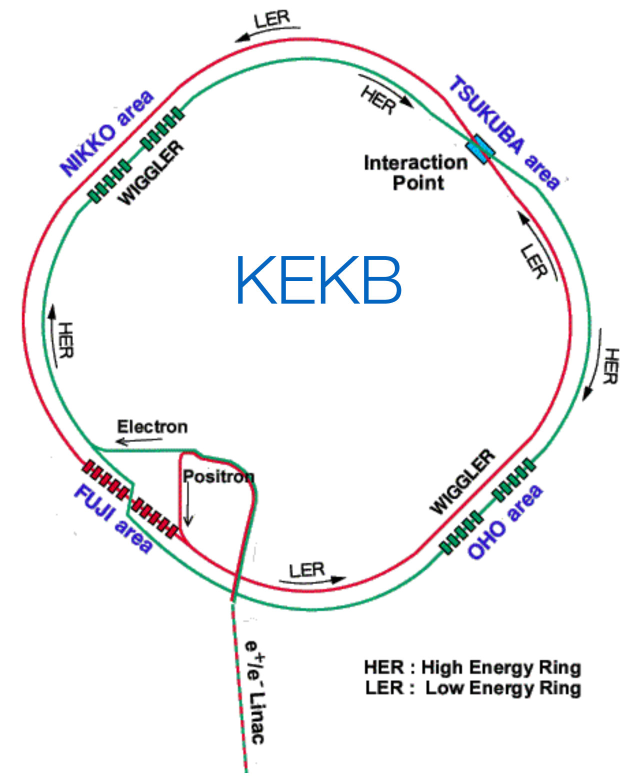
What you can measure without a problem, you cannot calculate.
What you can calculate easily, you cannot measure

Stolen from Martin Heck

The Belle II Experiment: Asymmetric Beam Energies

Asymmetric Beam energies: allow to directly observe CPV in B-system





Belle II

$$\sqrt{s} = 10.58\,\mathrm{GeV}$$

$$e^+ \longrightarrow \Upsilon(4S) \longleftarrow e^-$$

$E(e^+) = 4\,\mathrm{GeV}$ $\quad$ $E(e^-) = 7\,\mathrm{GeV}$

$\langle b\bar{b} \rangle$

$$\Upsilon(4S) \to B^0\, \overline{B}^0$$

$$\langle b\bar{b} \rangle \longrightarrow \langle \bar{b}d \rangle\, \langle b\bar{d} \rangle$$

$\beta\gamma = 0.28$

$$\Delta z \approx c\,\beta\,\gamma\,\tau_B \approx 126\,\mu\mathrm{m}$$

B-meson lifetime

BaBar	$E(e^-) = 9\,\mathrm{GeV}$	$E(e^+) = 3.1\,\mathrm{GeV}$	$\beta\gamma = 0.56$
Belle	$E(e^-) = 8\,\mathrm{GeV}$	$E(e^+) = 3.5\,\mathrm{GeV}$	$\beta\gamma = 0.42$

What is the difference between Belle and Belle II?

50:1

What is the difference between Belle and Belle II?

50:1

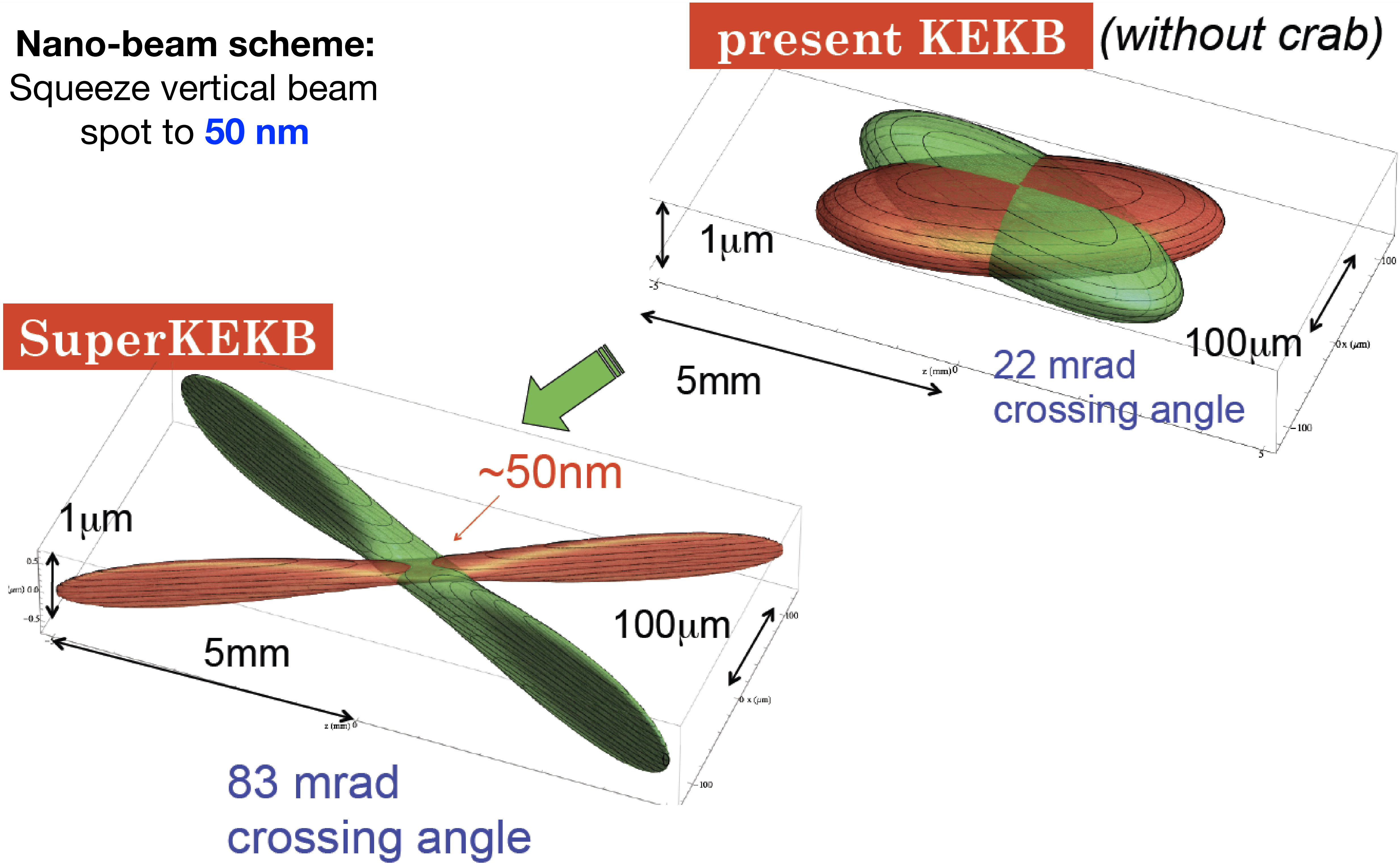
Expected data set increase and ~ increase in inst. Luminosity

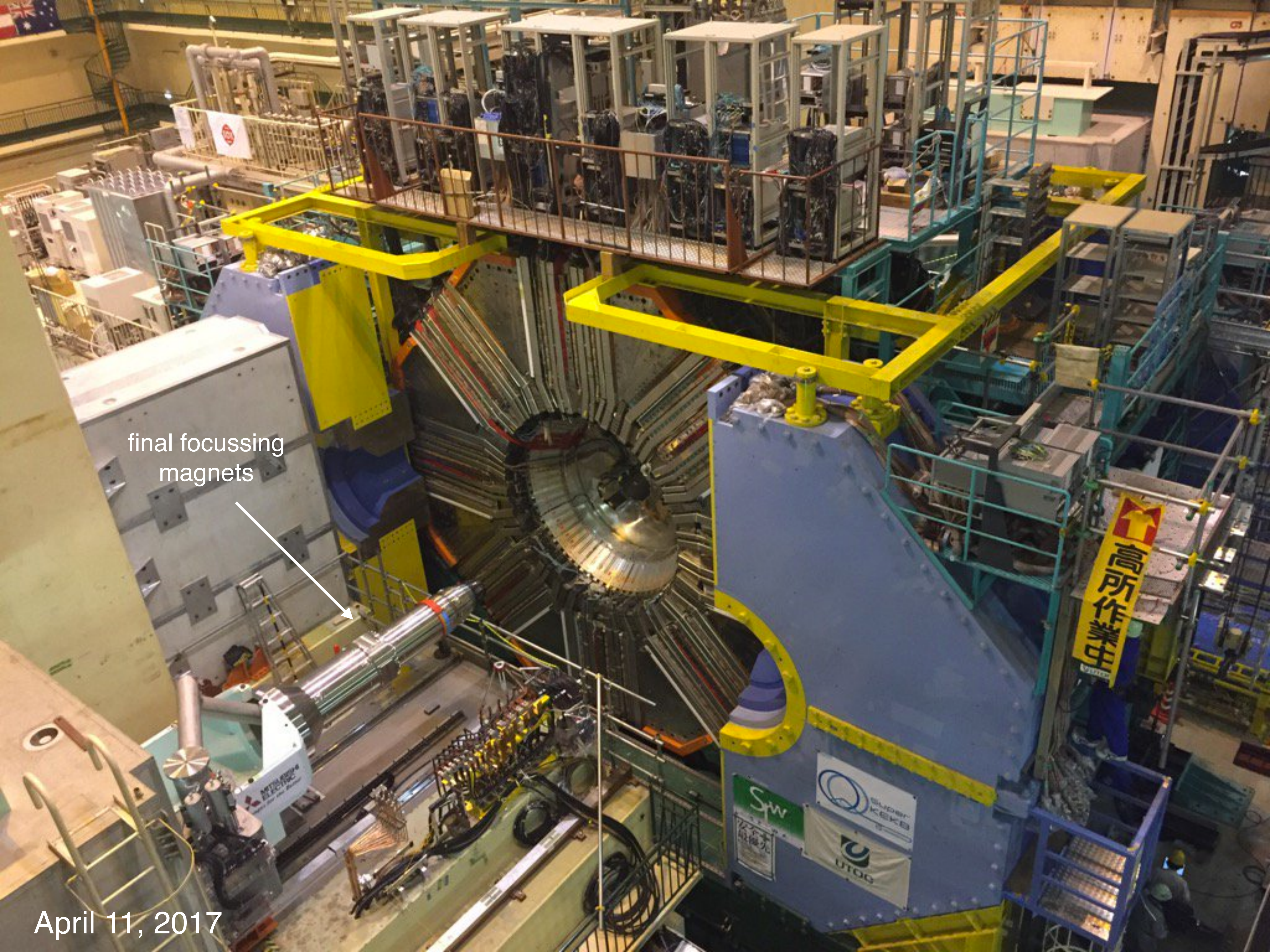
$$\frac{50}{1} = \frac{\text{LHCb Upgrade}}{\text{LHCb today}} = \frac{\text{Belle II}}{\text{BaBar and Belle}} = \frac{\text{BaBar and Belle}}{\text{CLEO}}$$

As significant for us as the energy increase from **7/8 TeV** to **13 TeV** at the **LHC**

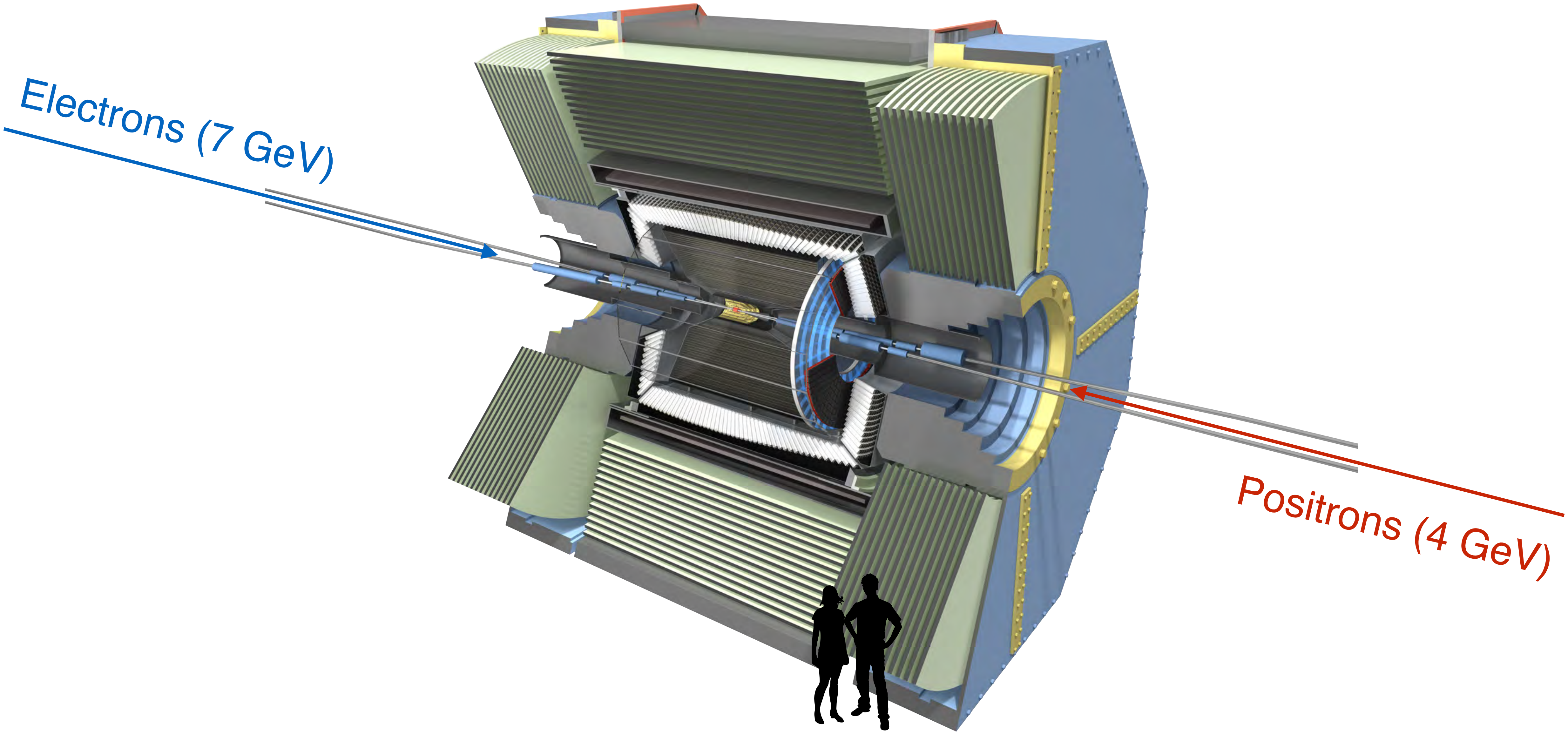
KEKB → SuperKEKB

Nano-beam scheme:
Squeeze vertical beam spot to **50 nm**




final focussing
magnets
高所作業中
April 11, 2017

Belle → Belle II



Increased luminosity comes at a price: much larger beam backgrounds

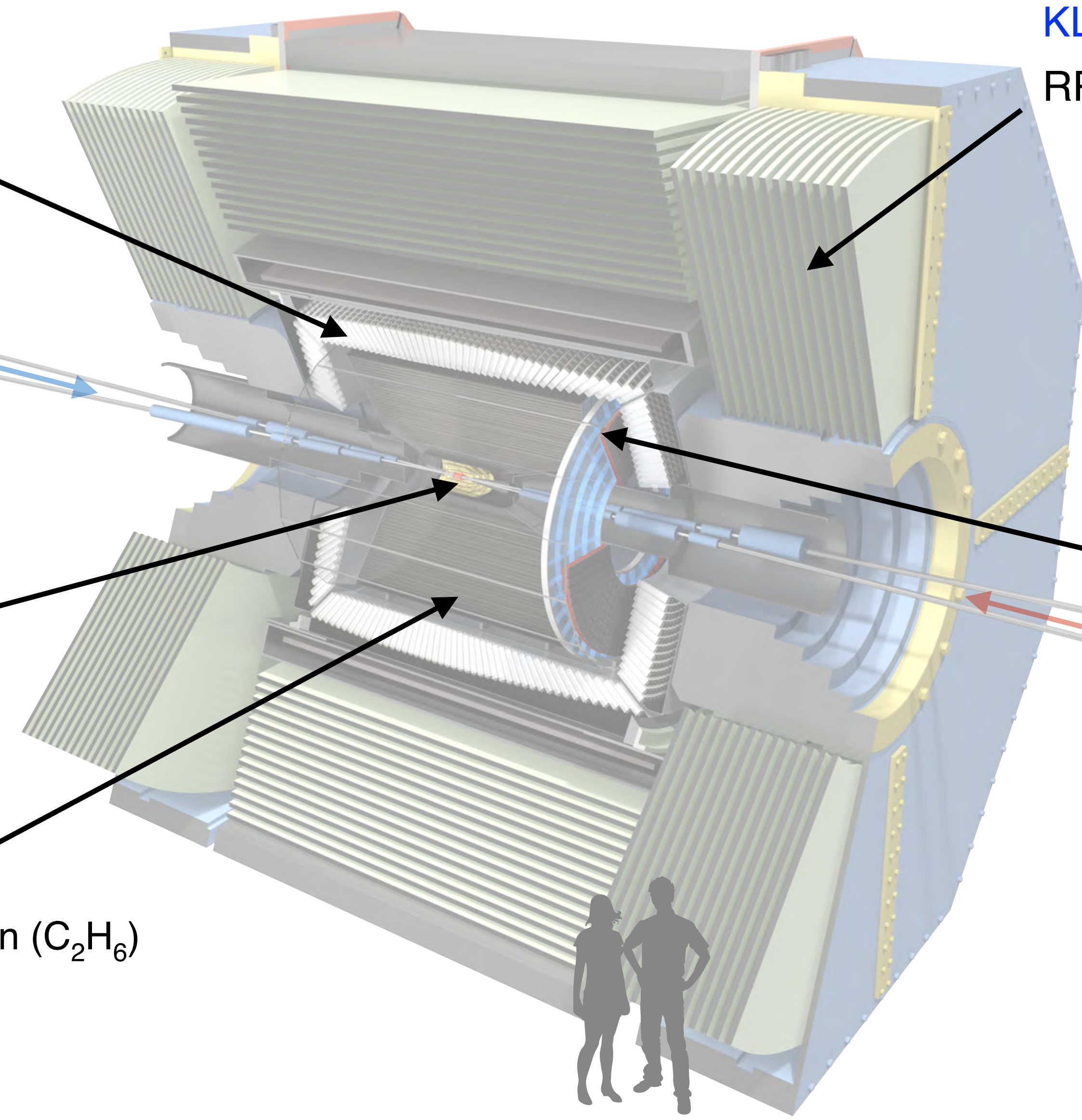
Belle → Belle II

Electromagnetic Calorimeter:

Thallium activated Caesium Iodide scintillation crystals

KL and Muon detection system

RPC based



Particle identification

Time-of-propagation counter,
Aerogel Cherenkov ring detector

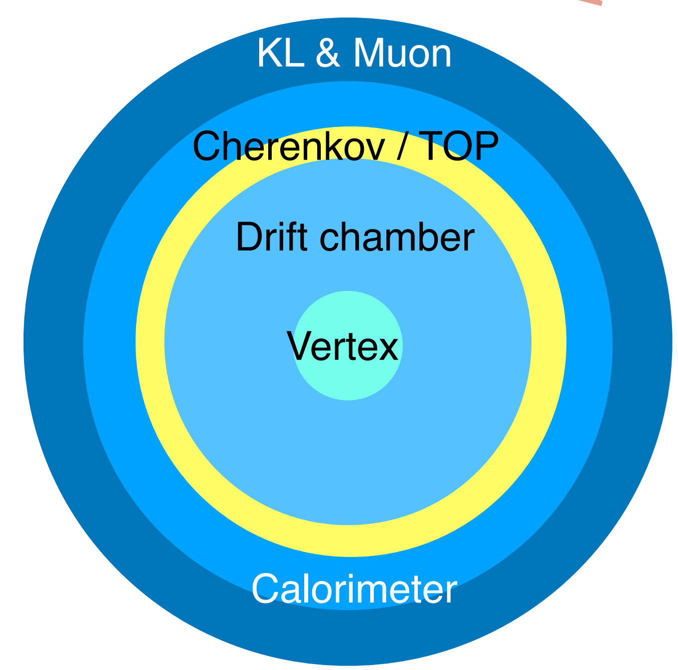
Vertex detectors

2 layers of Pixel (DEPFET)

+ 4 layers of strips (DSSD)

Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)



Belle → Belle II

Electromagnetic Calorimeter:

Thallium activated Caesium Iodide scintillation crystals

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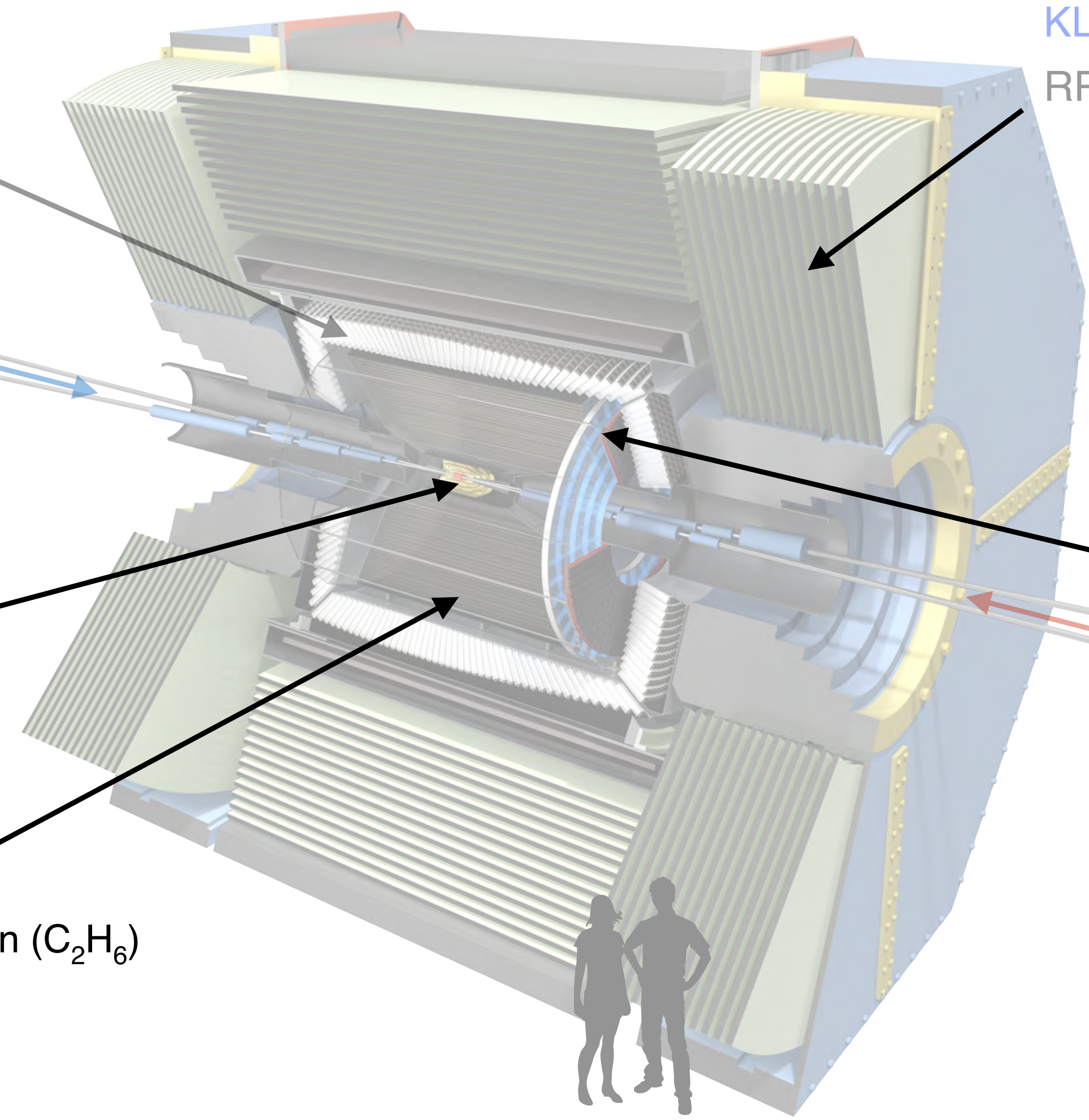


Vertex detectors

2 layers of Pixel (DEPFET)

+ 4 layers of strips (DSSD)

Particle identification

Time-of-propagation counter, Aerogel Cherenkov ring detector

Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)

Karlsruher Institut für Technologie

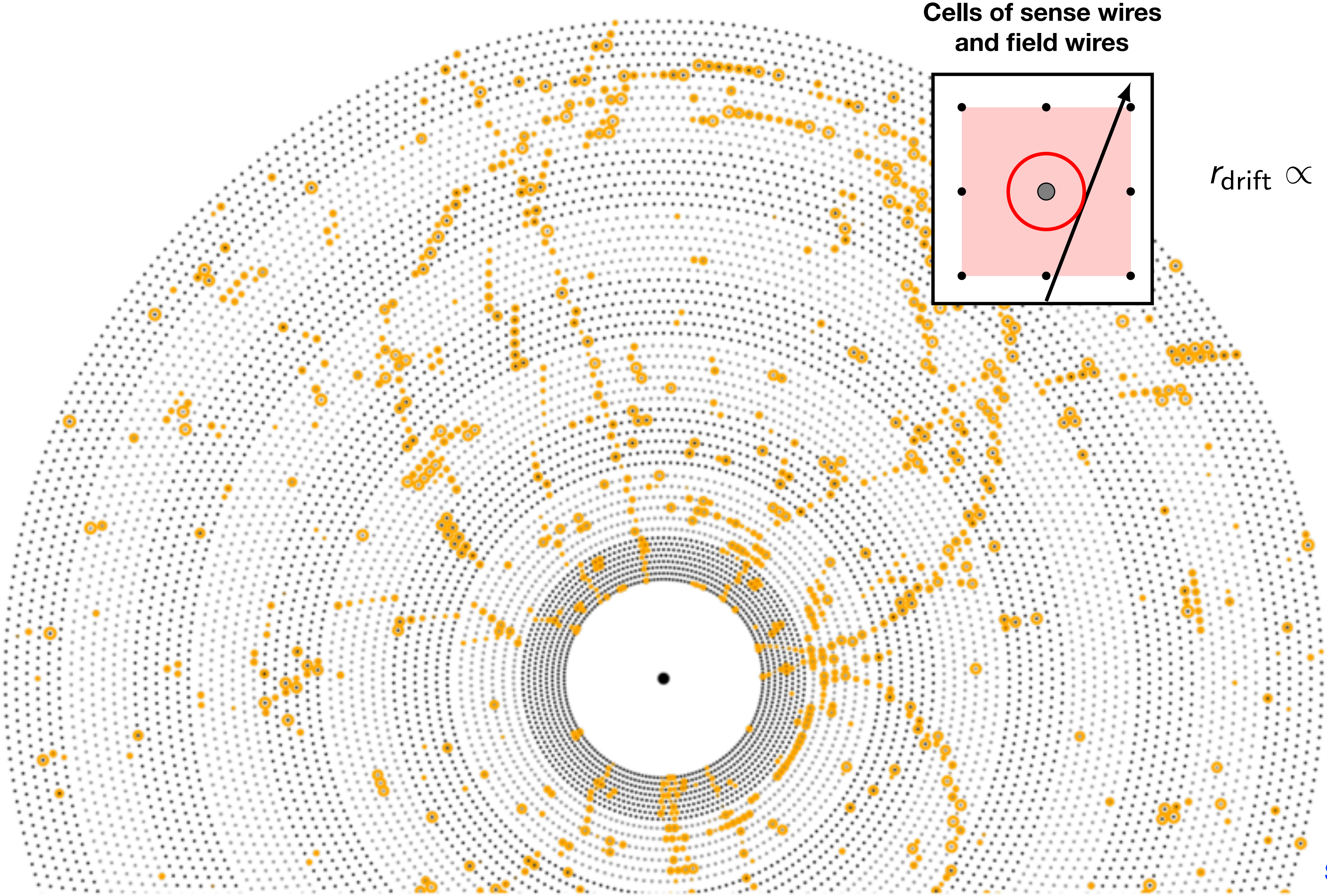
Tracks

Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)

14336 sense wires
56 layers

Aim: Convert unmarked Hits …



Cells of sense wires and field wires

$$r_{\text{drift}} \propto t_{\text{drift}}$$

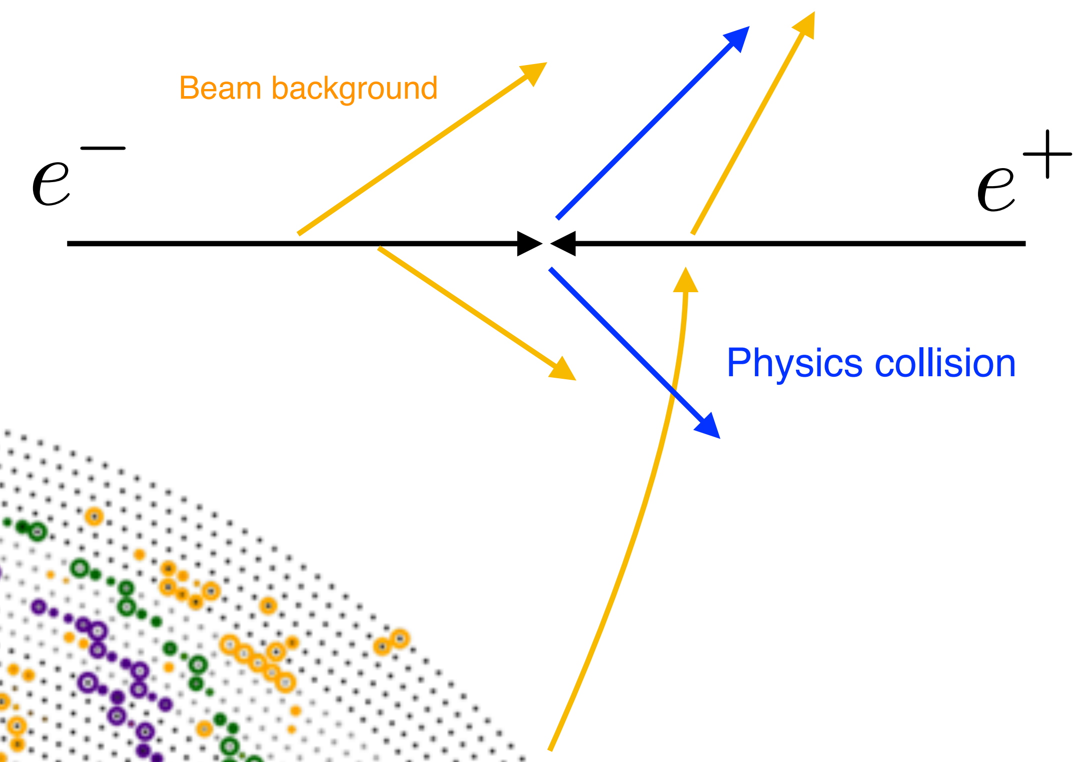
Illustrations: Oliver Frost, Sarah Neuhaus

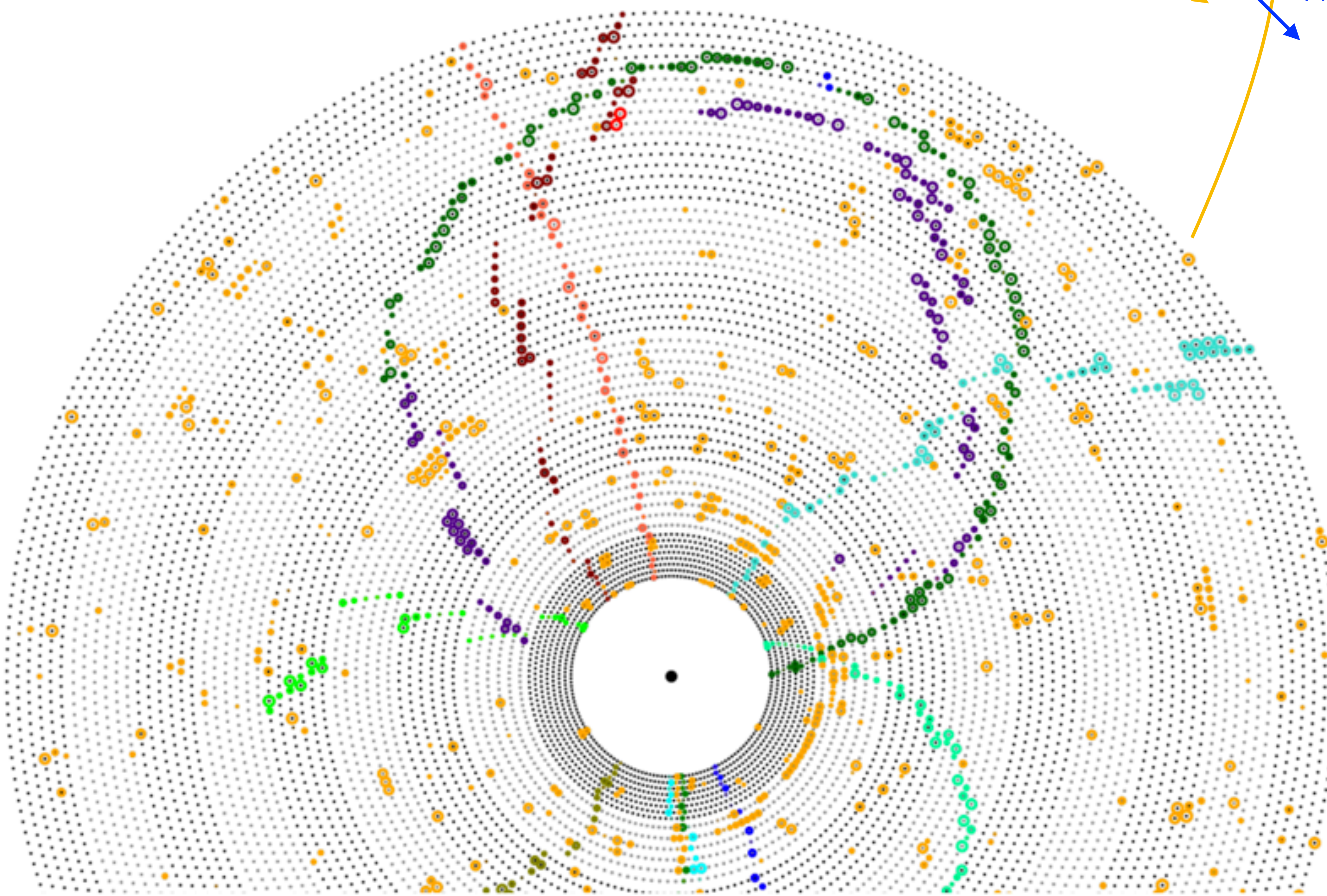
Central drift chamber:

Gas mixture of Helium and Ethan (C_2H_6)

14336 sense wires
56 layers

... into charged particle trajectories



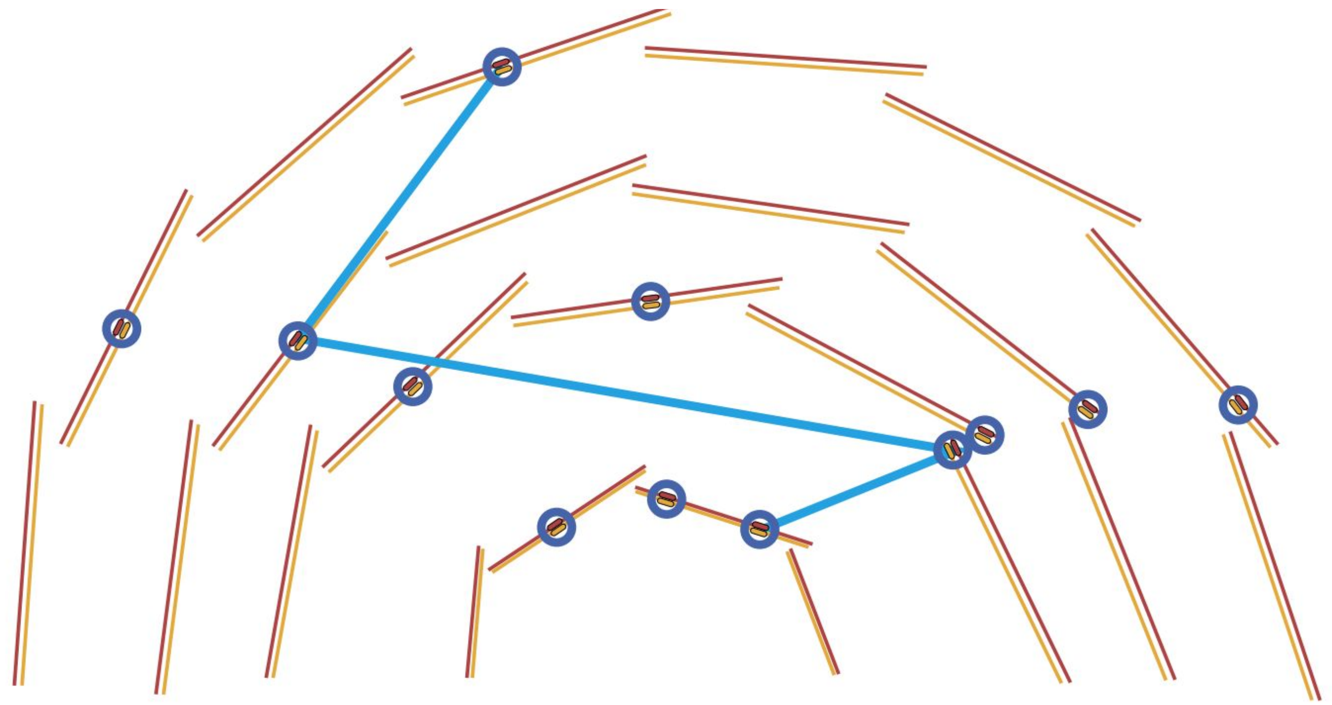


Illustrations: Oliver Frost, Sarah Neuhaus

Original question by E. Paoloni

VXD Online and Offline Tracking

Vertex detector (VXD)

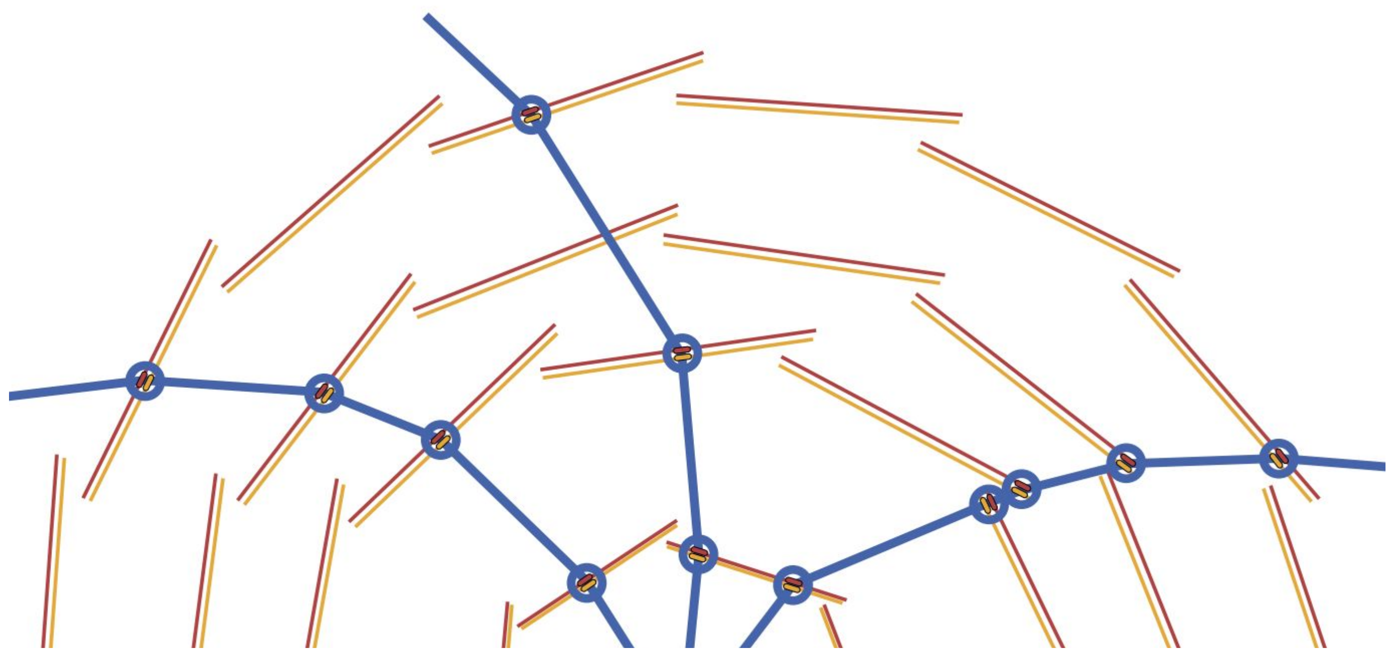


To reduce combinatorics:
Group hits into
sectors that will contain
a likely neighbouring hit

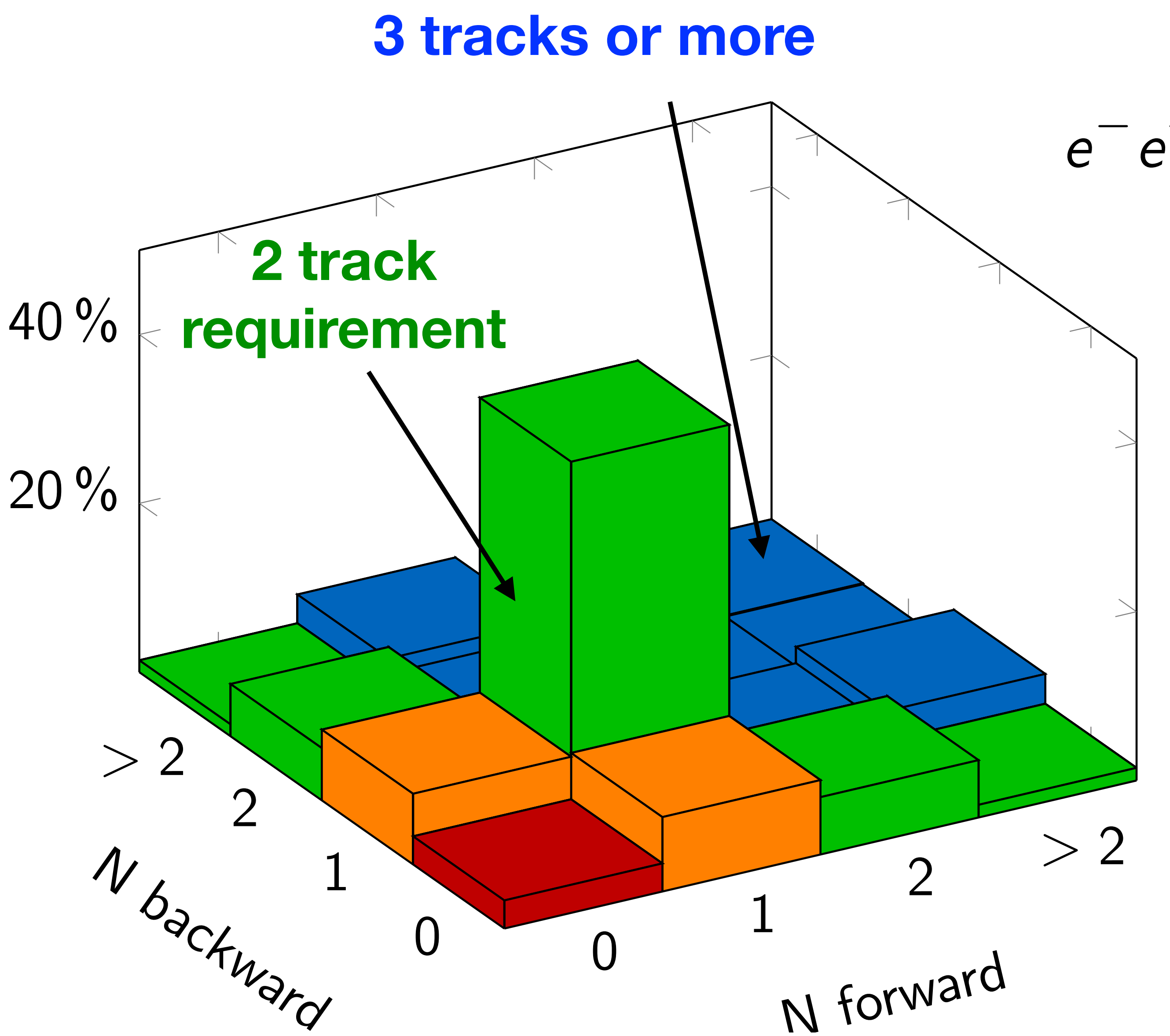
Done in 3D

↓

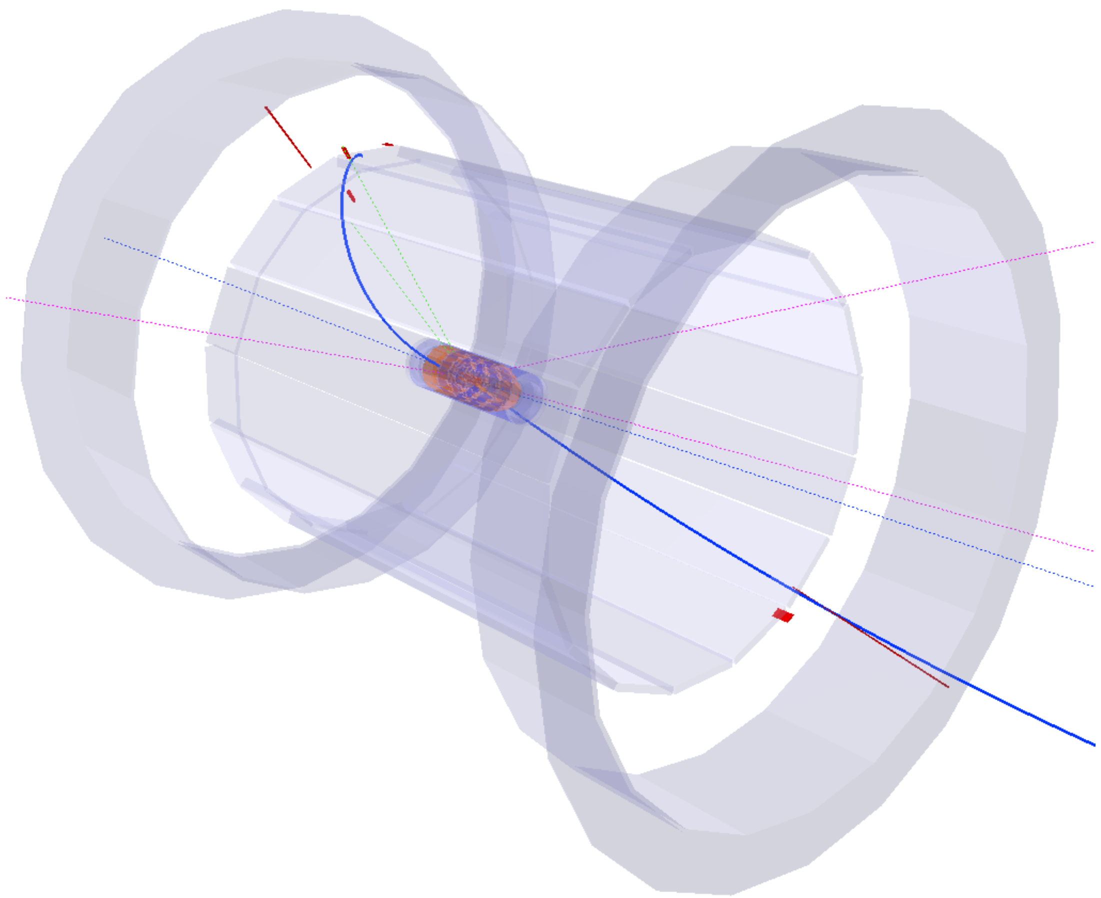
Used in track reconstruction



- Typical B-Meson trigger requires **3 tracks** (at least one in each hemisphere)
- A lot of interesting low-multiplicity events are missed

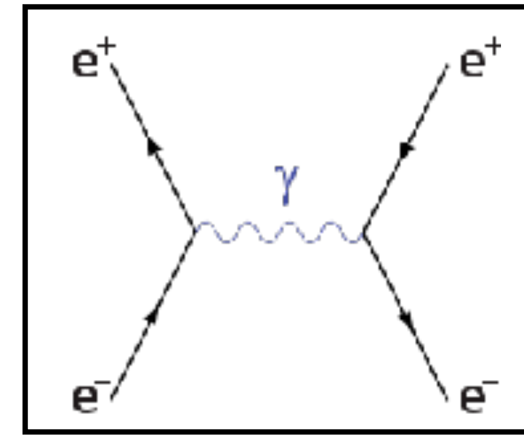


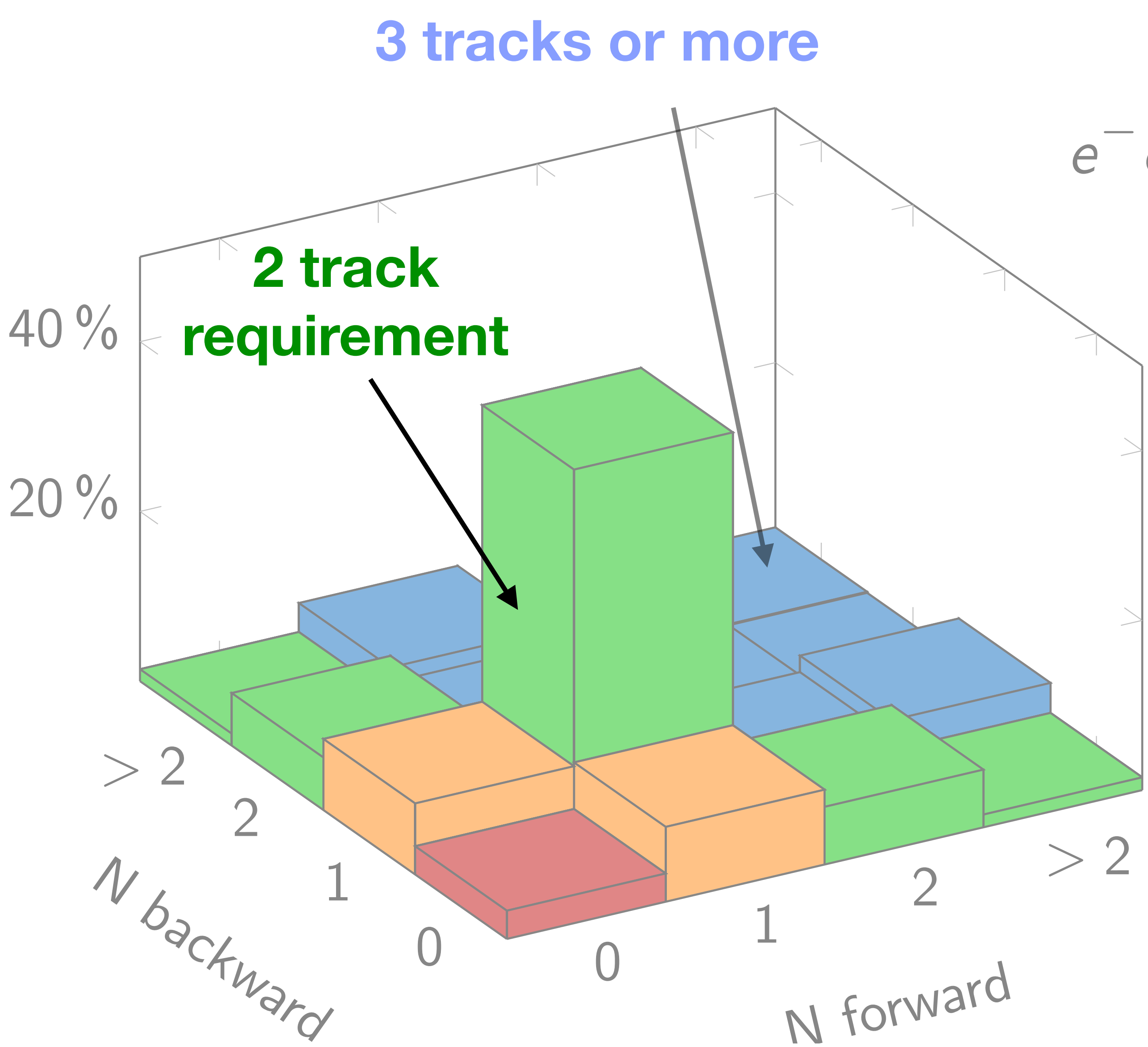
$e^- e^+ \longrightarrow \tau^- \tau^+$



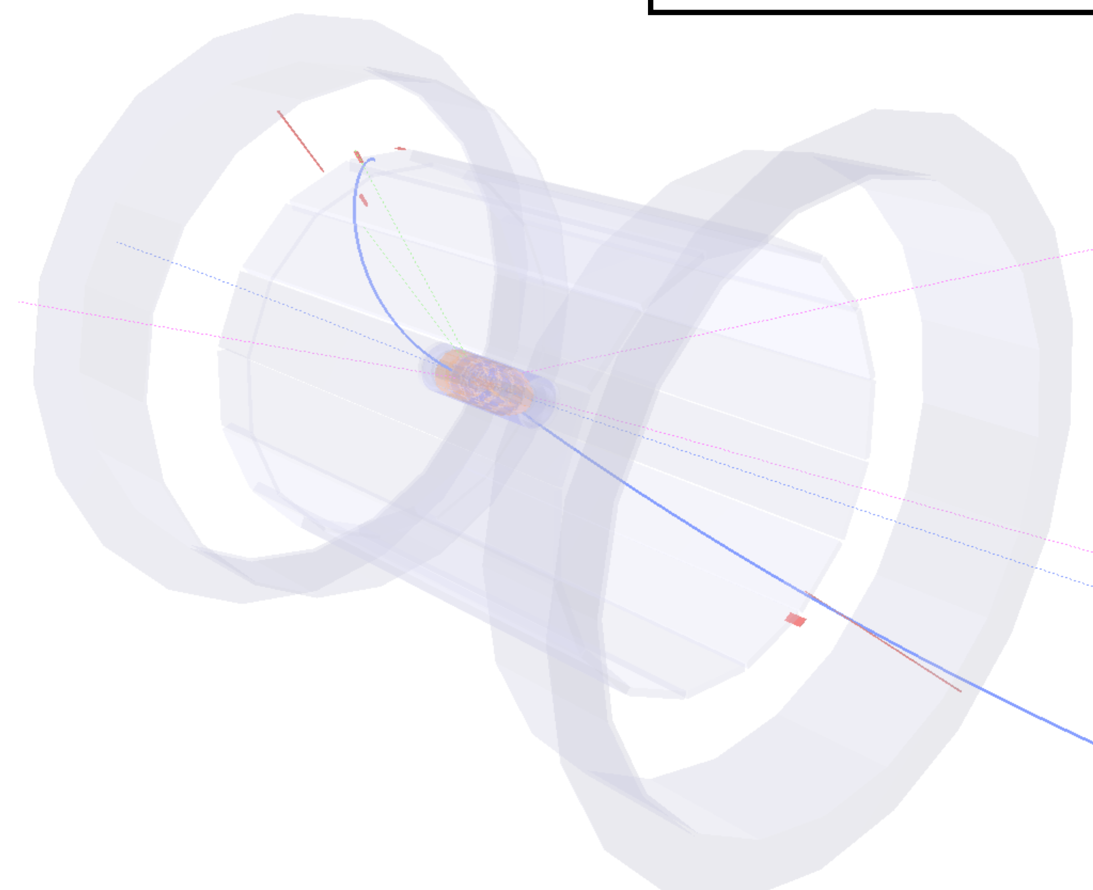
z-Vertex Trigger

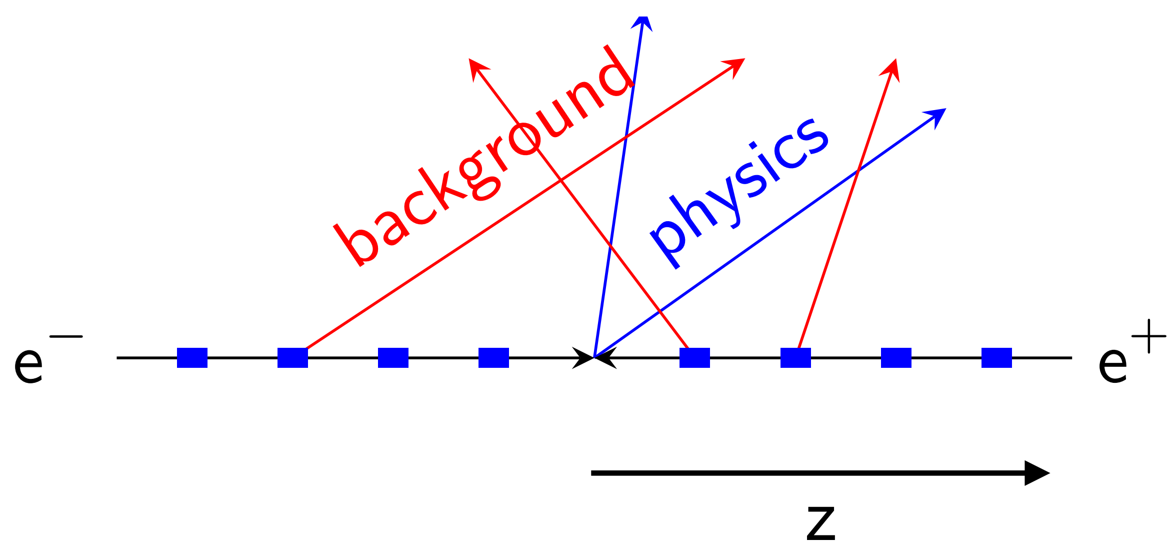
- Typical B-Meson trigger requires **3 tracks** (at least one in each hemisphere)
- A lot of interesting low-multiplicity events are missed

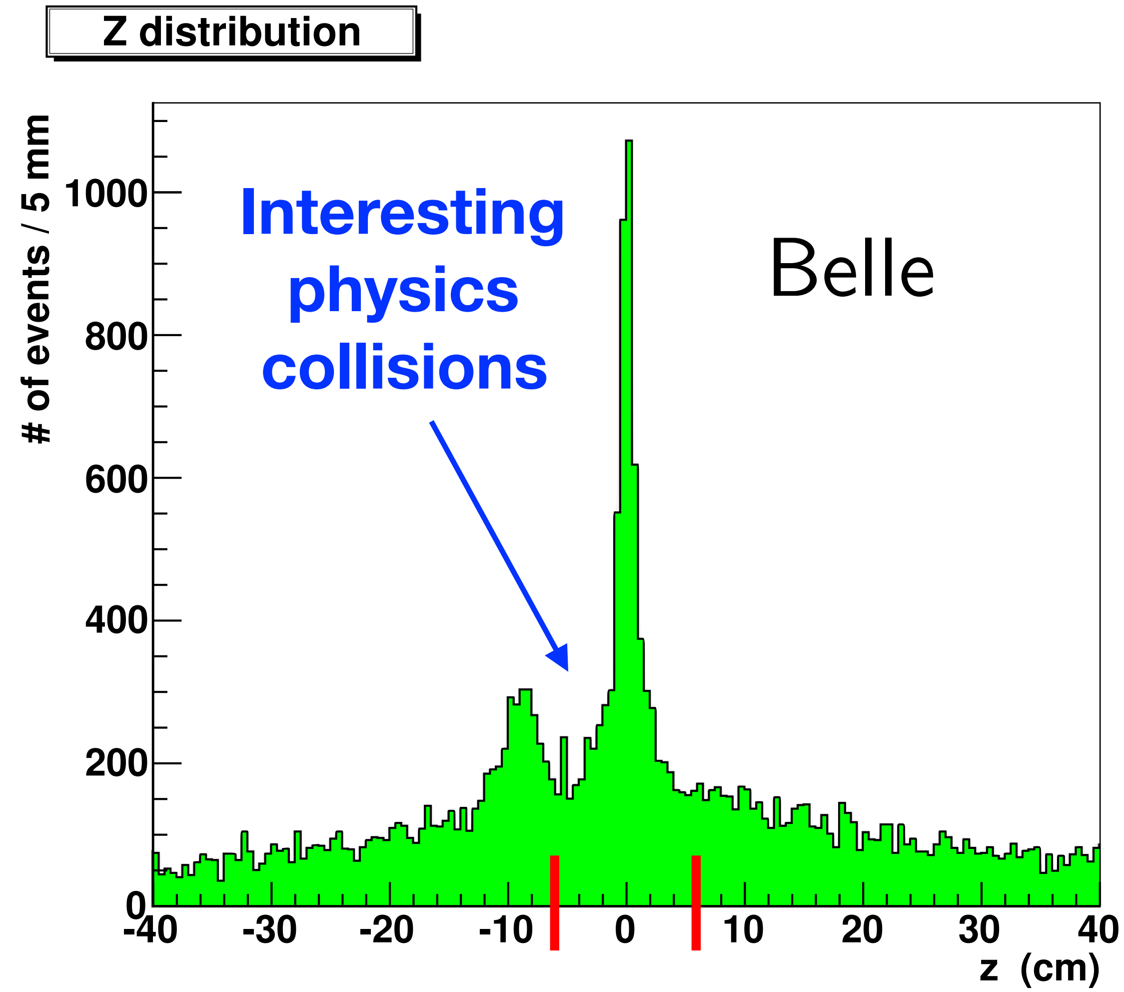




$$e^- e^+ \longrightarrow \tau^- \tau^+$$

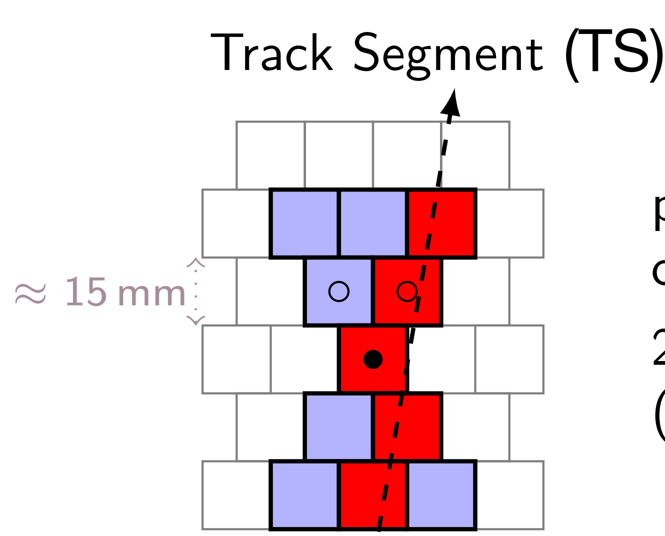






Use FPGA based L1 trigger with neural network to “learn” z direction from drift chamber input

Input:

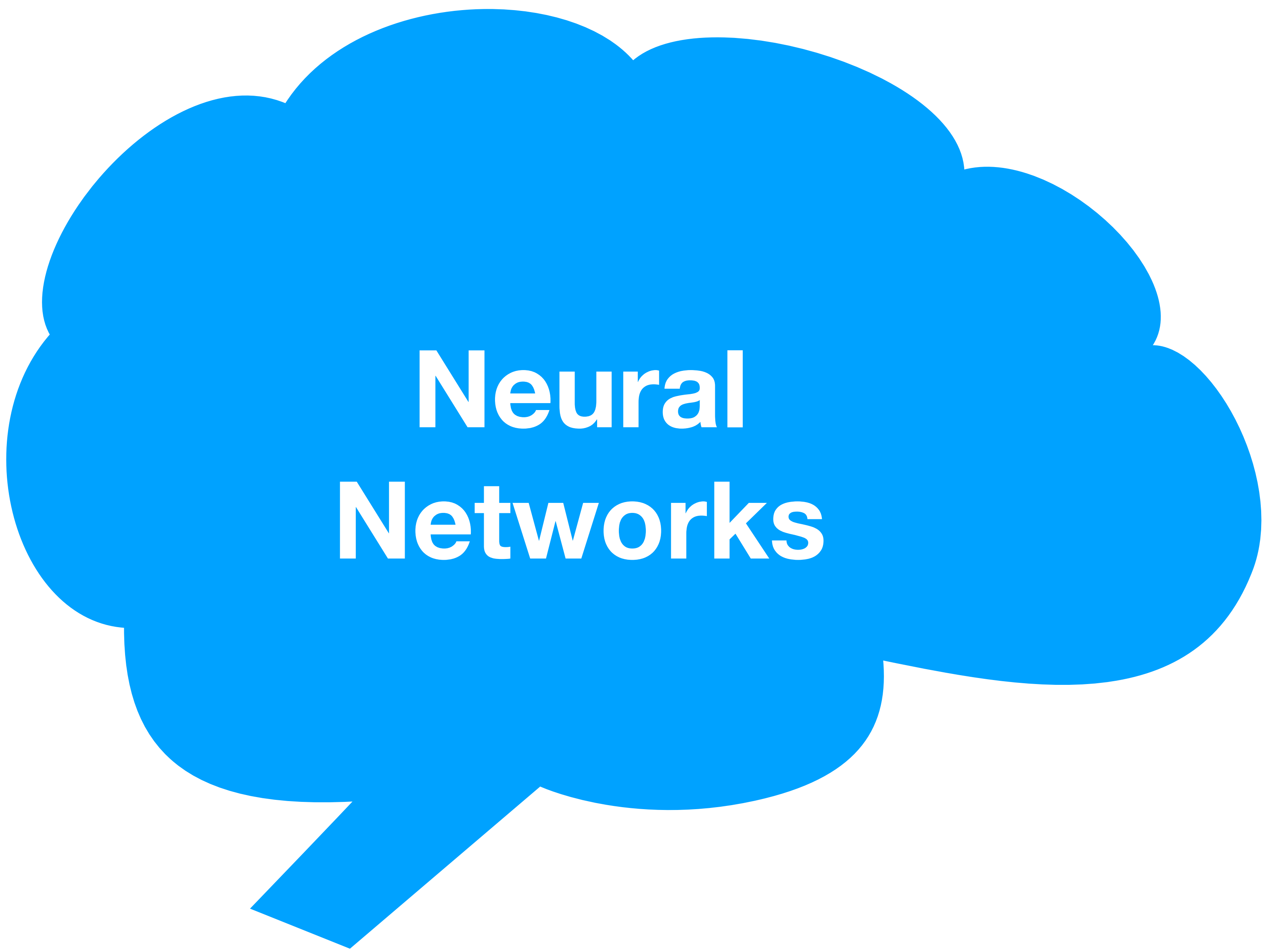


position and drift time of TS priority wires

2D track estimates (p_T, φ)

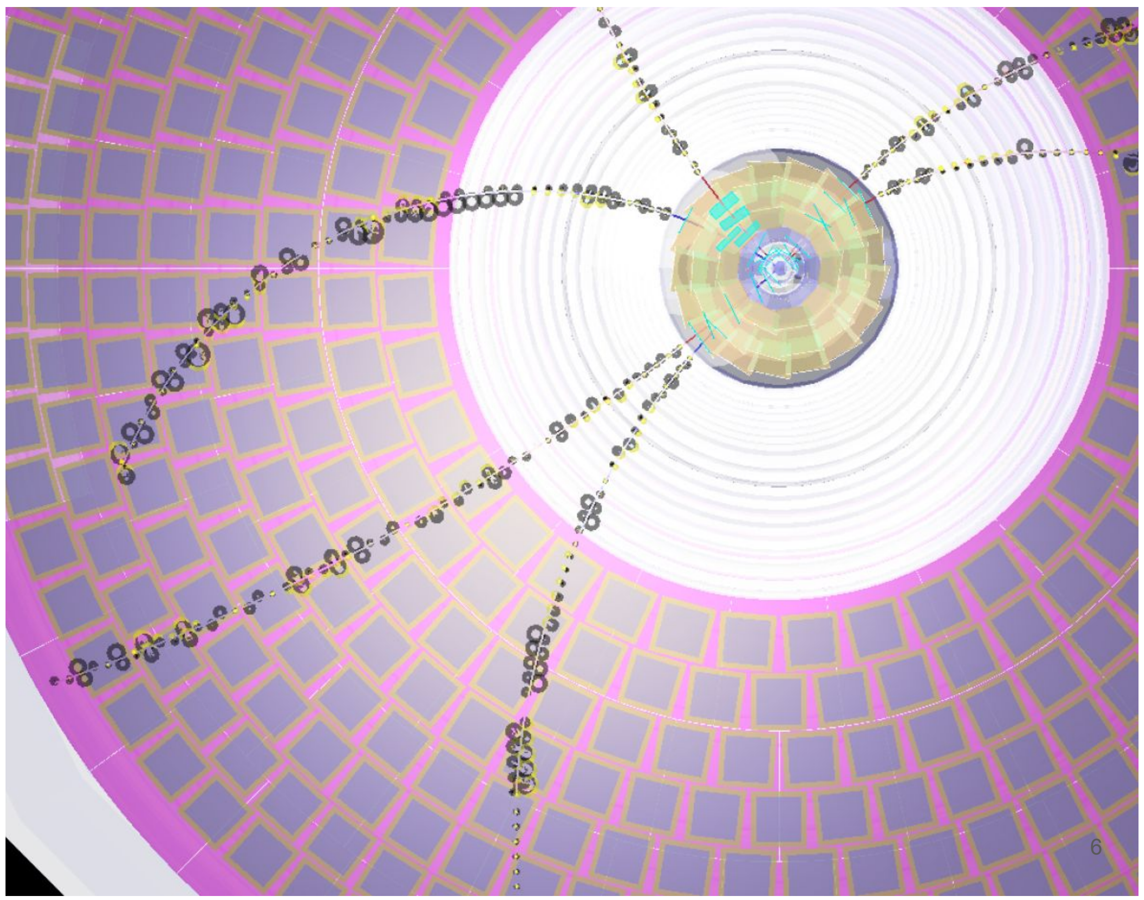
Output: z estimate

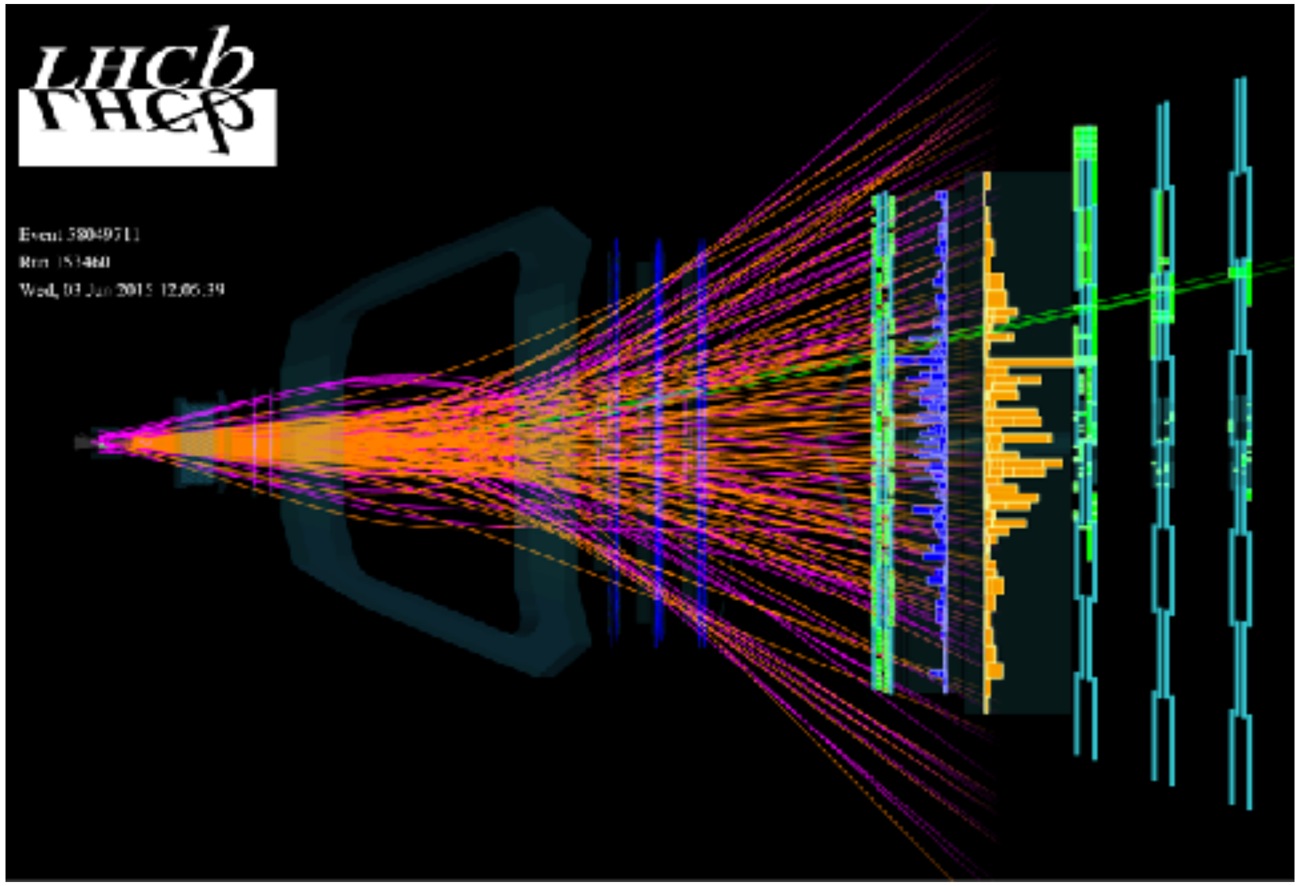
Plots: Sebastian Skambraks


Neural
Networks

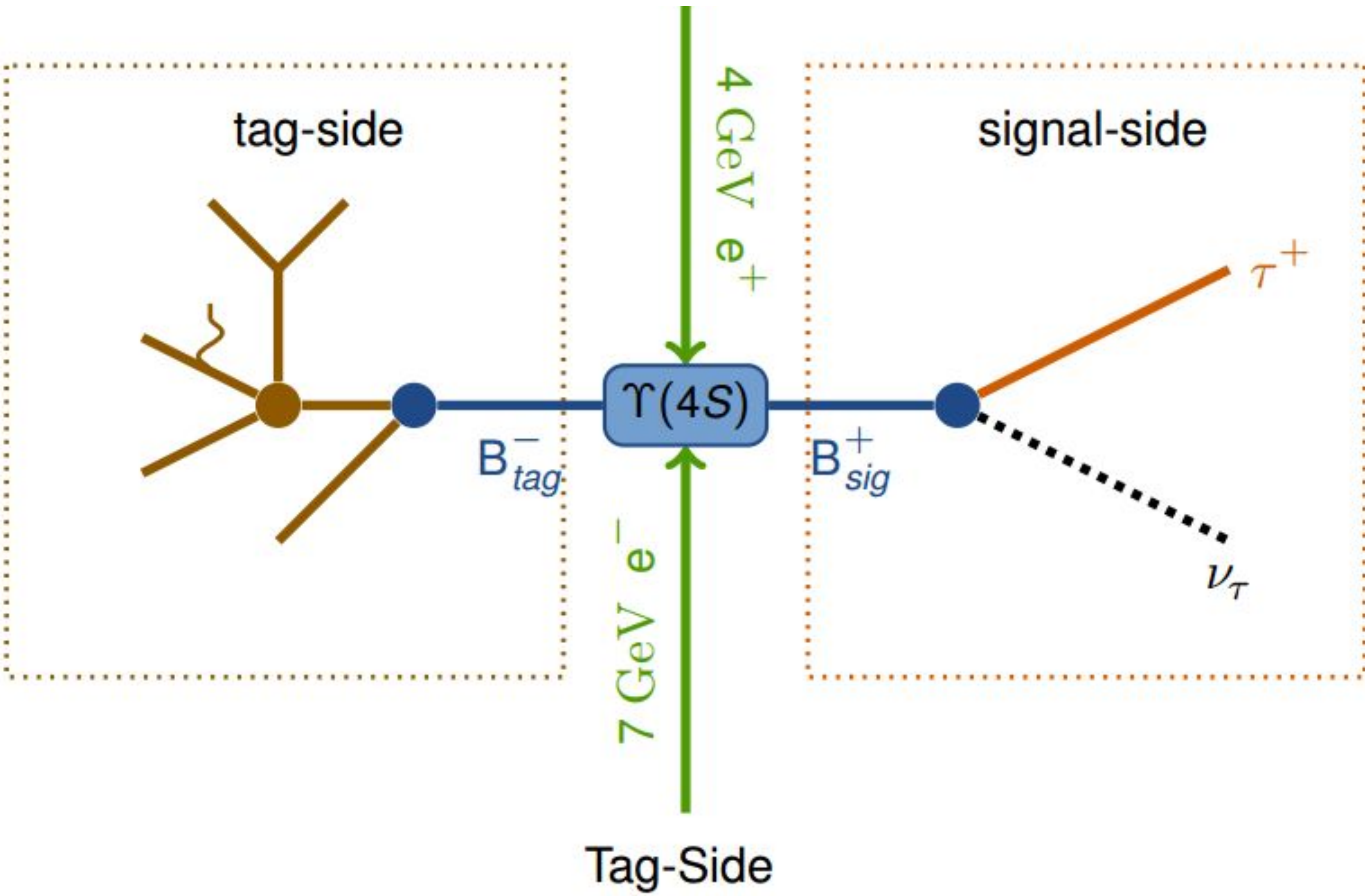
Neural Networks and Lepton colliders

- Fairly clean environment (even with beam background) and no pile-up



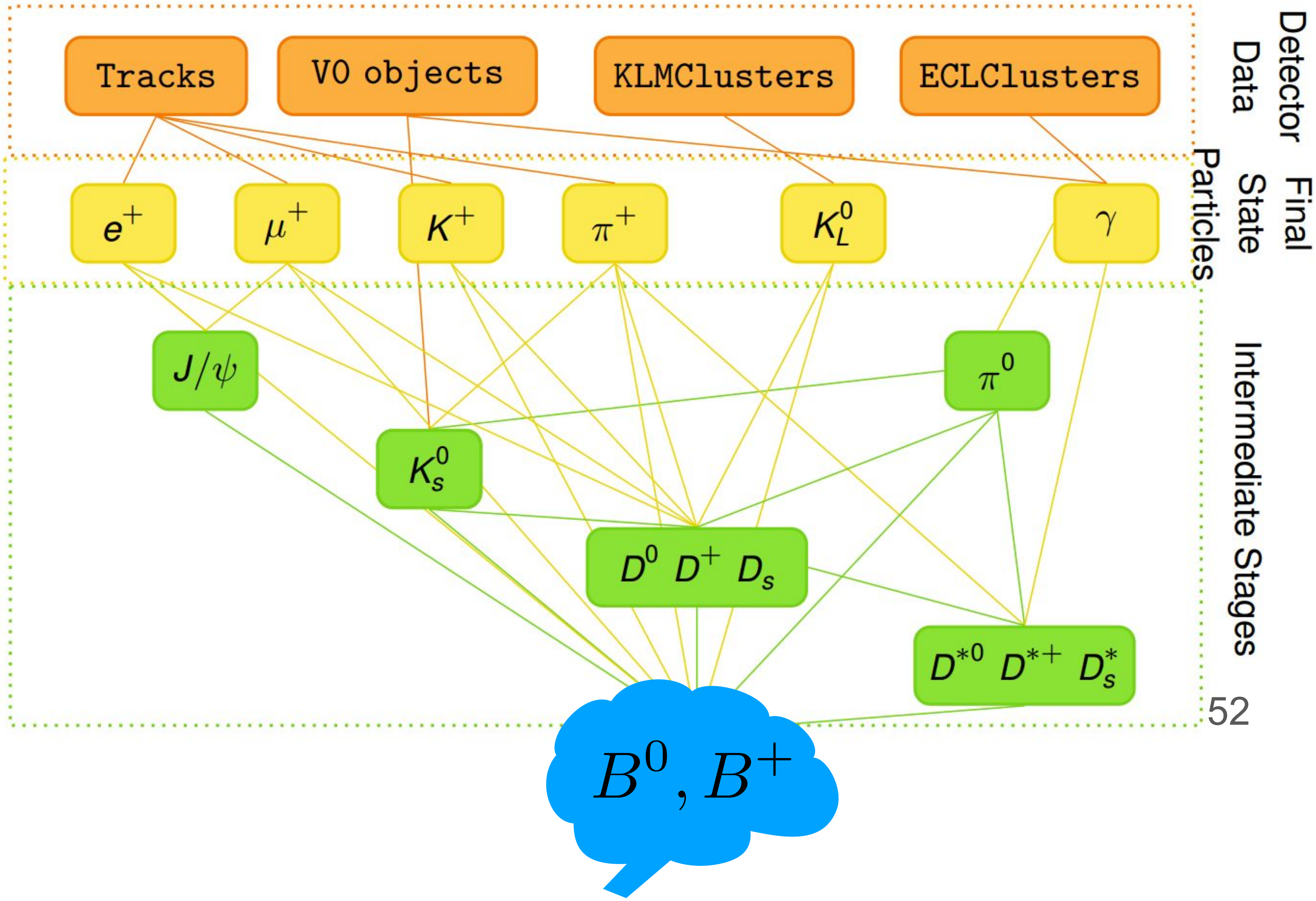


- Allows use of multivariate methods to implement a "Full Event Interpretation"



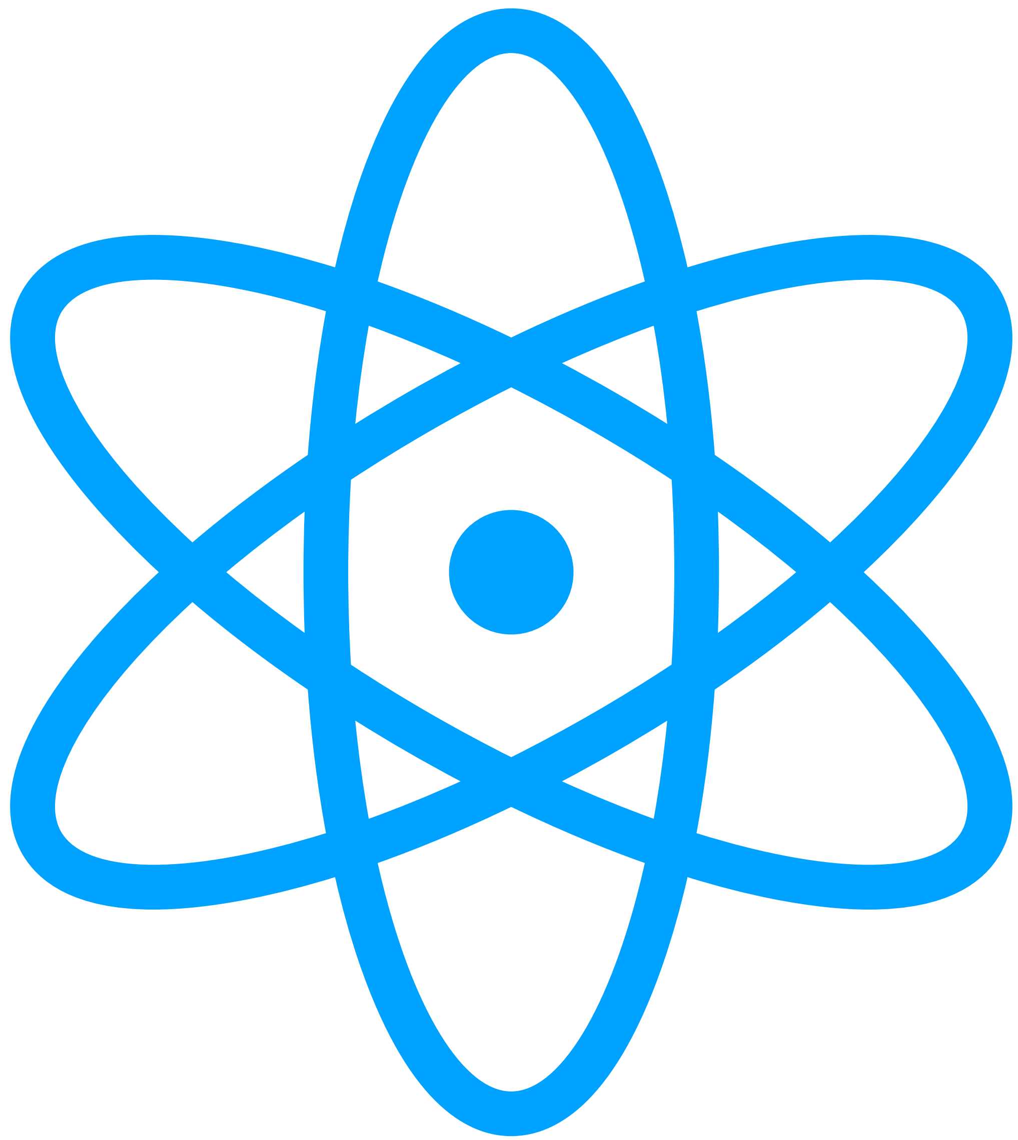
$$\vec{p}_{B_{\rm tag}} = -\vec{p}_{B_{\rm sig}} \longrightarrow$$

Allows one to reconstruct the missing Four-momentum on the **signal side**

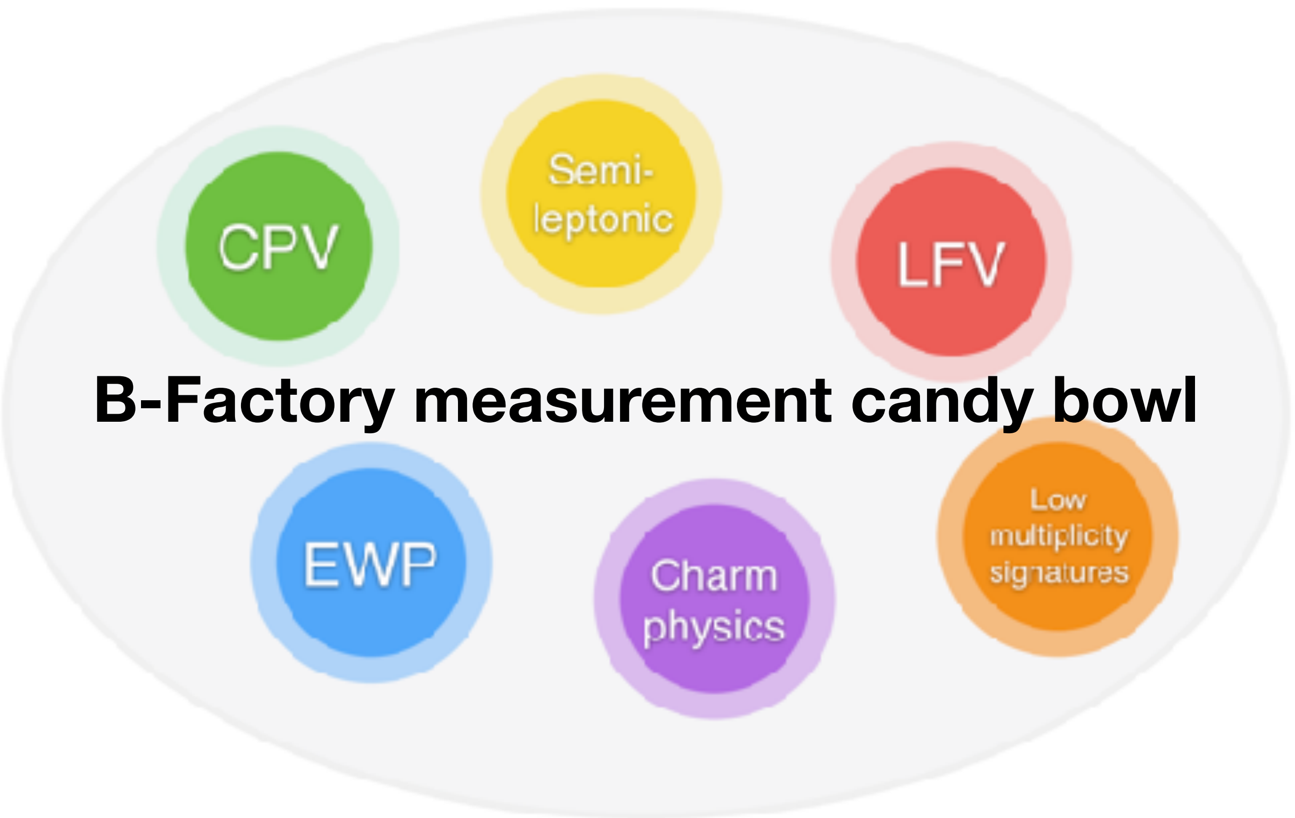


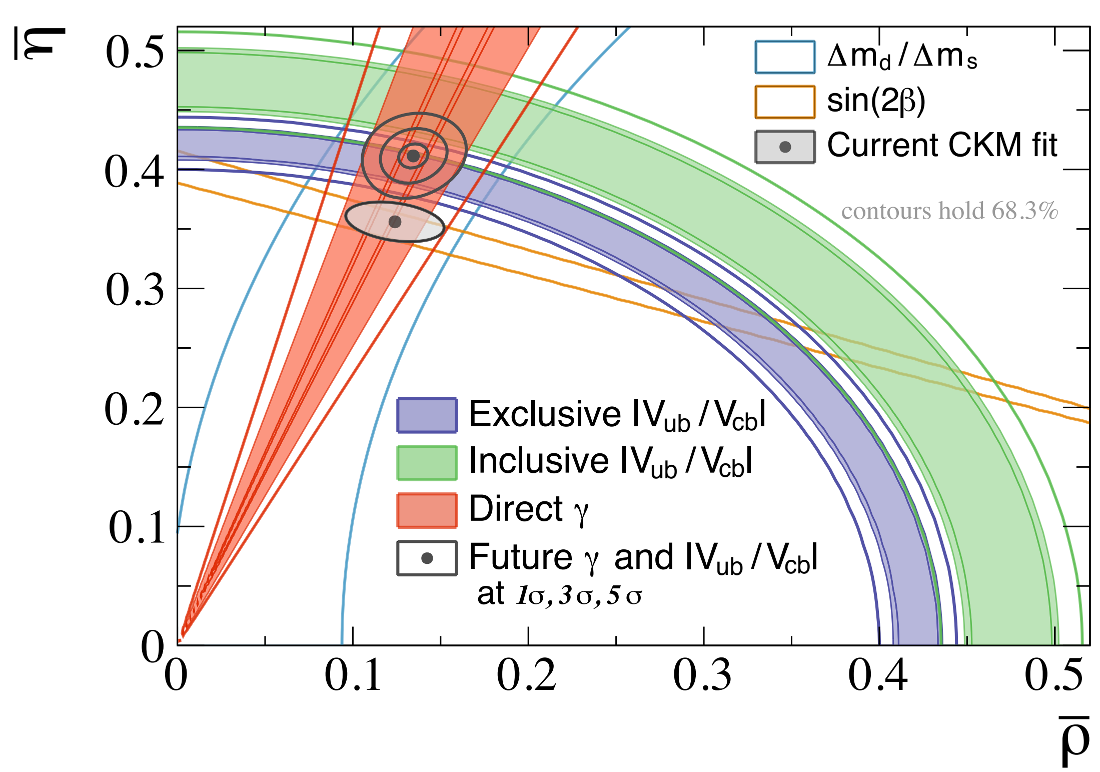
Reconstruct O(**1000-10000**) of hadronic and semileptonic modes, achieves an efficiency of about **O(1%)**

Physics

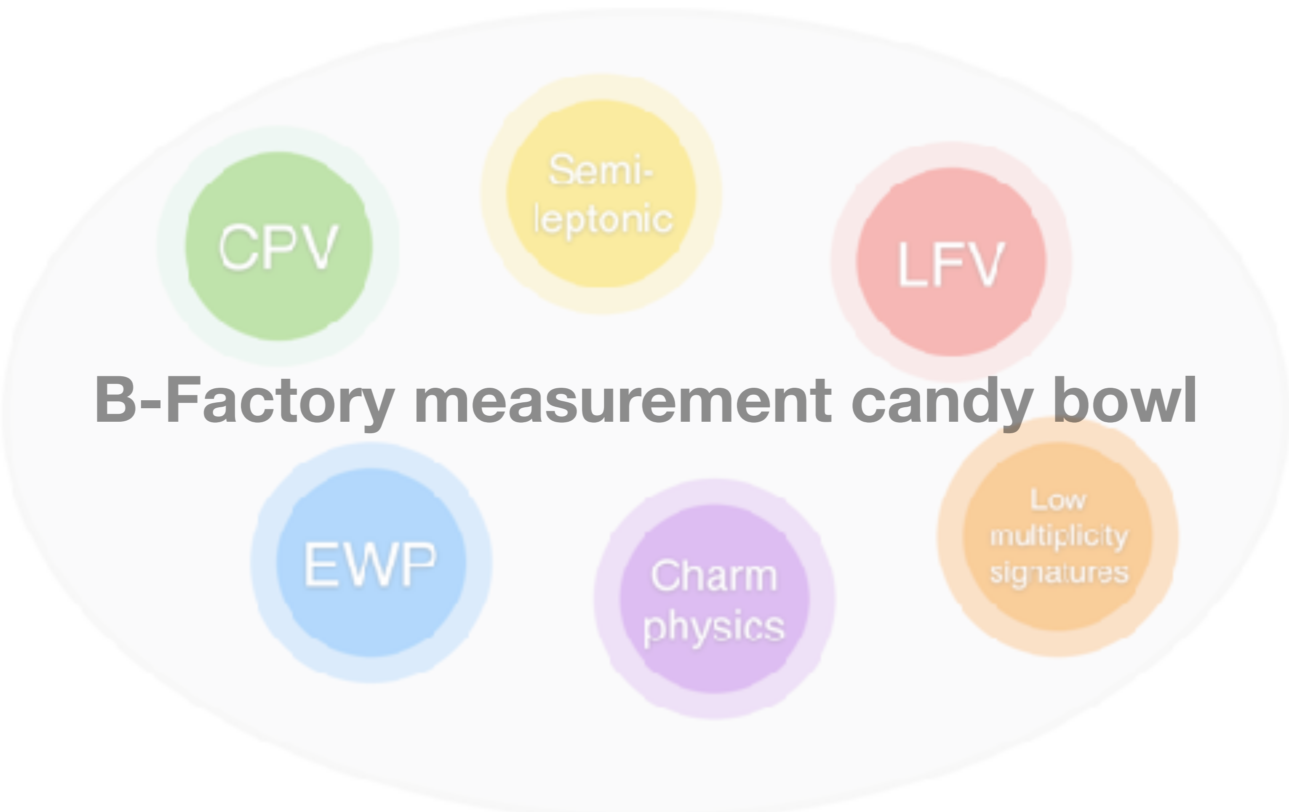


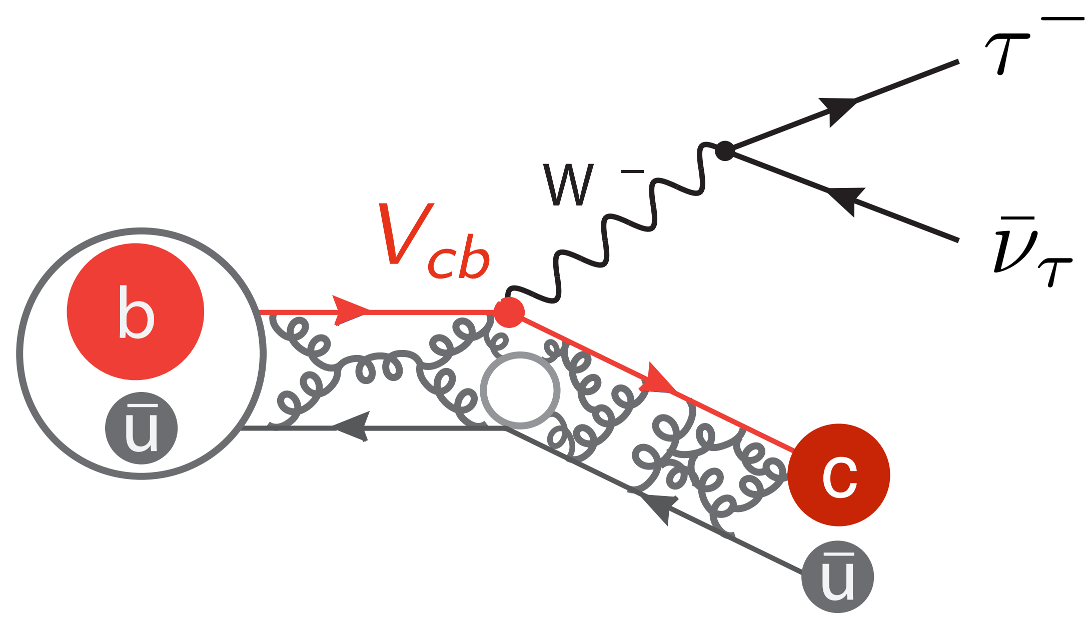
The big flavour questions and one anomaly

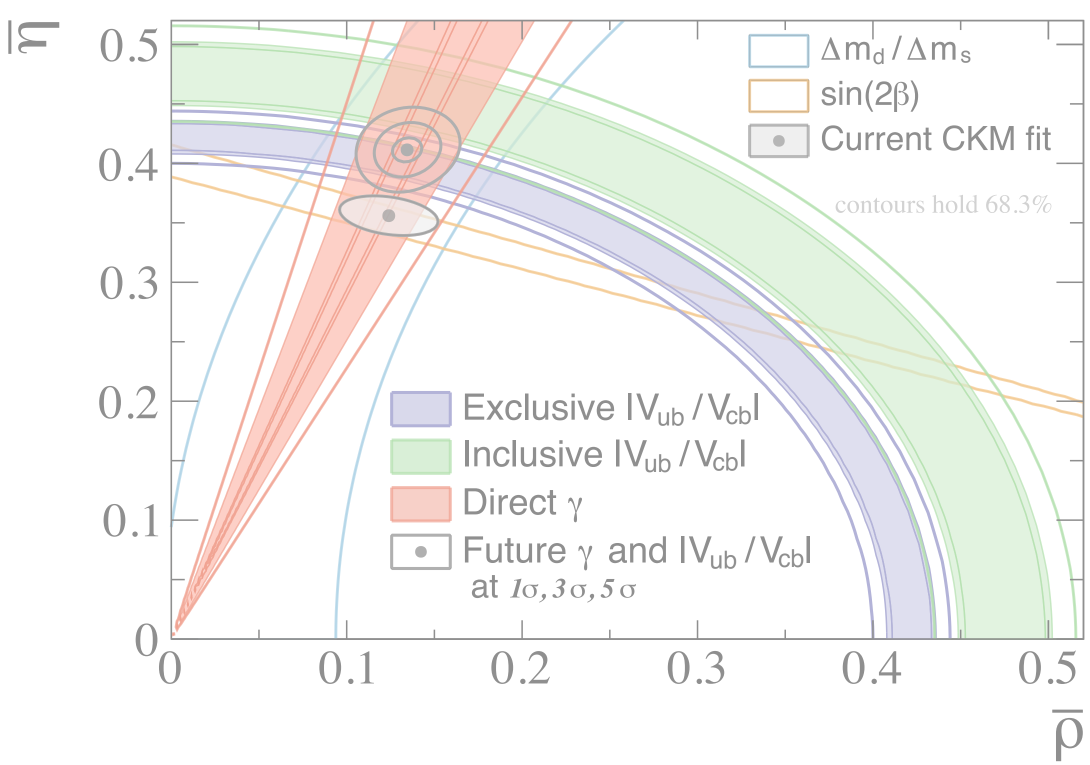


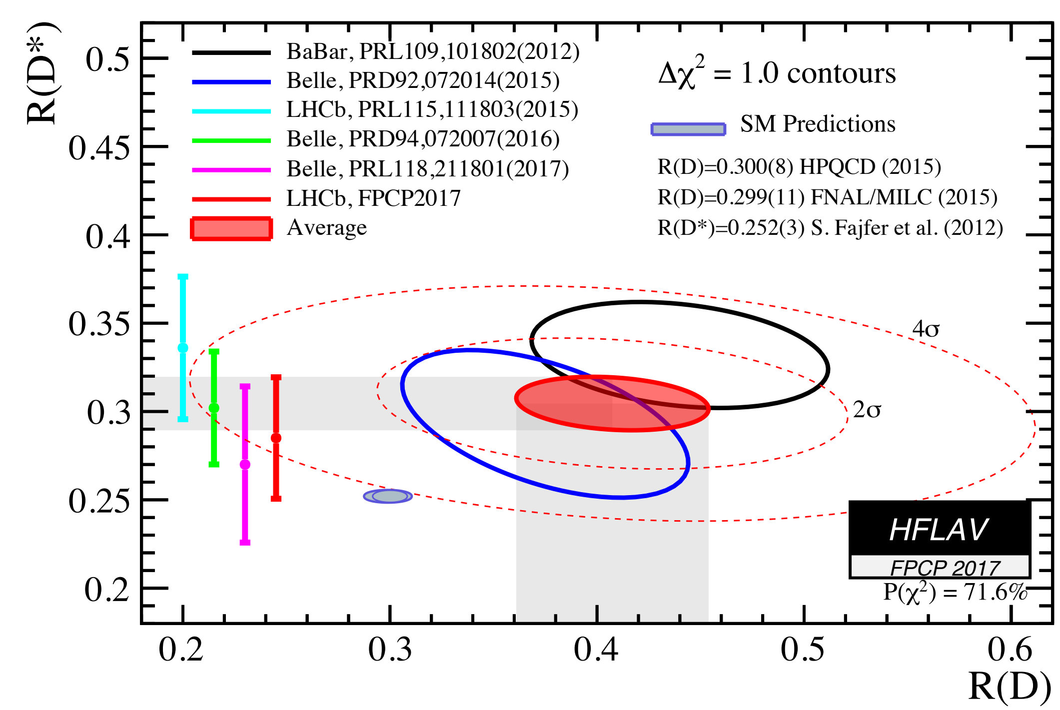


The big flavour questions and one anomaly

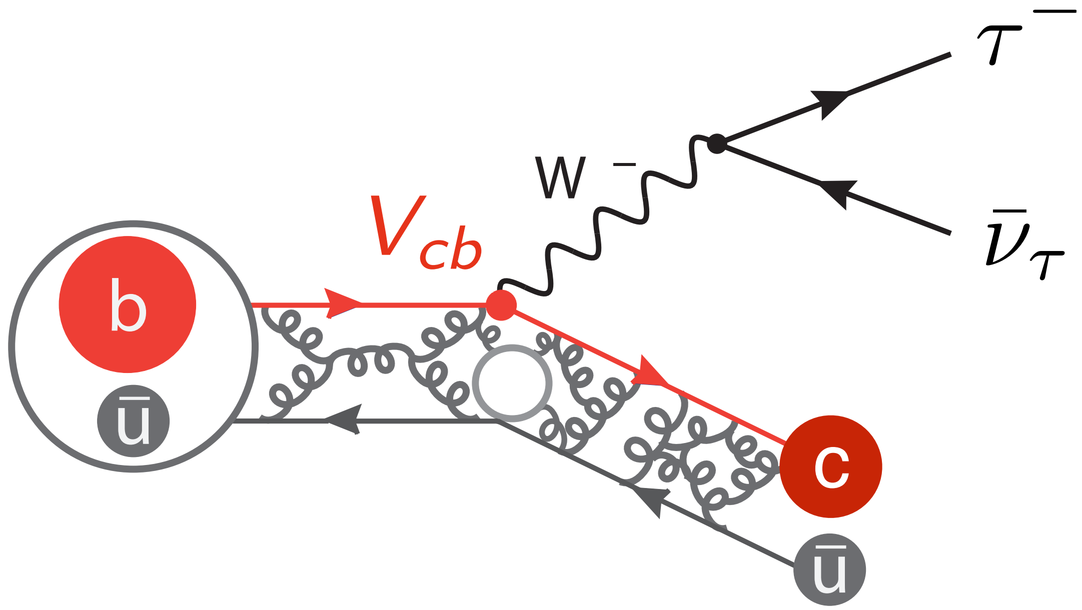




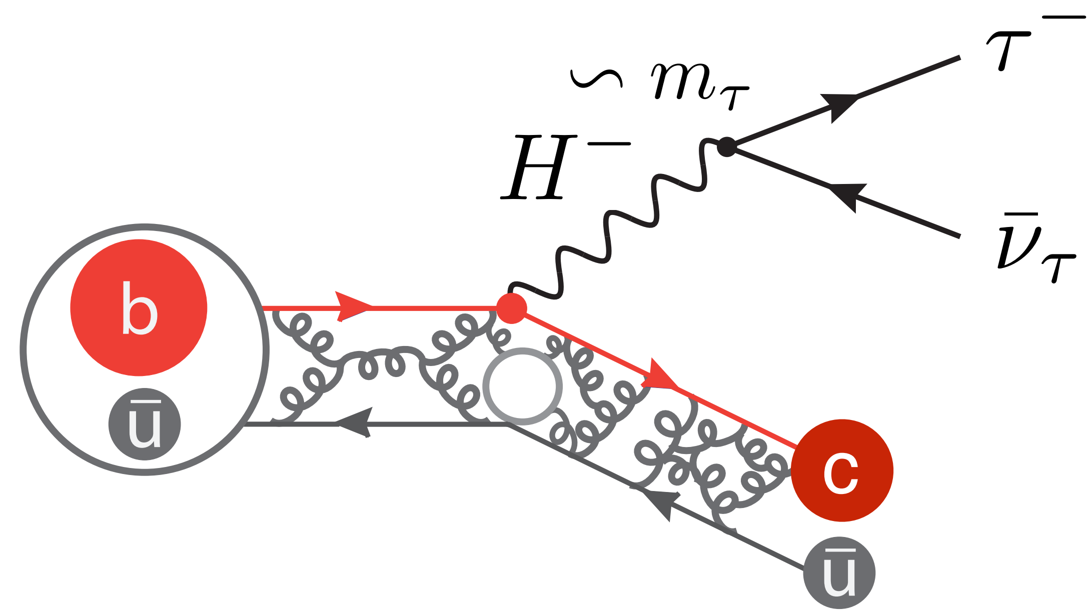




R(D/D*)



Decay in the Standard Model

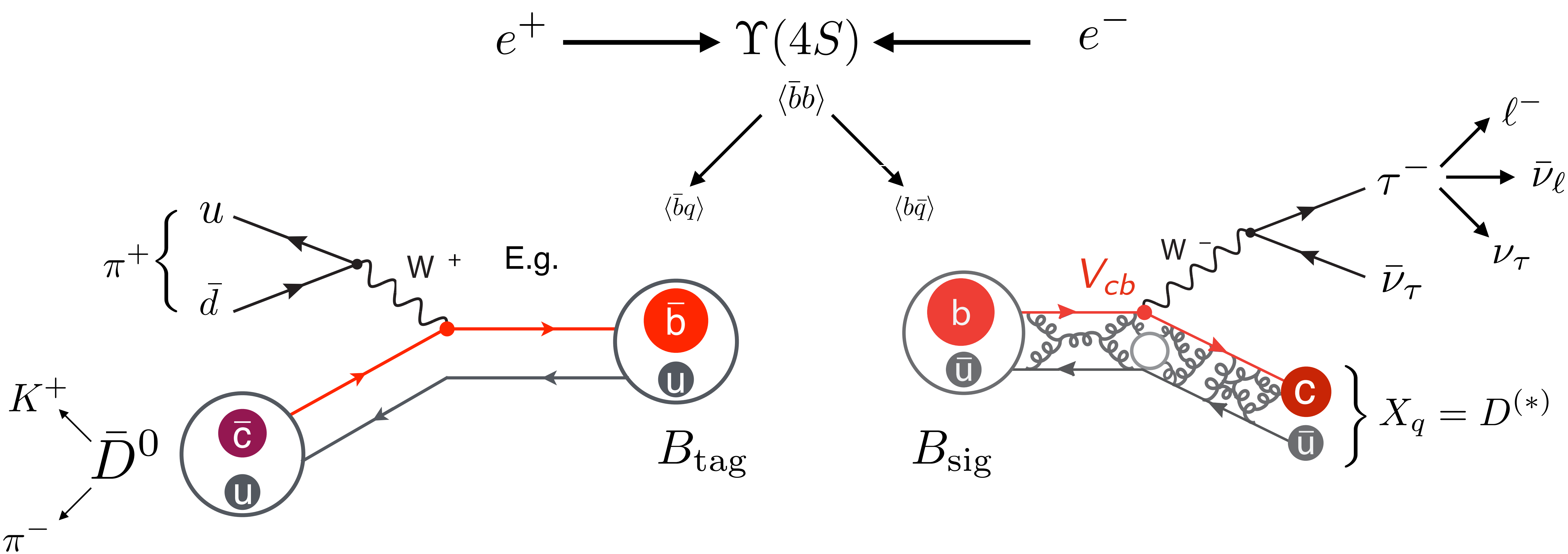


Decay with New Physics
e.g. with charged Higgs boson

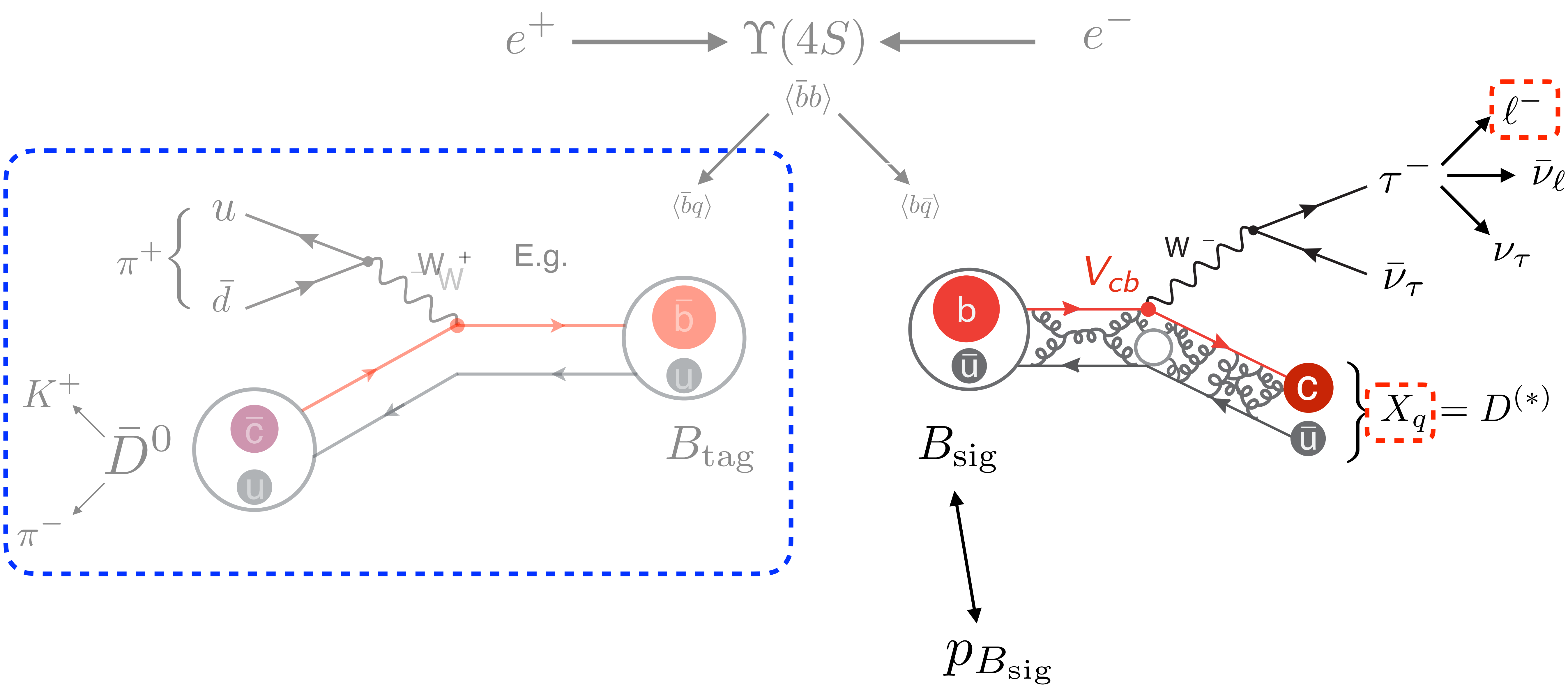
$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)}$$

Electron or Muon

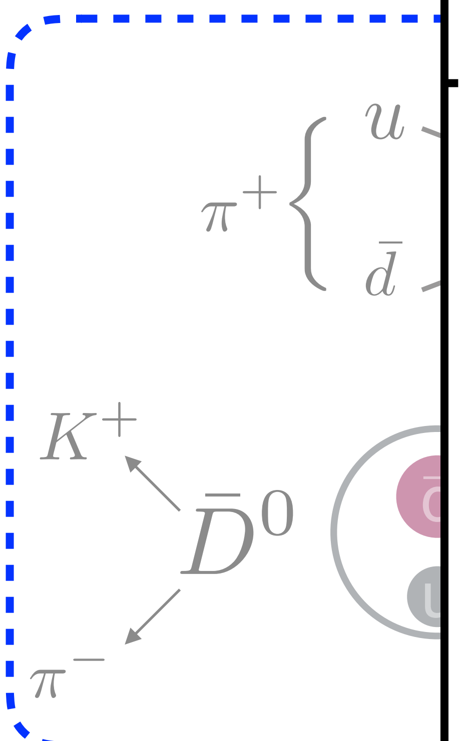
How does one measure R(D) or R(D*)?



How does one measure R(D) or R(D*)?

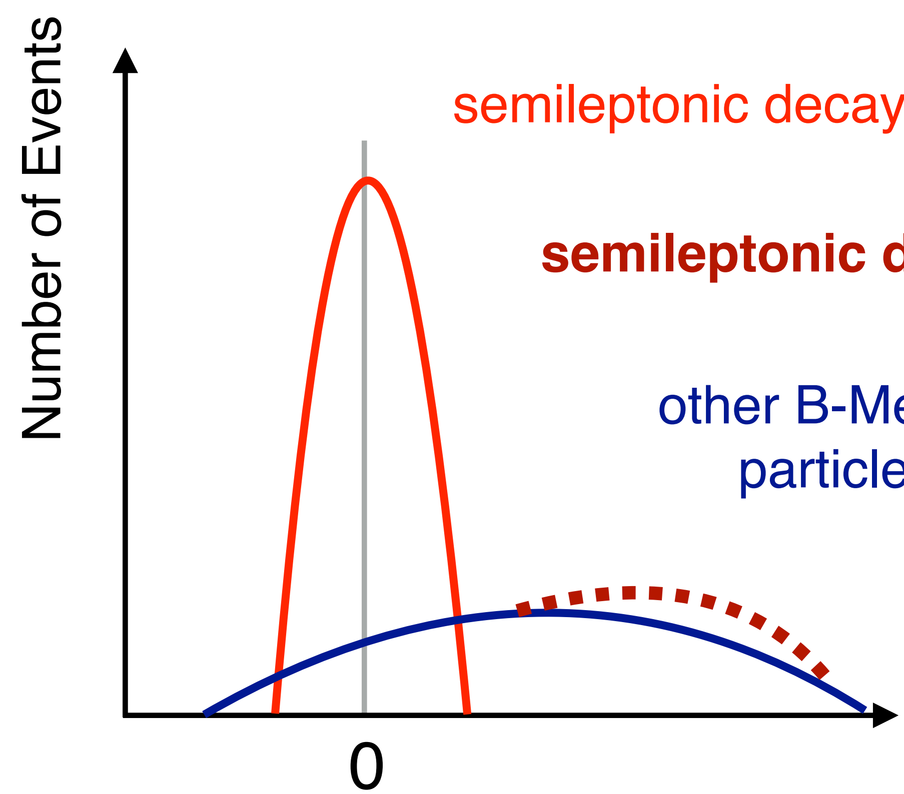


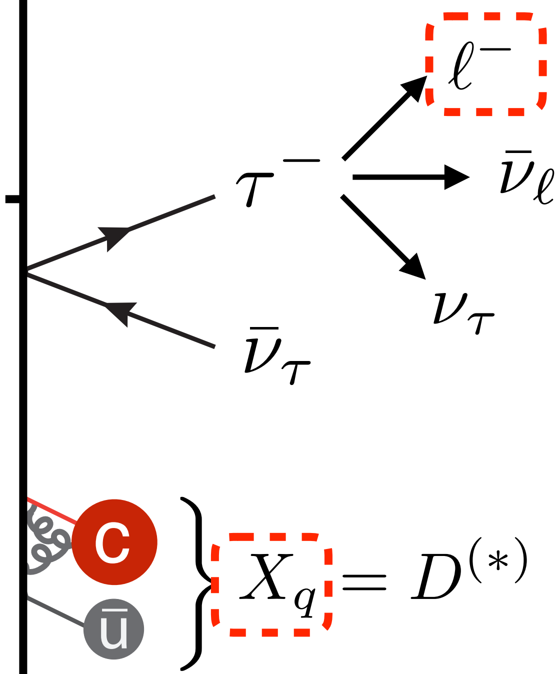
$$p_{\mathrm{miss}} = \big(\overbrace{p_{e^+e^-} - p_{\mathrm{tag}}}^{p_{B_{\mathrm{sig}}}} - p_{X_q} - p_\ell\big)$$



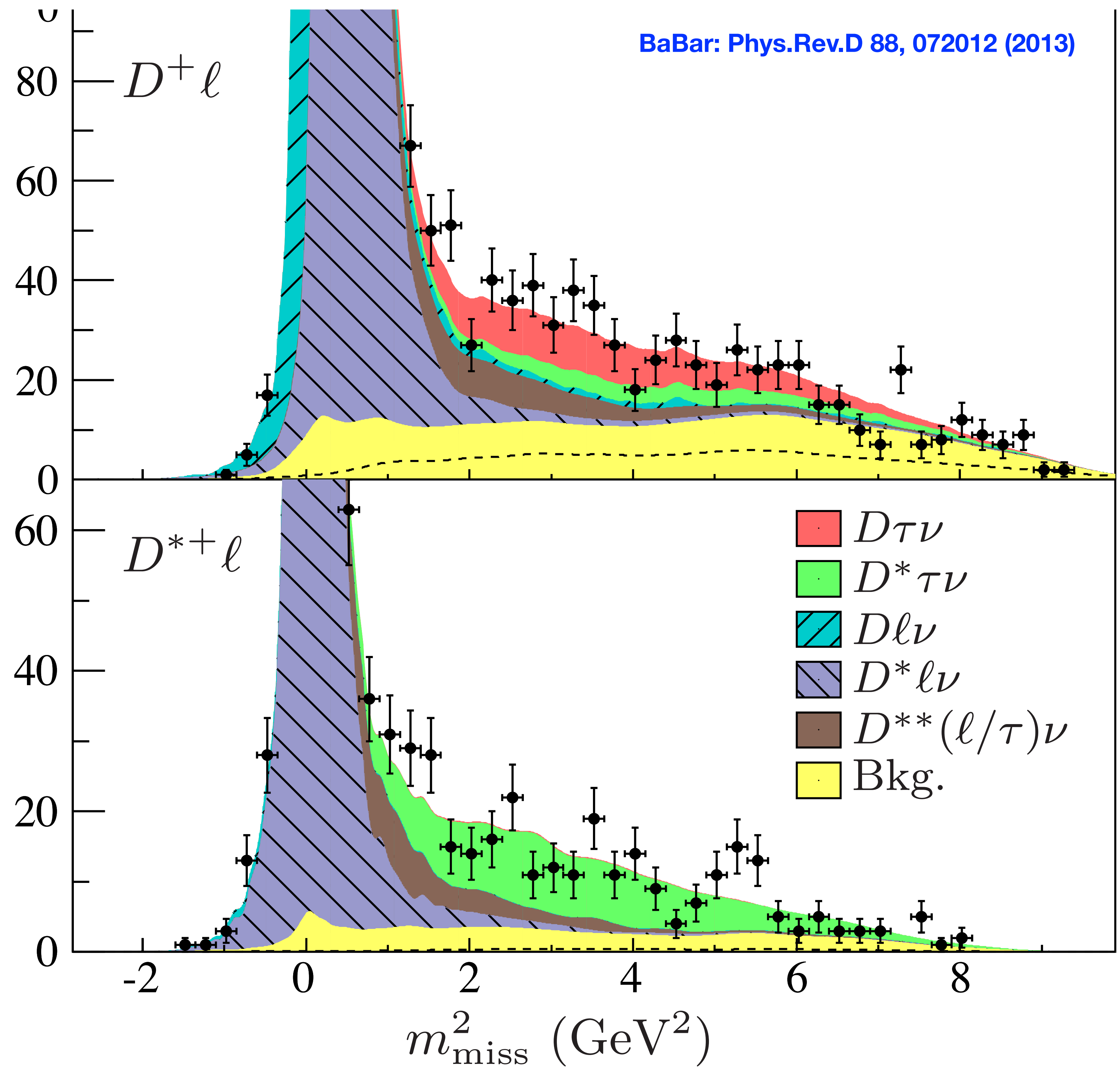
Separation of Signal and Background:

$$p^2_{\mathrm{miss}} = m^2_{\mathrm{miss}}$$



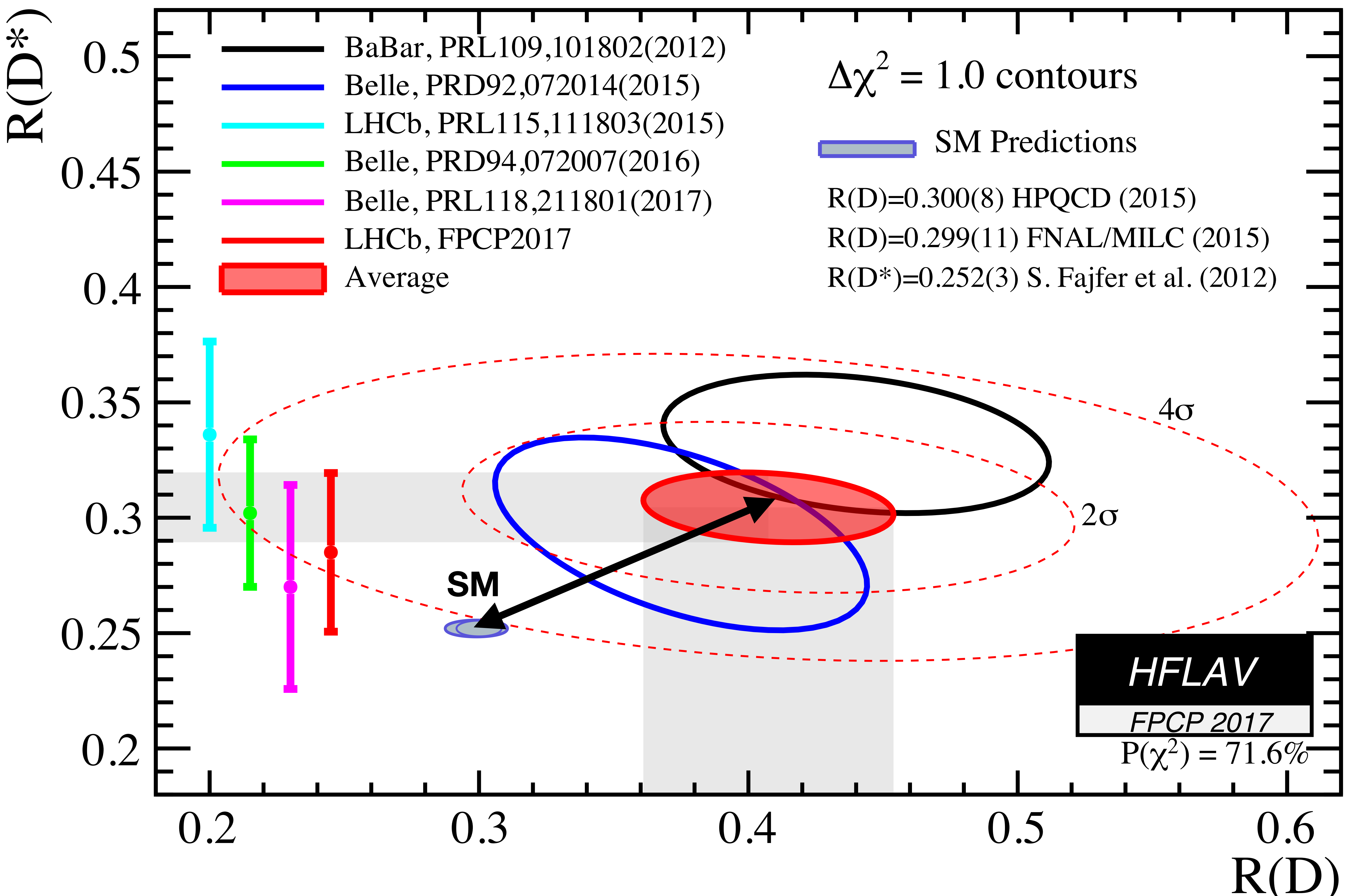


Light leptons: $p_\nu = \boxed{p_{\mathrm{miss}}} = \left(p_{e^+e^-} - p_{\mathrm{tag}} - p_{X_q} - p_\ell\right)$



BaBar: Phys.Rev.D 88, 072012 (2013)
$D^+\ell$
$D^{*+}\ell$
$D\tau\nu$
$D^*\tau\nu$
$D\ell\nu$
$D^*\ell\nu$
$D^{**}(\ell/\tau)\nu$
Bkg.
$m^2_{\rm miss}$ (GeV^2)

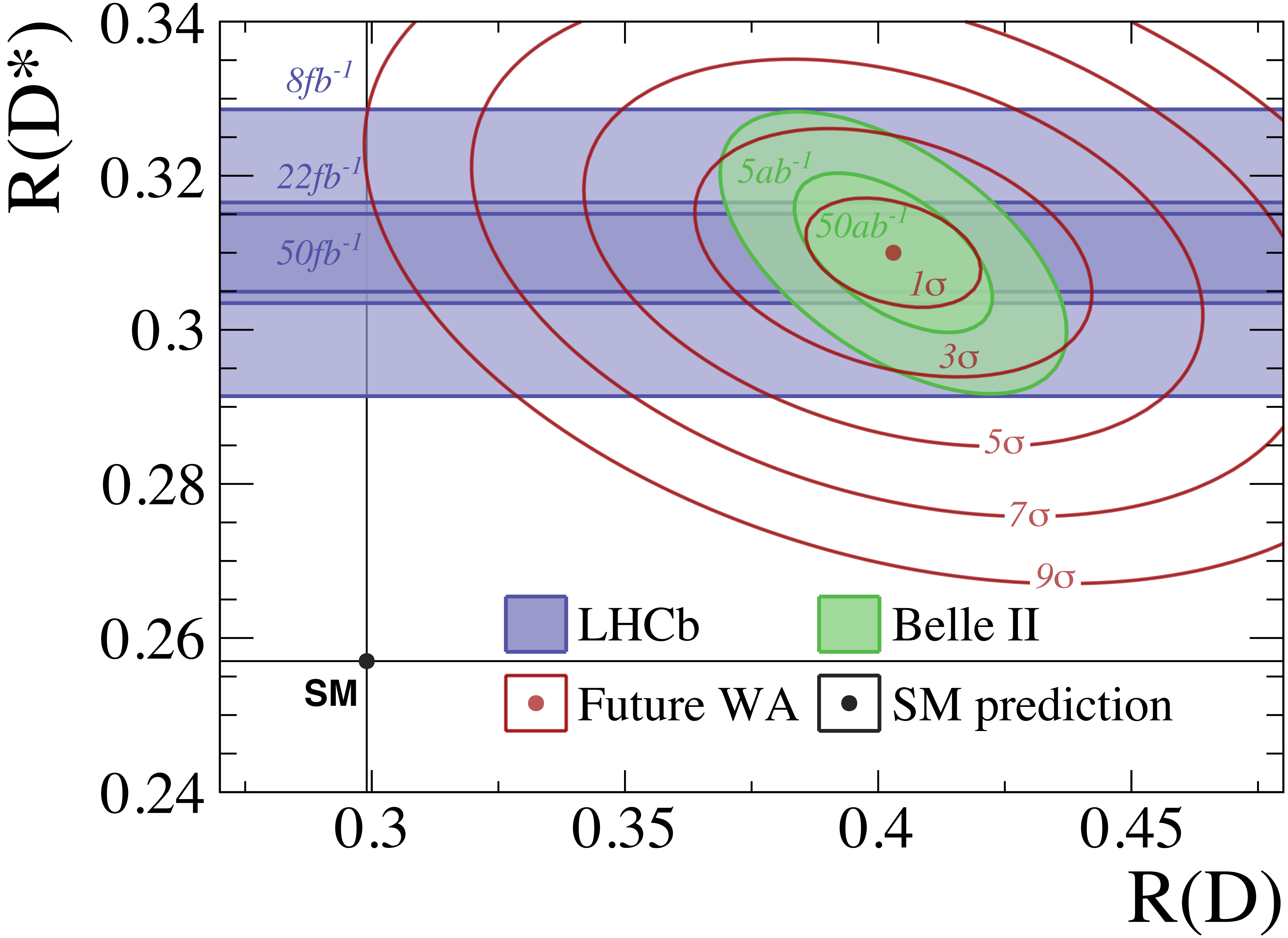
Plot: HFLAV 2017

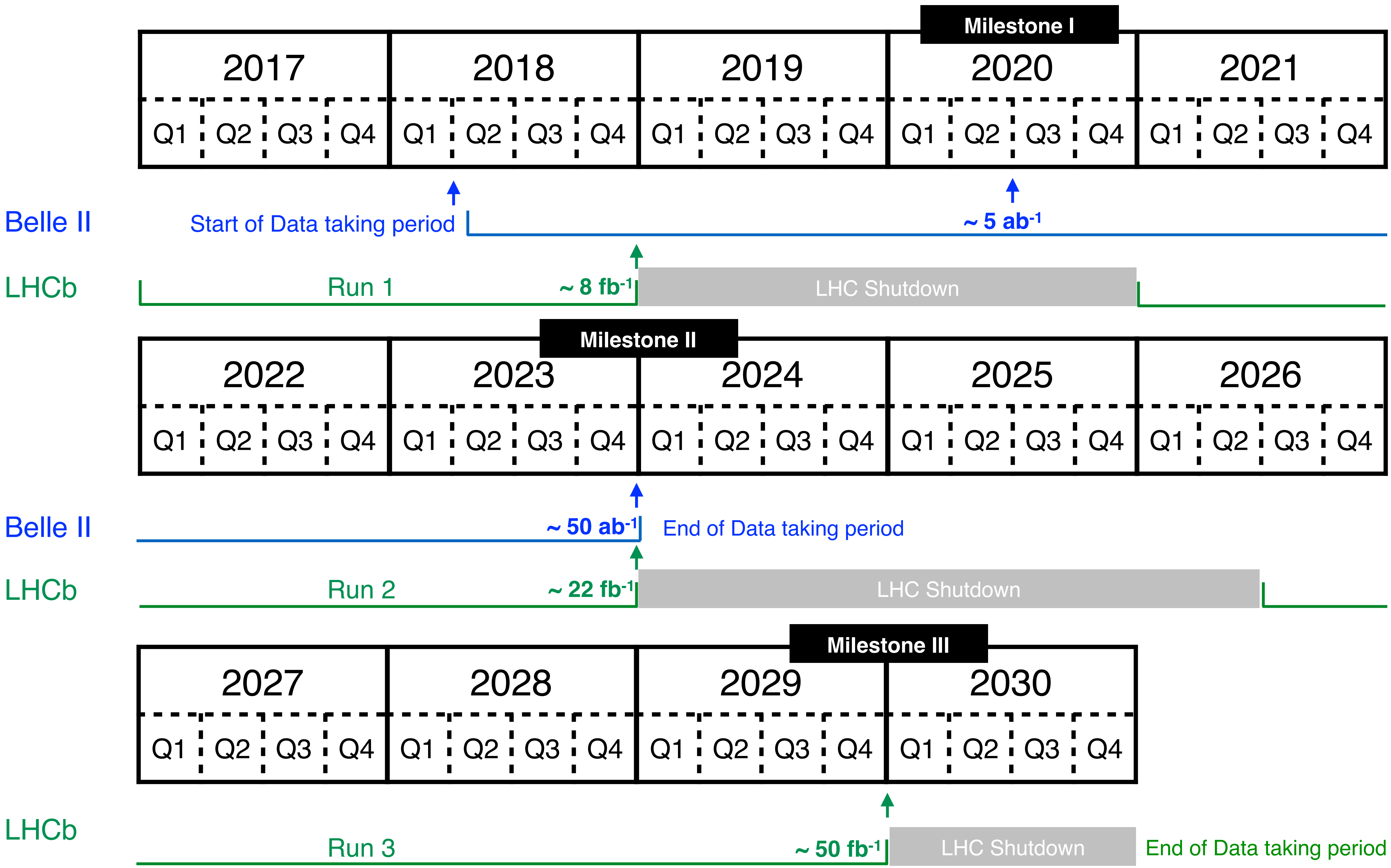


$R(D)_{\rm SM} = 0.299 \pm 0.003 \qquad R(D^*)_{\rm SM} = 0.257 \pm 0.003$

For SM prediction see also: FB et al, Phys. Rev. D 95, 115008 (2017)

Plot: FB, J. Albrecht M. Kenzie S. Reichert D. M. Straub A. Tully
(To appear)





Milestone I
2017
2018
2019
2020
2021
Q1 Q2 Q3 Q4
Belle II
Start of Data taking period
~ 5 ab-1
LHCb
Run 1
~ 8 fb-1
LHC Shutdown
Milestone II
2022
2023
2024
2025
2026
Belle II
~ 50 ab-1
End of Data taking period
LHCb
Run 2
~ 22 fb-1
LHC Shutdown
Milestone III
2027
2028
2029
2030
LHCb
Run 3
~ 50 fb-1
LHC Shutdown
End of Data taking period

Additional Material & Slides

KEKB → SuperKEKB

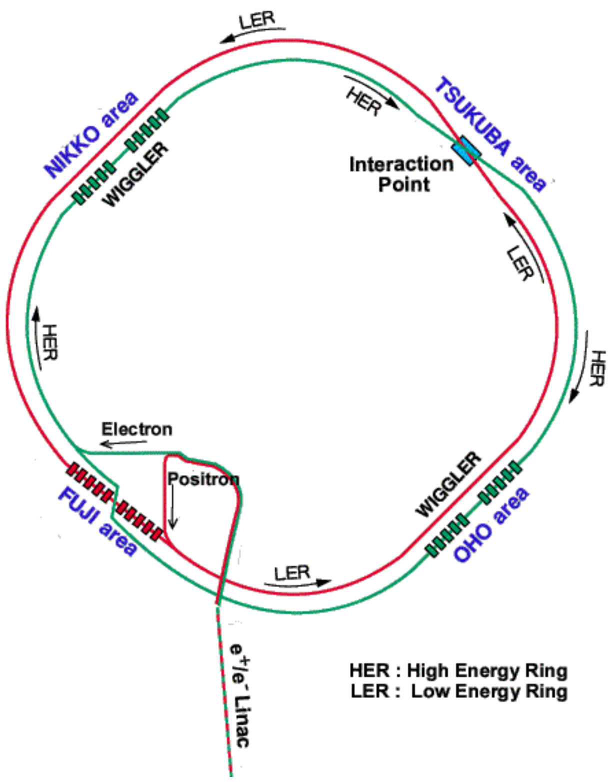
Lorentz factor, beam current, beam-beam parameter

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \, \zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

beam size aspect ratio, vertical β function, geometric factors

$$\zeta_{\pm y} \sim \sqrt{\beta^* / \epsilon} \longleftarrow \text{emittance}$$

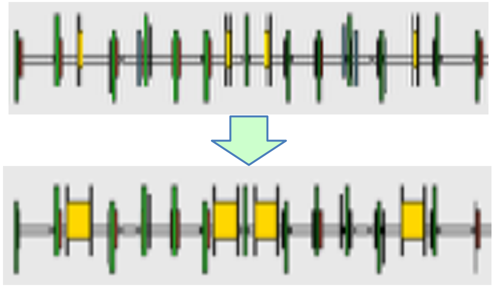
β function



LER / HER	KEKB	**SuperKEKB**
Energy [GeV]	3.5 / 8	4.0 / 7.0
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**
β_x^* [mm]	1200	**32 / 25**
$I_\pm$ [A]	1.64 / 1.19	**3.6 / 2.6**
$\zeta_{\pm y}$	0.129 / 0.09	**0.09 / 0.09**
ϵ [nm]	18 / 24	**3.2 / 4.6**
# of bunches	1584	2500
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	80

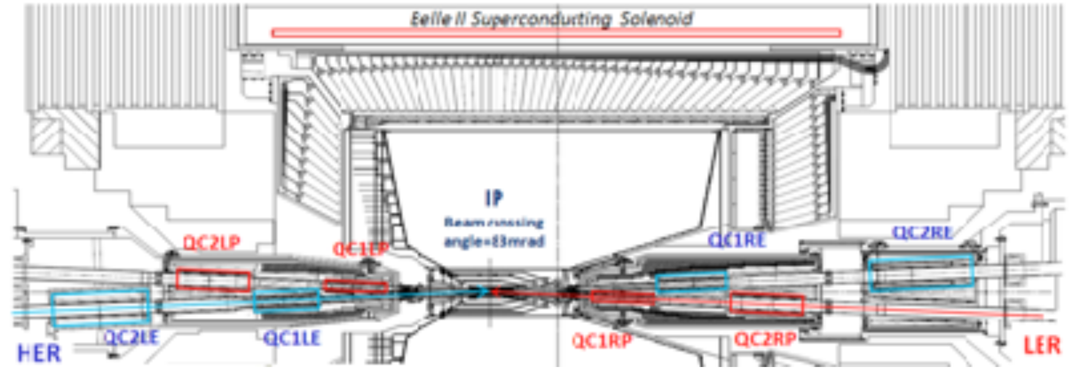
KEKB → SuperKEKB

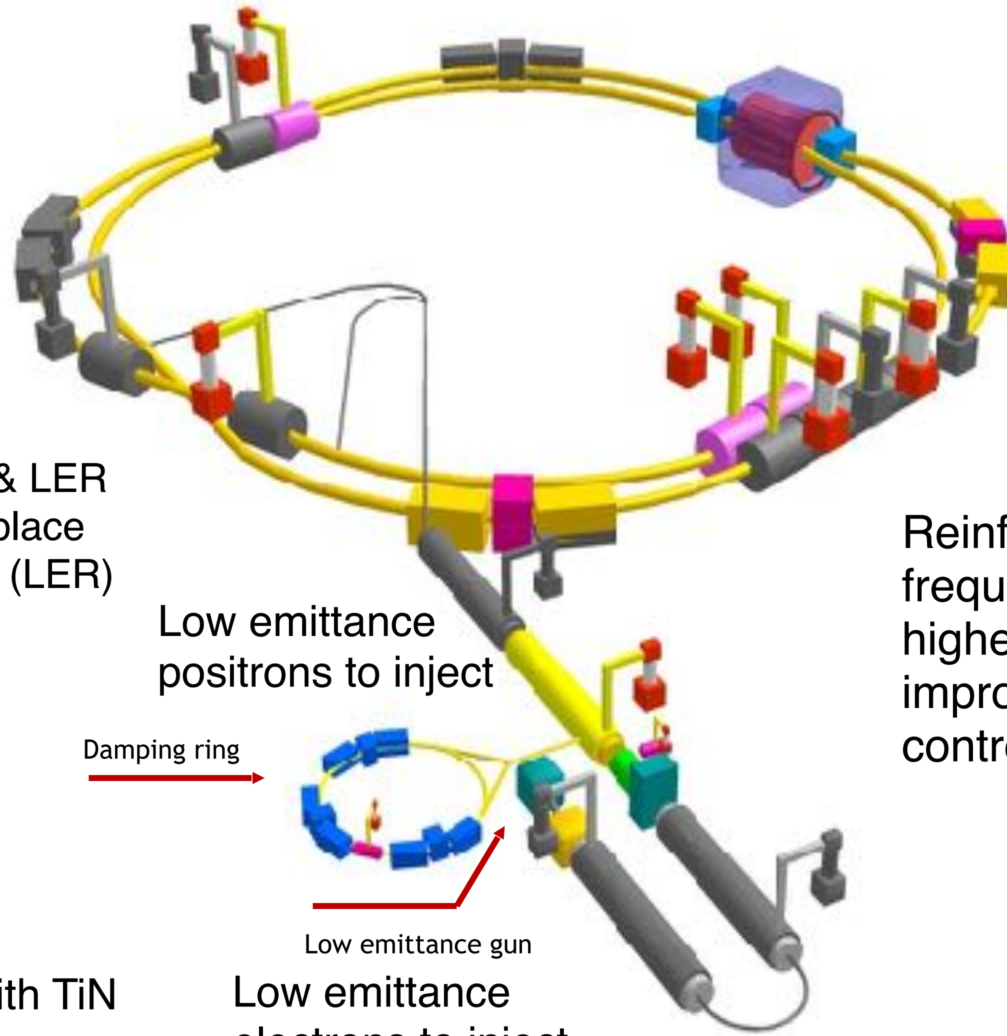
Redesign the lattices of HER & LER to squeeze the emittance. Replace short dipoles with longer ones (LER)



Replaced old beam pipes with TiN coated beam pipes with antechambers

New superconducting final focusing magnets near the IP



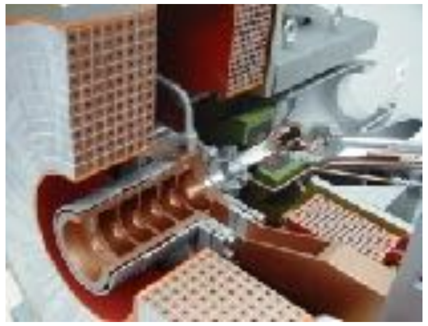


Low emittance positrons to inject

Low emittance electrons to inject

Reinforced RF (radio frequency) system for higher beam currents, improved monitoring & control system

Upgrade positron capture section



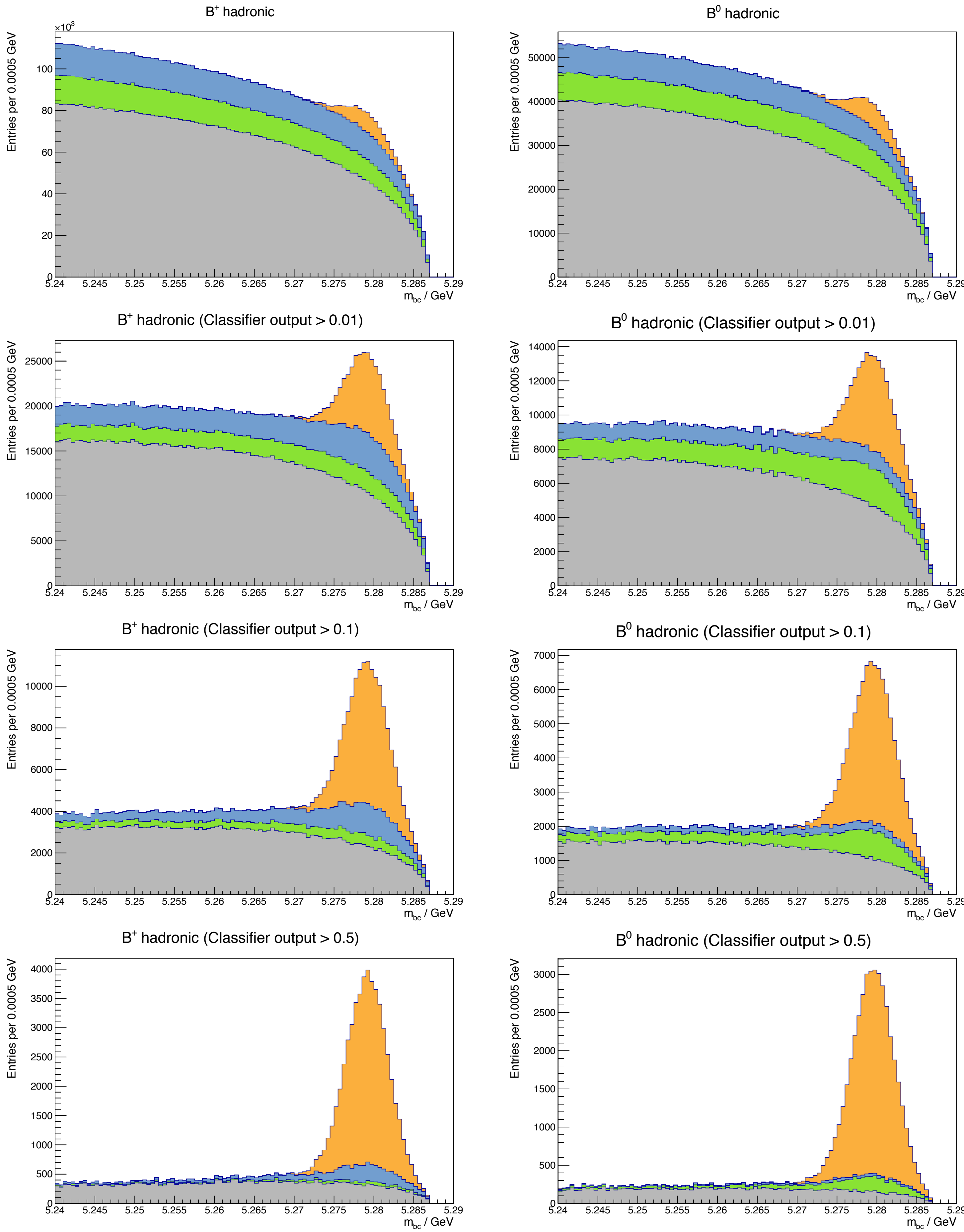
Original question by E. Paoloni

If you have 721 hits in the Belle II detector and you want to reconstruct 12 physical trajectories (11 from B-Meson decays, 1 from beam background)**, how many unique combinations do you need to consider?**

$$\left\{ {721 \atop 12} \right\} \approx 2.57 \times 10^{769}$$

$$\left\{ {n \atop k} \right\} = \frac{1}{k!} \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} j^n.$$

Number of ways to partition a set of ***n*** elements into ***k*** non-empty sets



Stronger cut On classifier

$$m_{\mathrm{bc}} = \sqrt{E^2_{\mathrm{beam,\ CMS}} - \vec{p}^{\,2}_{\mathrm{CMS}}},$$

Three momentum of tag-side B-Meson