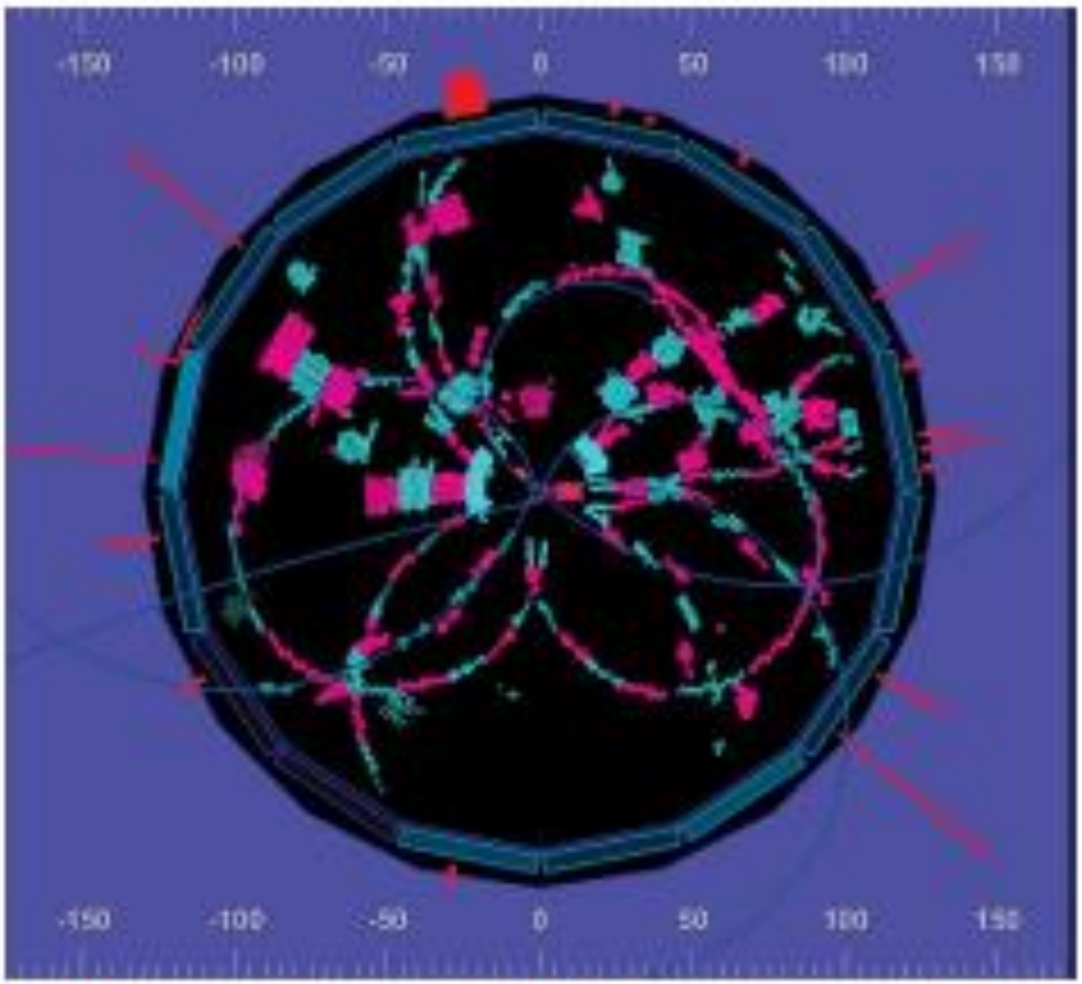
Belle II: flavour physics at the intensity frontier

Jim Libby (IIT Madras)
University of Warwick Seminar
9th October 2018

Overview

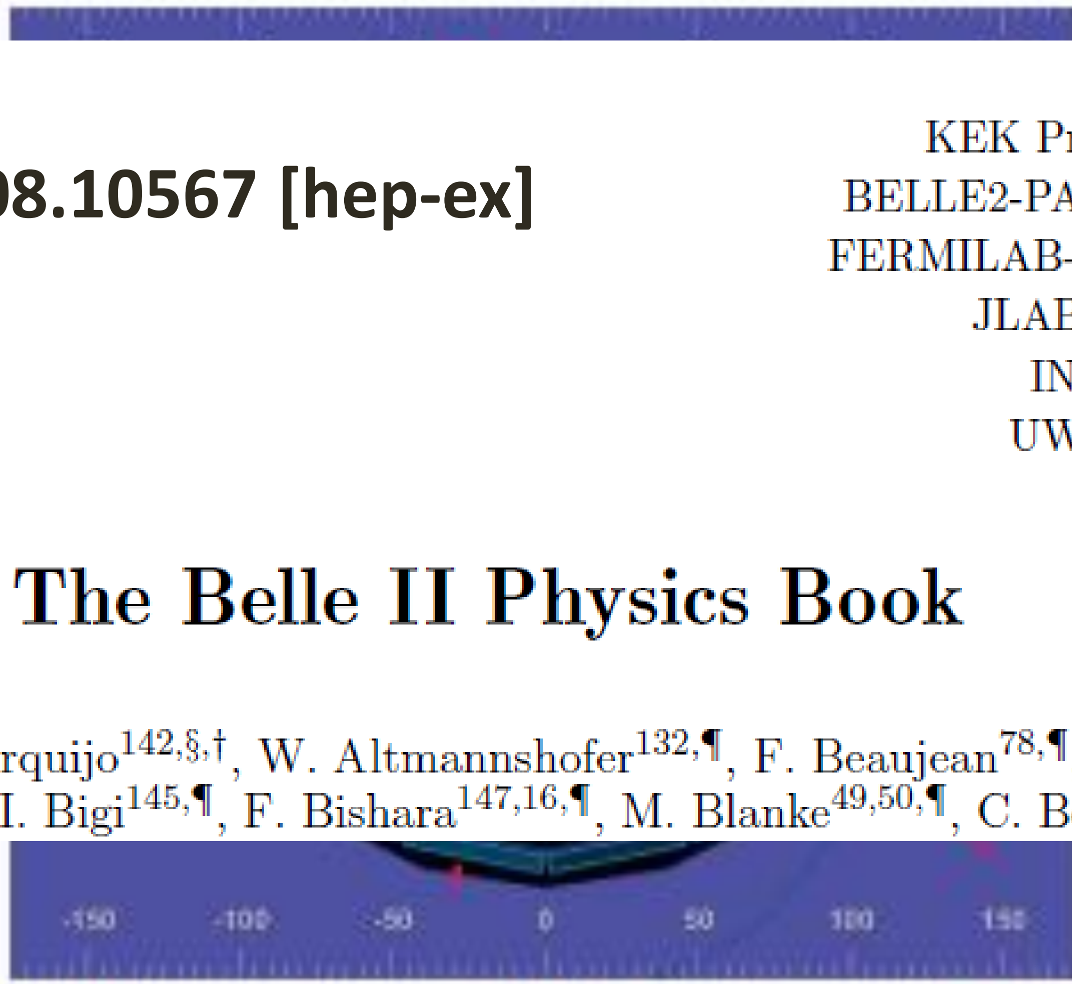
- Particle physics and frontiers
- Some flavour history
    - Flavour as a predictor
    - Belle
    - Complementarity with LHCb
- Belle II
    - Highlights of the instrumentation and first results
    - Some physics highlights
- Conclusion

Overview



Probably a Y(4S) event

Overview



arXiv:1808.10567 [hep-ex]

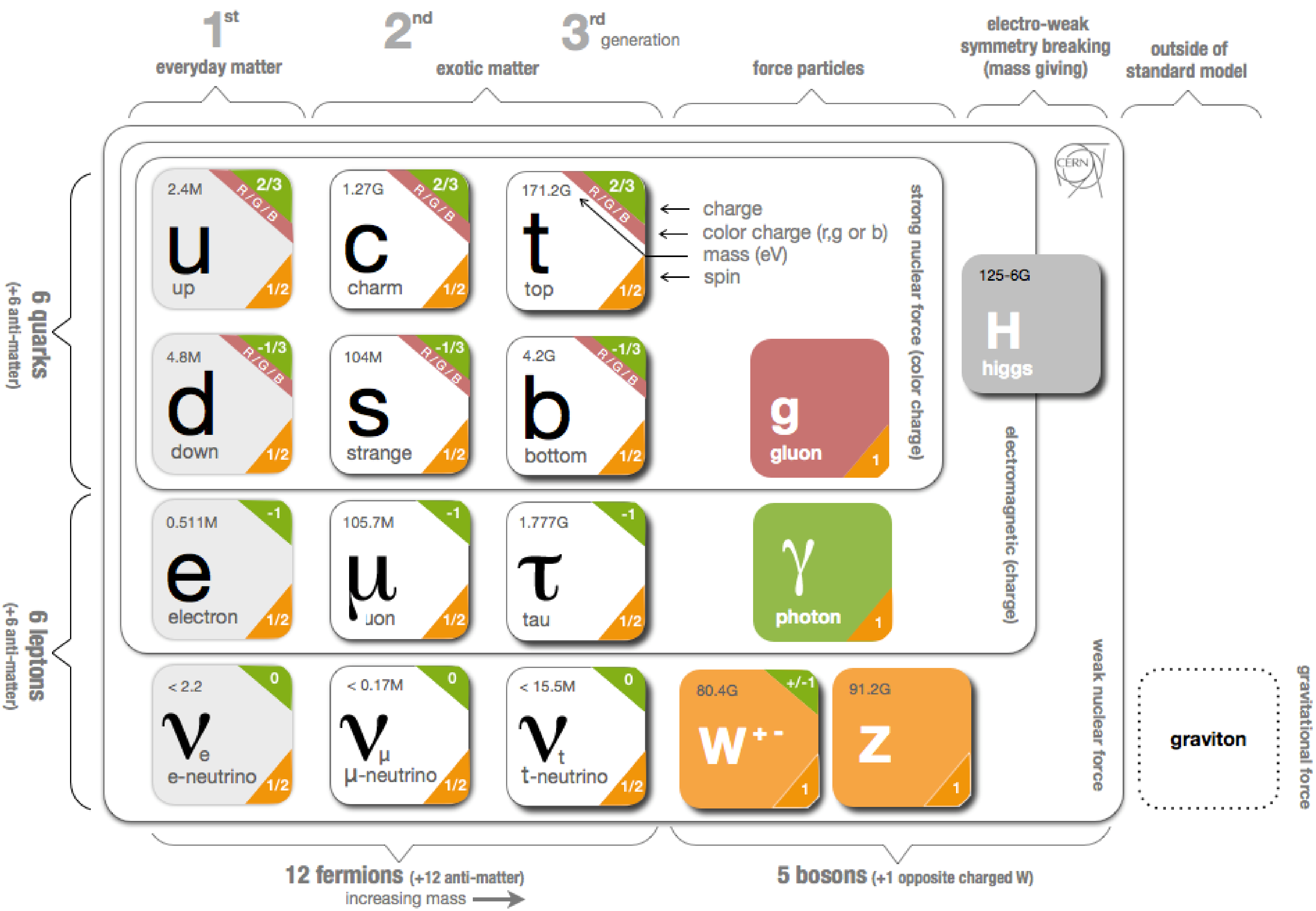
KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

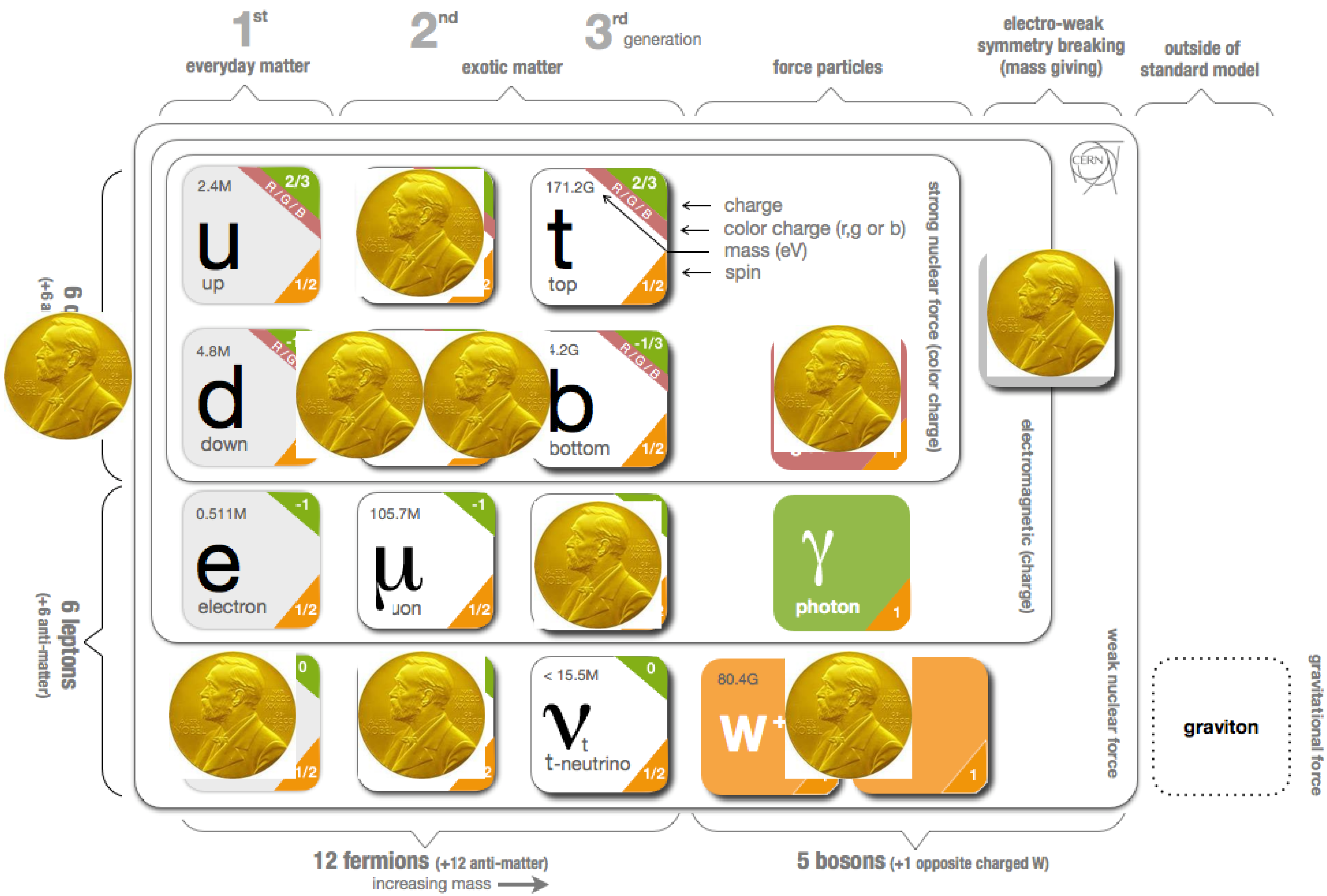
E. Kou[74,¶,†], P. Urquijo[142,§,†], W. Altmannshofer[132,¶], F. Beaujean[78,¶], G. Bell[119,¶], M. Beneke[111,¶], I. I. Bigi[145,¶], F. Bishara[147,16,¶], M. Blanke[49,50,¶], C. Bobeth[110,111,¶],

Probably a Y(4S) event

The standard model



The standard model

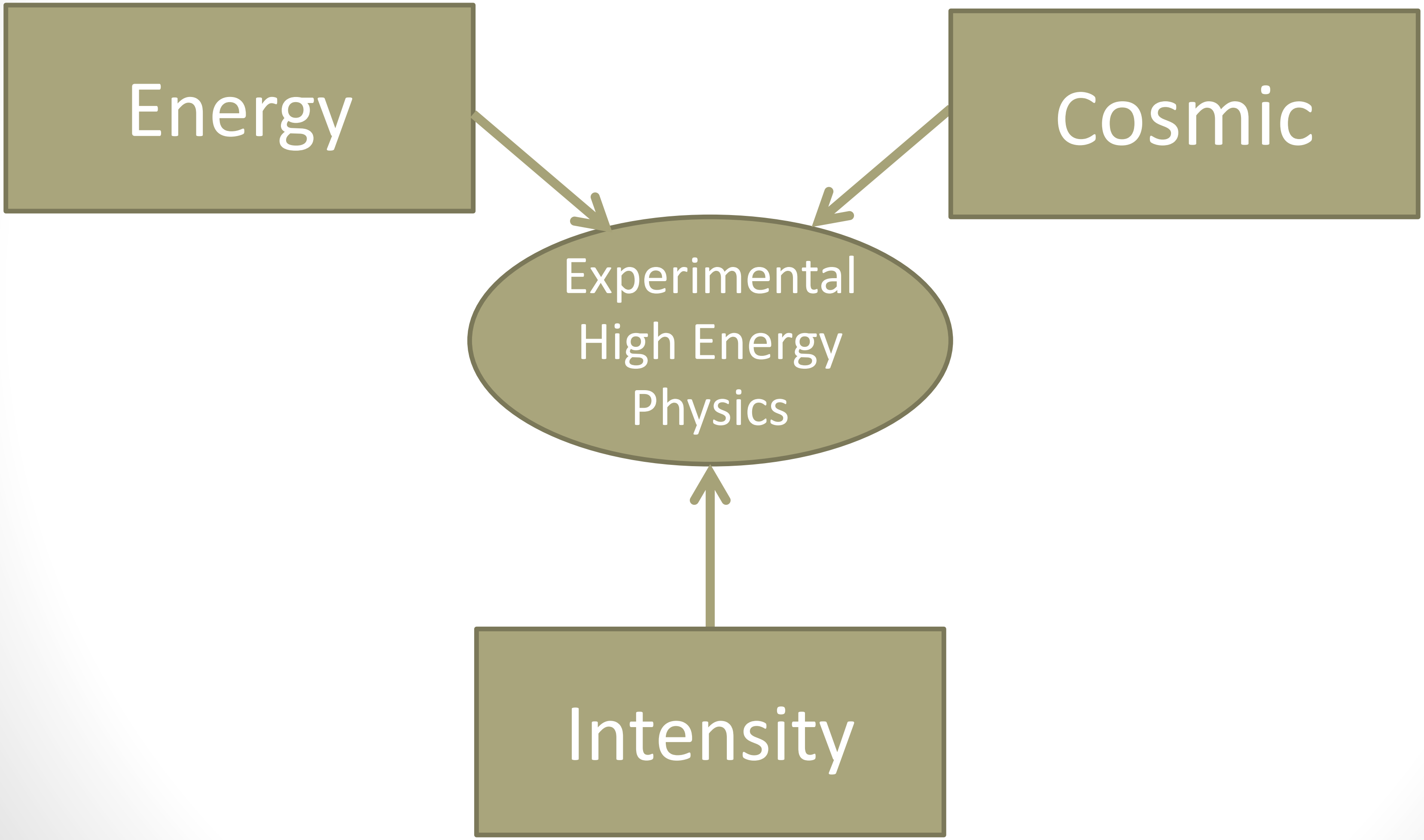


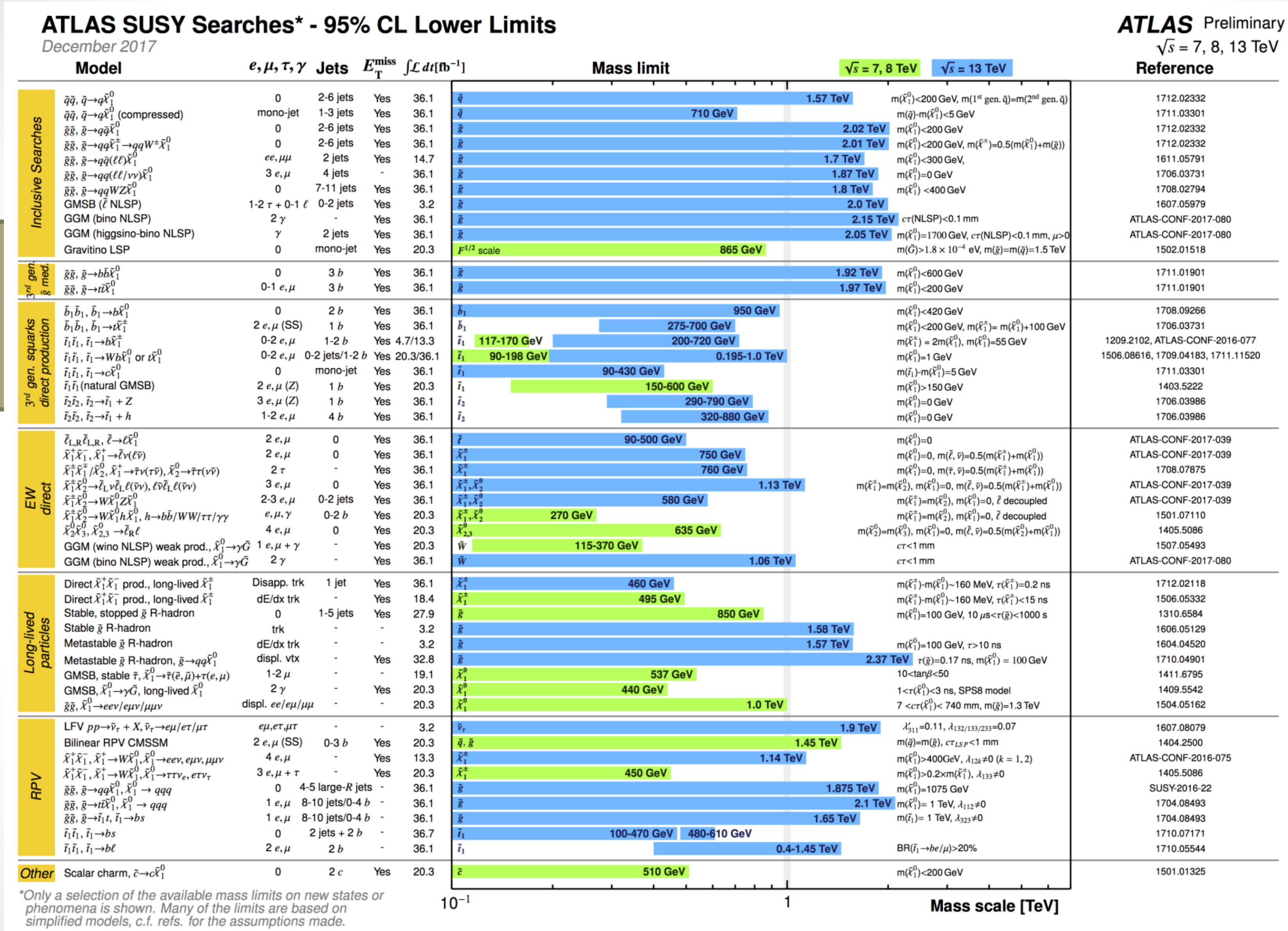
Problems

- **Empirical**
  - Neutrinos are massive
  - Dark matter
  - Dark energy!!!!
  - Matter rather than antimatter
  - Gravity

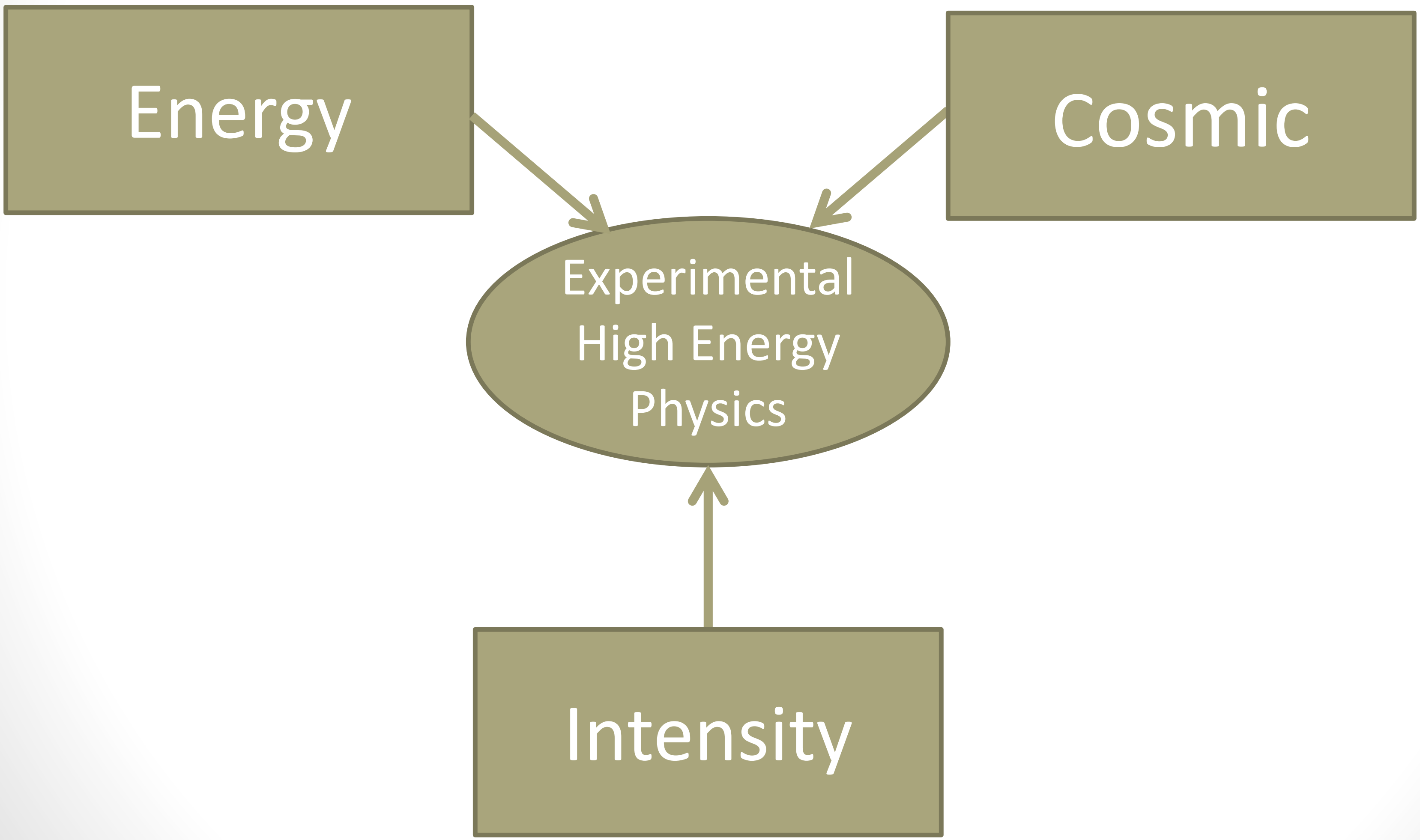
- **Aesthetic**
  - Why three of everything?
  - Why eighteen parameters?
    - Many with a distinct hierarchy?
  - Why do we need to know them to 18 decimal places?
  - Unification

Frontiers


Energy
Cosmic
Experimental High Energy Physics
Intensity

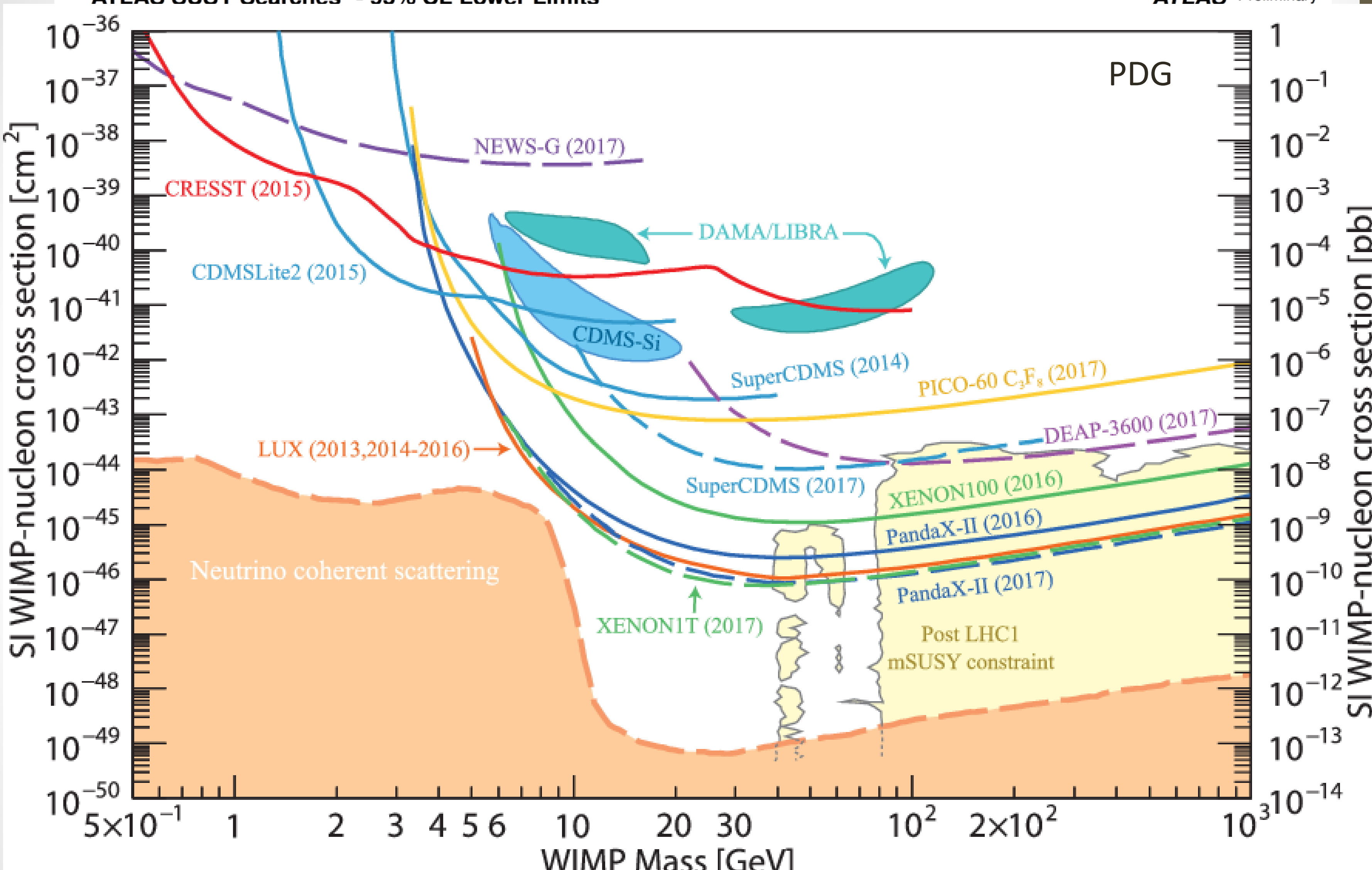

ATLAS SUSY Searches* - 95% CL Lower Limits
December 2017
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model | e, μ, τ, γ | Jets | E_T^miss | ∫L dt[fb^-1] | Mass limit | √s = 7, 8 TeV | √s = 13 TeV | Reference
Inclusive Searches
q̃q̃, q̃→qχ̃₁⁰ | 0 | 2-6 jets | Yes | 36.1 | q̃ 1.57 TeV | m(χ̃₁⁰)<200 GeV, m(1st gen. q̃)=m(2nd gen. q̃) | 1712.02332
q̃q̃, q̃→qχ̃₁⁰ (compressed) | mono-jet | 1-3 jets | Yes | 36.1 | q̃ 710 GeV | m(q̃)-m(χ̃₁⁰)<5 GeV | 1711.03301
g̃g̃, g̃→qq̄χ̃₁⁰ | 0 | 2-6 jets | Yes | 36.1 | g̃ 2.02 TeV | m(χ̃₁⁰)<200 GeV | 1712.02332
g̃g̃, g̃→qqχ̃₁±→qqW±χ̃₁⁰ | 0 | 2-6 jets | Yes | 36.1 | g̃ 2.01 TeV | m(χ̃₁⁰)<200 GeV, m(χ̃±)=0.5(m(χ̃₁⁰)+m(g̃)) | 1712.02332
g̃g̃, g̃→qq̄(ℓℓ)χ̃₁⁰ | ee, μμ | 2 jets | Yes | 14.7 | g̃ 1.7 TeV | m(χ̃₁⁰)<300 GeV, | 1611.05791
g̃g̃, g̃→qq(ℓℓ/νν)χ̃₁⁰ | 3 e, μ | 4 jets | - | 36.1 | g̃ 1.87 TeV | m(χ̃₁⁰)=0 GeV | 1706.03731
g̃g̃, g̃→qqWZχ̃₁⁰ | 0 | 7-11 jets | Yes | 36.1 | g̃ 1.8 TeV | m(χ̃₁⁰) <400 GeV | 1708.02794
GMSB (ℓ̃ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 3.2 | g̃ 2.0 TeV | 1607.05979
GGM (bino NLSP) | 2 γ | - | Yes | 36.1 | g̃ 2.15 TeV | cτ(NLSP)<0.1 mm | ATLAS-CONF-2017-080
GGM (higgsino-bino NLSP) | γ | 2 jets | Yes | 36.1 | g̃ 2.05 TeV | m(χ̃₁⁰)=1700 GeV, cτ(NLSP)<0.1 mm, μ>0 | ATLAS-CONF-2017-080
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | F^1/2 scale 865 GeV | m(G̃)>1.8 × 10⁻⁴ eV, m(g̃)=m(q̃)=1.5 TeV | 1502.01518
3rd gen. g̃ med.
g̃g̃, g̃→bb̄χ̃₁⁰ | 0 | 3 b | Yes | 36.1 | g̃ 1.92 TeV | m(χ̃₁⁰)<600 GeV | 1711.01901
g̃g̃, g̃→tt̄χ̃₁⁰ | 0-1 e, μ | 3 b | Yes | 36.1 | g̃ 1.97 TeV | m(χ̃₁⁰)<200 GeV | 1711.01901
3rd gen. squarks direct production
b̃₁b̃₁, b̃₁→bχ̃₁⁰ | 0 | 2 b | Yes | 36.1 | b̃₁ 950 GeV | m(χ̃₁⁰)<420 GeV | 1708.09266
b̃₁b̃₁, b̃₁→tχ̃₁± | 2 e, μ (SS) | 1 b | Yes | 36.1 | b̃₁ 275-700 GeV | m(χ̃₁⁰)<200 GeV, m(χ̃₁±)= m(χ̃₁⁰)+100 GeV | 1706.03731
t̃₁t̃₁, t̃₁→bχ̃₁± | 0-2 e, μ | 1-2 b | Yes | 4.7/13.3 | t̃₁ 117-170 GeV 200-720 GeV | m(χ̃₁±) = 2m(χ̃₁⁰), m(χ̃₁⁰)=55 GeV | 1209.2102, ATLAS-CONF-2016-077
t̃₁t̃₁, t̃₁→Wbχ̃₁⁰ or tχ̃₁⁰ | 0-2 e, μ | 0-2 jets/1-2 b | Yes | 20.3/36.1 | t̃₁ 90-198 GeV 0.195-1.0 TeV | m(χ̃₁⁰)=1 GeV | 1506.08616, 1709.04183, 1711.11520
t̃₁t̃₁, t̃₁→cχ̃₁⁰ | 0 | mono-jet | Yes | 36.1 | t̃₁ 90-430 GeV | m(t̃₁)-m(χ̃₁⁰)=5 GeV | 1711.03301
t̃₁t̃₁ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | t̃₁ 150-600 GeV | m(χ̃₁⁰)>150 GeV | 1403.5222
t̃₂t̃₂, t̃₂→t̃₁ + Z | 3 e, μ (Z) | 1 b | Yes | 36.1 | t̃₂ 290-790 GeV | m(χ̃₁⁰)=0 GeV | 1706.03986
t̃₂t̃₂, t̃₂→t̃₁ + h | 1-2 e, μ | 4 b | Yes | 36.1 | t̃₂ 320-880 GeV | m(χ̃₁⁰)=0 GeV | 1706.03986
EW direct
ℓ̃L,Rℓ̃L,R, ℓ̃→ℓχ̃₁⁰ | 2 e, μ | 0 | Yes | 36.1 | ℓ̃ 90-500 GeV | m(χ̃₁⁰)=0 | ATLAS-CONF-2017-039
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→ℓ̃ν(ℓν̃) | 2 e, μ | 0 | Yes | 36.1 | χ̃₁± 750 GeV | m(χ̃₁⁰)=0, m(ℓ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | ATLAS-CONF-2017-039
χ̃₁±χ̃₁∓/χ̃₂⁰, χ̃₁⁺→τ̃ν(τν̃), χ̃₂⁰→τ̃τ(νν̃) | 2 τ | - | Yes | 36.1 | χ̃₁± 760 GeV | m(χ̃₁⁰)=0, m(τ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | 1708.07875
χ̃₁±χ̃₂⁰→ℓ̃Lνℓ̃Lℓ(ν̃ν), ℓν̃ℓ̃Lℓ(ν̃ν) | 3 e, μ | 0 | Yes | 36.1 | χ̃₁±, χ̃₂⁰ 1.13 TeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, m(ℓ̃, ν̃)=0.5(m(χ̃₁±)+m(χ̃₁⁰)) | ATLAS-CONF-2017-039
χ̃₁±χ̃₂⁰→Wχ̃₁⁰Zχ̃₁⁰ | 2-3 e, μ | 0-2 jets | Yes | 36.1 | χ̃₁±, χ̃₂⁰ 580 GeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, ℓ̃ decoupled | ATLAS-CONF-2017-039
χ̃₁±χ̃₂⁰→Wχ̃₁⁰hχ̃₁⁰, h→bb̄/WW/ττ/γγ | e, μ, γ | 0-2 b | Yes | 20.3 | χ̃₁±, χ̃₂⁰ 270 GeV | m(χ̃₁±)=m(χ̃₂⁰), m(χ̃₁⁰)=0, ℓ̃ decoupled | 1501.07110
χ̃₂⁰χ̃₃⁰, χ̃₂,₃⁰ →ℓ̃Rℓ | 4 e, μ | 0 | Yes | 20.3 | χ̃₂,₃⁰ 635 GeV | m(χ̃₂⁰)=m(χ̃₃⁰), m(χ̃₁⁰)=0, m(ℓ̃, ν̃)=0.5(m(χ̃₂⁰)+m(χ̃₁⁰)) | 1405.5086
GGM (wino NLSP) weak prod., χ̃₁⁰→γG̃ | 1 e, μ + γ | - | Yes | 20.3 | W̃ 115-370 GeV | cτ<1 mm | 1507.05493
GGM (bino NLSP) weak prod., χ̃₁⁰→γG̃ | 2 γ | - | Yes | 36.1 | W̃ 1.06 TeV | cτ<1 mm | ATLAS-CONF-2017-080
Long-lived particles
Direct χ̃₁⁺χ̃₁⁻ prod., long-lived χ̃₁± | Disapp. trk | 1 jet | Yes | 36.1 | χ̃₁± 460 GeV | m(χ̃₁±)-m(χ̃₁⁰)~160 MeV, τ(χ̃₁±)=0.2 ns | 1712.02118
Direct χ̃₁⁺χ̃₁⁻ prod., long-lived χ̃₁± | dE/dx trk | - | Yes | 18.4 | χ̃₁± 495 GeV | m(χ̃₁±)-m(χ̃₁⁰)~160 MeV, τ(χ̃₁±)<15 ns | 1506.05332
Stable, stopped g̃ R-hadron | 0 | 1-5 jets | Yes | 27.9 | g̃ 850 GeV | m(χ̃₁⁰)=100 GeV, 10 μs<τ(g̃)<1000 s | 1310.6584
Stable g̃ R-hadron | trk | - | - | 3.2 | g̃ 1.58 TeV | 1606.05129
Metastable g̃ R-hadron | dE/dx trk | - | - | 3.2 | g̃ 1.57 TeV | m(χ̃₁⁰)=100 GeV, τ>10 ns | 1604.04520
Metastable g̃ R-hadron, g̃→qqχ̃₁⁰ | displ. vtx | - | Yes | 32.8 | g̃ 2.37 TeV | τ(g̃)=0.17 ns, m(χ̃₁⁰) = 100 GeV | 1710.04901
GMSB, stable τ̃, χ̃₁⁰→τ̃(ẽ, μ̃)+τ(e, μ) | 1-2 μ | - | - | 19.1 | χ̃₁⁰ 537 GeV | 10<tanβ<50 | 1411.6795
GMSB, χ̃₁⁰→γG̃, long-lived χ̃₁⁰ | 2 γ | - | Yes | 20.3 | χ̃₁⁰ 440 GeV | 1<τ(χ̃₁⁰)<3 ns, SPS8 model | 1409.5542
g̃g̃, χ̃₁⁰→eeν/eμν/μμν | displ. ee/eμ/μμ | - | - | 20.3 | χ̃₁⁰ 1.0 TeV | 7 <cτ(χ̃₁⁰)< 740 mm, m(g̃)=1.3 TeV | 1504.05162
RPV
LFV pp→ν̃τ + X, ν̃τ→eμ/eτ/μτ | eμ, eτ, μτ | - | - | 3.2 | ν̃τ 1.9 TeV | λ'311=0.11, λ132/133/233=0.07 | 1607.08079
Bilinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | q̃, g̃ 1.45 TeV | m(q̃)=m(g̃), cτLSP<1 mm | 1404.2500
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→Wχ̃₁⁰, χ̃₁⁰→eeν, eμν, μμν | 4 e, μ | - | Yes | 13.3 | χ̃₁± 1.14 TeV | m(χ̃₁⁰)>400GeV, λ12k≠0 (k = 1, 2) | ATLAS-CONF-2016-075
χ̃₁⁺χ̃₁⁻, χ̃₁⁺→Wχ̃₁⁰, χ̃₁⁰→ττνe, eτντ | 3 e, μ + τ | - | Yes | 20.3 | χ̃₁± 450 GeV | m(χ̃₁⁰)>0.2×m(χ̃₁±), λ133≠0 | 1405.5086
g̃g̃, g̃→qqχ̃₁⁰, χ̃₁⁰ → qqq | 0 | 4-5 large-R jets | - | 36.1 | g̃ 1.875 TeV | m(χ̃₁⁰)=1075 GeV | SUSY-2016-22
g̃g̃, g̃→tt̄χ̃₁⁰, χ̃₁⁰ → qqq | 1 e, μ | 8-10 jets/0-4 b | - | 36.1 | g̃ 2.1 TeV | m(χ̃₁⁰)= 1 TeV, λ112≠0 | 1704.08493
g̃g̃, g̃→t̃₁t, t̃₁→bs | 1 e, μ | 8-10 jets/0-4 b | - | 36.1 | g̃ 1.65 TeV | m(t̃₁)= 1 TeV, λ323≠0 | 1704.08493
t̃₁t̃₁, t̃₁→bs | 0 | 2 jets + 2 b | - | 36.7 | t̃₁ 100-470 GeV 480-610 GeV | 1710.07171
t̃₁t̃₁, t̃₁→bℓ | 2 e, μ | 2 b | - | 36.1 | t̃₁ 0.4-1.45 TeV | BR(t̃₁→be/μ)>20% | 1710.05544
Other
Scalar charm, c̃→cχ̃₁⁰ | 0 | 2 c | Yes | 20.3 | c̃ 510 GeV | m(χ̃₁⁰)<200 GeV | 1501.01325
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
10⁻¹
1
Mass scale [TeV]

Frontiers


Energy
Cosmic
Experimental High Energy Physics
Intensity

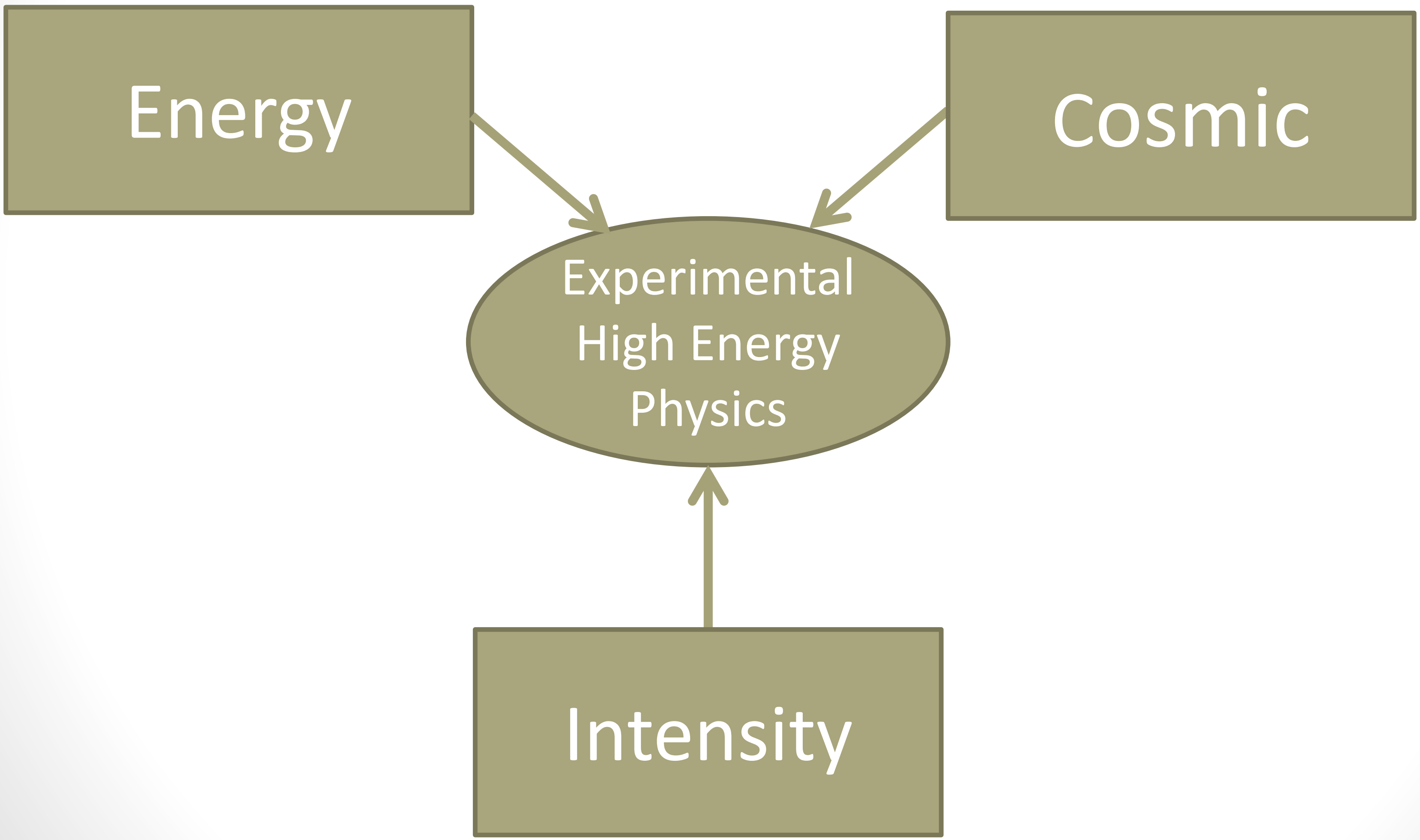
ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary



simplified models, c.f. refs. for the assumptions made.

Frontiers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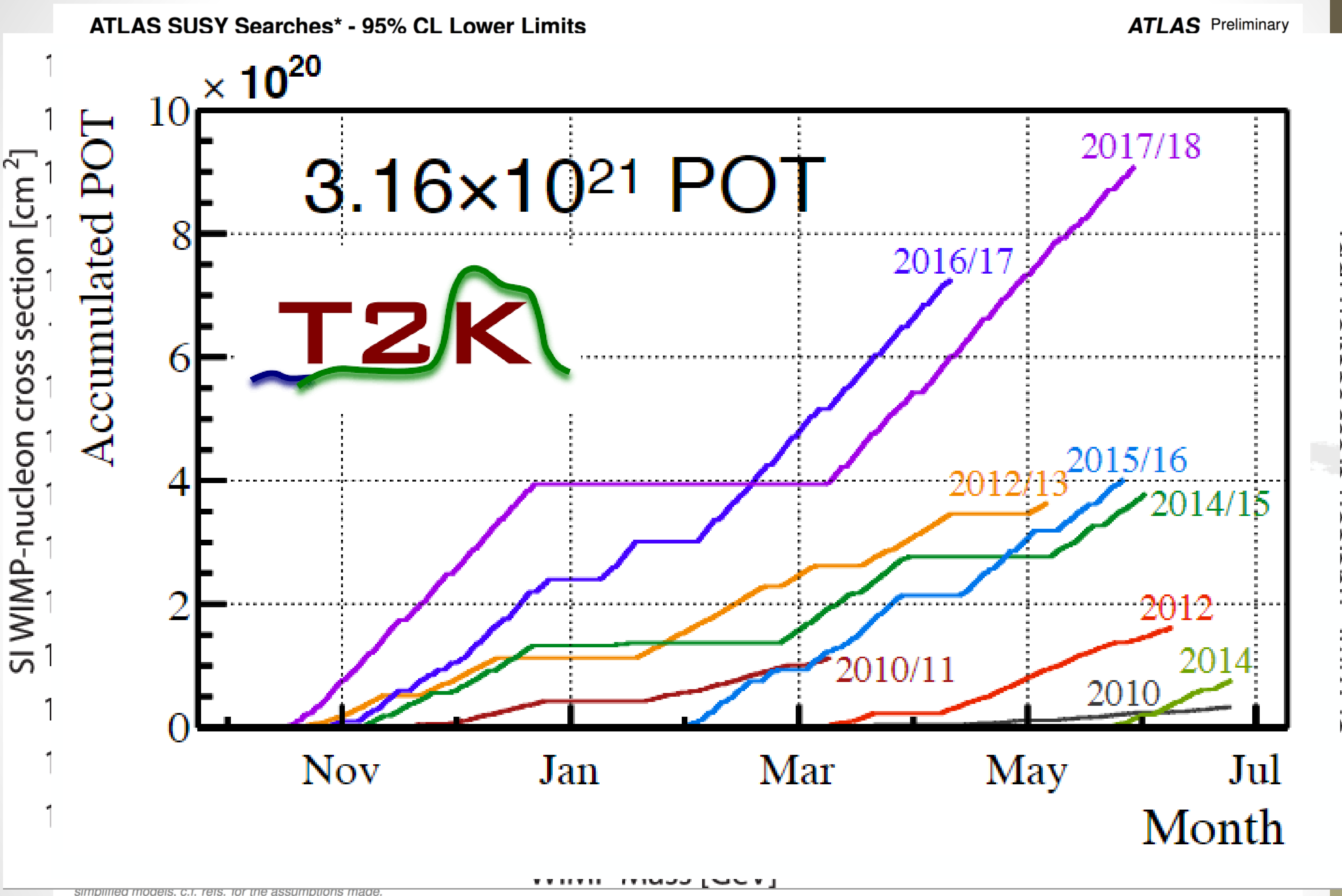
ATLAS SUSY Searches* - 95% CL Lower Limits
ATLAS Preliminary
3.16×10²¹ POT
T2K
× 10²⁰
Accumulated POT
10
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6
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2
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2017/18
2016/17
2015/16
2012/13
2014/15
2012
2010/11
2014
2010
Nov
Jan
Mar
May
Jul
Month
SI WIMP-nucleon cross section [cm²]
simplified models, c.f. refs. for the assumptions made.


SISTER MARGARET'S DEAD POOL
PLAYER
BET
PICK
AGE
CHUCK T
DAVE
JAK
WEASEL
TAD
WADE
JOHN
HANK
SERGE
SEAN
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$75
$200
$175
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$110
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SHEEN, C
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WILSON, W
PUTIN, V
BOOTHE, J
REYNOLDS, R
MILLER, TJ
LOHAN, L
CYRUS, M
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FRANKIE
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JIMBO
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JIRIK
MOORS
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Physics HAS
A NEW FACE


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Belle II

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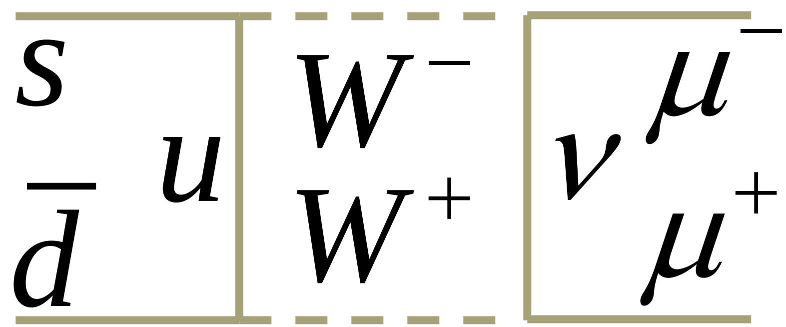
Flavour physics – history of discovery

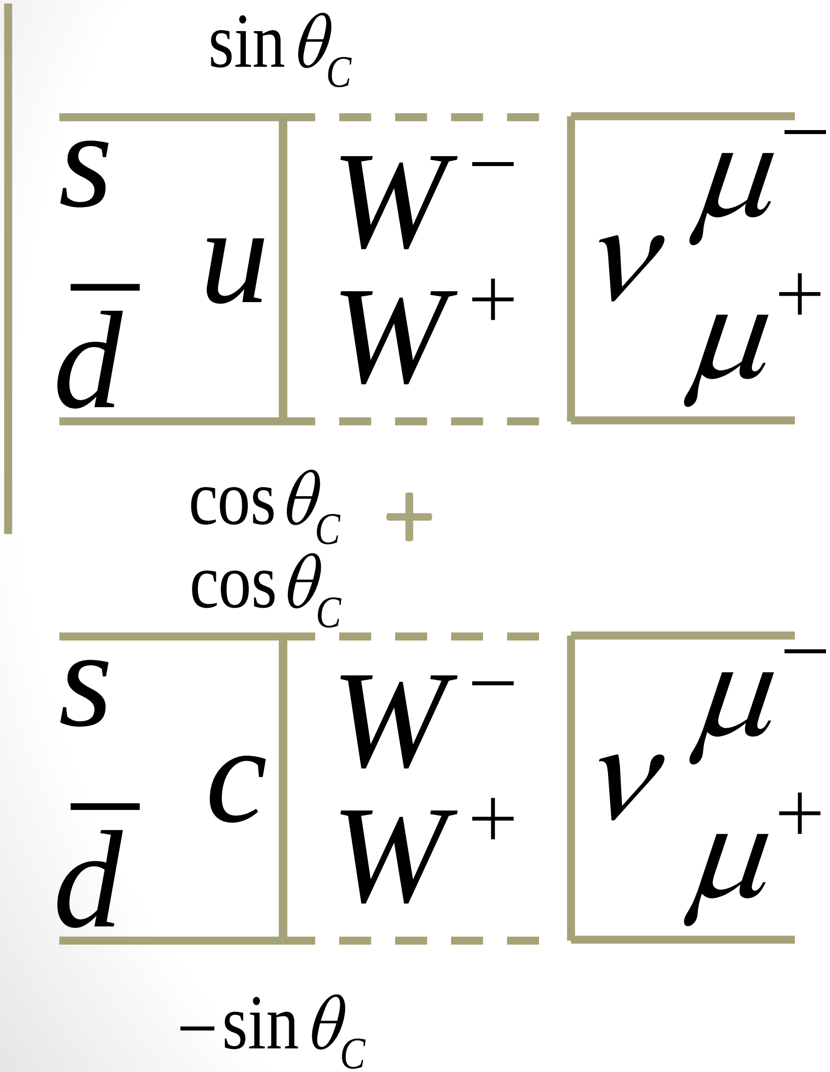
- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
    - up (u)
    - down (d)
    - strange (s)
- An allowed but rare decay such as

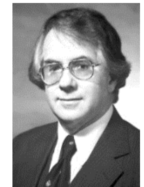
$$K_L^0(s\bar{d}) \rightarrow \mu^+\mu^-$$

- **Predicted but not seen!**



Flavour physics – history of discovery





Glashow

Iliopoulos

Maiani

Phys. Rev. **D** 2, 1285 (1970)

2 $\propto$ Rate ~ 0

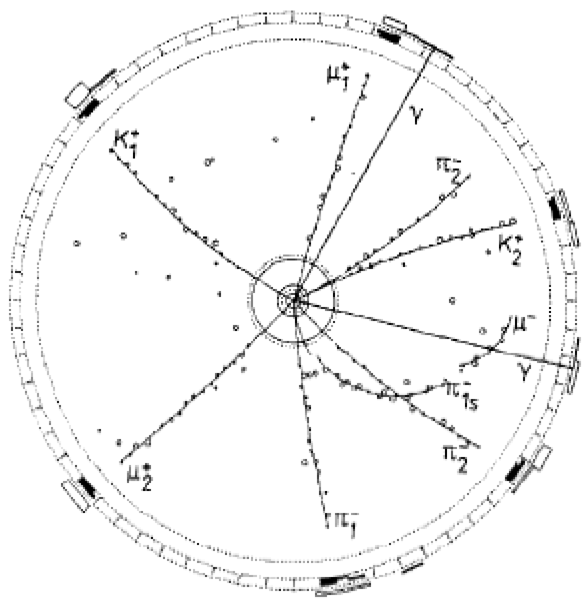
$m_c > m_K$

Such rare virtual processes tell you about higher energy particles

ARGUS: B mixing ⇒ heavy top

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration



reconstructed event consisting of the decay Υ

$B_1^0 \to D_1^{*-} \mu_1^+ \nu_1$

$\downarrow$

$D_1^{*-} \to \pi_1^- \bar{D}^0$

$\downarrow$

$\bar{D}^0 \to K_1^+ \pi_1^-$,

and

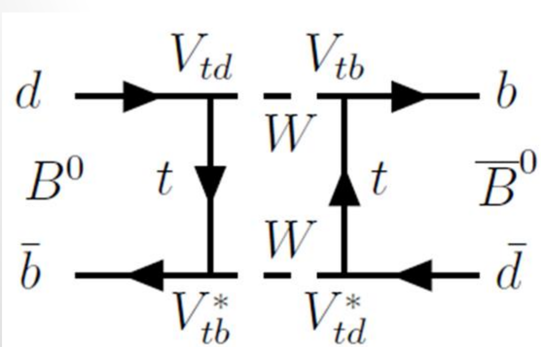
$B_2^0 \to D_2^{*-} \mu_2^+ \nu_2$

$\downarrow$

$D_2^{*-} \to \pi^0 D^-$

$\downarrow$

$D^- \to K_2^+ \pi_2^- \pi_2^-$.

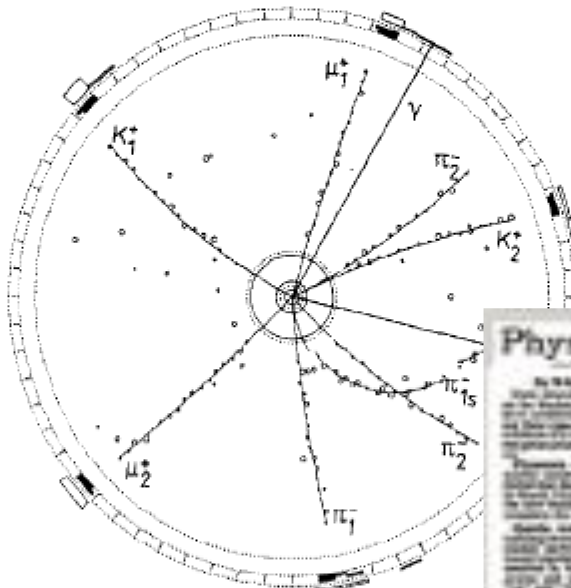


m_t> 50 Gev

ARGUS: B mixing ⇒ heavy top

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration



$B_1^0 \rightarrow D_1^{*-} \mu_1^+ \nu_1$

↓

$D_1^{*-} \rightarrow \pi_1^- \bar{D}^0$

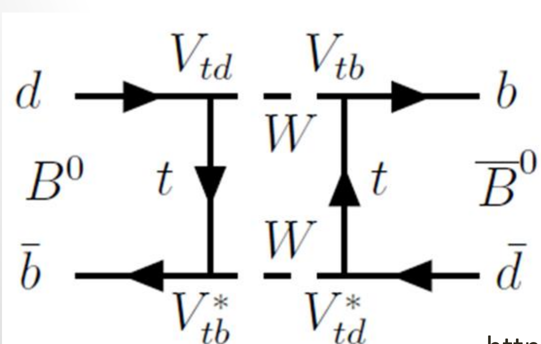
↓

$\bar{D}^0 \rightarrow K_1^+ \pi_1^-$,

and

reconstructed event consisting of

Physicists May Have Tracked Last Quark to Lair



m_t> 50 Gev

https://www.nytimes.com/1984/06/25/us/physicists-may-have-tracked-last-quark-to-lair.html

CKM matrix

$$\begin{pmatrix} u & c \end{pmatrix} \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

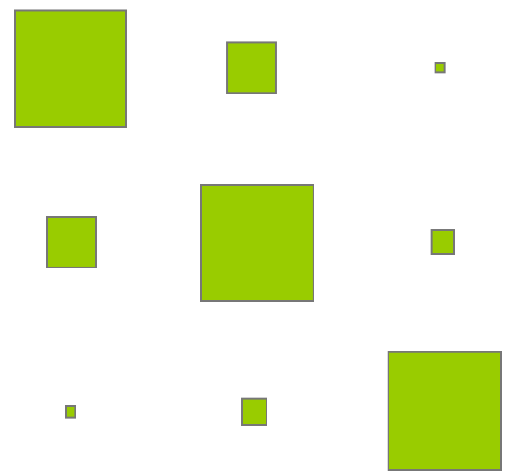
- Two by two mixing matrix proposed Cabibbo

CKM matrix

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Two by two mixing matrix proposed Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

Relative magnitude of elements



Responsible for CP violation

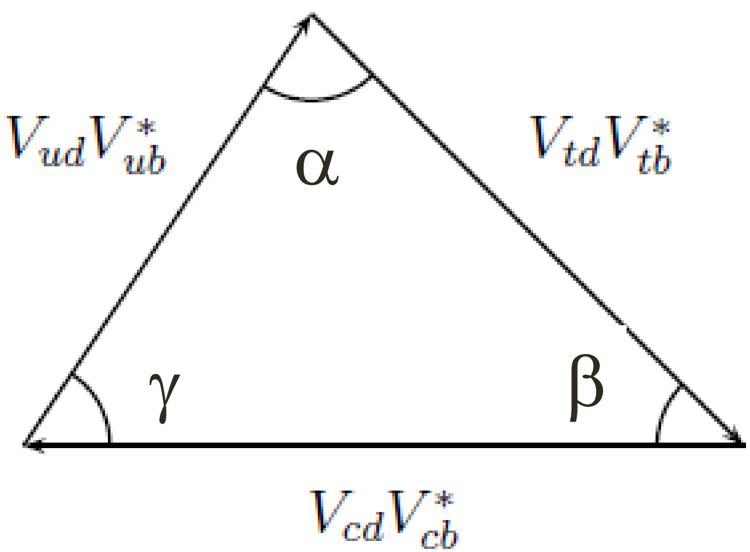
Visualising CP violation: the unitarity triangle

1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho - i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

2) Exploit unitarity (1st and 3rd col.)

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

3)

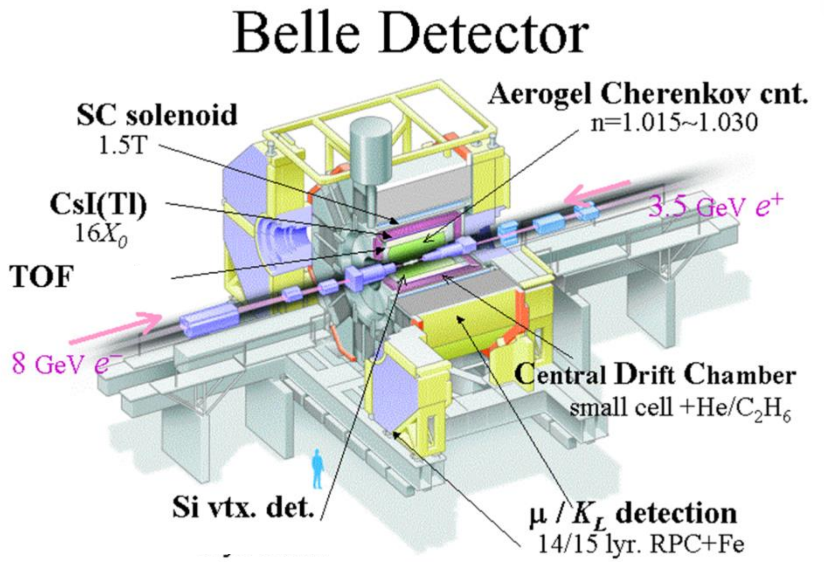


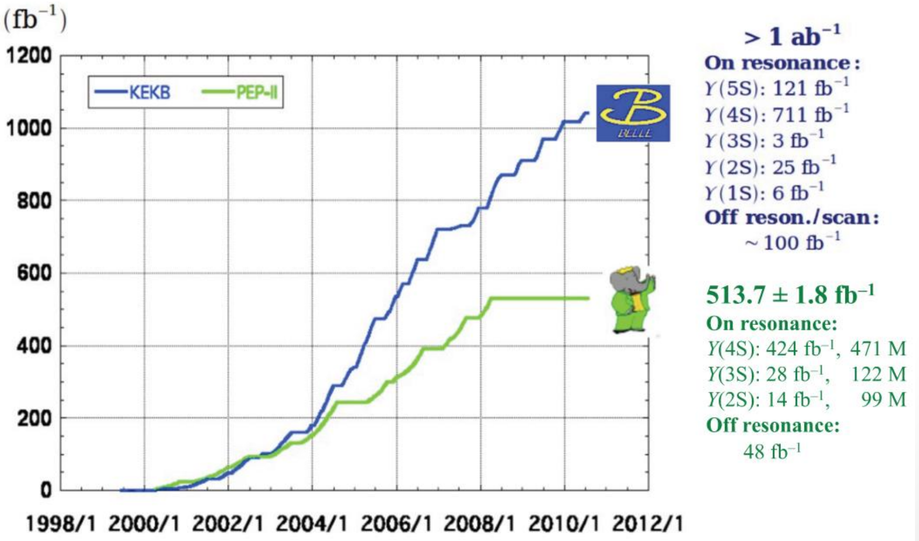
$$\phi_1 = \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\simeq \arg\left(\frac{1}{1-\rho - i\eta}\right)$$

Belle

- Operation from 1999 to 2010
- $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ for CKM measurements
- Asymmetric energy to allow time-dependent measurements
- Coherent production of $B^0\overline{B^0}$
- Low multiplicity
- Detectors with good tracking, PID and calorimetry
  - plus hermeticity for full event reconstruction/tagging

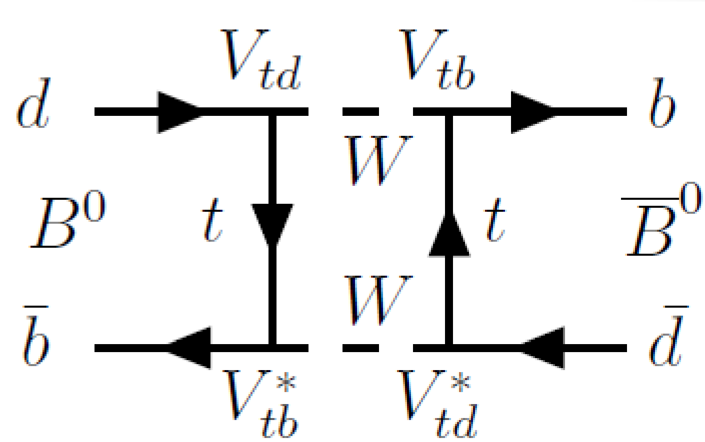


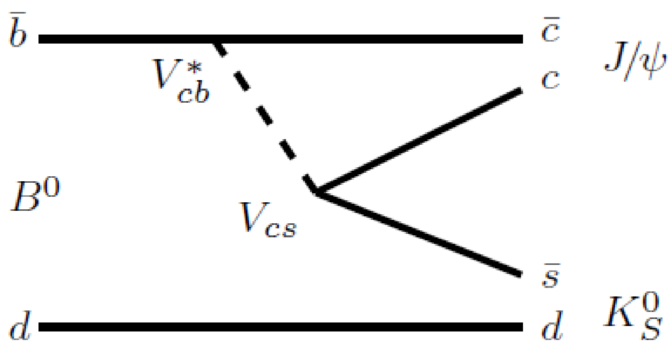


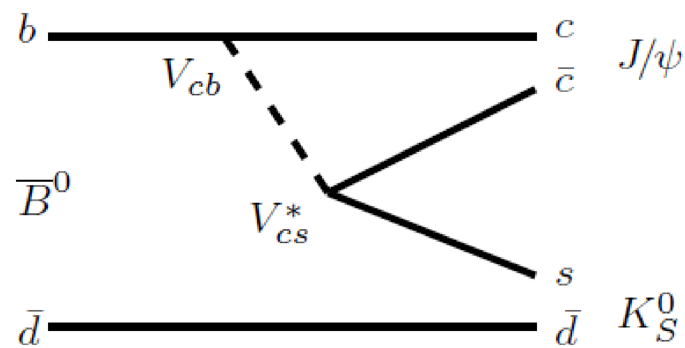
The Golden Mode

$B^0 \to J/\psi K_S^0$ sensitive to

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$







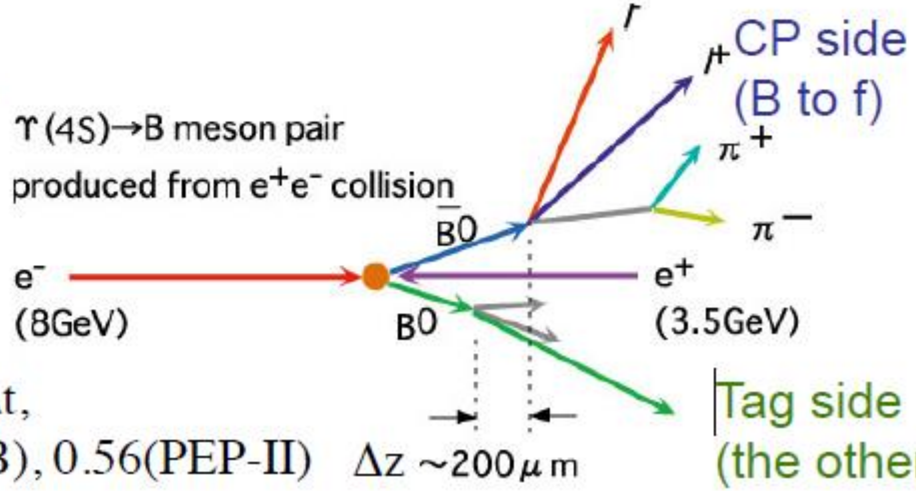
CP violation in the 'interference of mixing and decay amplitudes'

$$A_{CP}(\Delta t) = \frac{\Gamma\left[\bar{B}^0(\Delta t)\to f\right]-\Gamma\left[B^0(\Delta t)\to f\right]}{\Gamma\left[\bar{B}^0(\Delta t)\to f\right]+\Gamma\left[B^0(\Delta t)\to f\right]} = S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)$$

In SM $S_f = \sin 2\beta$ and $C_f = 0$ when no CPV in f

Time-dependent CPV violation

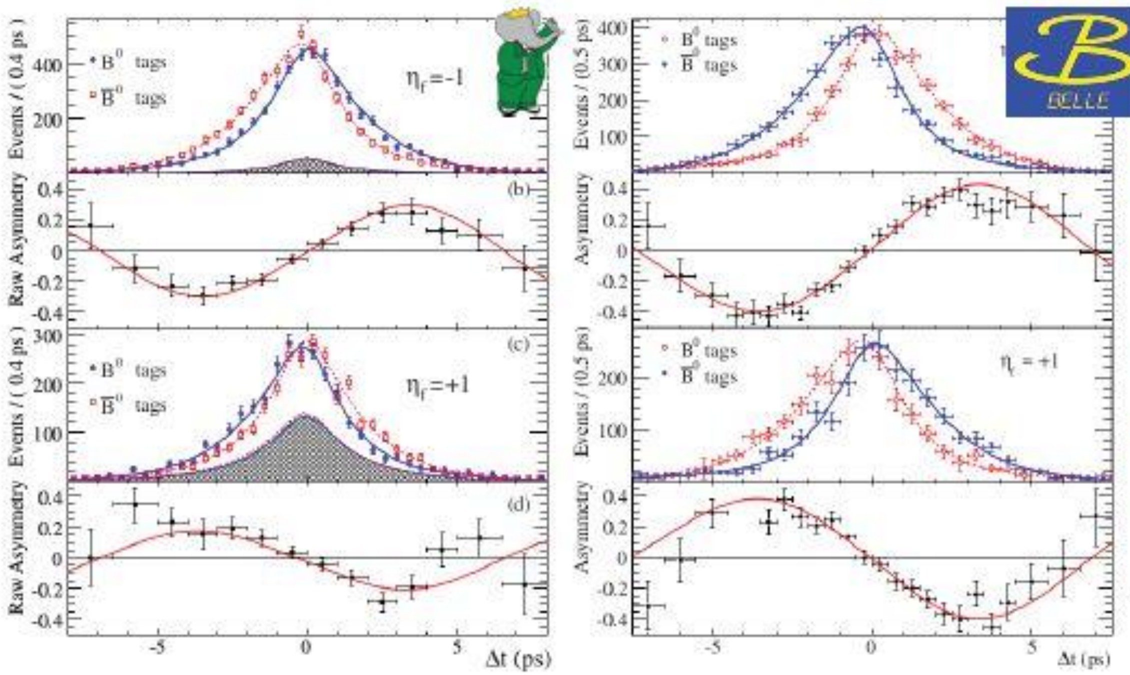
In order to see CPV by interference between decay and mixing.

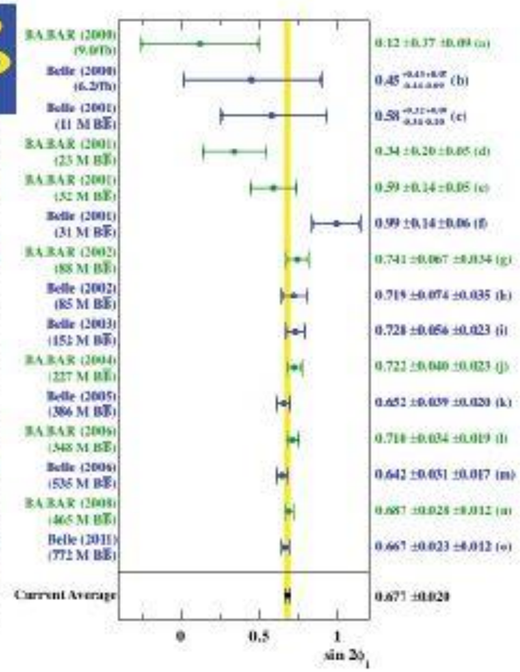


$\Delta z = \beta\gamma c \Delta t$,

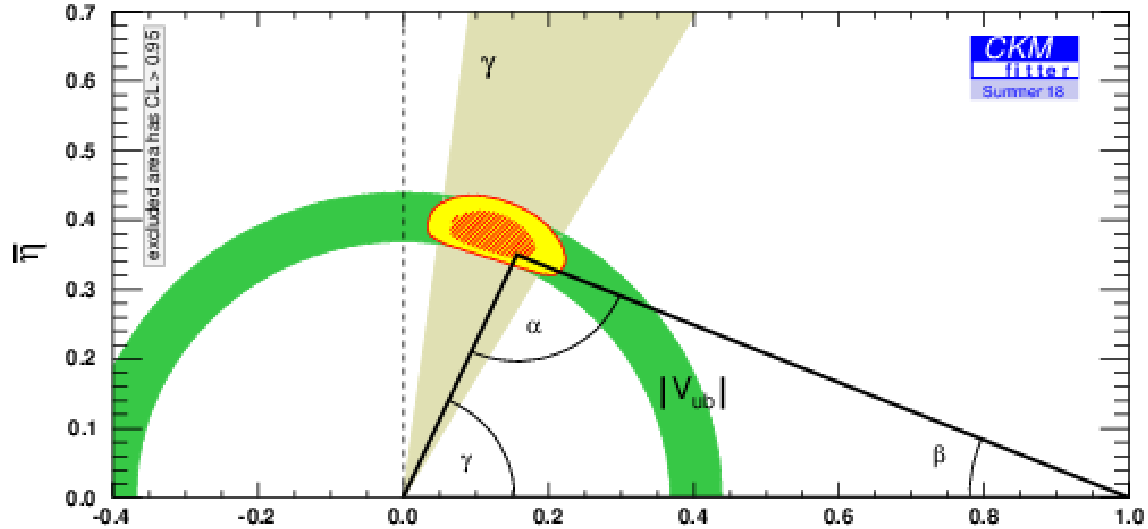
$\beta\gamma = 0.425$(KEKB), 0.56(PEP-II)

Tagging power $= \varepsilon(1-2\omega)^2 \approx 30\%$

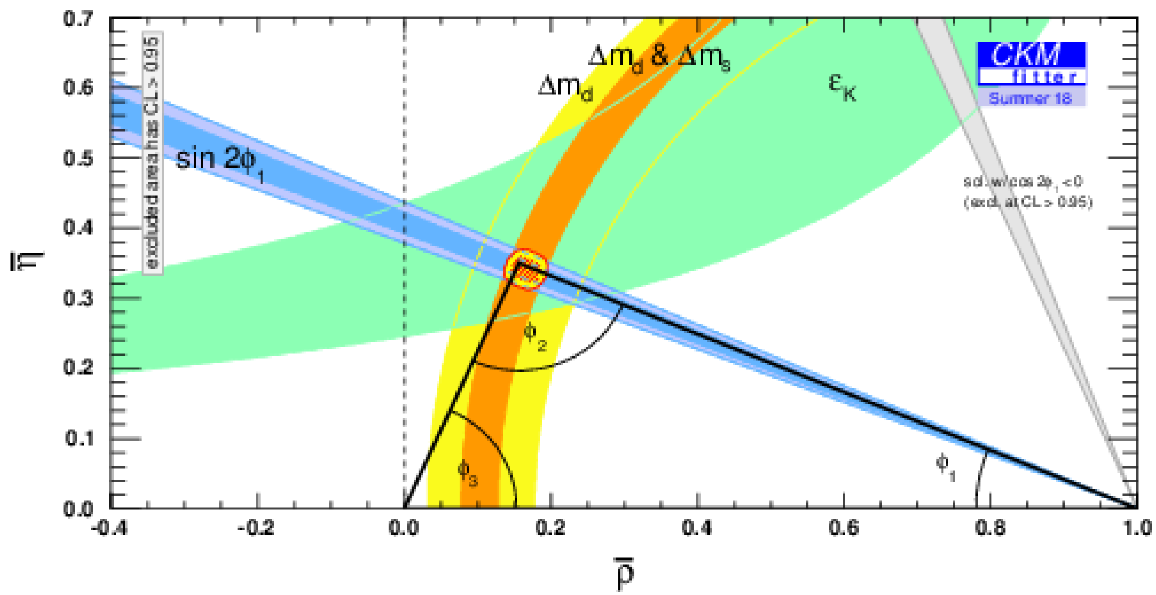




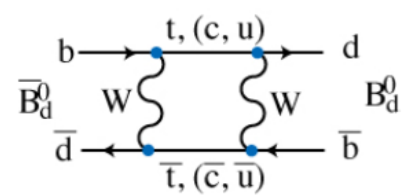
Over constraint



Tree level only



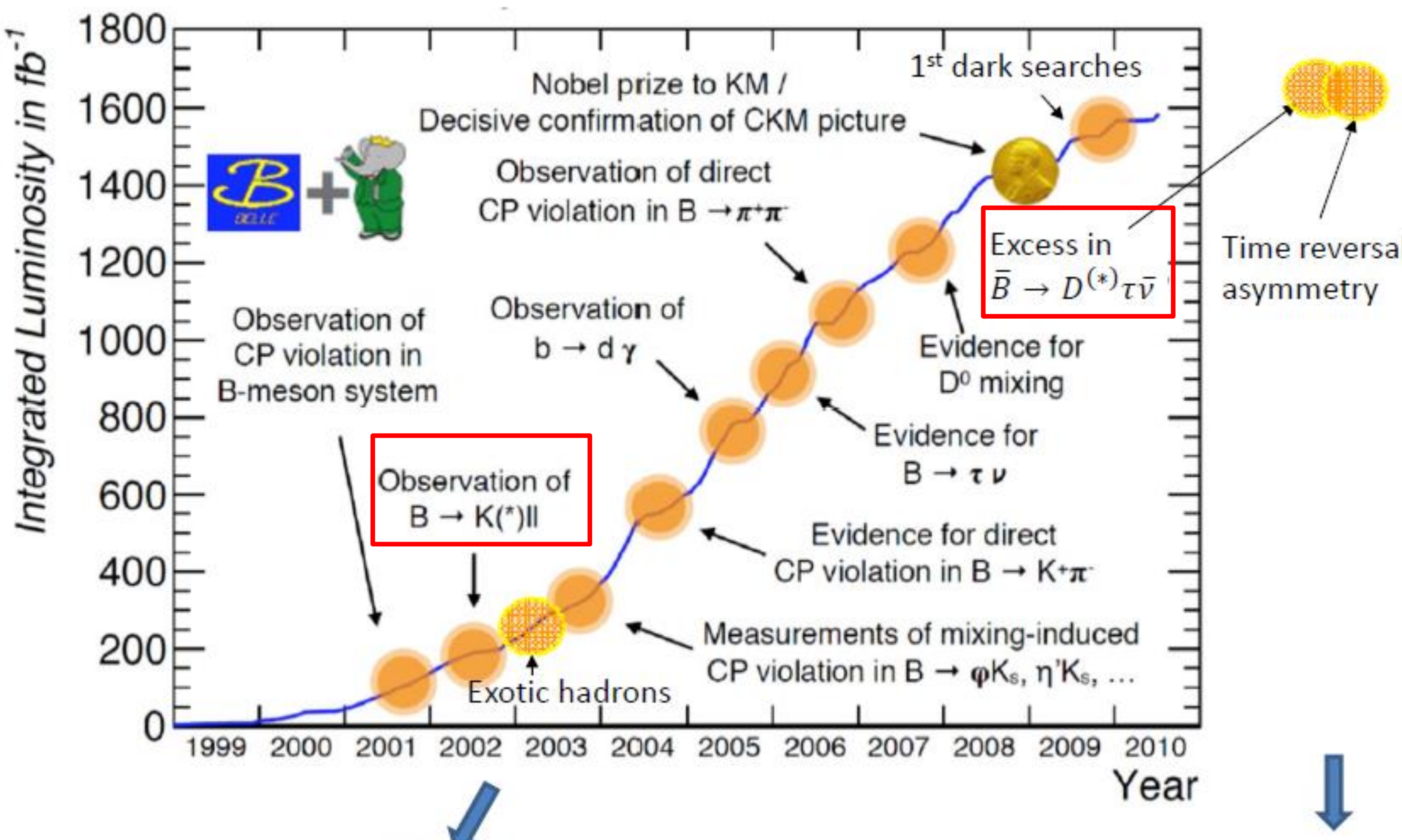
Loop-level only



NP at O(>TeV)?

Belle achievements

From Abi Soffer: HEPMAD



>100 unique CPV results

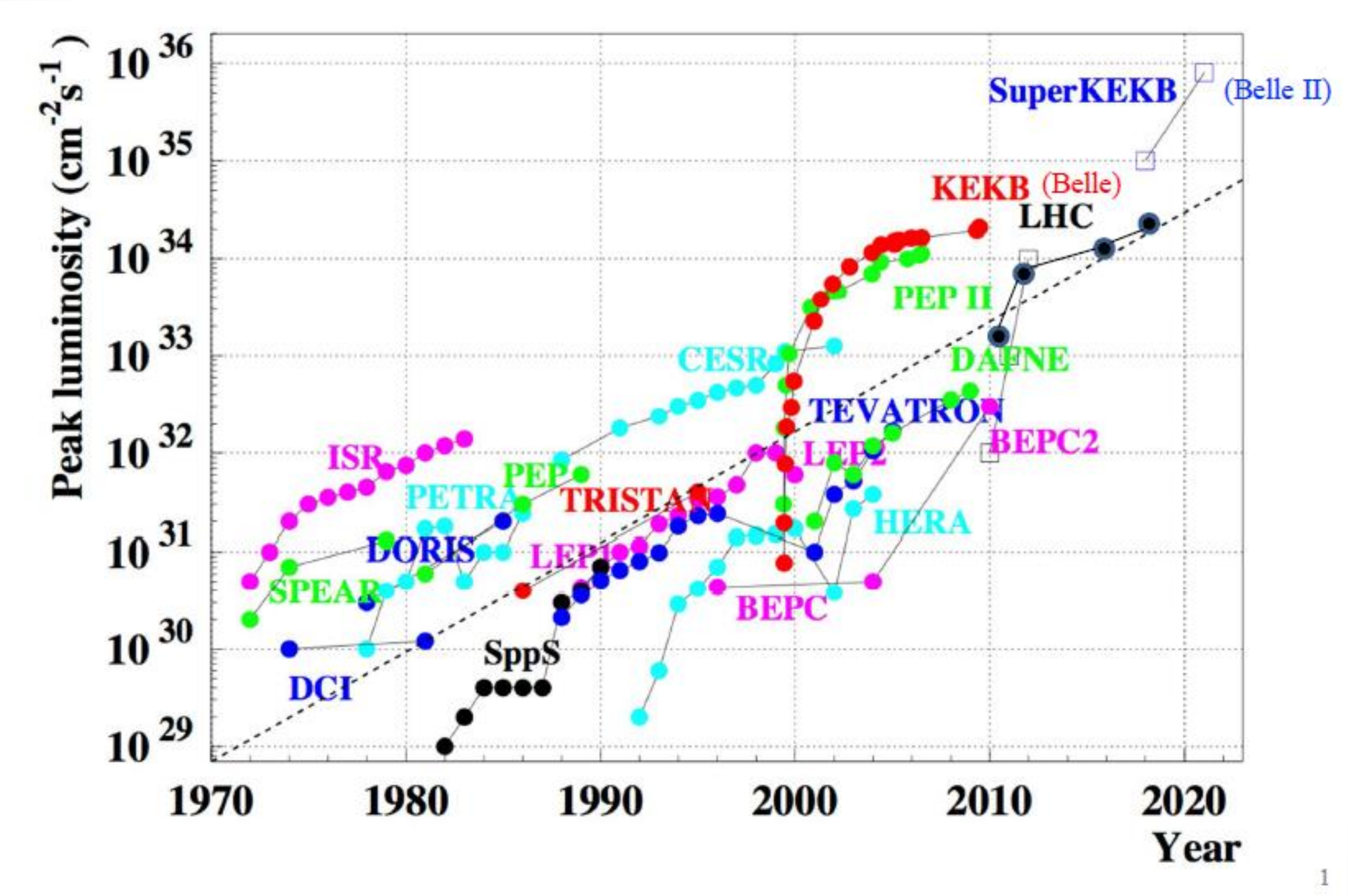
~350 papers published after shutdown, 21 in 2018

Belle II: can never have too much of a good thing (x 50 Belle)

- But isn't LHCb doing this already?

Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\ dt$ (fb^{-1}) by ~2024	~25	~50,000
Background level	Very high	Low
Typical efficiency	Low	High
π^0, K_S reconstruction	Inefficient	Efficient
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large	Tiny
Heavy bottom hadrons	B_s, B_c, b-baryons	Partly B_s
τ physics capability	Limited	Excellent
B-flavor tagging efficiency	3.5 - 6%	36%

“Moore’s” Law of Luminosity



The path to higher luminosity

$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$

Lorentz factor

Beam current

Beam-beam parameter

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

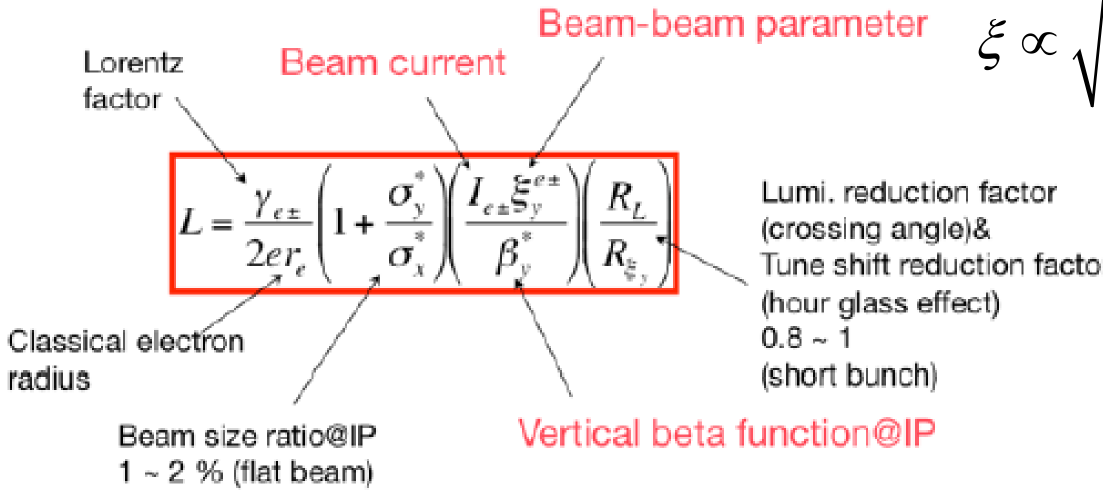
Beam size ratio@IP 1 ~ 2 % (flat beam)

Vertical beta function@IP

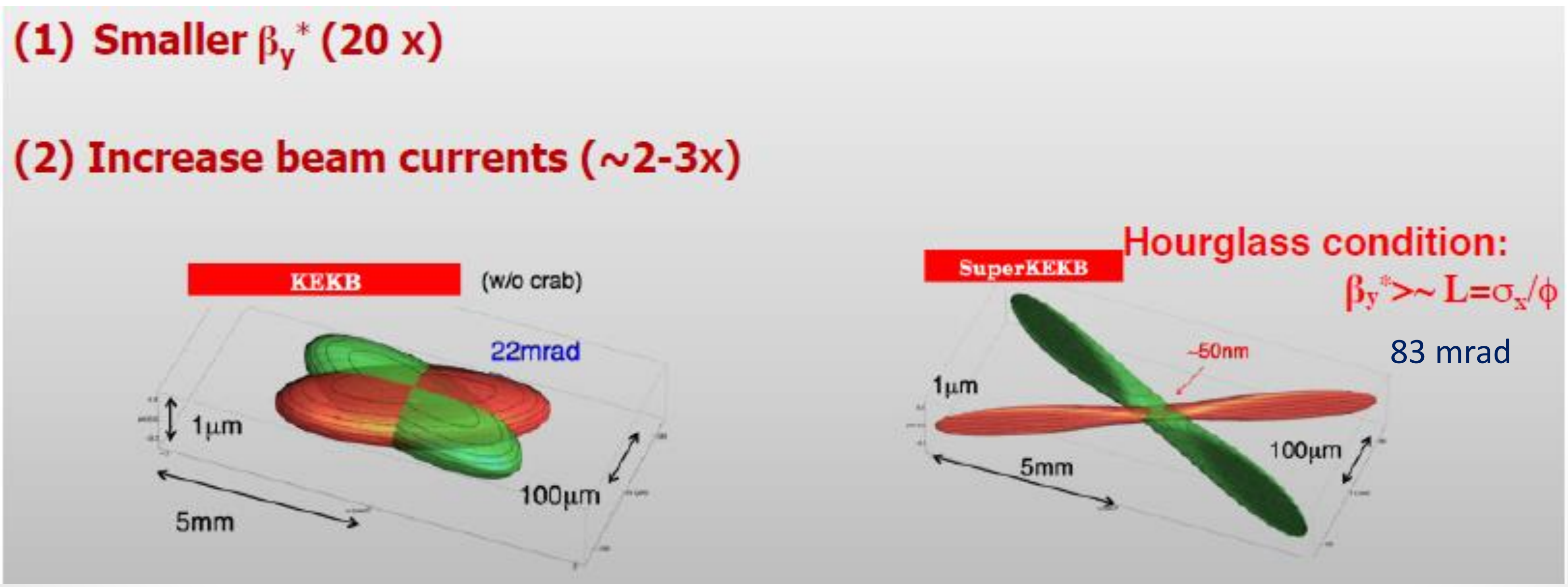
Brute force: Increase beam currents by a factor of 5-10 ! Increase the beam-beam parameter by a factor of a few (crab cavities).
Too hard, too expensive (power, melt beam pipes)

The path to higher luminosity

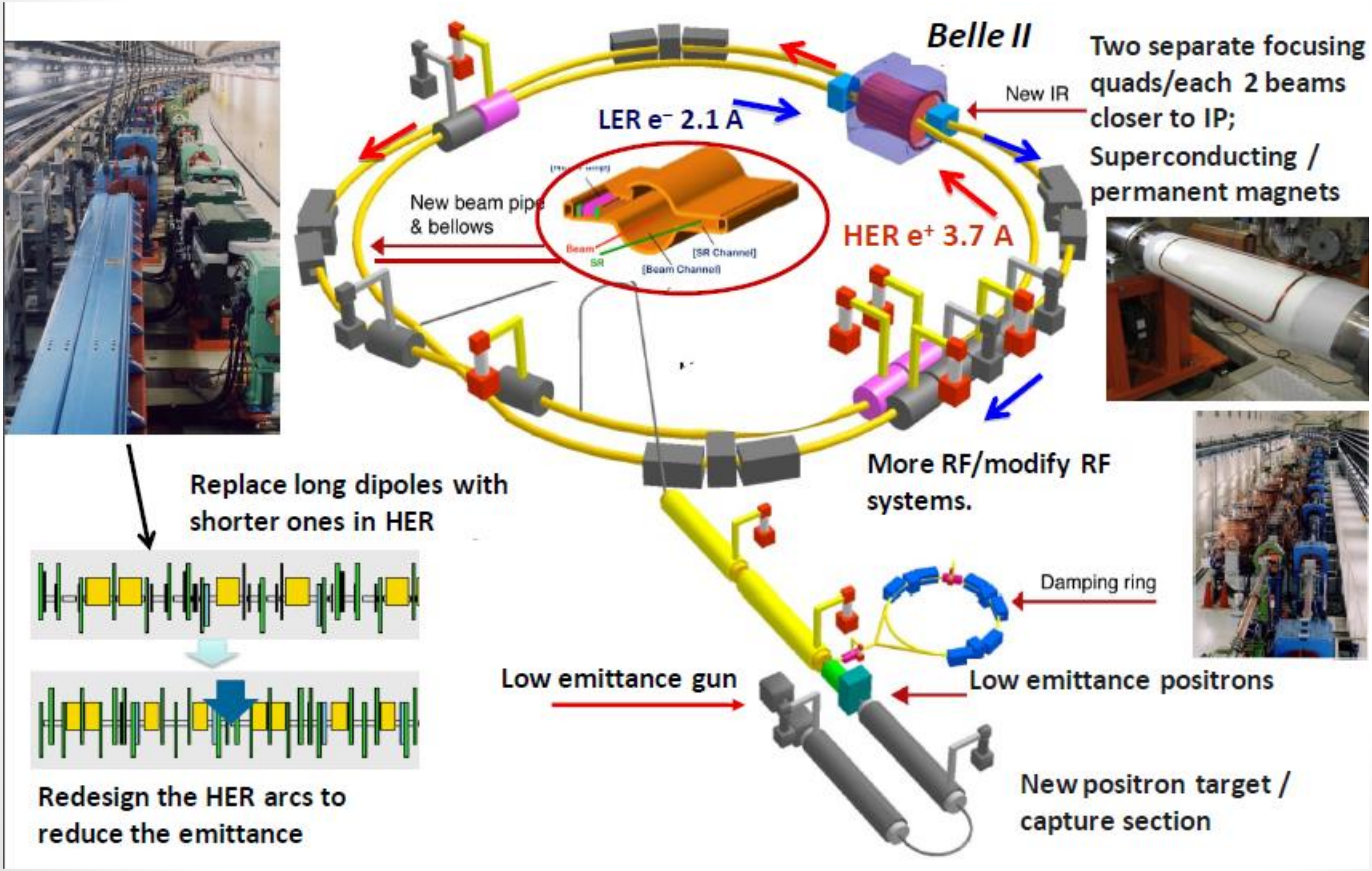
$$\xi \propto \sqrt{\frac{\beta^*}{\varepsilon}}$$



$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

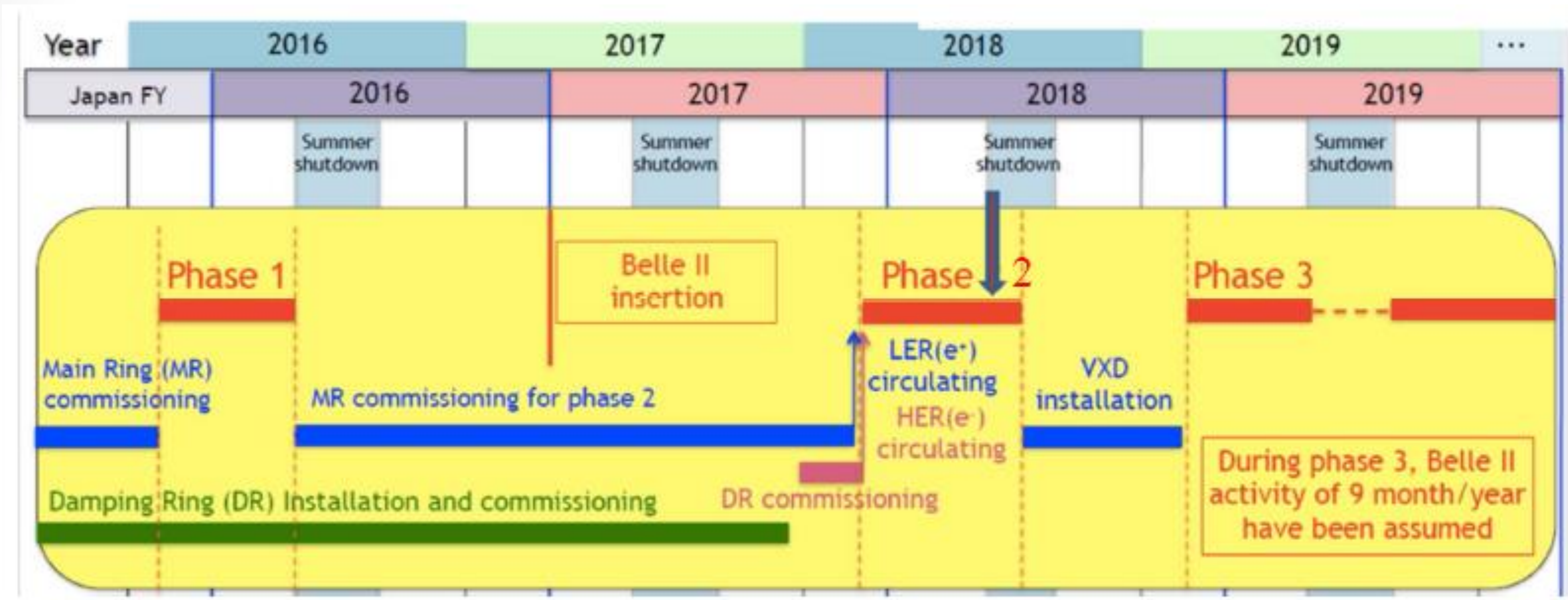


SUPERKEKB



Belle II
Two separate focusing quads/each 2 beams closer to IP;
Superconducting / permanent magnets
New IR
LER e⁻ 2.1 A
HER e⁺ 3.7 A
New beam pipe & bellows
Beam
SR
[SR Channel]
[Beam Channel]
More RF/modify RF systems.
Replace long dipoles with shorter ones in HER
Redesign the HER arcs to reduce the emittance
Damping ring
Low emittance gun
Low emittance positrons
New positron target / capture section

Schedule and status



First collisions, 26 April, 2018

Phase 2 goals:

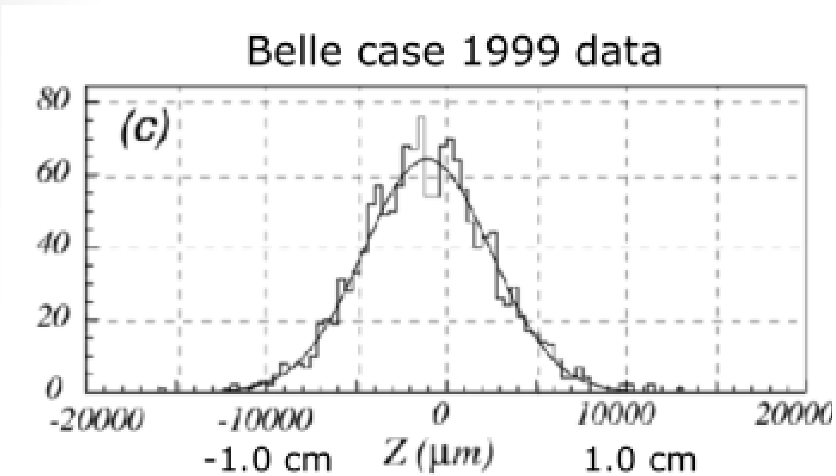
- Progress toward high luminosity
- Progress toward stable operation

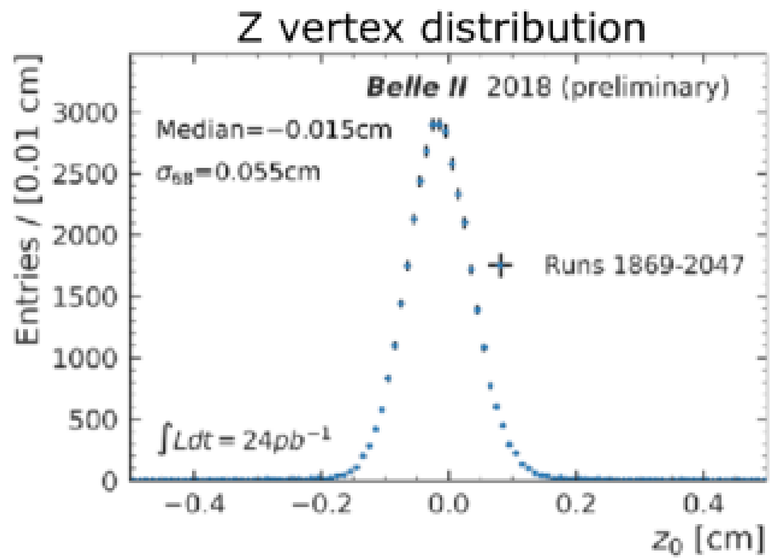
Achievements:

- $L = 5.5 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Collected $\sim 0.5\ \mathrm{fb}^{-1}$ for commissioning & calibration

Ohnishi-san eeFACT, HKUST

Super KEKB performance

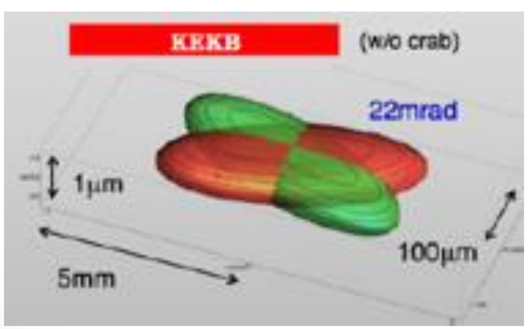


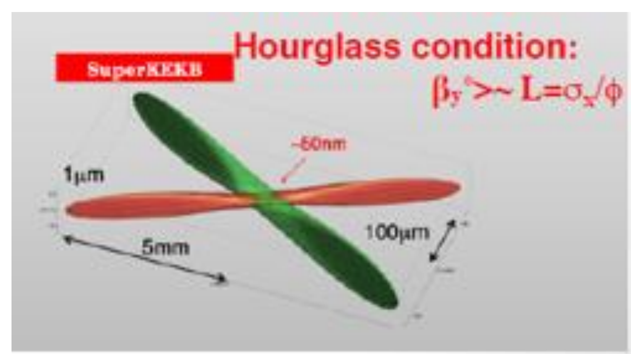


σ = 4.5 mm

σ = 550 μm

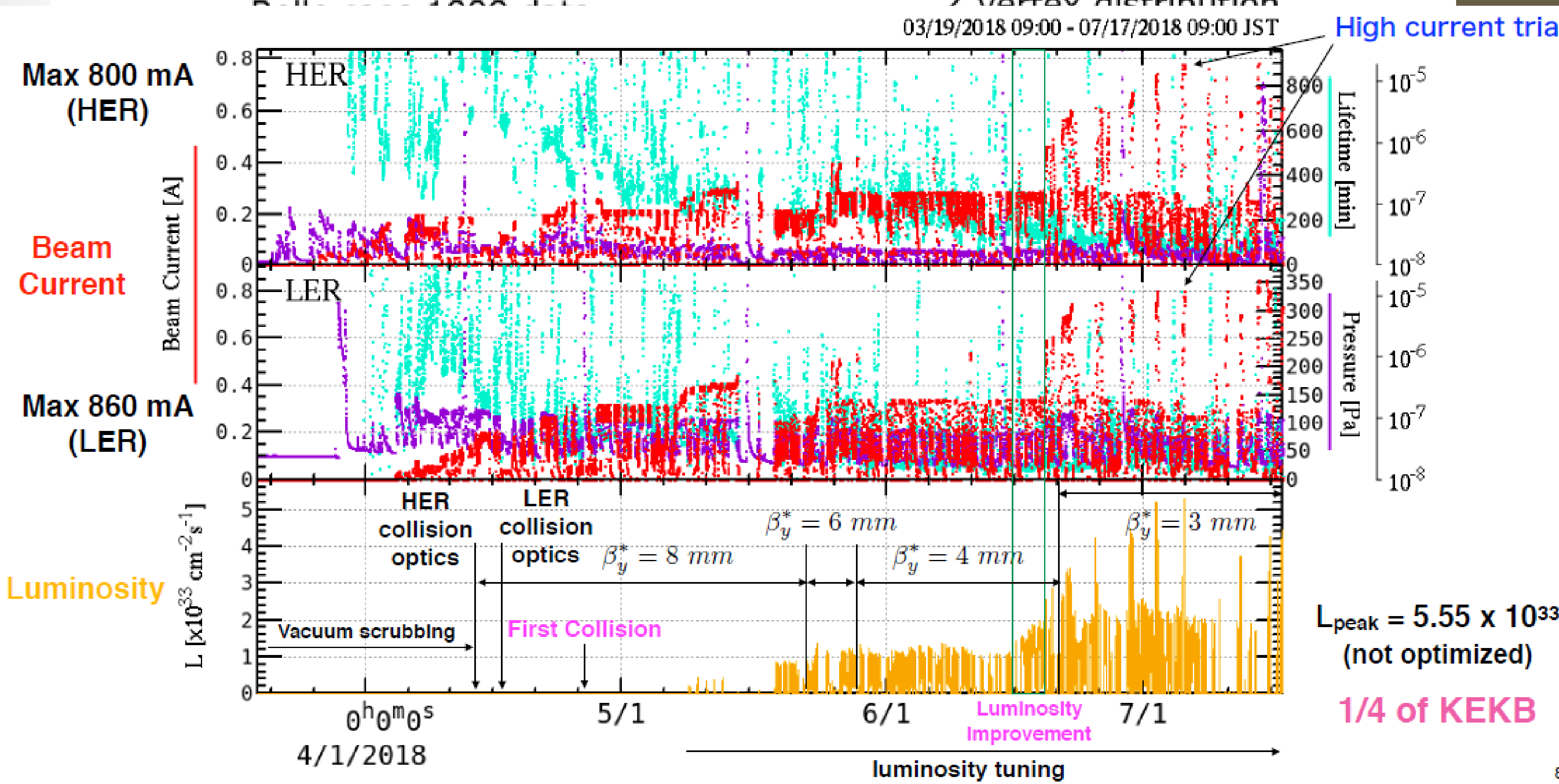
measurement at Belle II



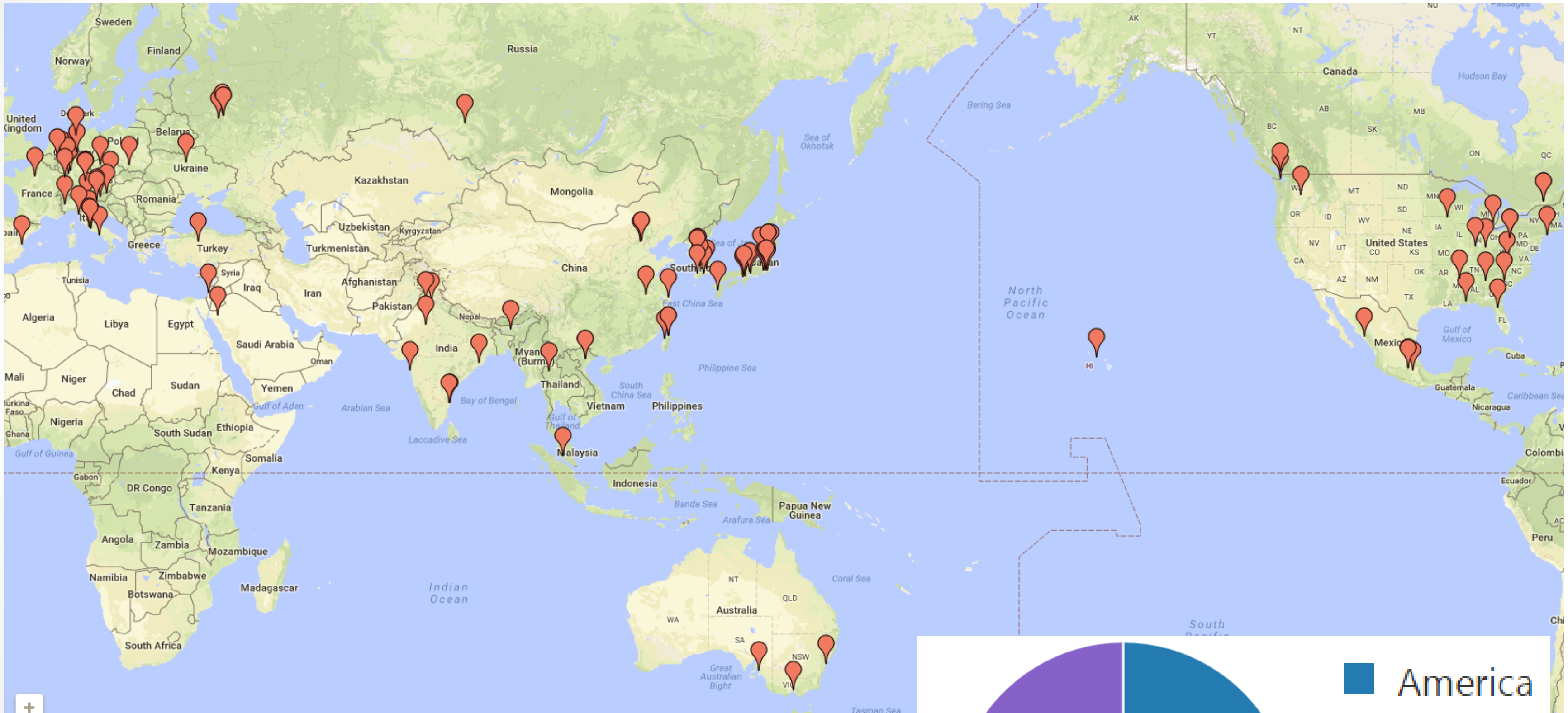


Ohnishi-san eeFACT, HKUST

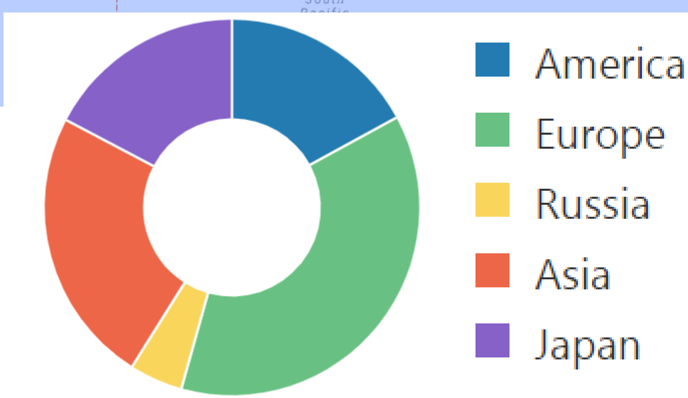
Super KEKB performance



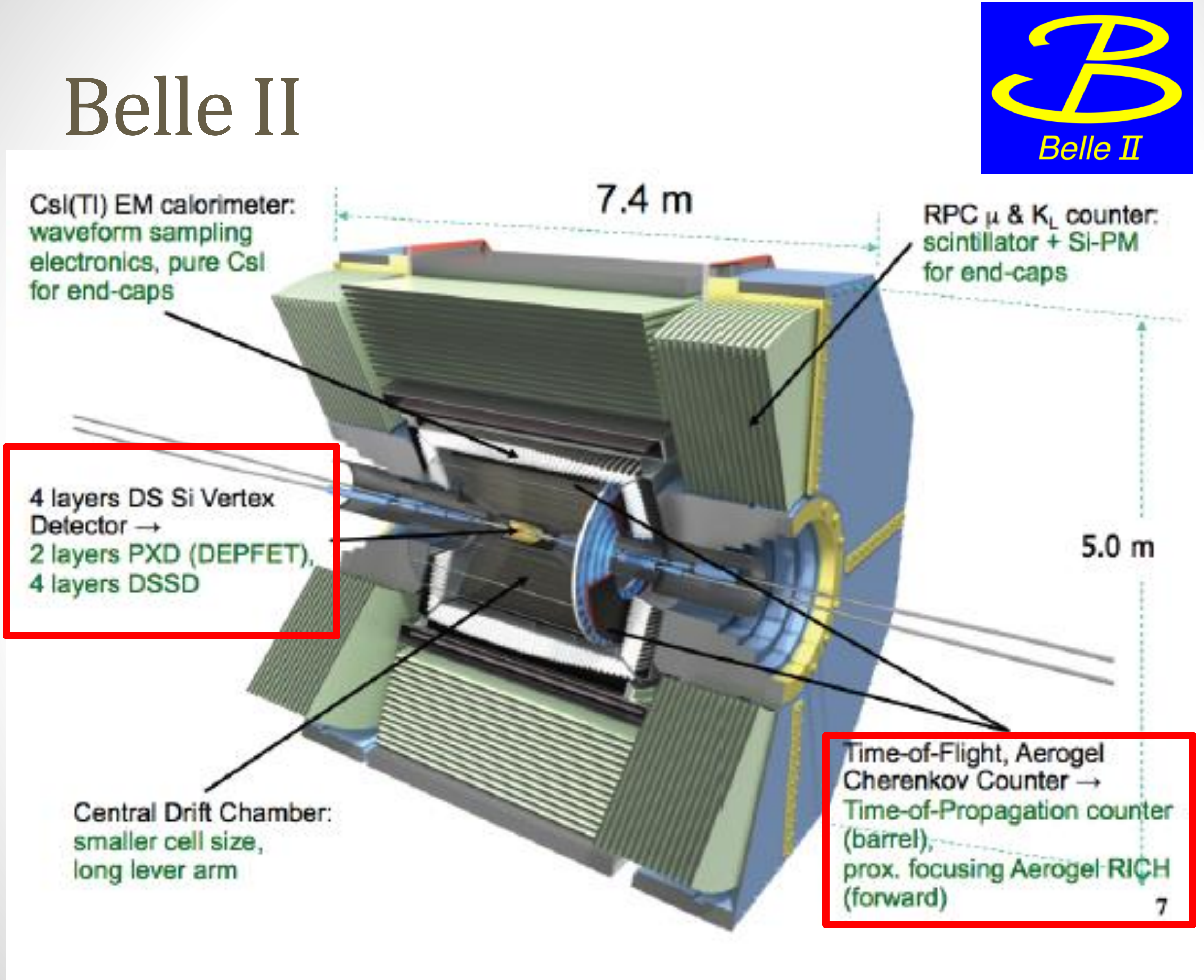
Belle II Collaboration



800 physicists from 25 countries



Belle II

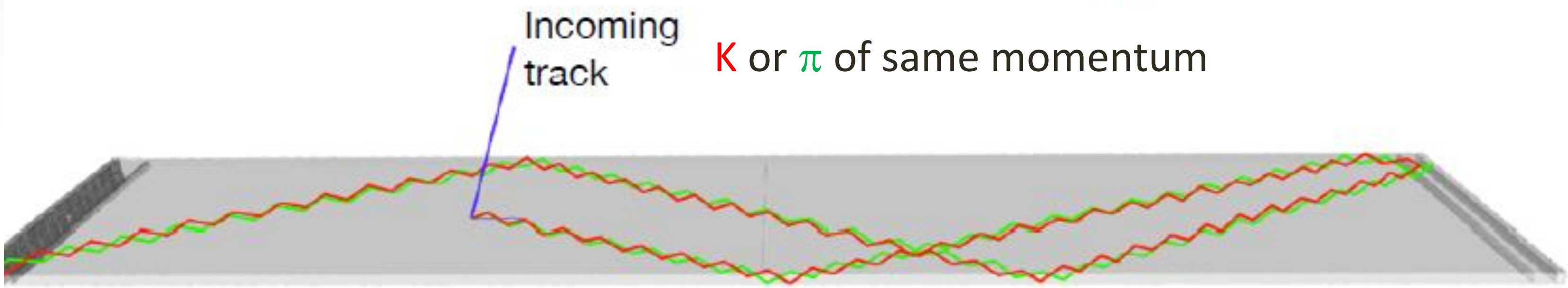


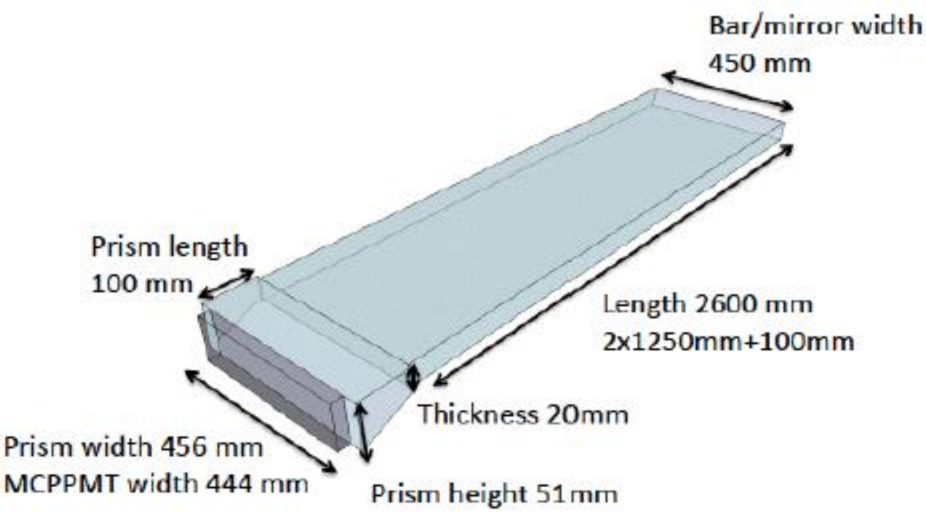
Belle II
7.4 m
CsI(Tl) EM calorimeter:
waveform sampling electronics, pure CsI for end-caps
RPC μ & K_L counter:
scintillator + Si-PM for end-caps
4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET), 4 layers DSSD
5.0 m
Central Drift Chamber:
smaller cell size, long lever arm
Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)
7

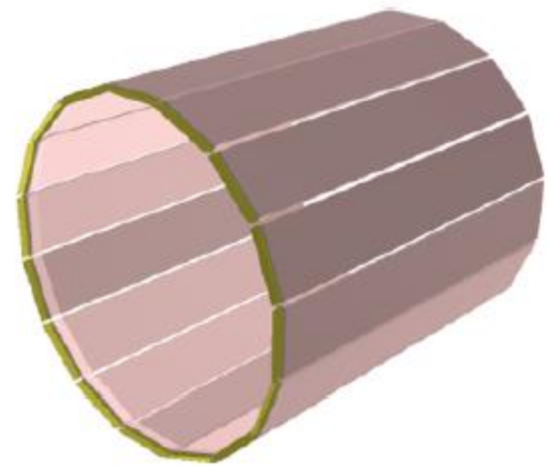
Belle II - TOP

Simulation of a 2 GeV pion and kaon interacting in a quartz bar.

K or π of same momentum

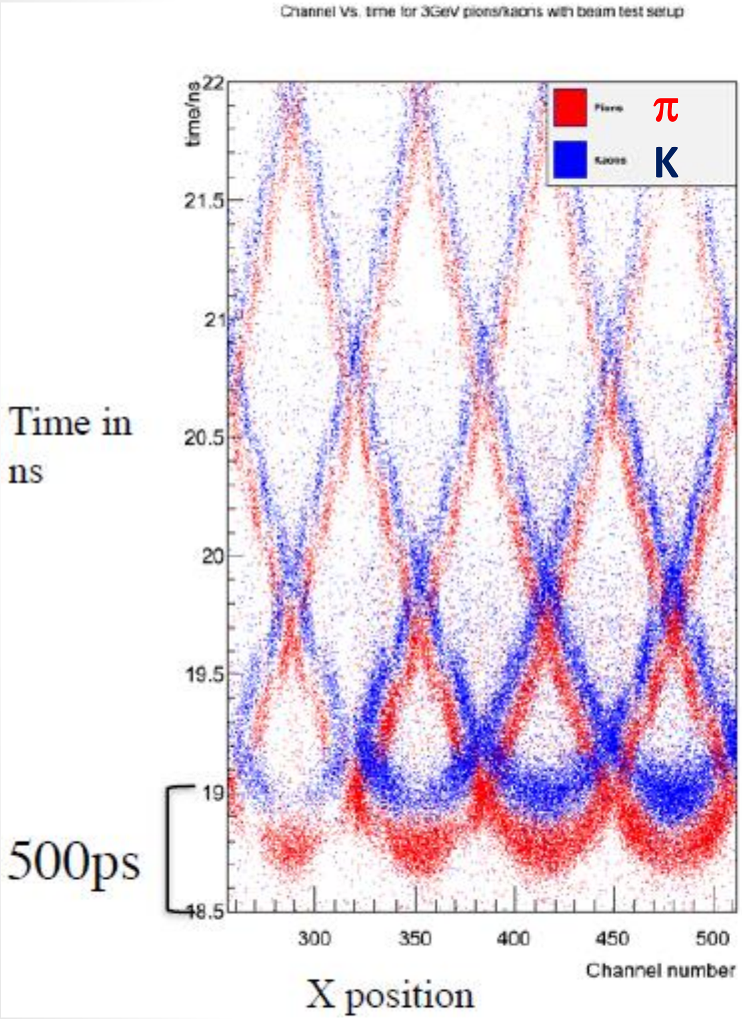




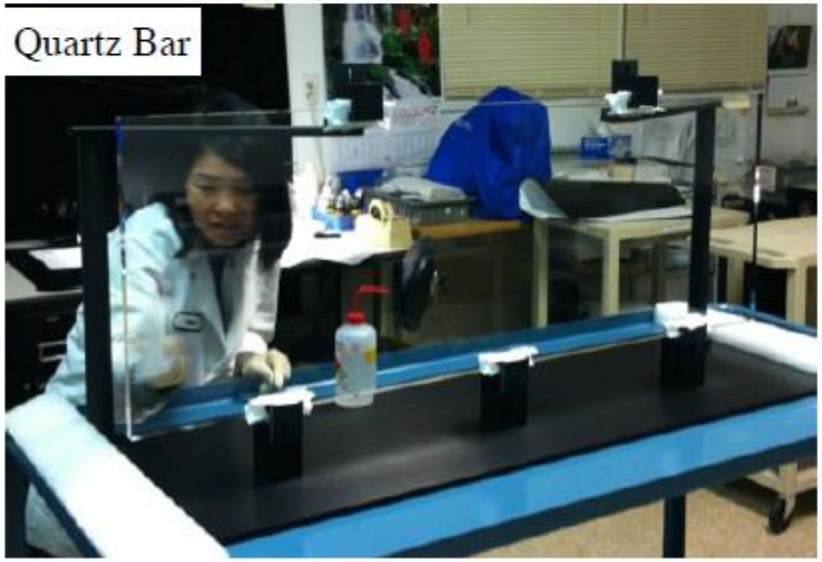


16 bar modules arranged in a "roman arch"

Belle II - TOP

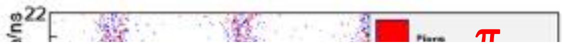


At 3 GeV *Timing at the ~100 ps level is needed to separate pion and Kaon*



Belle II - TOP

Channel Vs. time for 3GeV pions/kaons with beam test setup

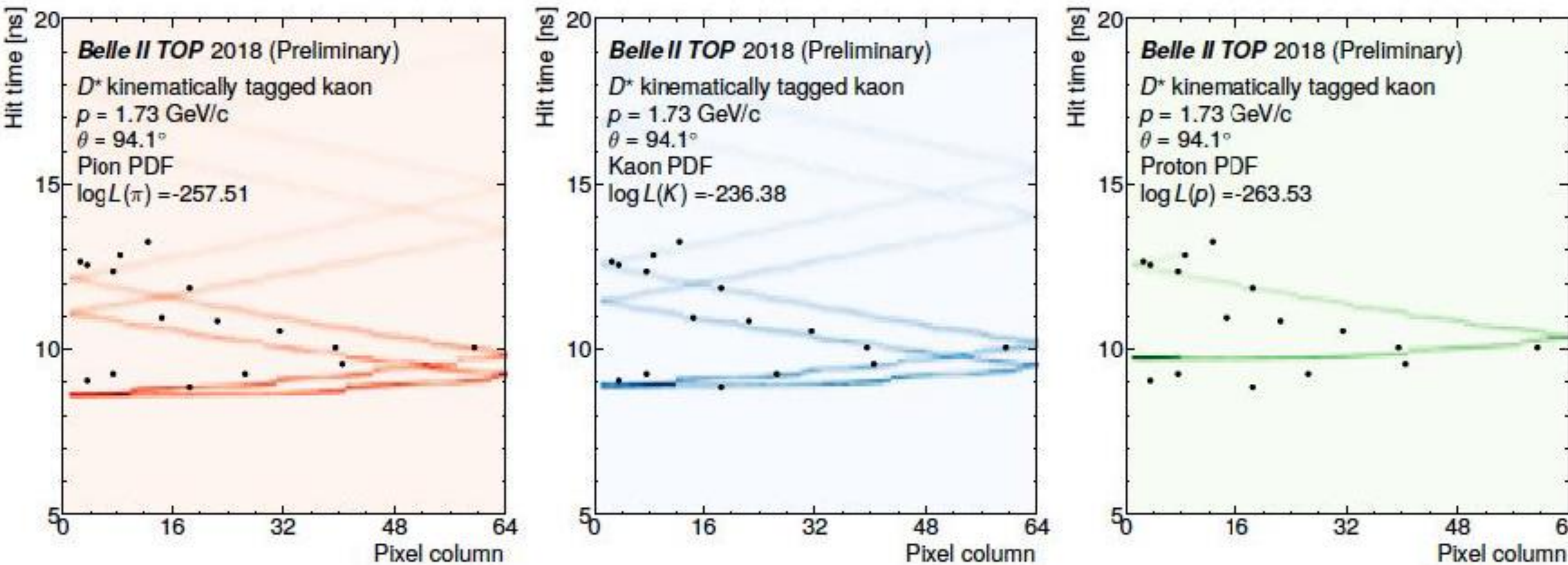


At 3 GeV *Timing at the ~100 ps level is needed to separate pion and Kaon*

ToP signature of kaon identified kinematically via $D^{*+} \rightarrow D^0 \pi_s^+ ; D^0 \rightarrow K^- \pi^+$

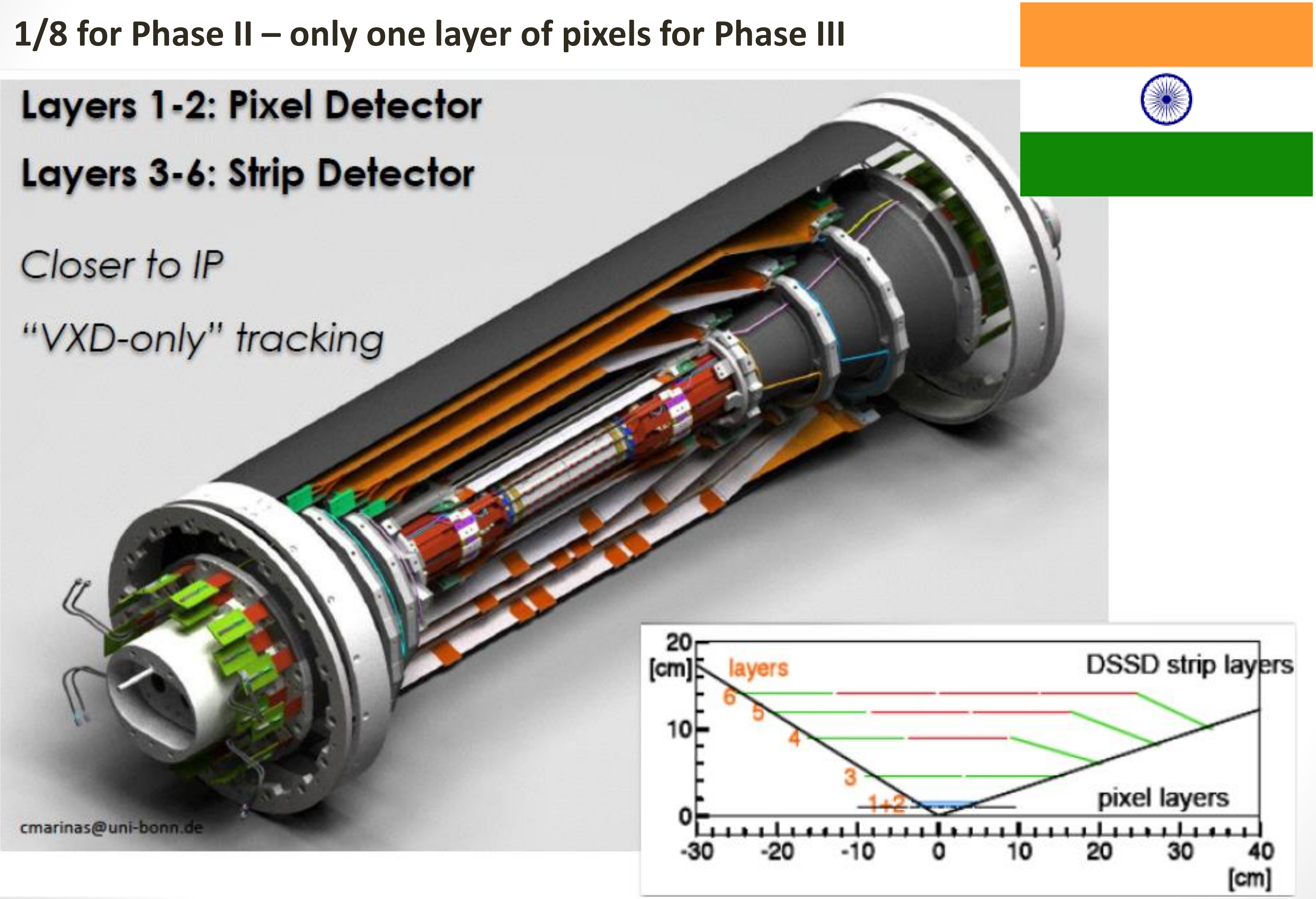
is visibly more consistent with being a kaon than a pion or proton

Phase II data

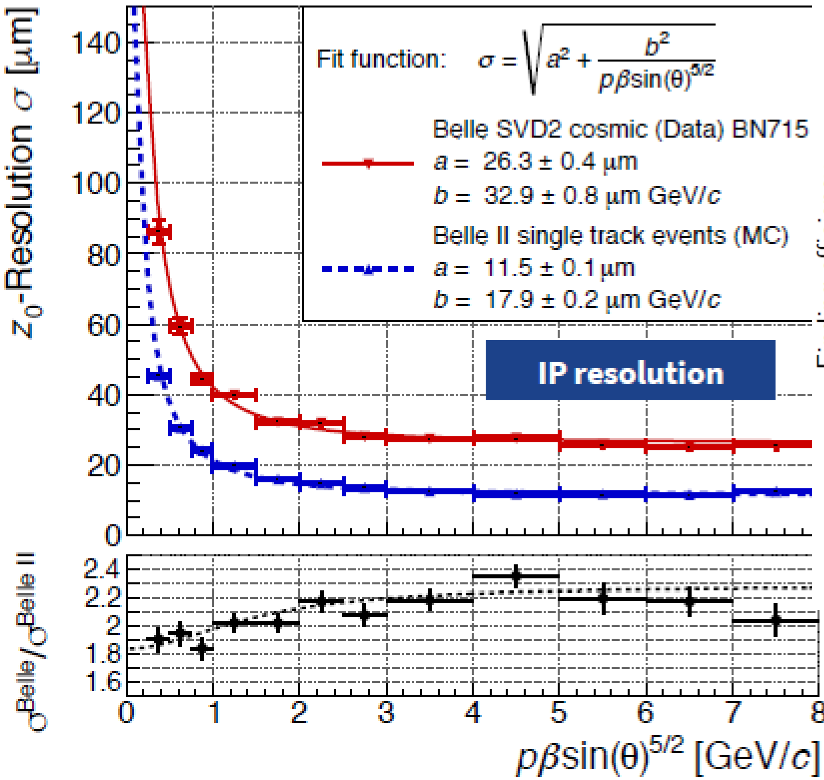


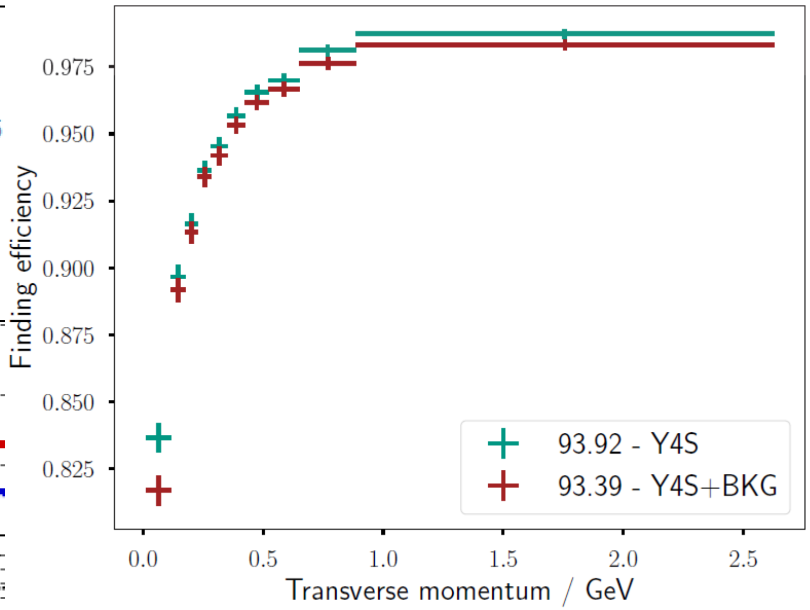
Belle II – Silicon Vertex Dectector

1/8 for Phase II – only one layer of pixels for Phase III



SVD performance

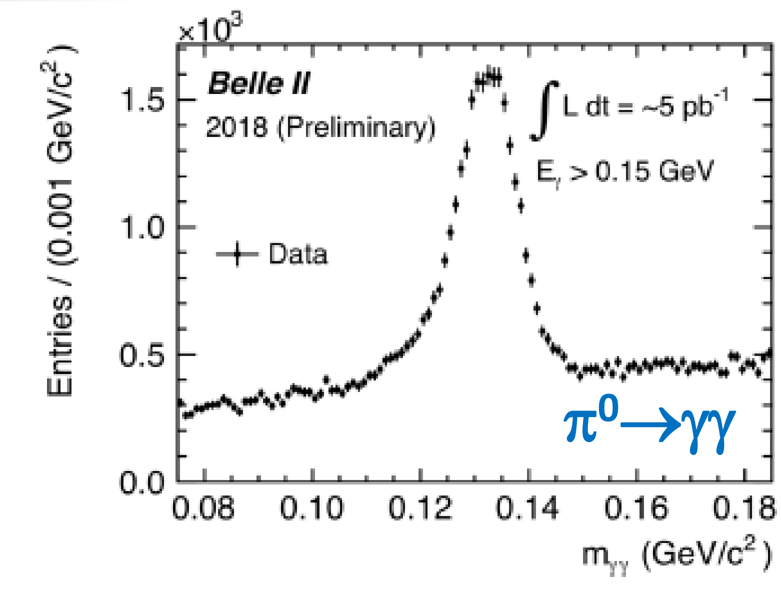


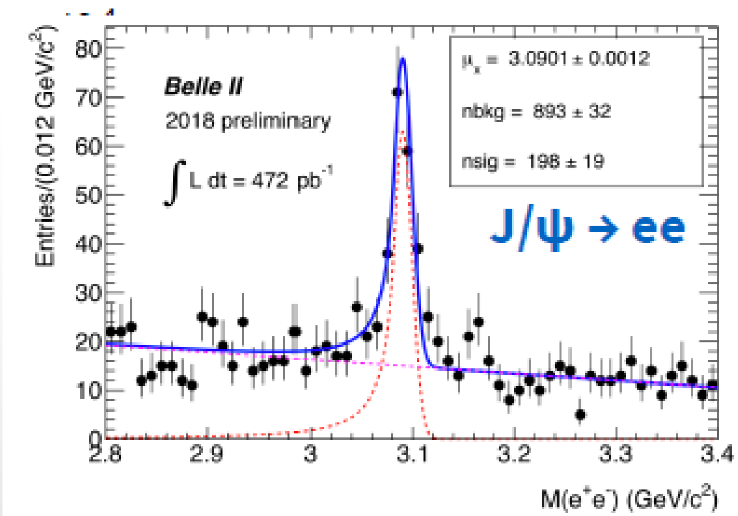


Belle a factor two worse than Belle II

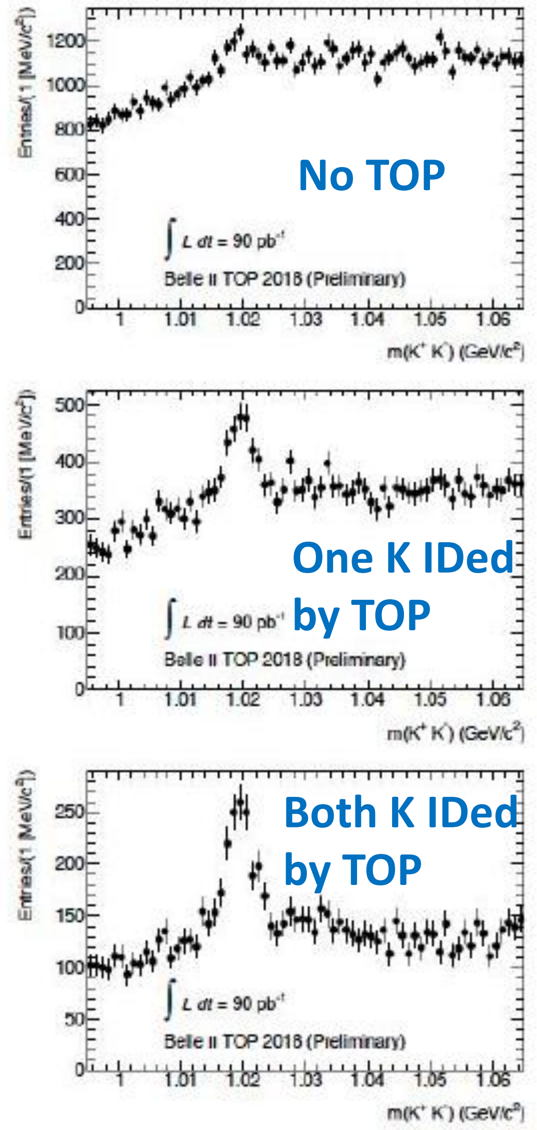
Stand alone SVD track finding efficiency good for K_S finding (30% over Belle) and slow π from D*

Particle reconstruction

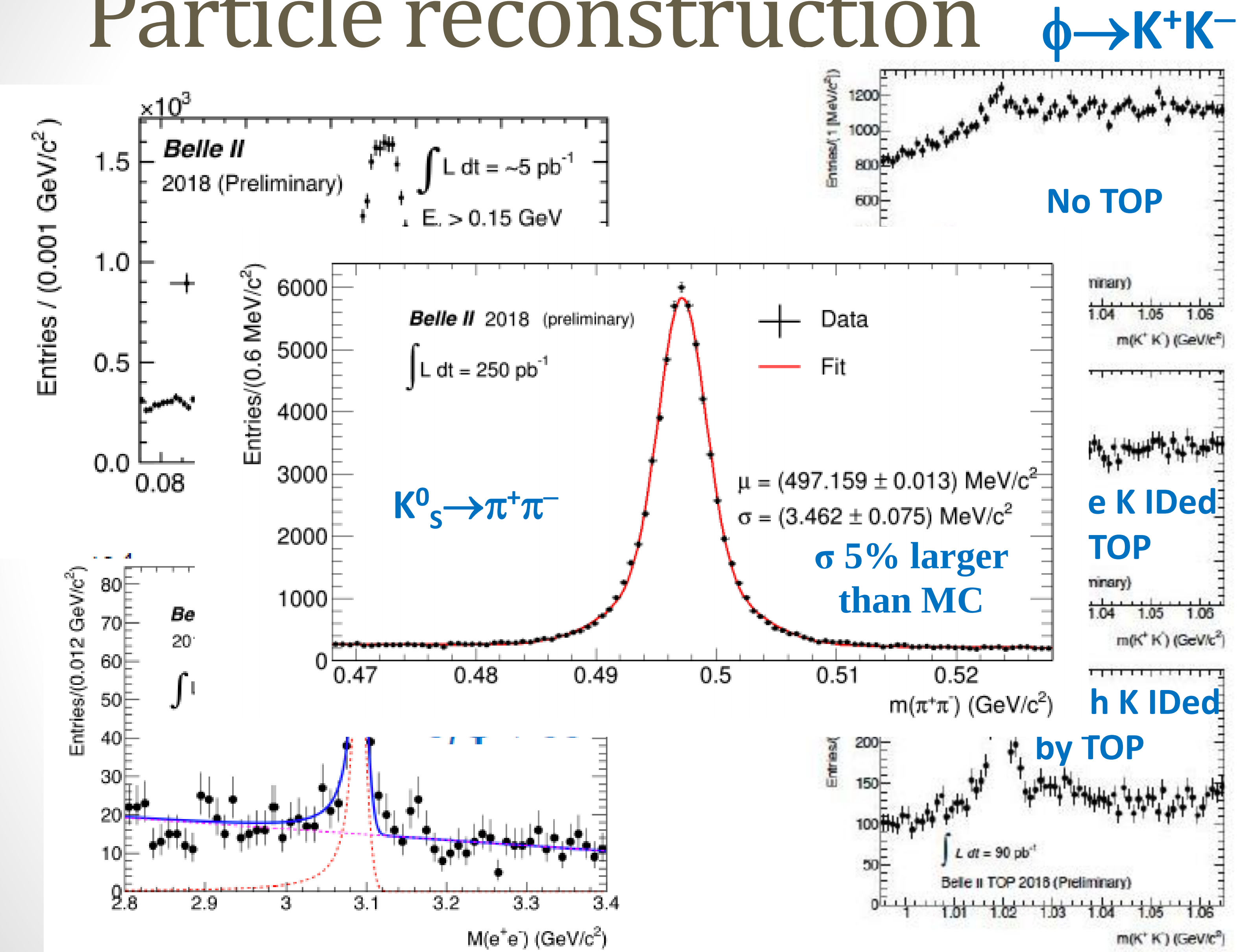




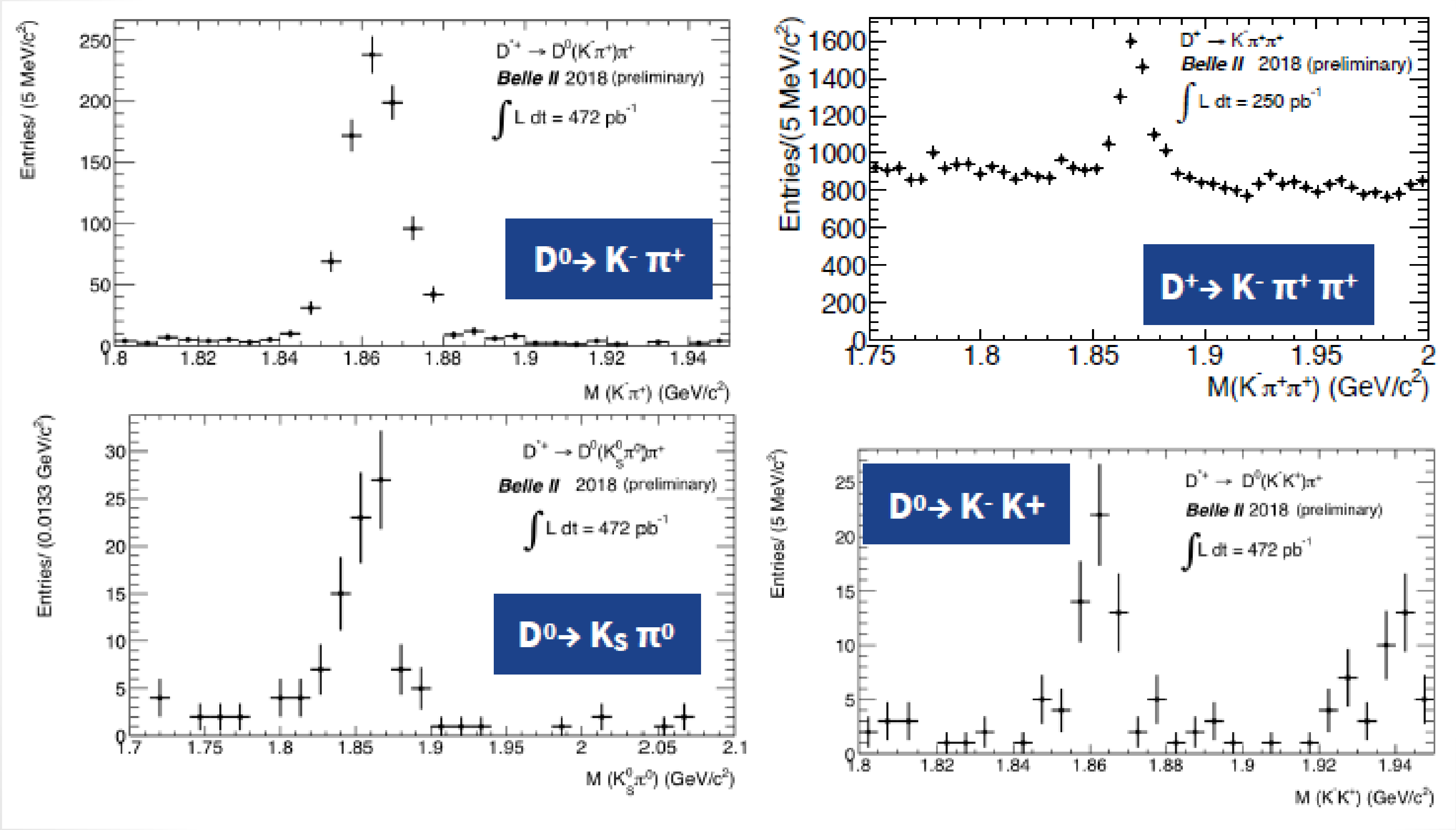
φ→K⁺K⁻



Particle reconstruction

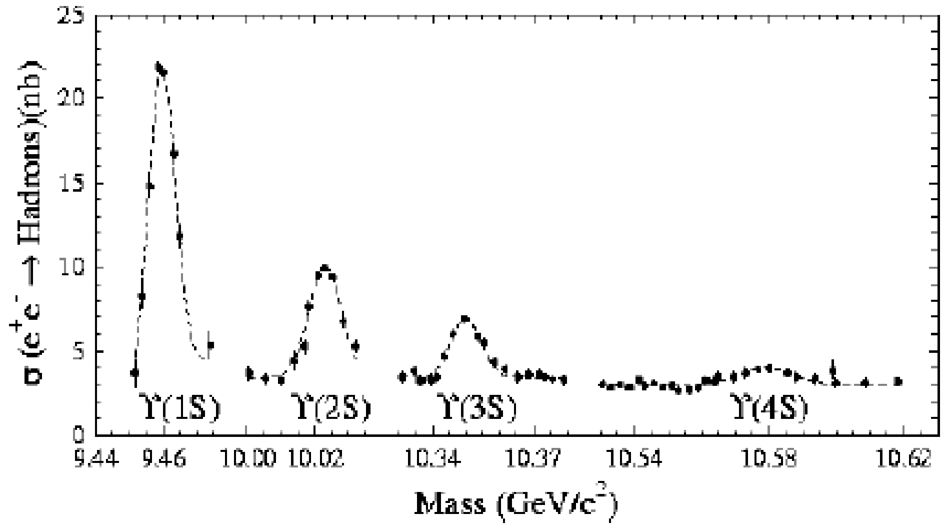


Charm meson reconstruction

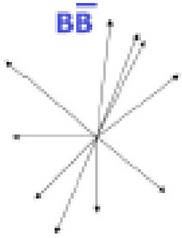


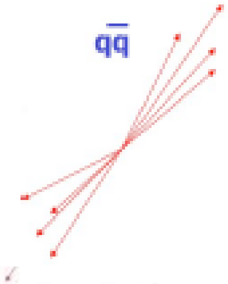
Many charm decays seen including CP eigenstates used in CP violation measurements – reasonable agreement with expectations

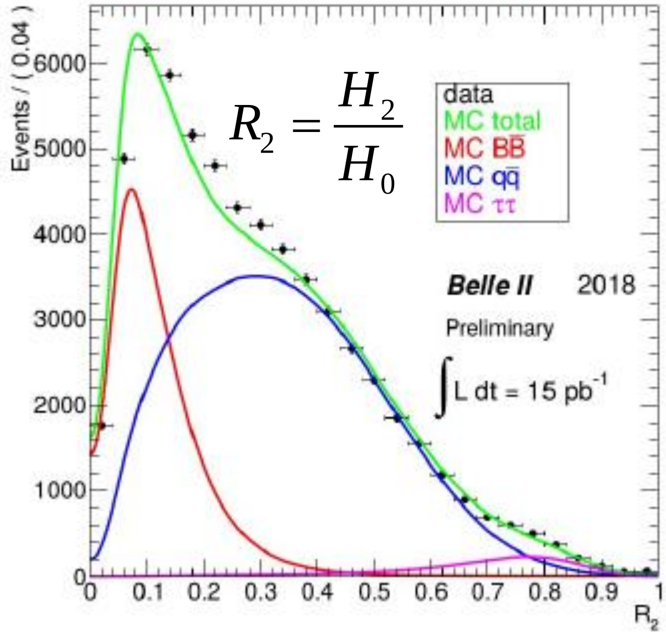
Beauty measurements



- We are on the Y(4S) resonance and recording B anti-B pairs with ~99% efficiency.
- *Not so obvious: When we change accelerator optics, we remain on Y(4S).*



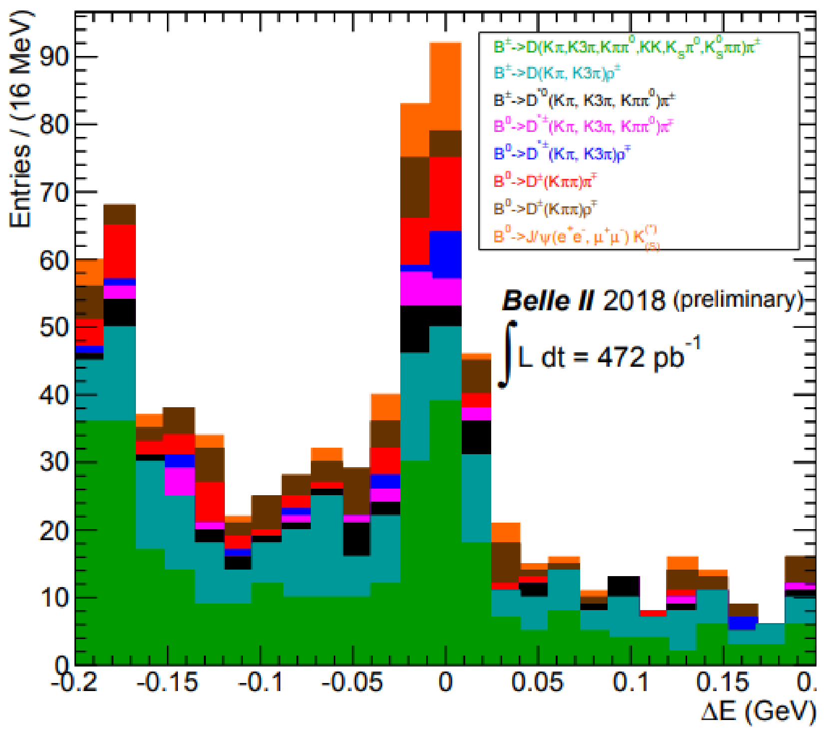


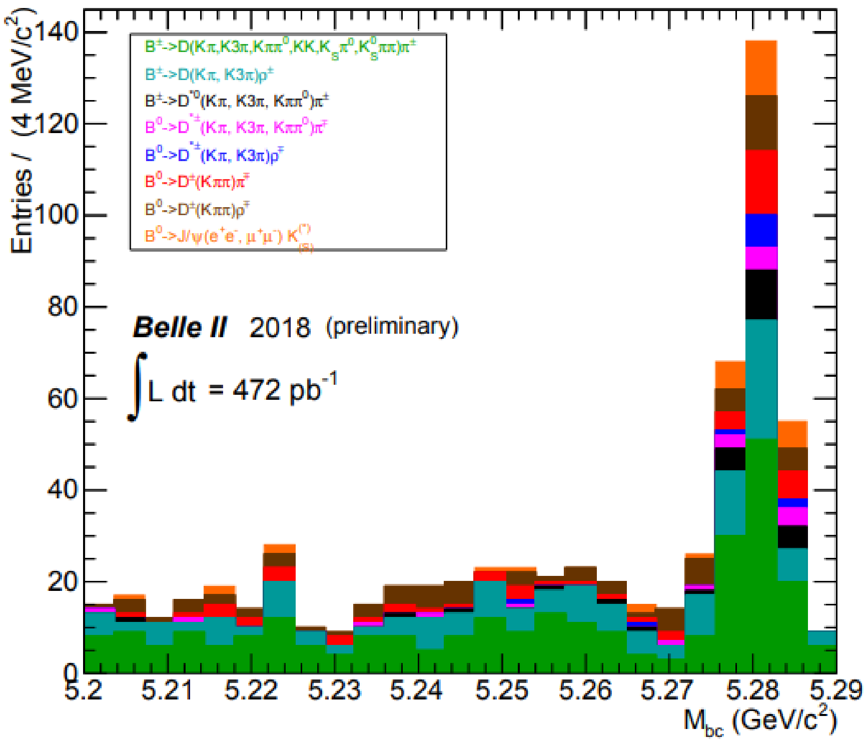


$$H_l = \sum_{i,j} \frac{|\mathbf{p}_i|\,|\mathbf{p}_j|}{E_{\text{vis}}^2} P_l(\cos\theta_{ij})$$

B meson reconstruction

$$\Delta E = \frac{E_{CM}}{2} - E_B \qquad M_{\mathrm{BC}} = \sqrt{\left(\frac{E_{\mathrm{CM}}}{2}\right) - \left|\vec{\mathbf{p}}_B\right|^2}$$





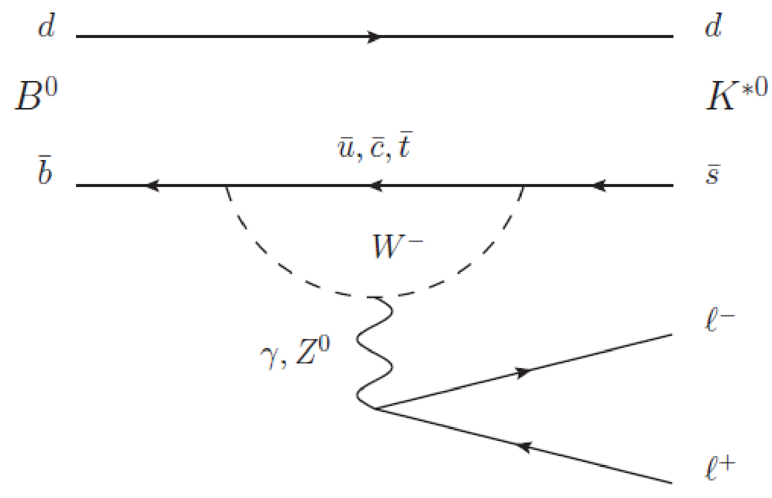
$B \rightarrow D^{(*)}h$ ($h=\pi,\rho$) and $B \rightarrow J/\psi K^{(*)}$

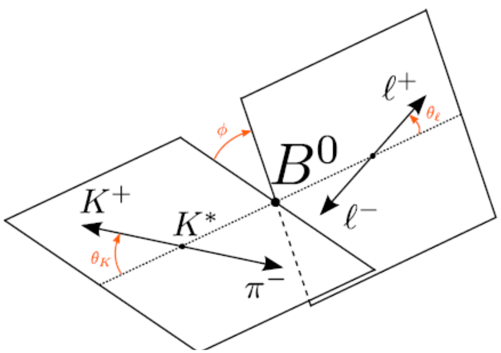
Reconstructed > 200 B events

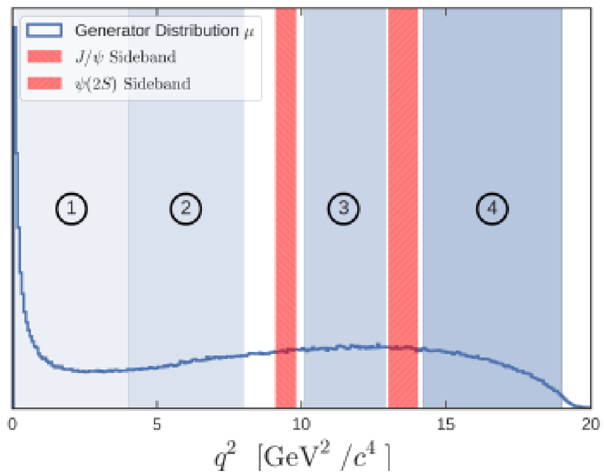
A FEW PHYSICS PROSPECTS

$B \to K^*(892) l^+ l^-$

- This is a rare flavour changing neutral current process
- The four-body final state allows differential distributions to be probed
  - Large new physics contributions possible as they appear via interference c.f. forward-backward asymmetries in e^+e^-
- Also variation with the invariant mass of the l^+l^- system - q^2

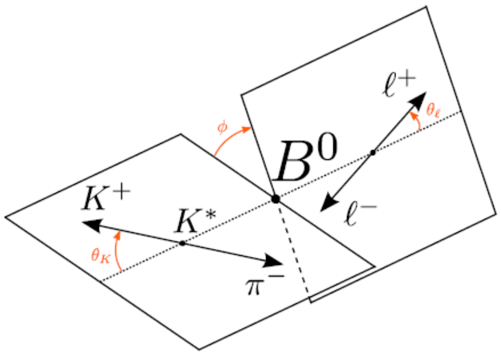






$B\to K^*(892)l^+l^-$ nomenclature

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L - F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi + S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi + S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\right]$$

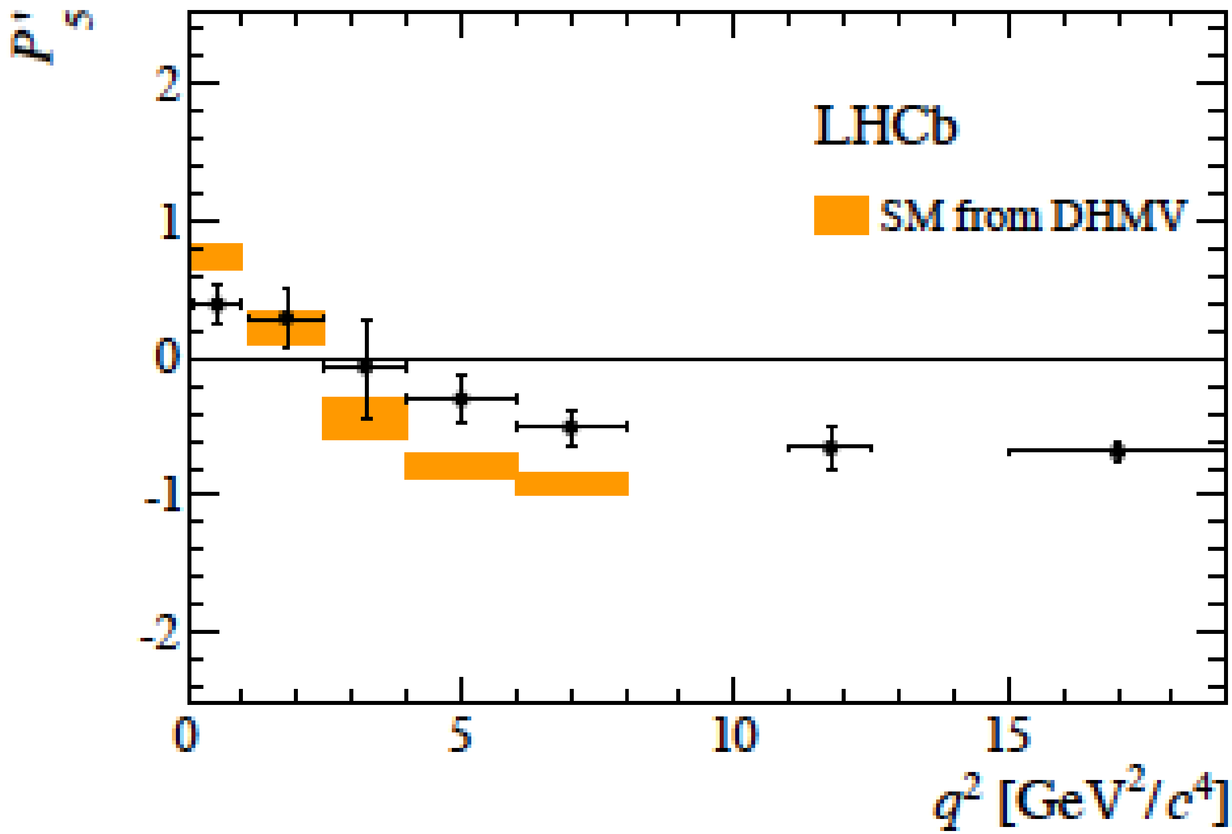


- Goal is to measure this 4D differential distribution and extract the coefficients from data to compare to the SM predictions
- Much work on defining observables with minimal theoretical uncertainties
- Let us focus on S_5 which get normalized as $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ to minimize form factor uncertainties

LHCb

Exp.: R. Aaij et al., JHEP 02 (2016) 104
Theory: S. Descotes-Genon et al., JHEP 12 (2014) 125

Angular Asymmetries based on 2398±57 B→K*μμ events

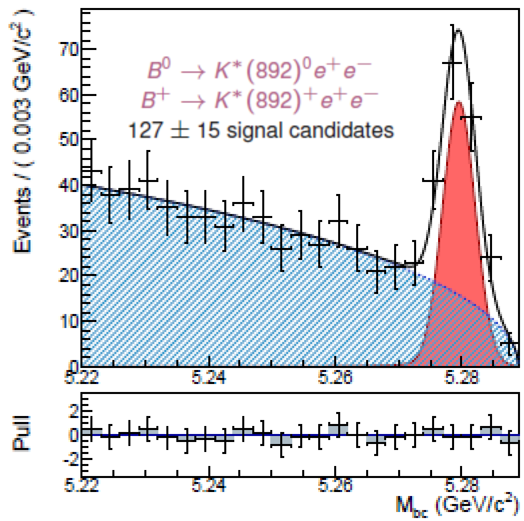


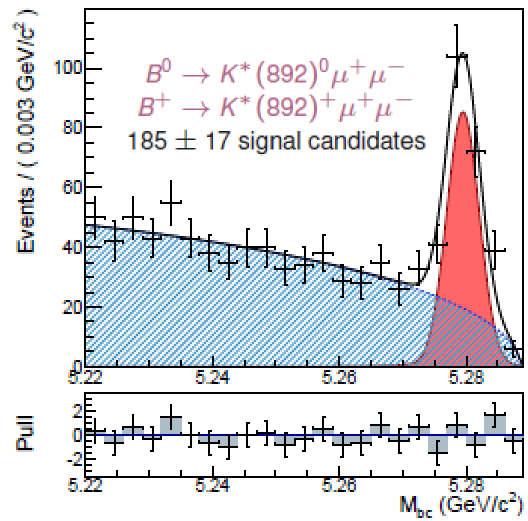
3.7 σ disagreement with Standard Model

Other analyses of the data also show inconsistency i.e. RH currents at large q^2
A. Karan et al. arXiv:1603.04355 [hep-ph]

Belle

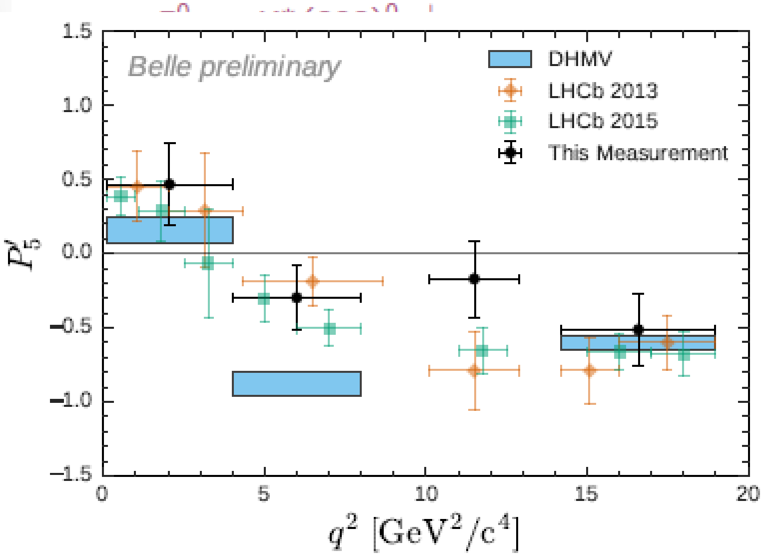
PRL118, 111801 (2017)

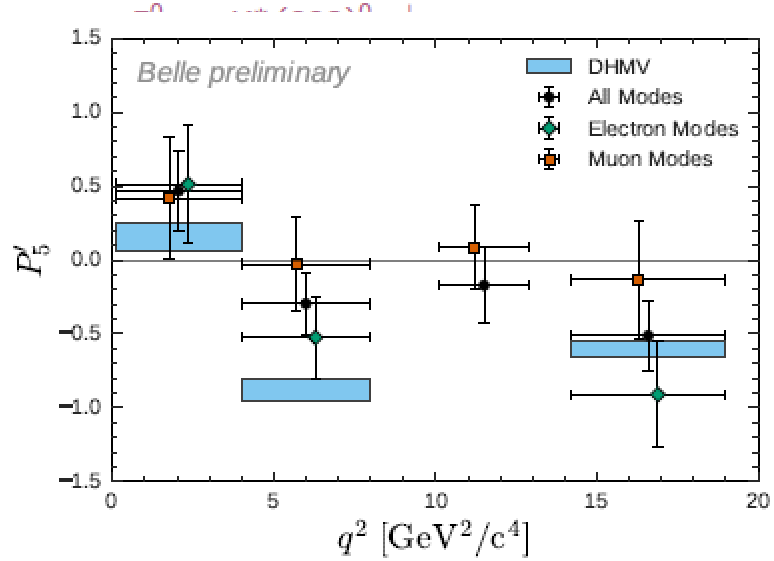




Smaller sample than LHCb, but e and μ

Tests of LUV more in a moment

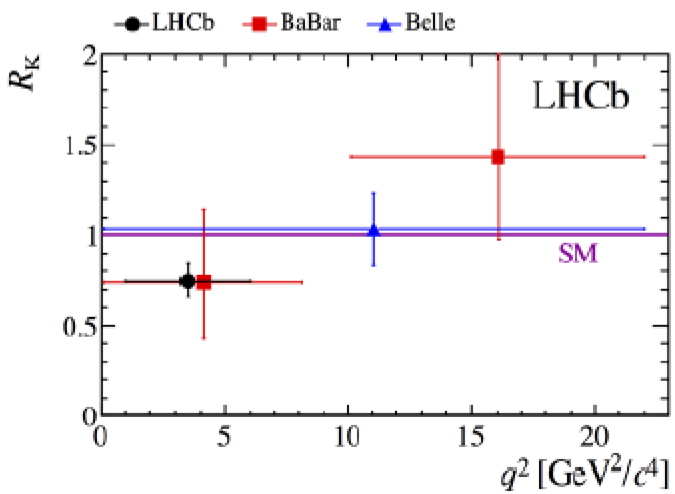




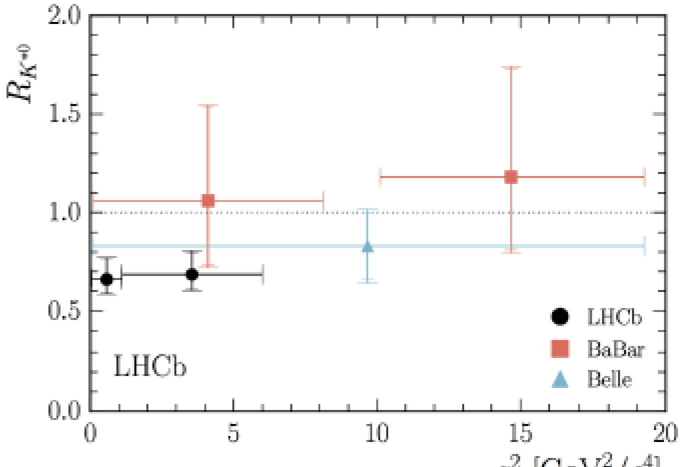
Lepton Universality Violation (LUV)

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2},$$

2-3 standard deviations for H = K and K*

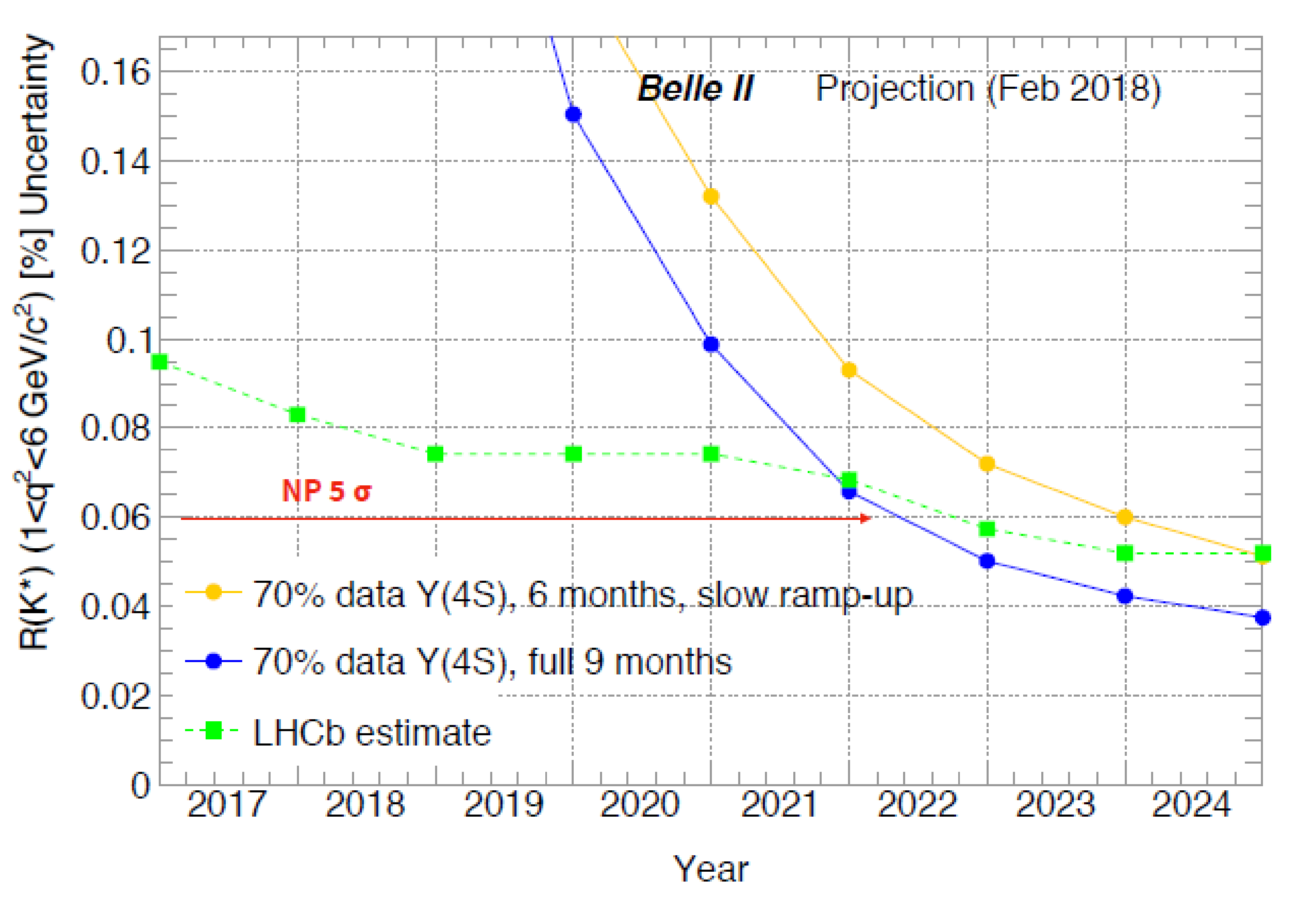


R_K is ~2.6σ from the SM



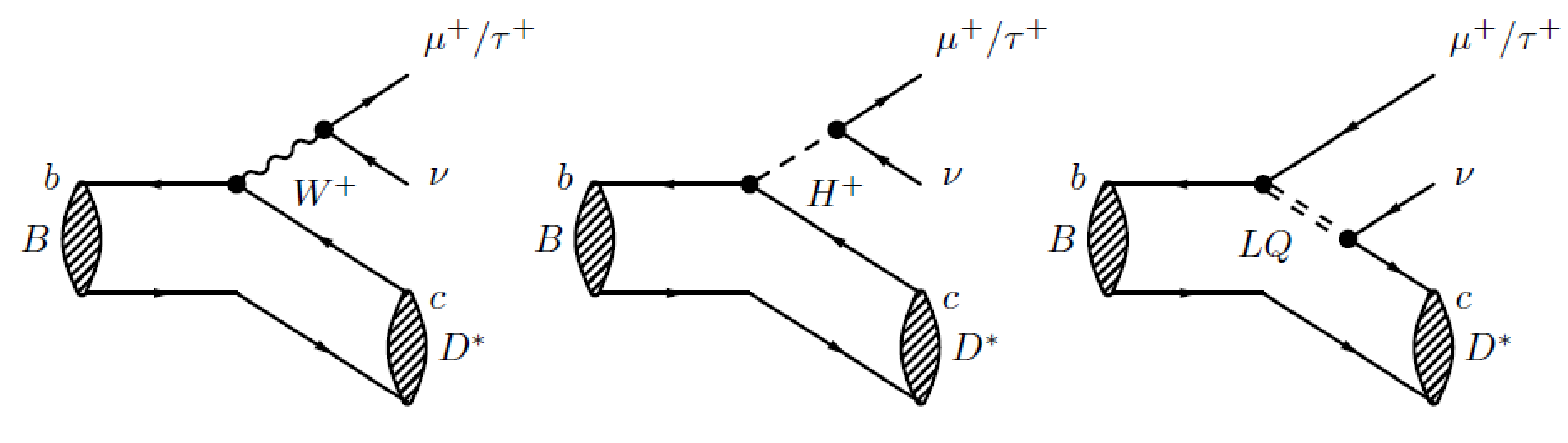
R_{K^*} ~2.1σ (low bin), 2.5σ (central bin)

Belle II predictions



Semi-tauonic decays

- Tree level in the SM but allows lepton universality tests

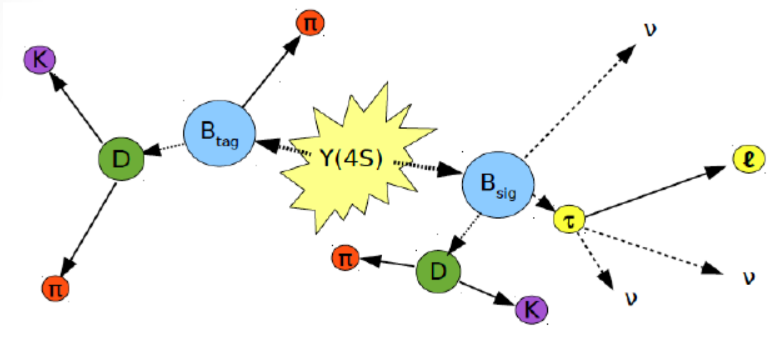


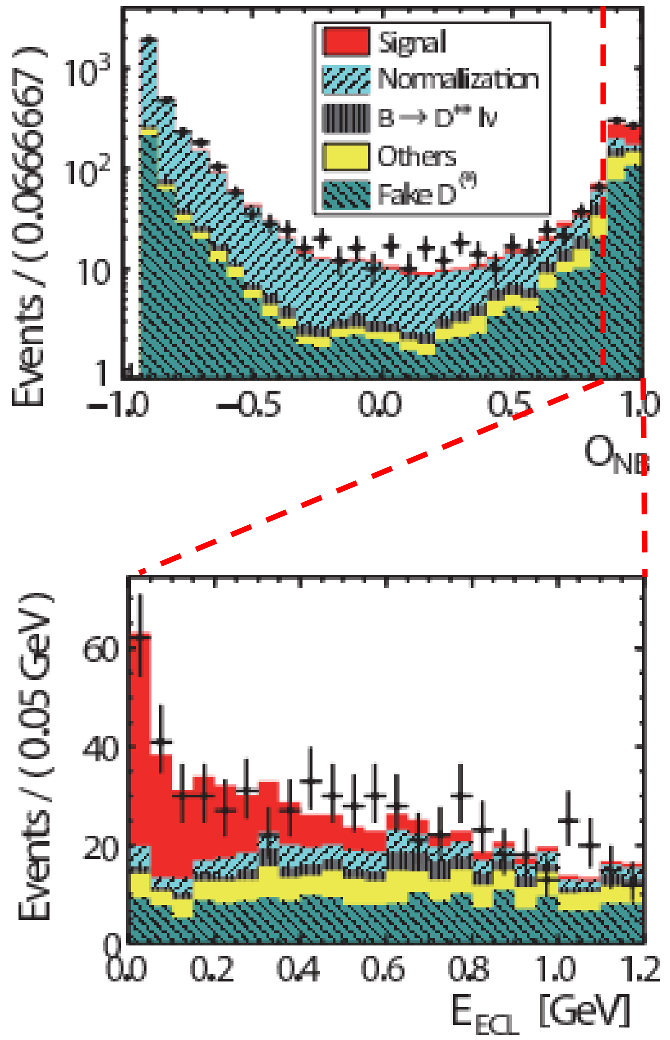
- Measure ratios to reduce theoretical and experimental uncertainties

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

- Babar reported an anomalous result PRL 109, 101802 (2012) much activity since

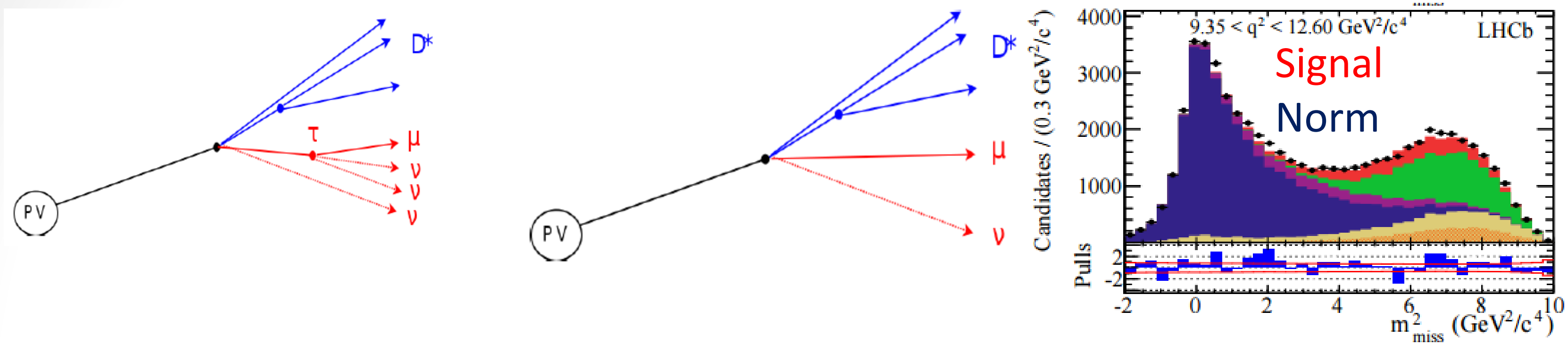
Belle results

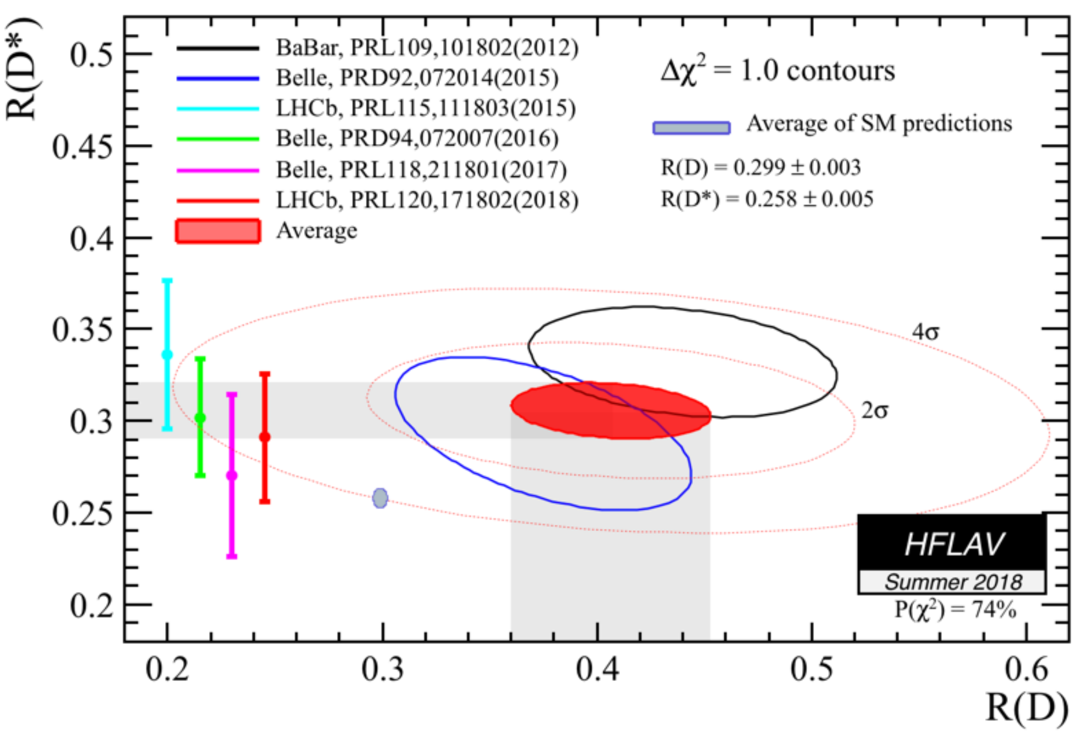




- Tag signal by fully reconstructing or identifying a semileptonic (SL) decay of the other B
- Then use residual energy in ECL, missing mass, multivariates and/or lepton momentum to separate signal
- Example: Phys. Rev. D 94, 072007 (2016) – SL tag

- LHCb also in the game using their vertexing prowess

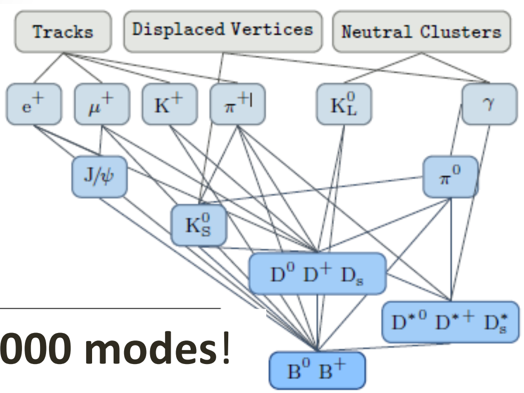




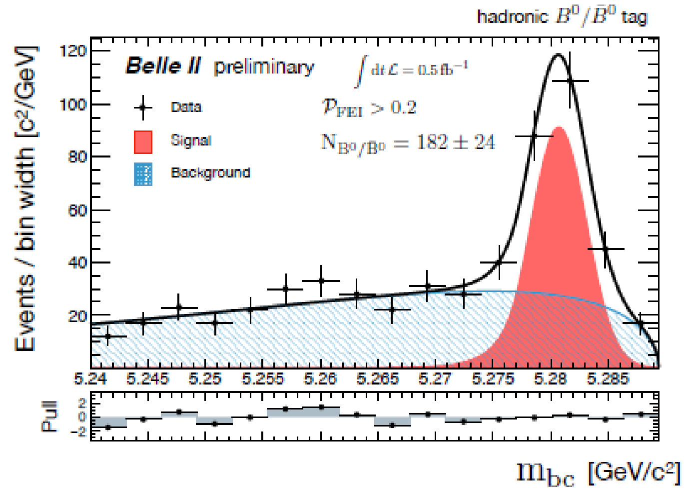
- Average 3.9σ from SM
- Several NP ideas but it is hard to get all the anomalies in a single framework

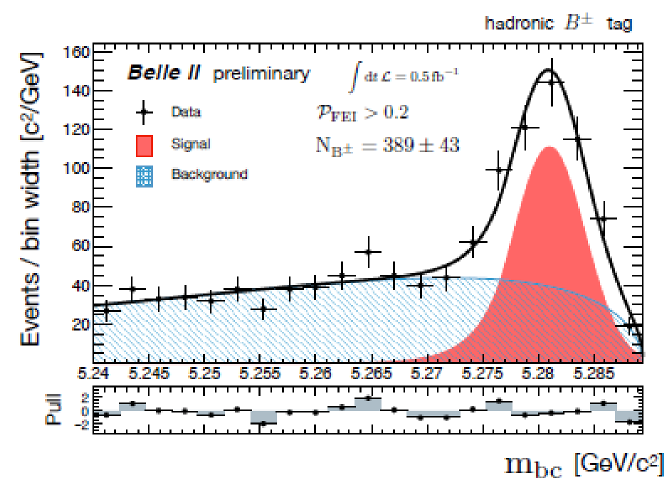
Belle II predictions

- More modes for tagging Full Event Interpretation

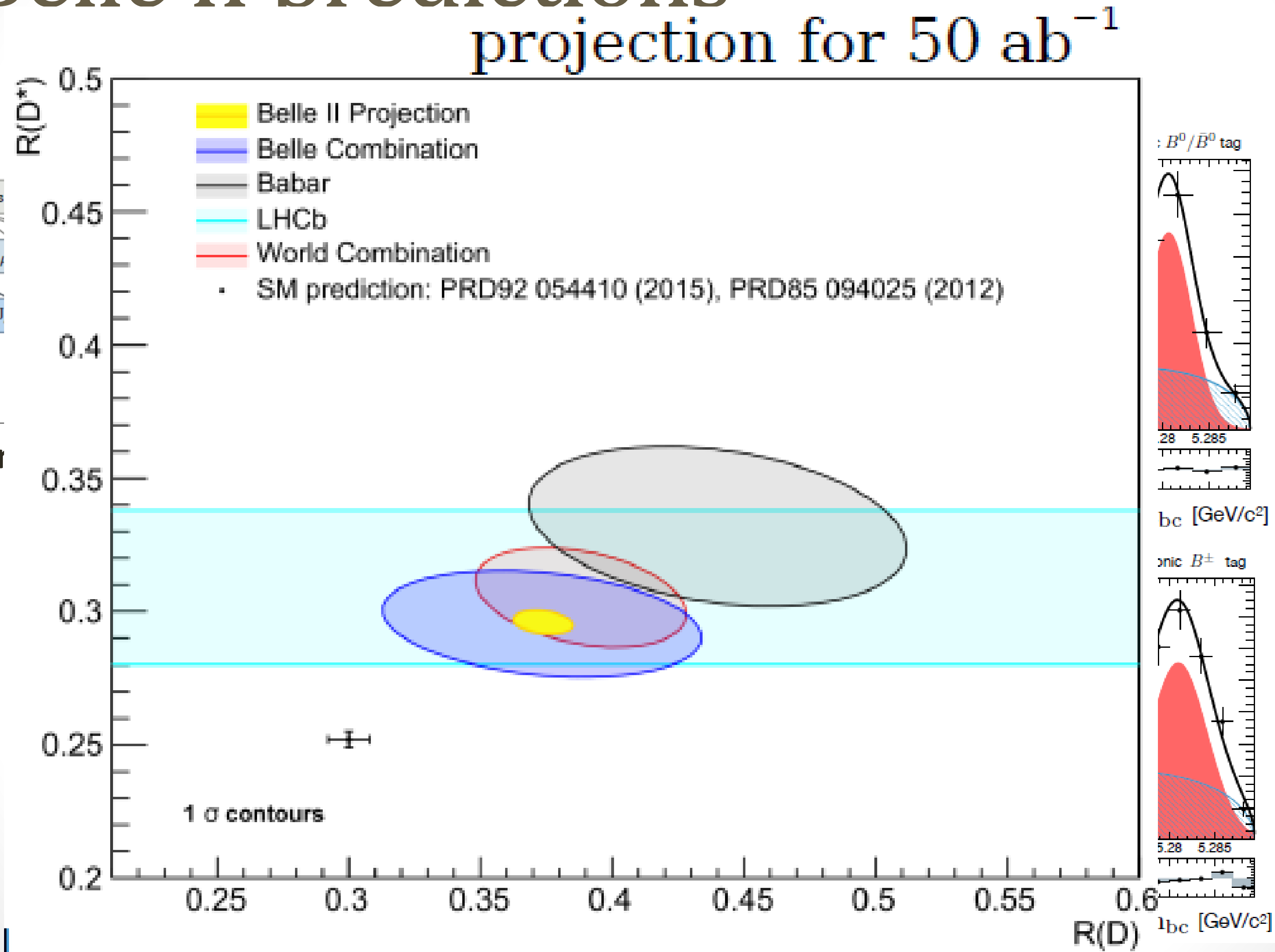


>5000 modes!





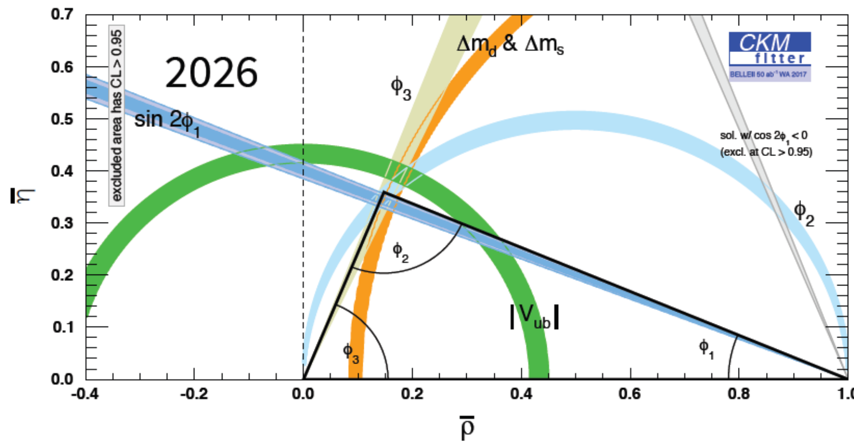
Belle II predictions

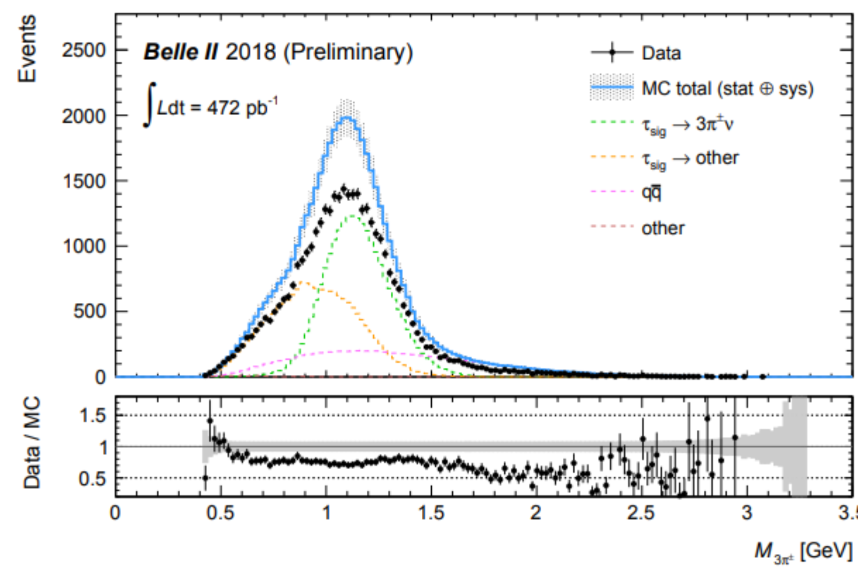


>5000 r

Many other measurements

- CKM metrology
  - ϕ_3/γ - 1.5 degrees
    - Same from LHCb
  - V_{ub} – 1.2%
- Other rare decays
  - $B \to \tau\nu$ - 1.5-2.0%
  - $B \to \mu\nu$ - 5%
  - $B \to X_s l^+ l^-$ - R_X 3-5%
  - $b \to s\tau\tau$, $b \to s\nu\nu$ and LFV versions
- CPV – gluonic penguins
  - $B \to \eta' K^0_S$ $\sin 2\phi_1$ to 0.02
- LFV $\tau \to \mu\gamma$ 10^{-9} limit at 90% C.L
- + charm, XYZ spectroscopy, dark photon





Conclusion

- Particle physics is tackling its problems on three complementary frontiers
  1. Energy
  2. Cosmic
  3. Intensity
- Flavour physics has played a significant role in the development of the Standard Model
- **Belle II** is a project that will continue flavour physics at the intensity frontier until the middle of the next decade along with LHCb
  - First collisions this year much more to come..