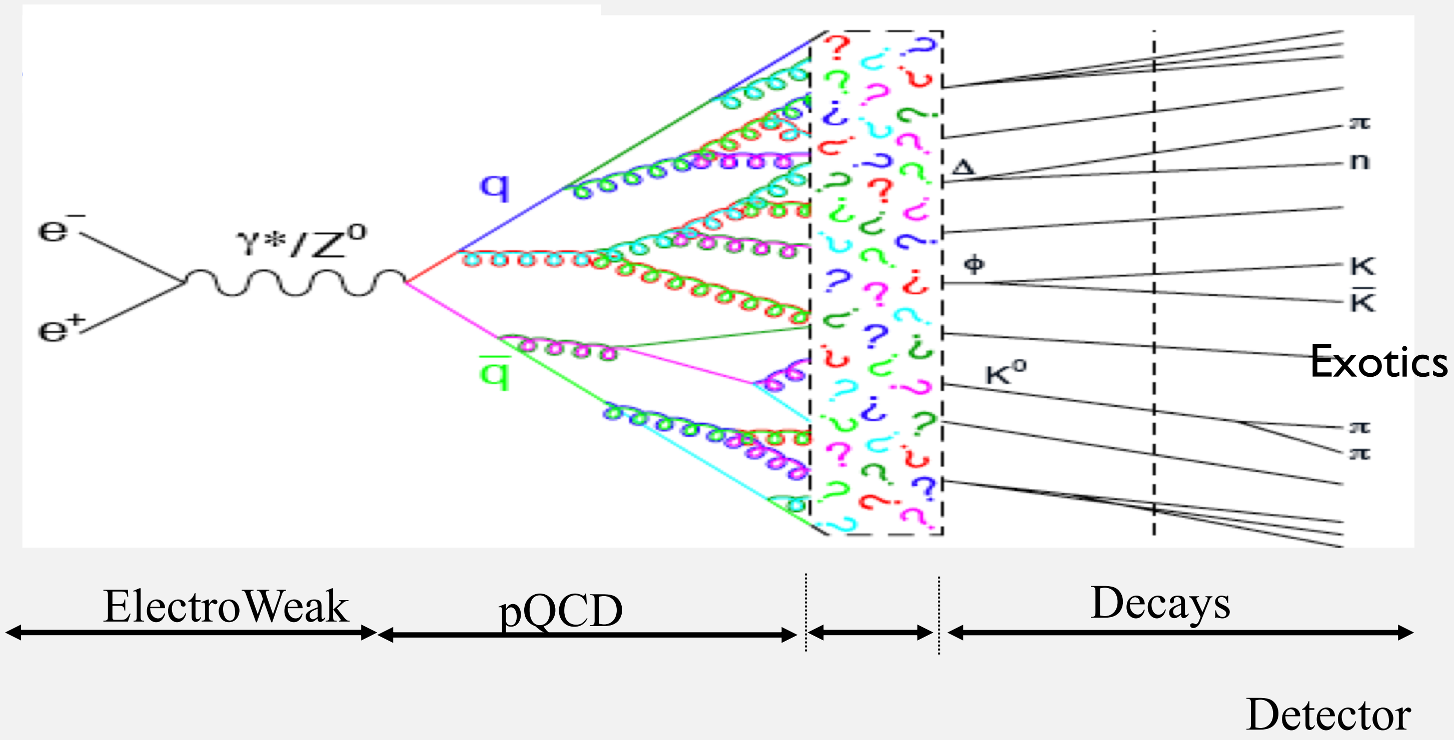
RECENT RESULTS ON HADRONIC PHYSICS FROM BELLE AND PROSPECTS AT BELLE II

Anselm Vossen

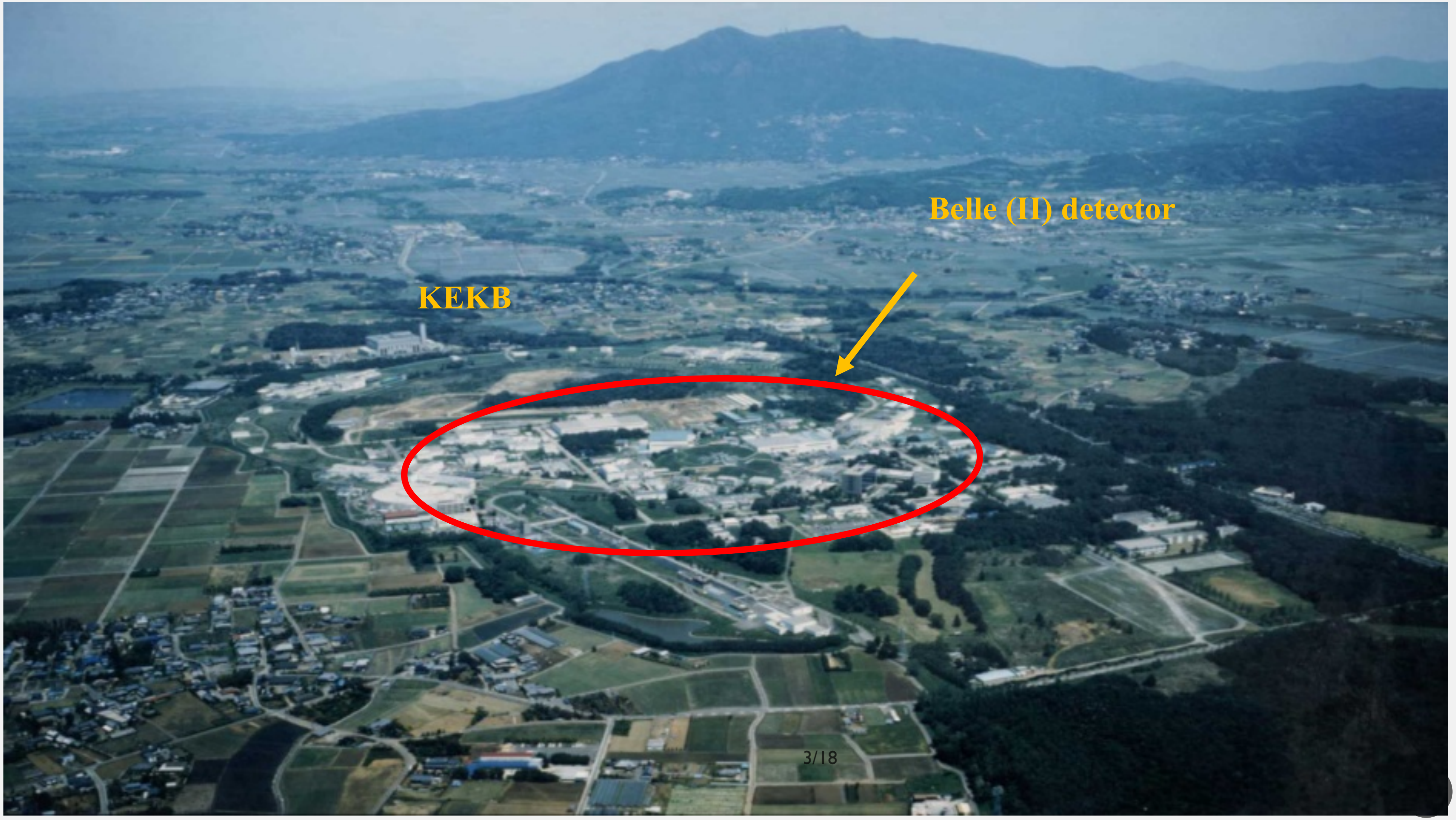
For the Belle & Belle II Collaborations

Lightcone 2018
5/14 - 5/18

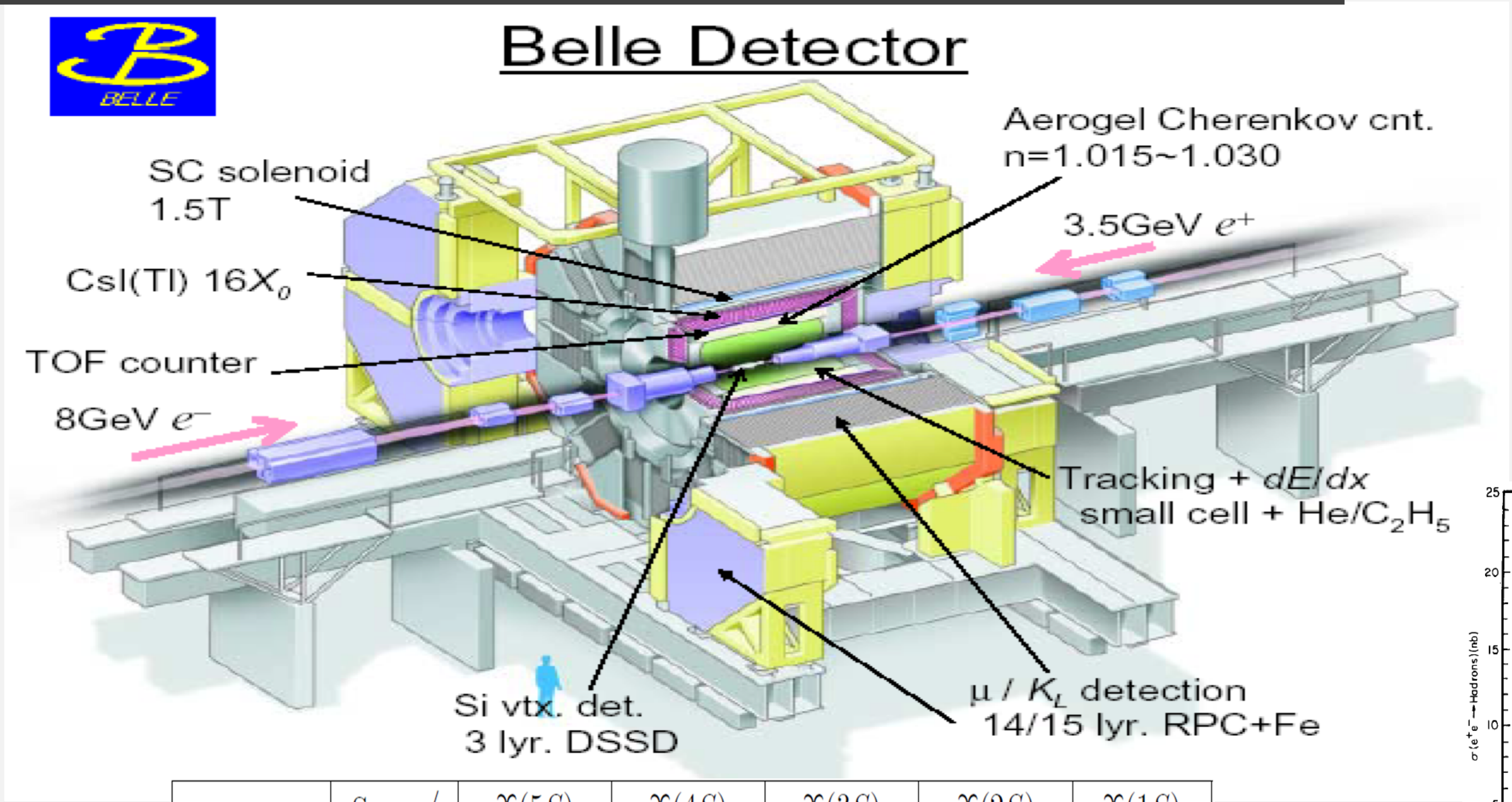
HADRONIC PHYSICS IN e+e- B FACTORIES

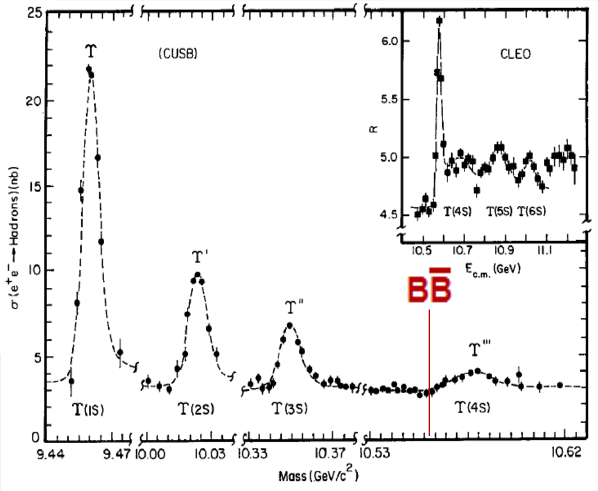


- Study of the formation of hadrons →e.g. Phys.Rev. D97 (2018) no.7, 072005
- Study of hadronization, microscopic quark properties ←→ macroscopic hadron properties
  - Relativisitc, non-perturbative QCD dynamics →Fragmentation functions
- Study of the produced hadrons, spectroscopy


Belle (II) detector
KEKB

BELLE EXPERIMENT (1999 - 2010)





Experiment	Scans/ Off. Res. fb^{-1}	$\Upsilon(5S)$ 10876 MeV fb^{-1}	10^6	$\Upsilon(4S)$ 10580 MeV fb^{-1}	10^6	$\Upsilon(3S)$ 10355 MeV fb^{-1}	10^6	$\Upsilon(2S)$ 10023 MeV fb^{-1}	10^6	$\Upsilon(1S)$ 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102

+About 4x10^6 events per fb in continuum

KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40

e^+ 4GeV 3.6 A

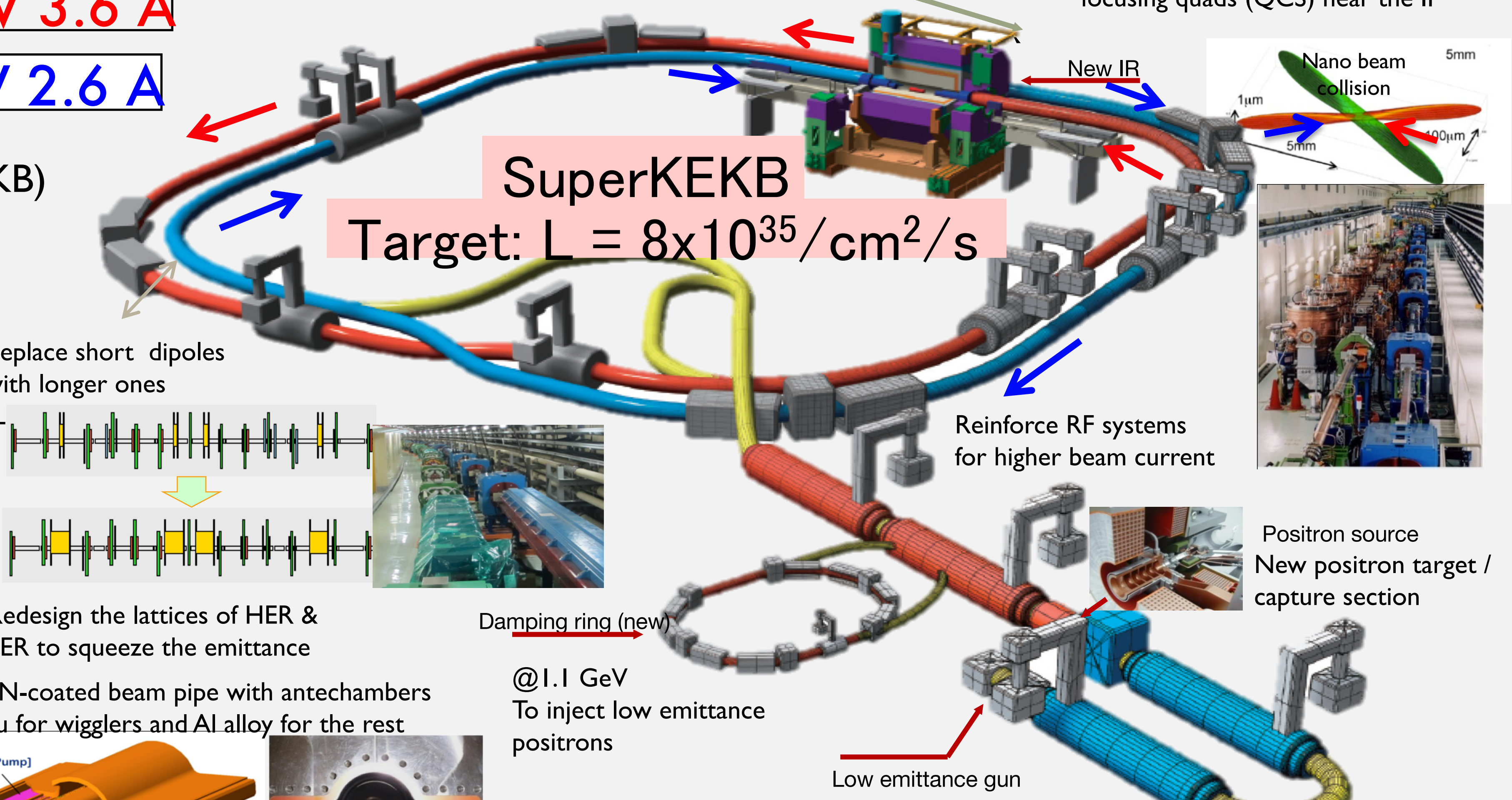
e^- 7GeV 2.6 A

(~2x KEKB)

Belle II

SuperKEKB

Target: L = $8 \times 10^{35}/cm^2/s$



New superconducting final focusing quads (QCS) near the IP

New IR

Reinforce RF systems for higher beam current

Replace short dipoles with longer ones

(L

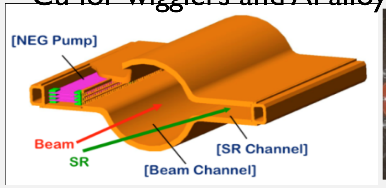
Redesign the lattices of HER & LER to squeeze the emittance

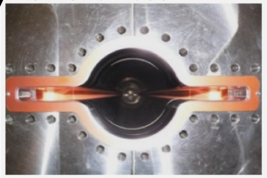
Damping ring (new)

@1.1 GeV
To inject low emittance positrons

Positron source
New positron target / capture section

TiN-coated beam pipe with antechambers
Cu for wigglers and Al alloy for the rest

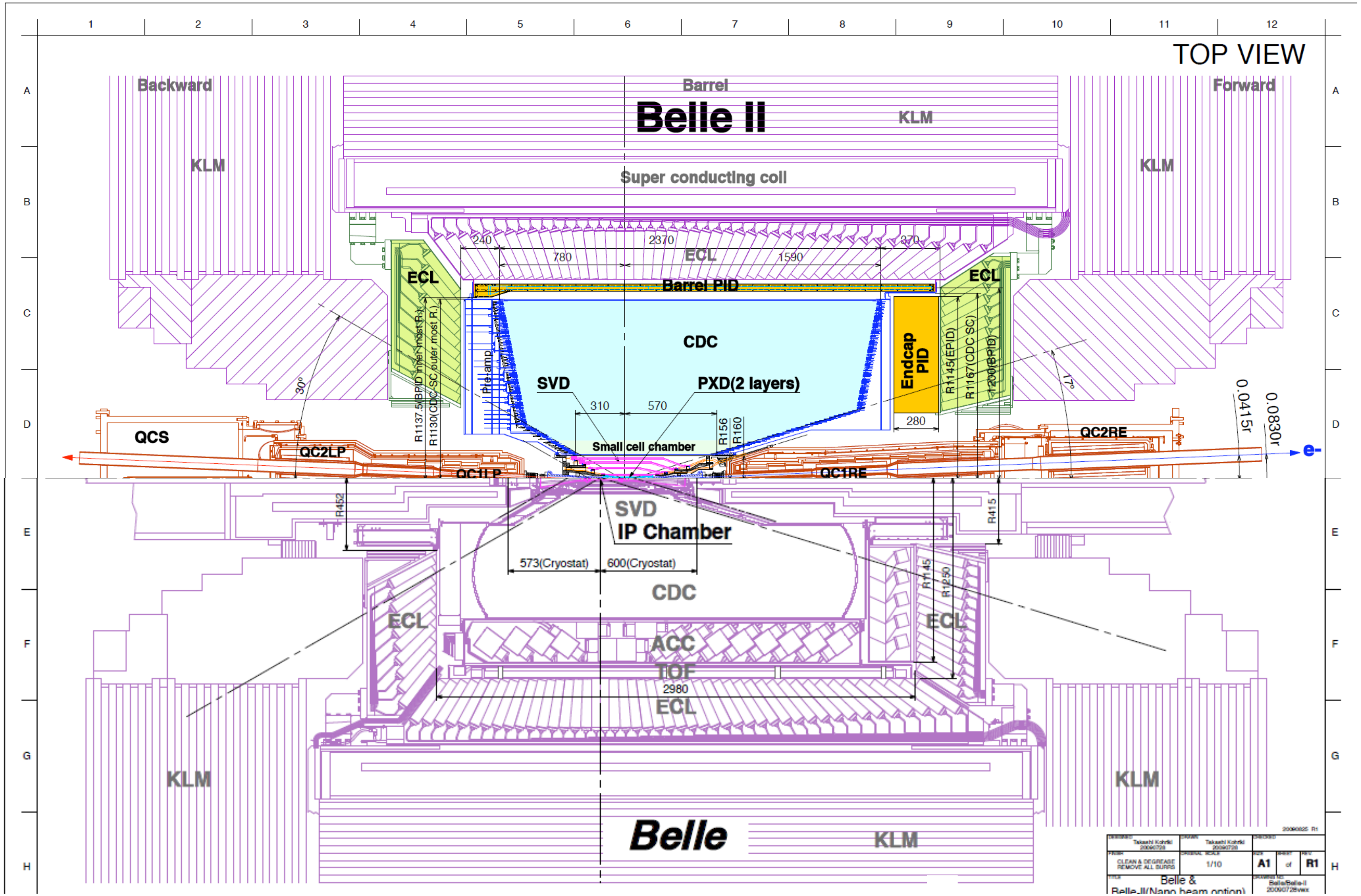




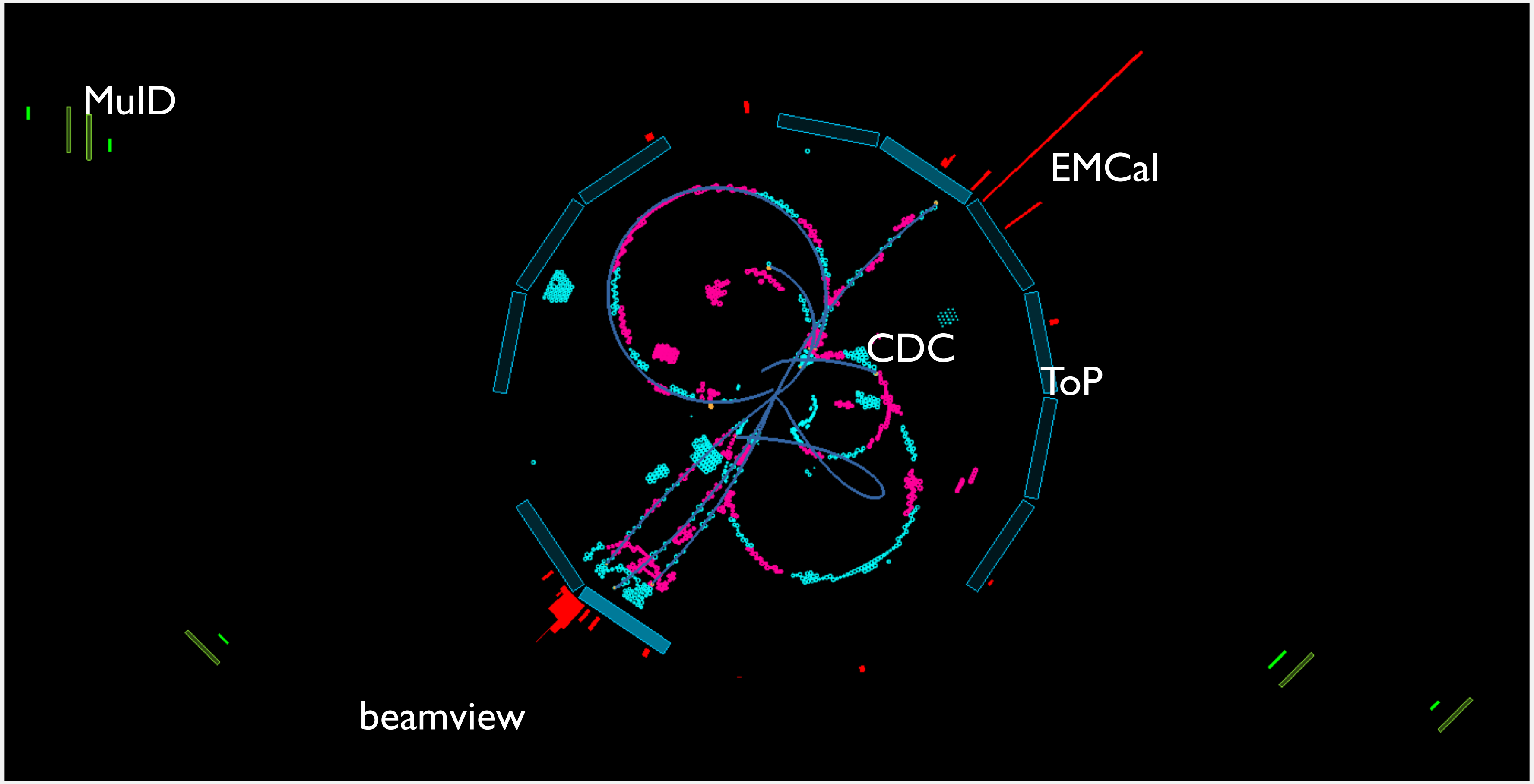
Low emittance gun
To inject low emittance electrons

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

BELLE II DETECTOR (COMP. TO BELLE)

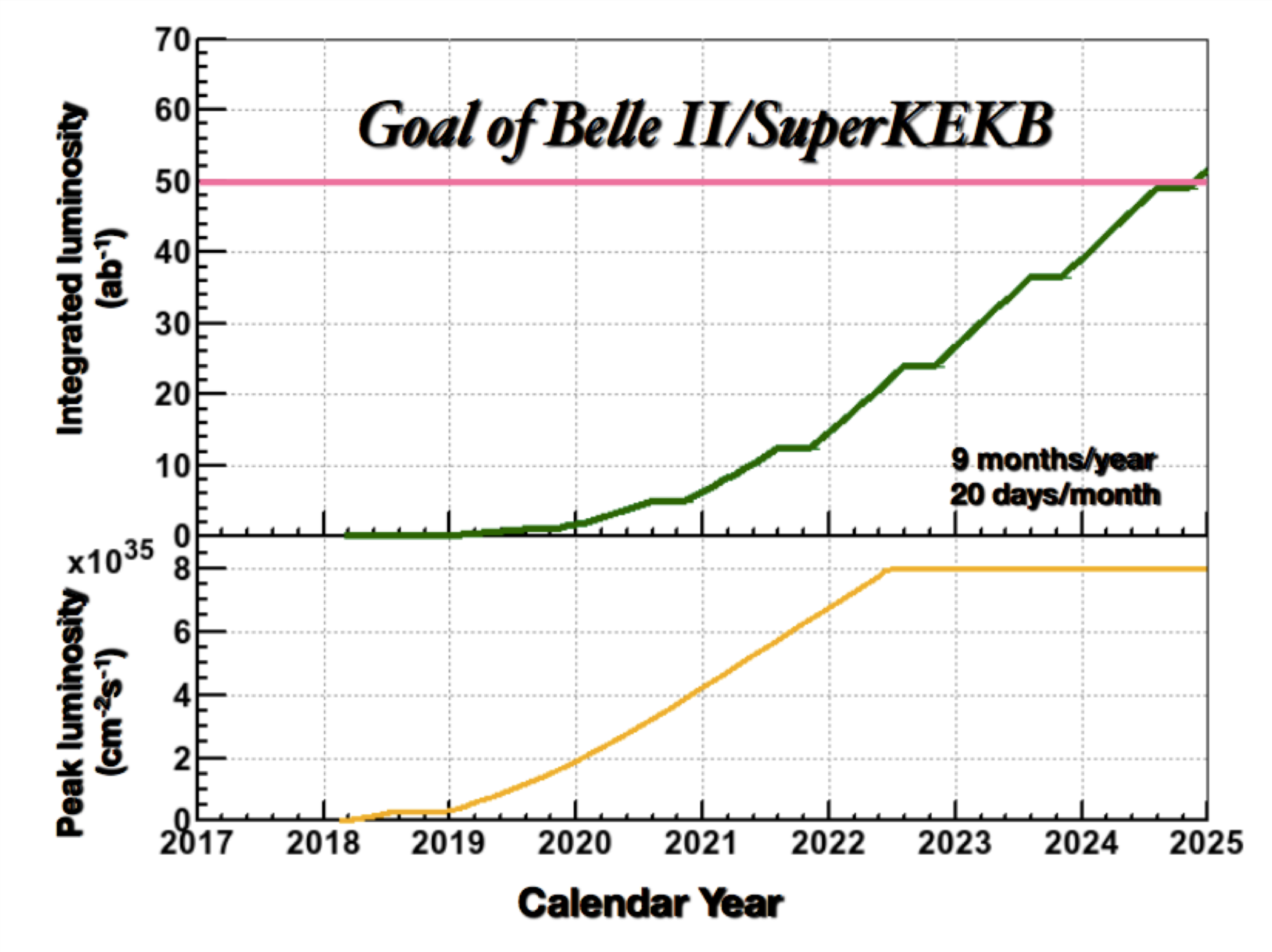


26 APRIL 2018 00:38 GMT+09:00: FIRST COLLISIONS



CURRENT STATUS AND SCHEDULE

- Phase 1 (complete)
  - Accelerator commissioning
- Phase 2 (now)
  - First collisions (20±20 fb^{-1})
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 (“Run 1”, early 2019)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**

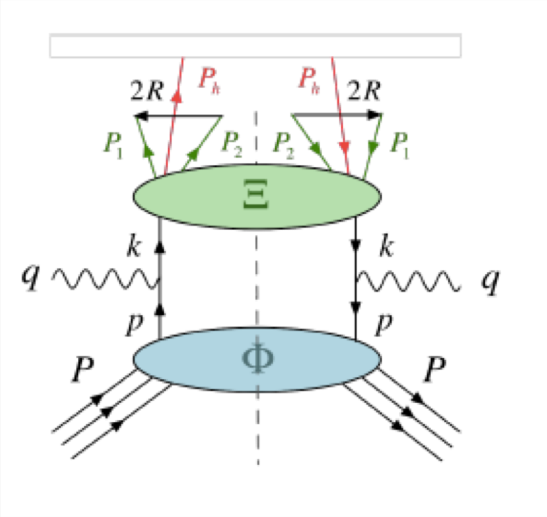


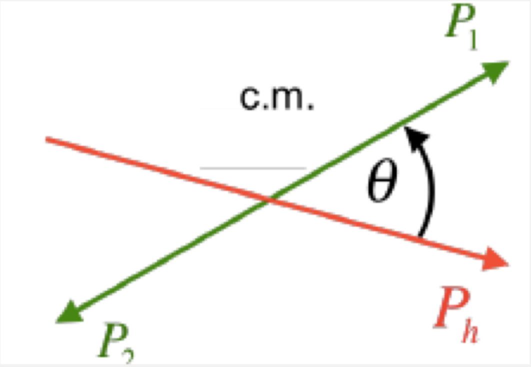
FRAGMENTATION FUNCTIONS WITH ADDITIONAL DEGREES OF FREEDOM: NOVEL PROBES OF THE NUCLEON STRUCTURE AND HADRONIZATION

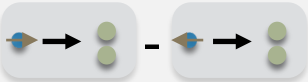
- Di-hadron fragmentation functions
- Polarized Hyperons

DI-HADRON FRAGMENTATION FUNCTIONS

- Additional degree of freedom ($\vec{R} = \vec{P_1} - \vec{P_2}$)
  - Plus z, P_T
- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs
  - Analogue of 1h production with spin in final state
- Transverse polarization dependence in collinear framework
- Makes 'new' FFs possible, such as $G_1^{\perp}$: T-odd chiral even. In 1h case, this needs polarized hadron in the final state →**See H. Matevosyan's talk!**
- **Similar to Λ FF, chiral-even, T-odd: Important to check factorization**







EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

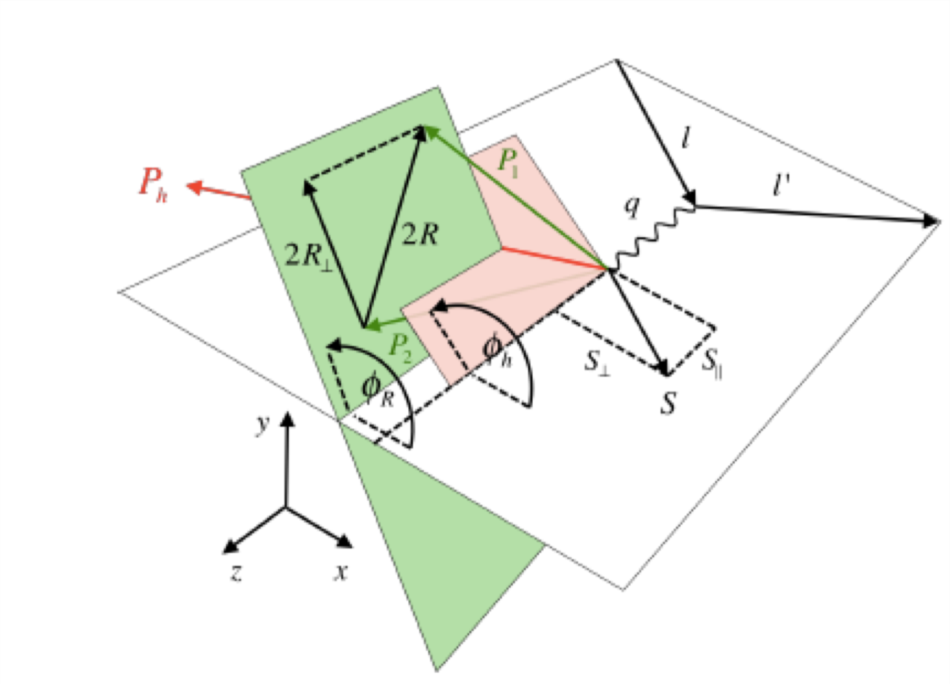
- Di-hadron cross section

WW Approximation

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right],$$

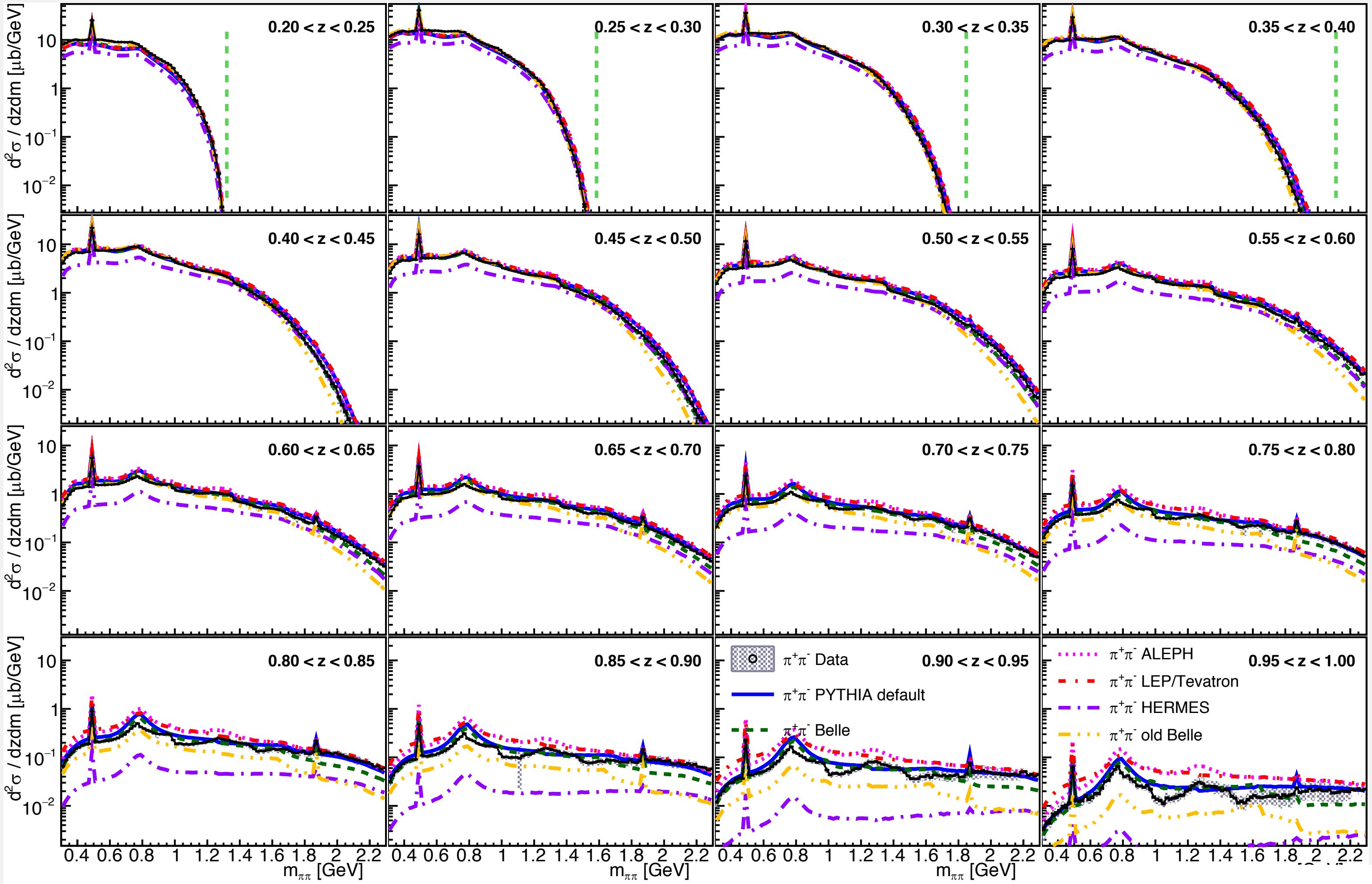
- Single hadron cross-section: mixes other contributions:

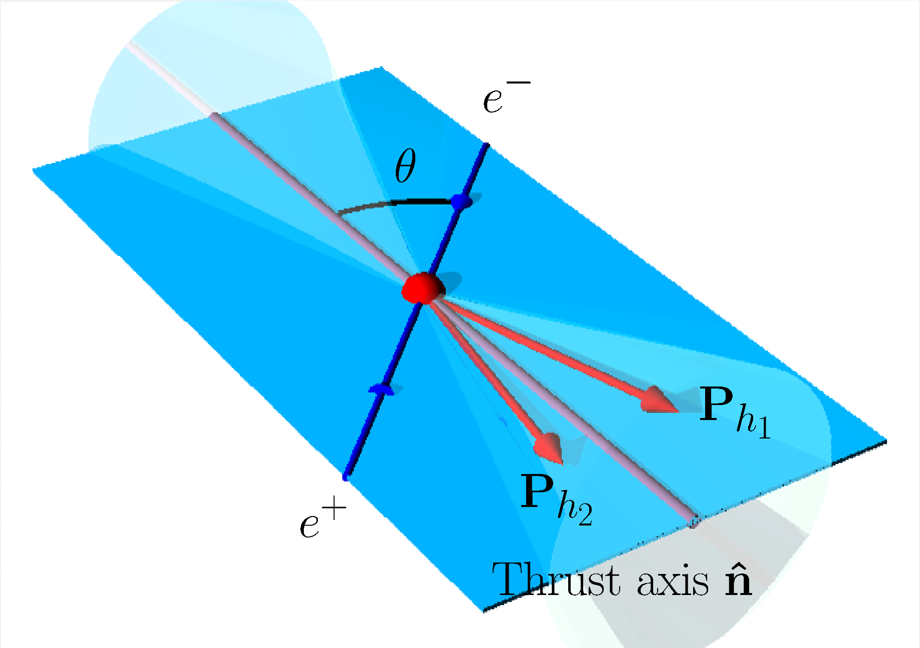
$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q}\mathcal{I}\left[-\frac{k_T\hat{P}_{h\perp}}{M_h}\left(xeH_1^\perp + \frac{M_h}{Mz}f_1\tilde{G}^\perp\right) + \frac{p_T\hat{P}_{h\perp}}{M}\left(xg^\perp D_1 + \frac{M_h}{Mz}h_1^\perp\tilde{E}\right)\right]$$



RECENT BELLE RESULT

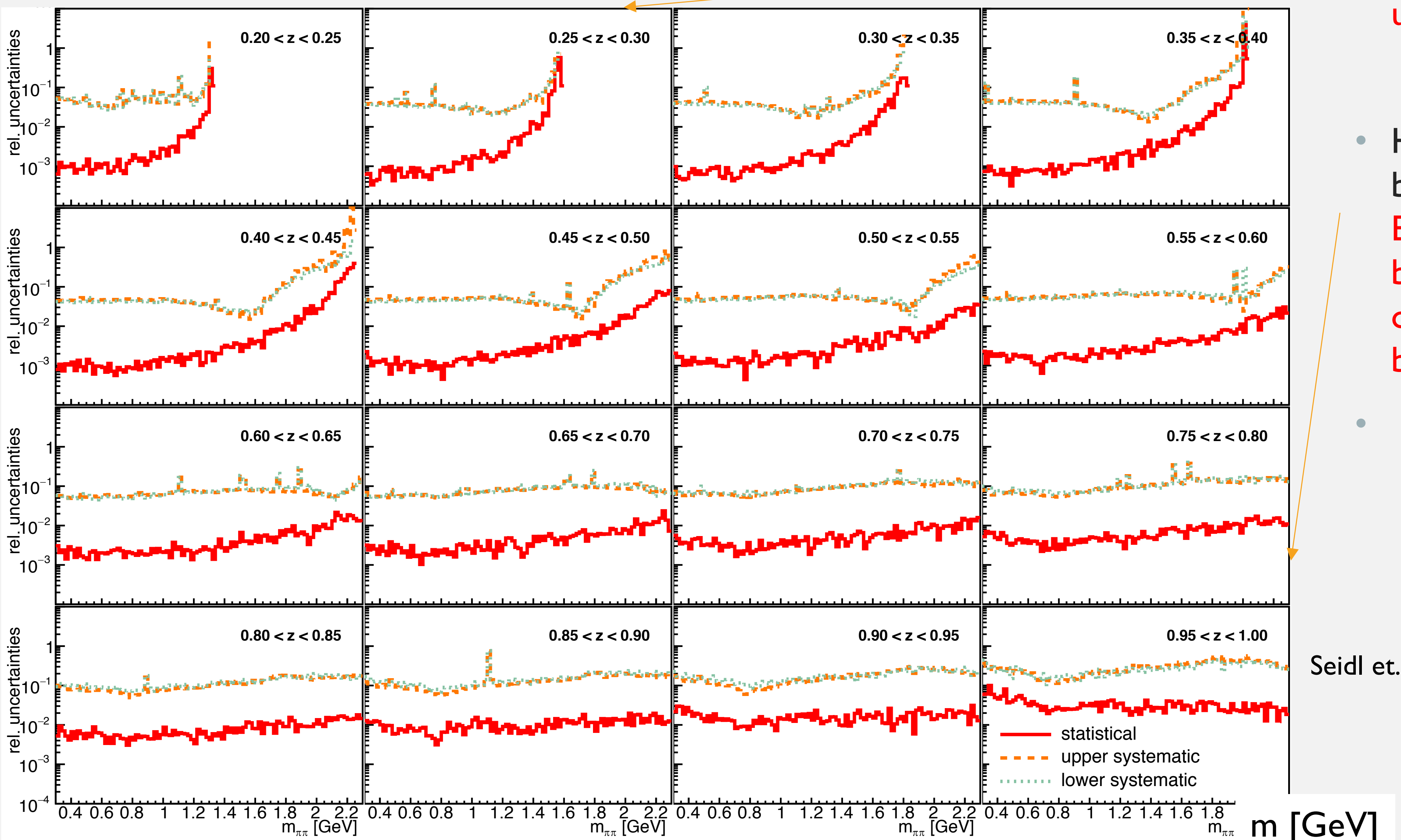
(Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005)





m [GeV]

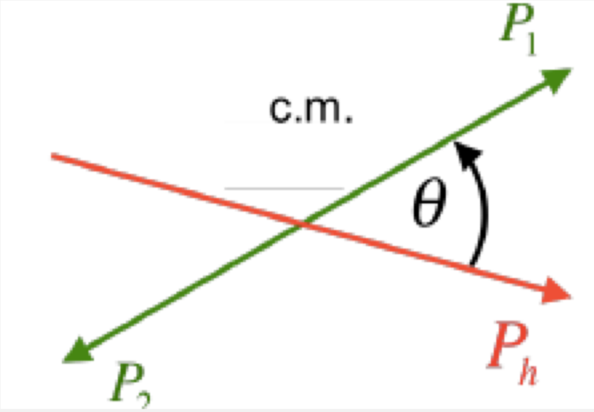
RESULTS SYSTEMATICS DOMINATED



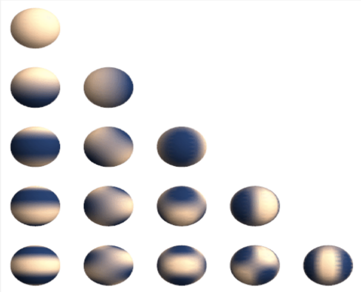
- Low z: Dominated by PID uncertainties
  Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID
- High z: Dominated by ISR uncertainties
  Belle II prospects: better understanding of ISR radiation with better statistics
-

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

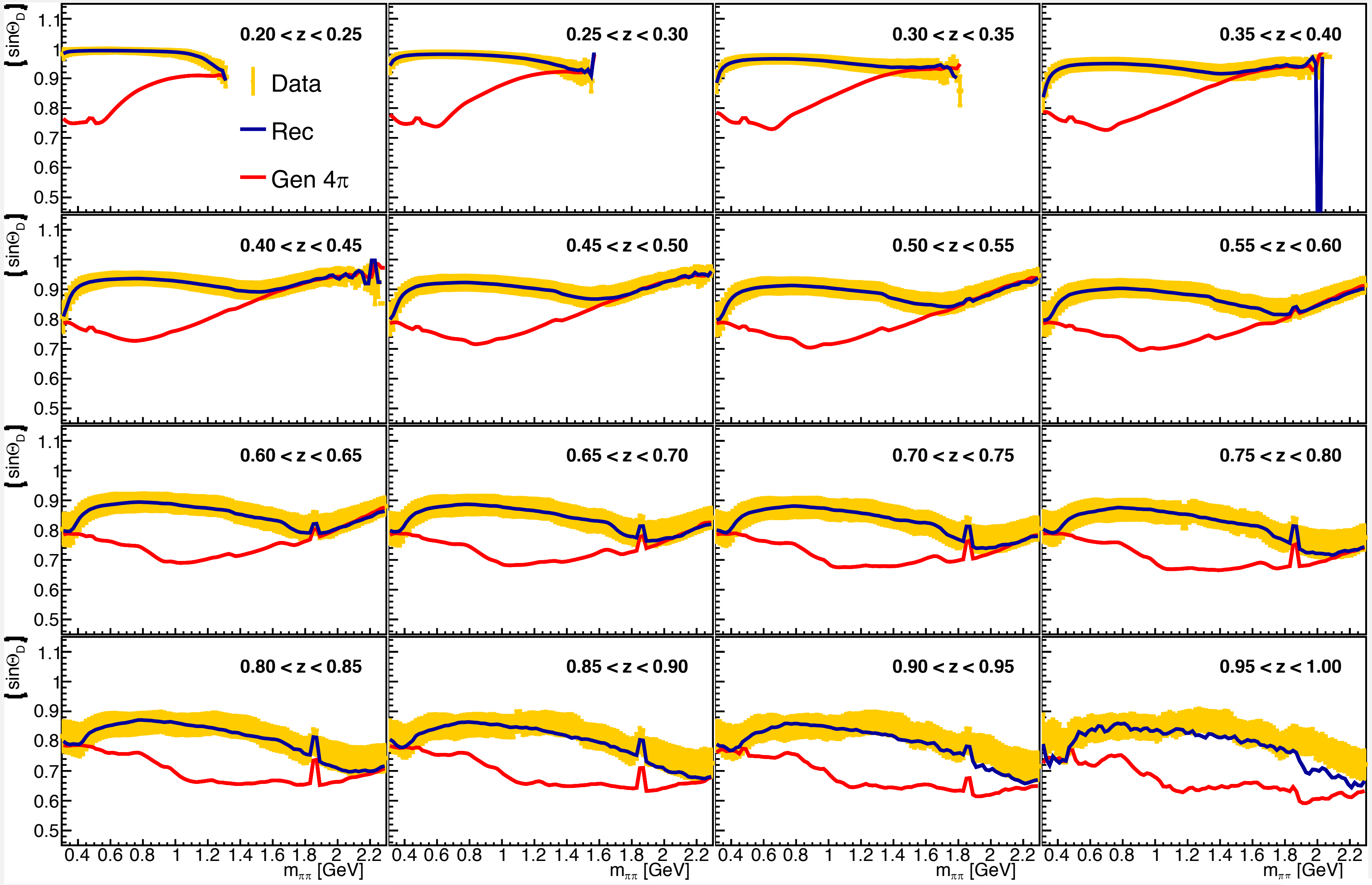
BELLE II PROSPECTS



- Partial Wave decomposition (more general: θ dependence)
- Higher order PWs lead to different moments in θ and ϕ
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity



ACCEPTANCE IMPACT ON PARTIAL WAVE COMPOSITION



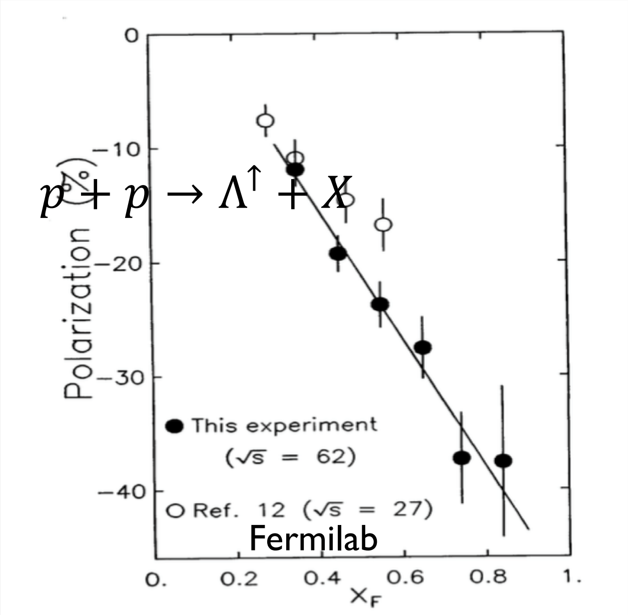
m [GeV]

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

- Belle II prospects: Sufficient statistics for full partial wave decomposition

POLARIZED HYPERON PRODUCTION

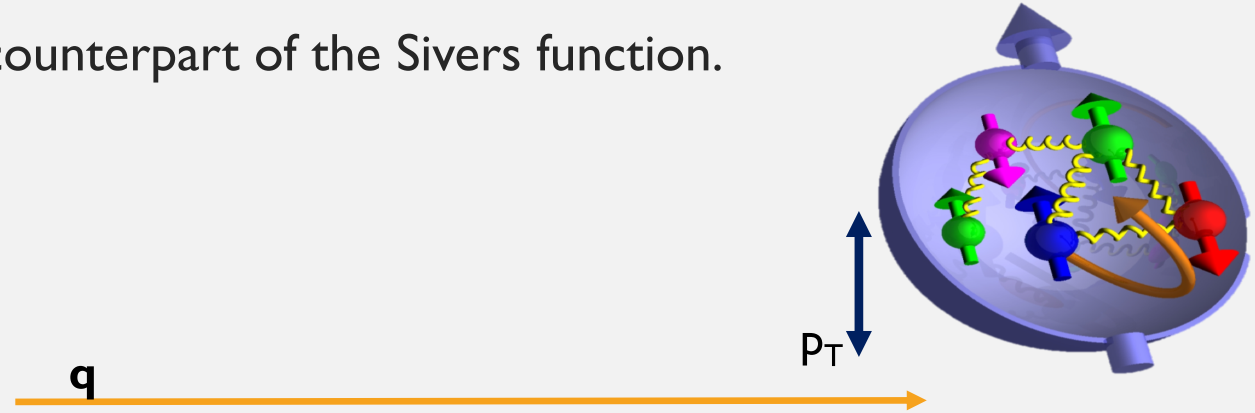
- Large Λ transverse polarization in unpolarized pp collision **PRL36, 1113 (1976); PRL41, 607 (1978)**
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of universality. **PRL105,202001 (2010)**
- OPAL experiment at LEP has studied transverse Λ polarization, no significant signal was observed. **Eur. Phys. J. C2, 49 (1998)**
- FF counterpart of the Sivers function.



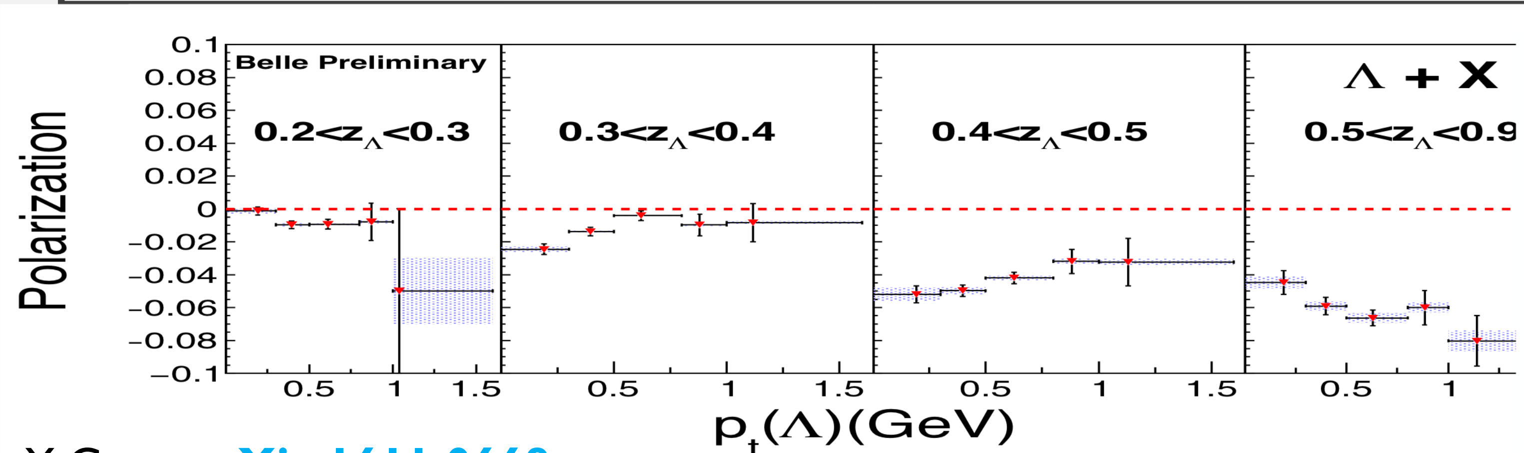
ISR data

(Phys.Lett. B185 (1987) 209)

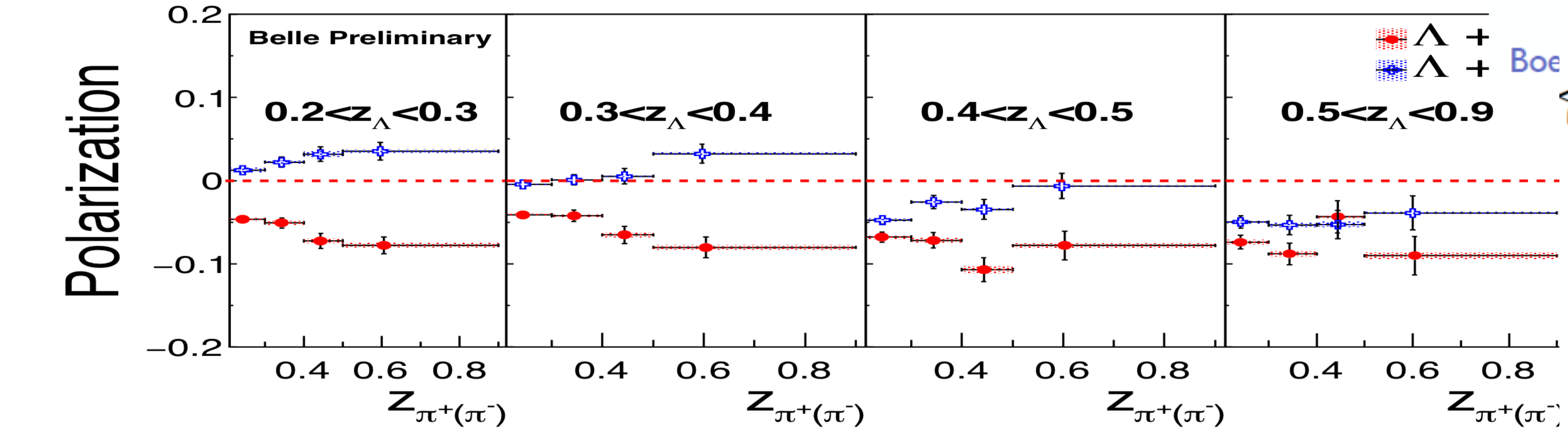
$x_F = p_L / \max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$

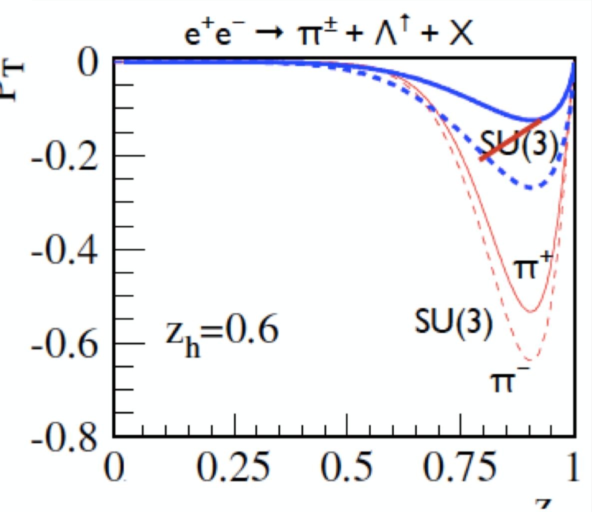


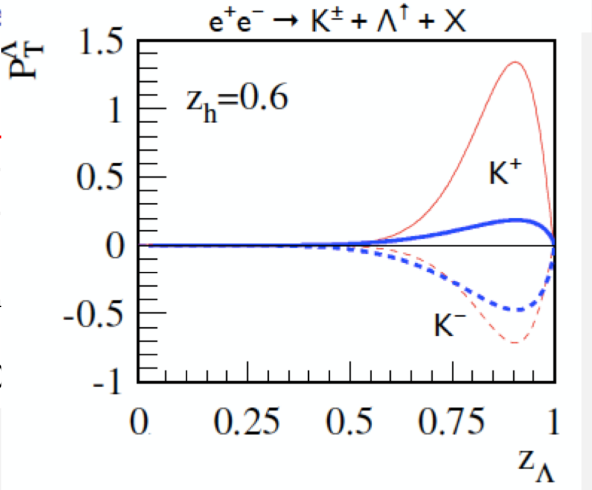
z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION



Y. Guan, arXiv:1611.0668

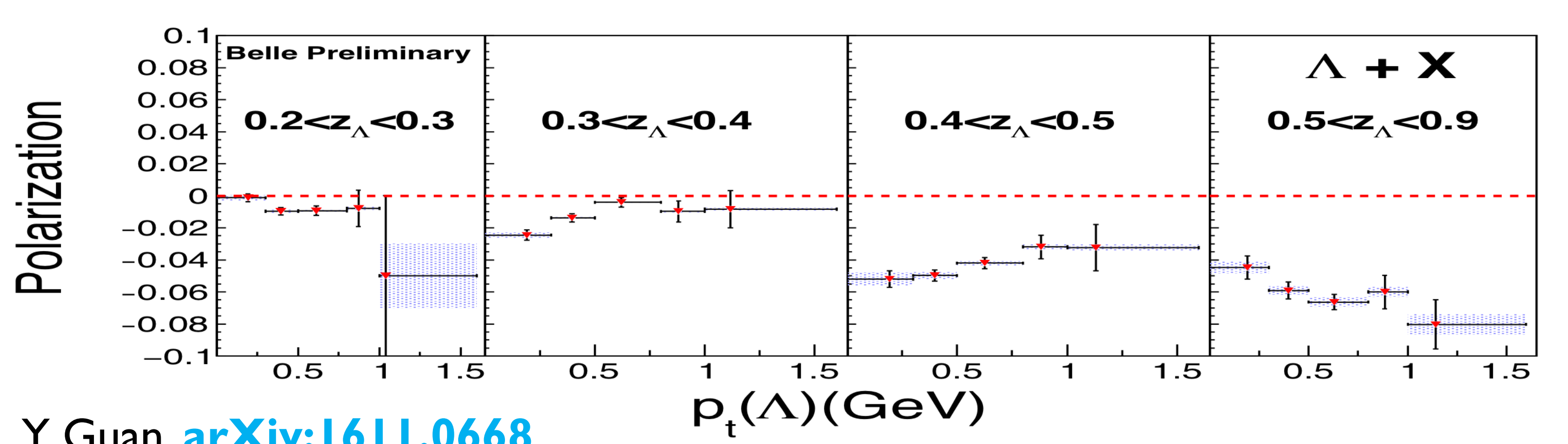






- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!** (might be related to fragmenting quark flavor dependence on z_1,z_2)
- Correlation with opposite hemisphere light meson →quark flav/charge dependence

BELLE II PROSPECTS

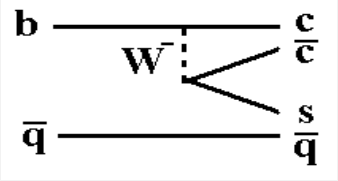


Y. Guan, arXiv:1611.0668

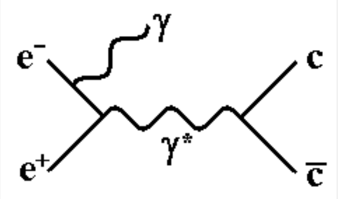
- Explore low pT region with higher statistics and better tracking resolution
- Feed down correction for pT dependence and associated production
  - (currently only for z dependence, introduces large uncertainties)
  - $\Lambda^{\uparrow} - \Lambda^{\uparrow}$ correlations
  - ….

BELLE LEGACY IN HADRONIC PHYSICS – QUARKONIUM (-LIKE) PRODUCTION

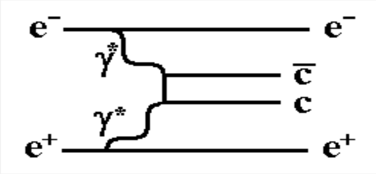
- B decays
  - Charmonium only
  - All quantum numbers available



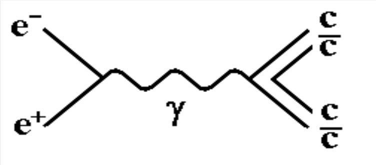
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$



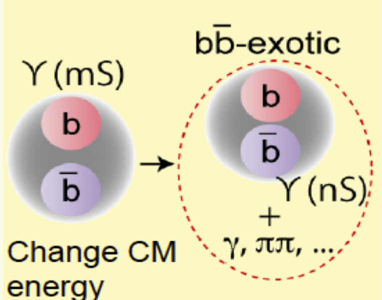
- Two-photon interaction
  - J^{PC} = 0-+, 0++, 2++



- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, ψ(2S)) plus J=0 states (C=1?)

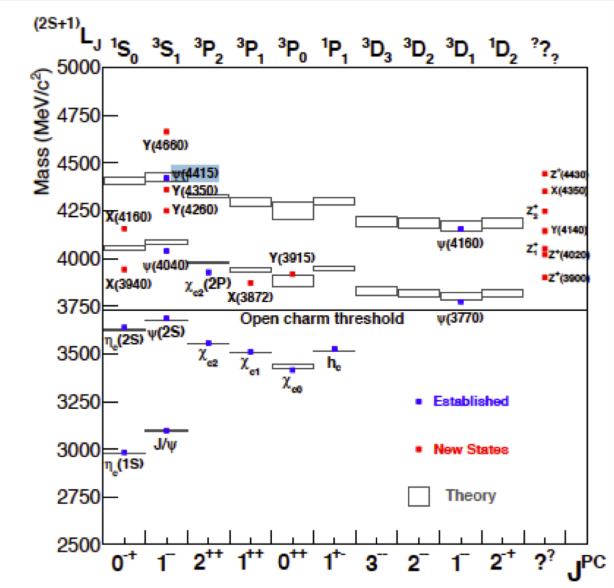


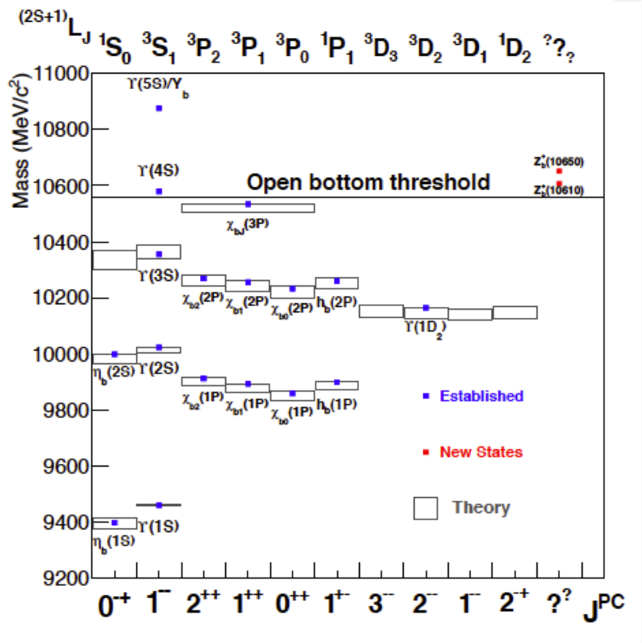
- Quarkonium transitions
  - Hadronic/radiative decays between states

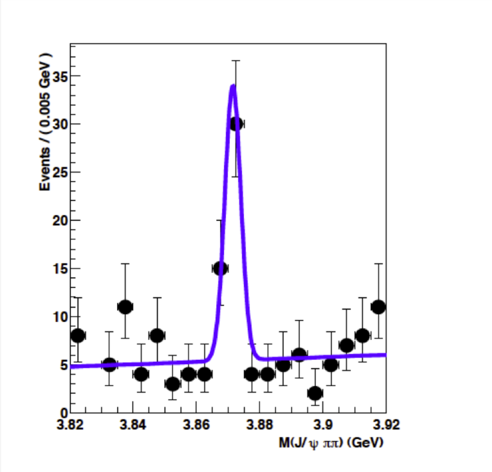


QUARKONIUM STUDIES AT BELLE II BUILD ON THE SUCCESSFUL BELLE PROGRAM

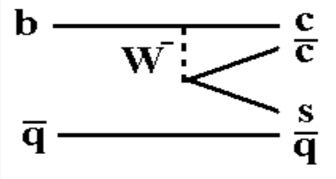
- XYZ revolution kicked off by discovery of X(3872) at Belle 2003
  - Strong violation of isospin symmetry in decays $\rho J/\psi$, $\omega J/\psi$
  - More states not consistent with quarkonium, usually higher than expected transitions to lower quarkonia.
- Precision study of Charmonium: States above the DDbar threshold are a strongsuit of B factories → can access energy spectrum continuously)
- Precision studies of Bottomonium states and transitions







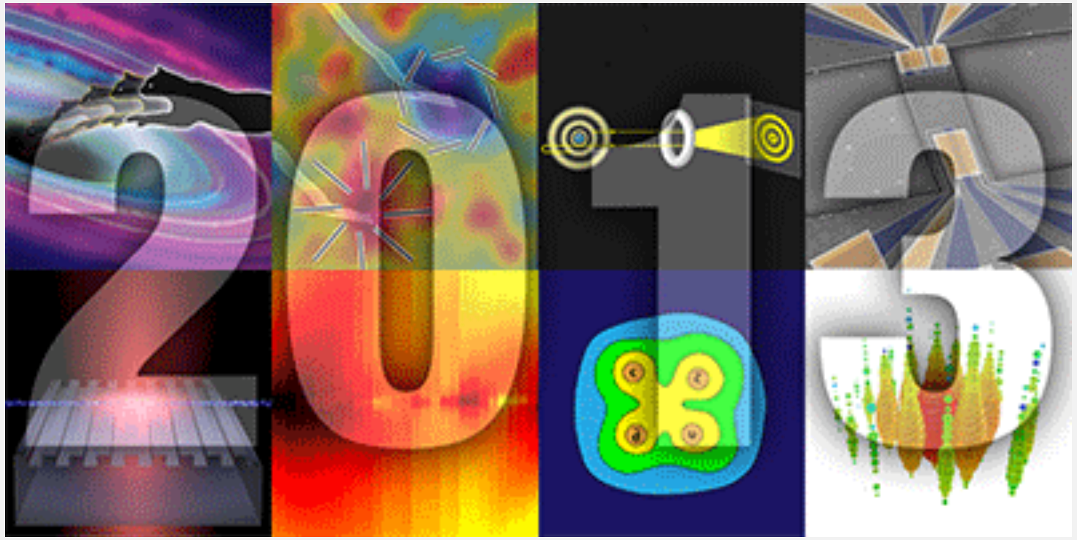
(Choi et al, PRL91 (26) 262001)



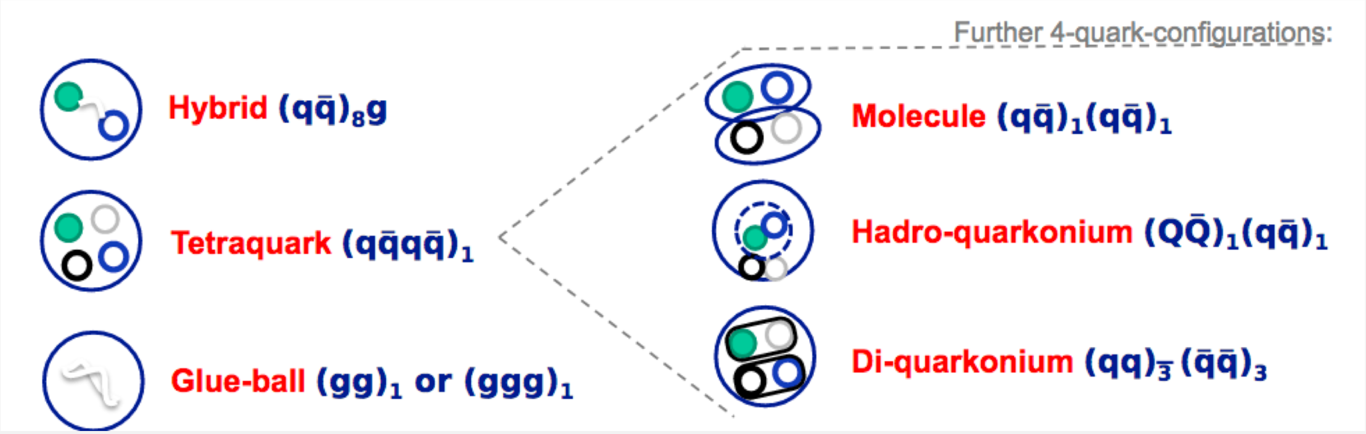
X(3872)

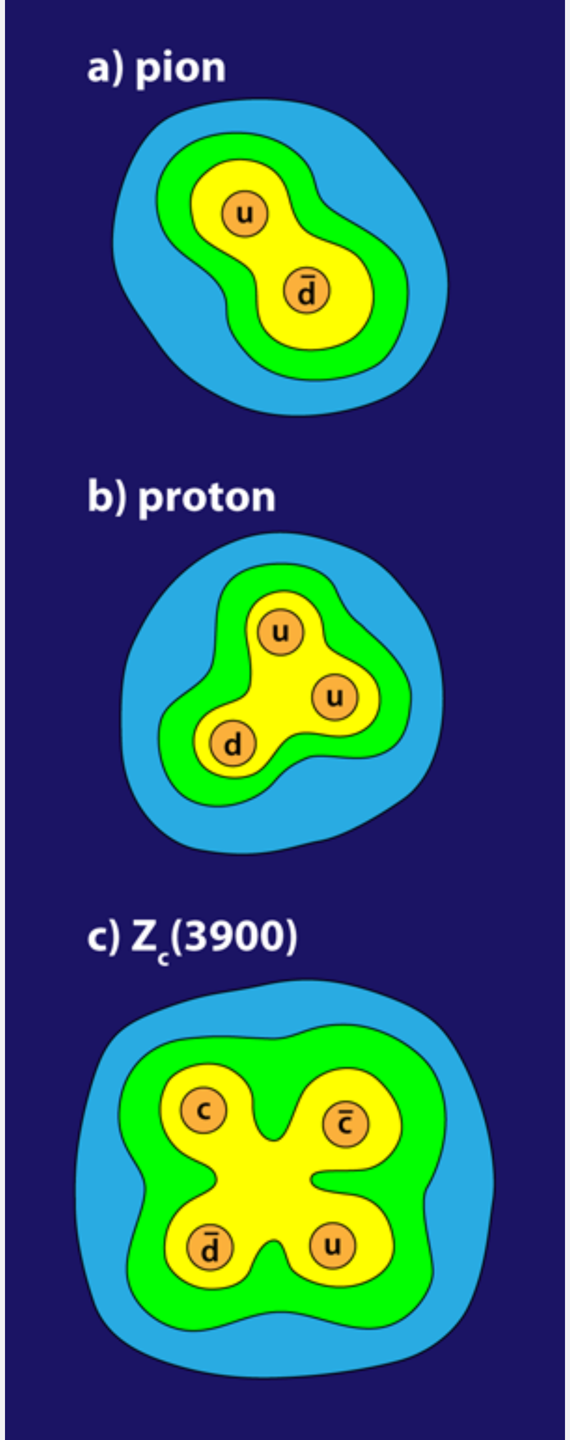
K

Z: EVIDENTLY EXOTIC, NEEDS 4 QUARKS



- APS highlight 2013

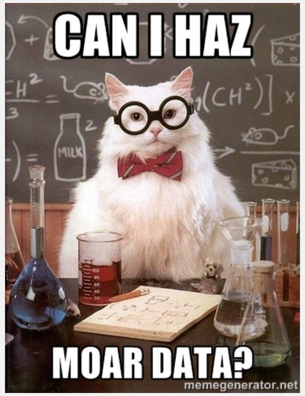




RECENT SPECTROSCOPY RESULTS

- Phys. Rev. D 95, 112003 (2017) **Observation of an alternative $\chi_{c0}(2P)$ candidate in $e^+e^-\to J/\psi D\bar{D}$**
- Phys. Rev. D 97, 012002 (2018) **Angular analysis of the $e^+e^-\to D^{(*)\pm}D^{*\mp}$ process near the open charm threshold using initial-state radiation**
- Phys. Rev. D 97, 012005 (2018) **Measurements of the absolute branching fractions of $B^+\to X_{c\bar{c}}K^+$ and $B^+\to \bar{D}^{(*)0}\pi^+$ at Belle**
- Phys. Rev. D 96, 051102 (2017) **Search for $\Lambda^+_c\to\phi p\pi^0$ and branching fraction measurement of $\Lambda^+_c\to K^-\pi^+p\pi^0$**
- Phys. Rev. D 95, 012001 (2017) **Search for the 0^{--} Glueball in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays**
  - Phys. Rev. D 96, 052005 (2017) **Study of η and dipion transitions in $\Upsilon(4S)$ decays to lower bottomonia**
- Phys. Rev. D 96, 112002 (2017) **Search for light tetraquark states in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays**

WISHLIST



- **More data will help Quarkonium**
  - Map out resonances
  - Can reach Υ(6S) with same boost as Υ(4S)
  - More data at/above Υ(4S)→search molecular structures near open bottom thresholds
  - Experimental information of charmonium > Ddbar threshold very incomplete,
  - More data below Y(4S) →test predictions for unobserved bottomium states
  - Determine transitions and quantum numbers
  - Precision scans of bottomium sector, comparison with charmonium states should shed light on some properties (spin symmetry suppression not as strong)
  - Need enough data for amplitude analysis to check if found states are the expected ones

BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab^{-1}: **opportunity for other results in Phase 2/3?**

Experiment	Scans/ Off. Res.	$\Upsilon(5S)$ 10876 MeV		$\Upsilon(4S)$ 10580 MeV		$\Upsilon(3S)$ 10355 MeV		$\Upsilon(2S)$ 10023 MeV		$\Upsilon(1S)$ 9460 MeV	
	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
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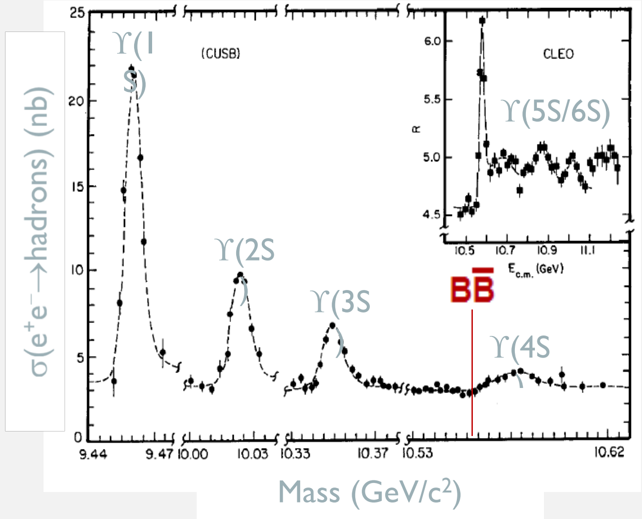
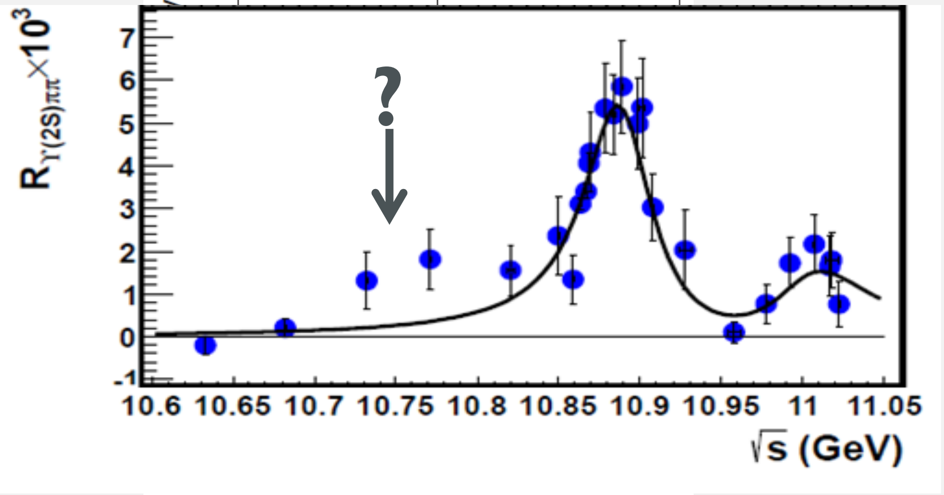
Potential impact with O(10-100) fb^{-1}



- Early phase 3: Above $\Upsilon(4S)$
  - Study of Y(nS) states in (hadronic) transitions
  - Study of exotic four-quark states (e.g. Z_b at Y(6S))
  - BB** threshold? : R_b dip versus $\pi\pi\Upsilon$ rise

Phys.Rev.Lett. 117 (2016) no.14, 142001



SUMMARY & OUTLOOK

- Belle II will integrate 50x Belle luminosity (= 50 ab^{-1})over ~6 years
- State of the art detector
- Precision studies of Quarkonia, hadronization
- Physics program with first data focusing on $E_{CM}>\Upsilon(4S)$ already promising!
- Precision hadronization studies crucial for JLab12 SIDIS program

BACKUP

BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab^{-1}: **opportunity for other results in Phase 2/3?**

Phys.Rev.Lett.102:012001,2009, (Babar)
PRD 82, 091106 (2010). 0810.3829. (Belle)

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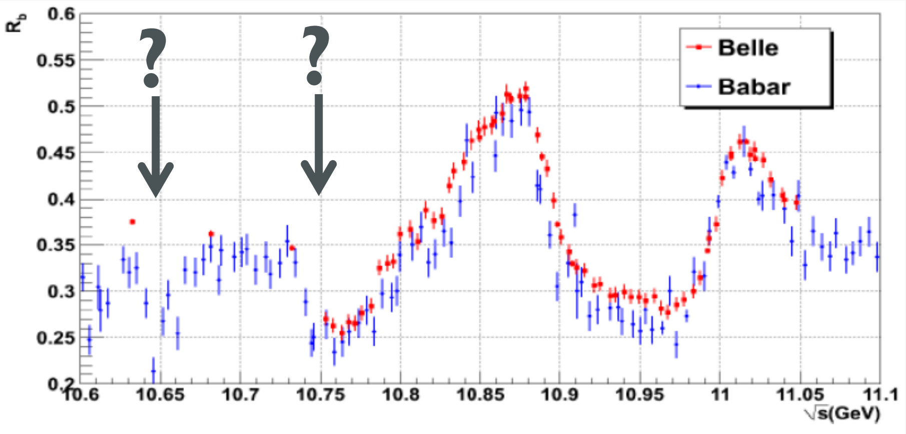
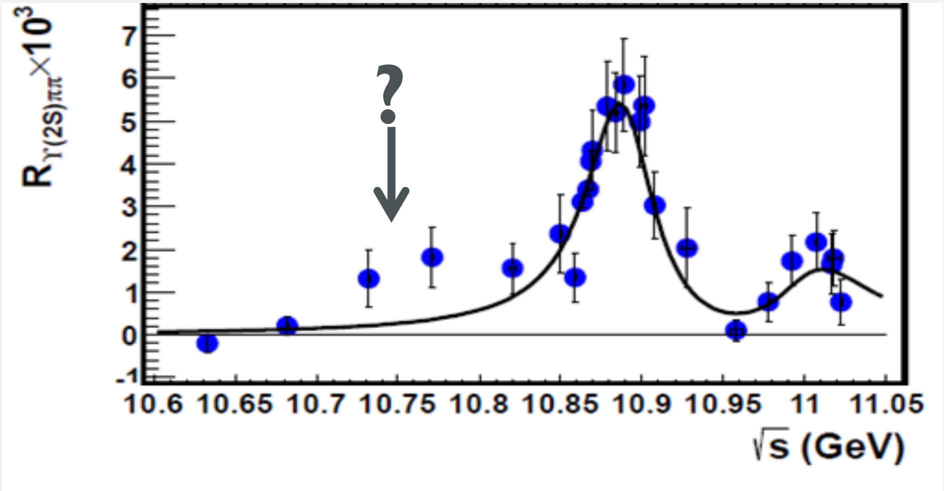
Belle	100	121	36	711	772	3	12	25	158	6	102

Potential impact with O(10-100) fb^{-1}



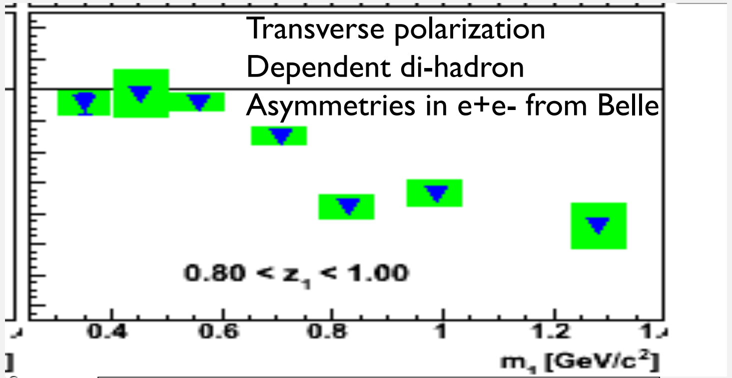
- Phase 2: Above $\Upsilon(4S)$
  - Study of exotic four-quark states (e.g. Zb at Υ(6S))
    →Study possible with limited tracking resolution
  - BB** threshold? : R_b dip versus $\pi\pi\Upsilon$ rise
  - <6fb^{-1} accumulated by Belle at $E_{CM}=\Upsilon(6S)$

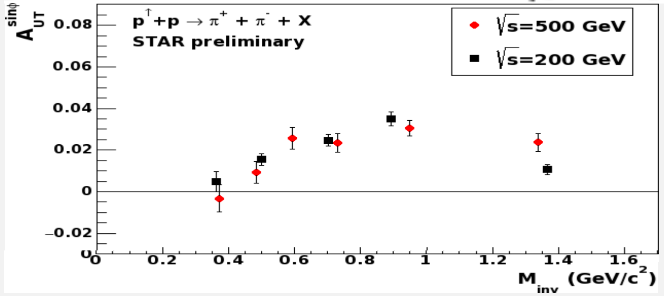


- Early phase 3: Below $\Upsilon(4S)$
  - $\Upsilon(2S,3S)$ access to bottomonium
  - Scan for direct production of $\Upsilon(1^3D_J)$ triplet, $\eta_b(1S,2S)$ studies

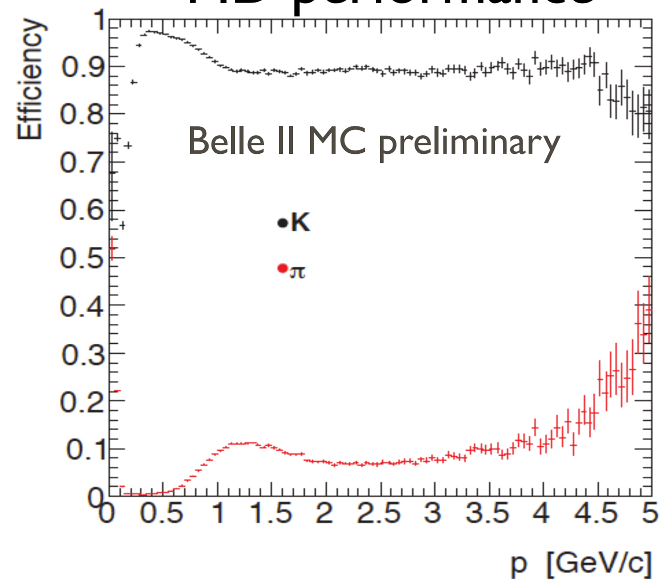
OTHER PERKS

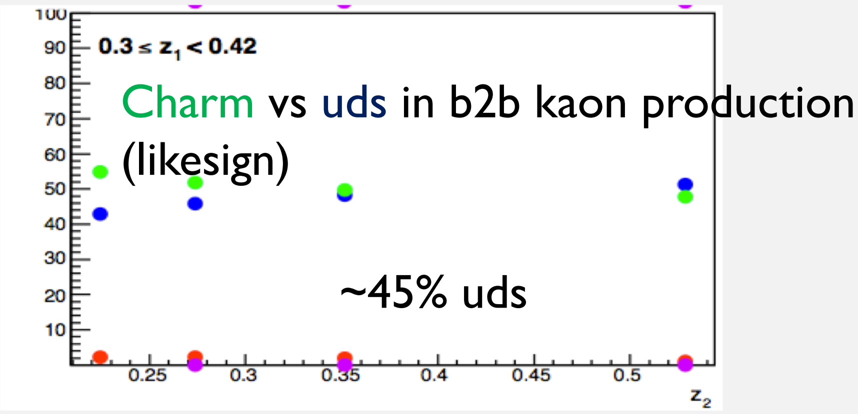
- More statistics and better vertexing will help with charm corrections
- Systematics will also be reduced since the main sources are dependent on MC statistics
- Better PID will help with multi-kaon final states





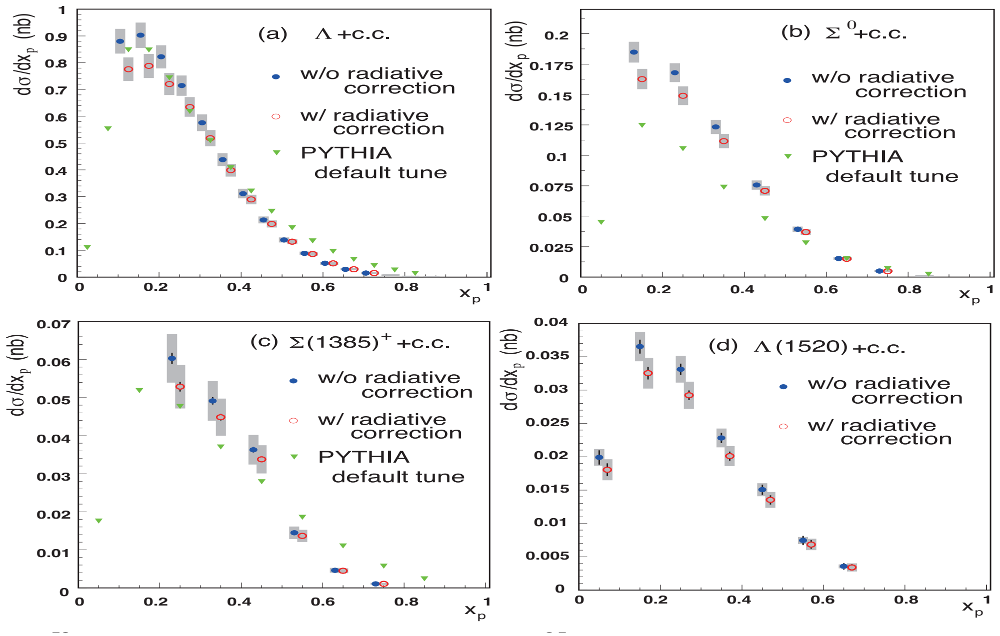
PID performance

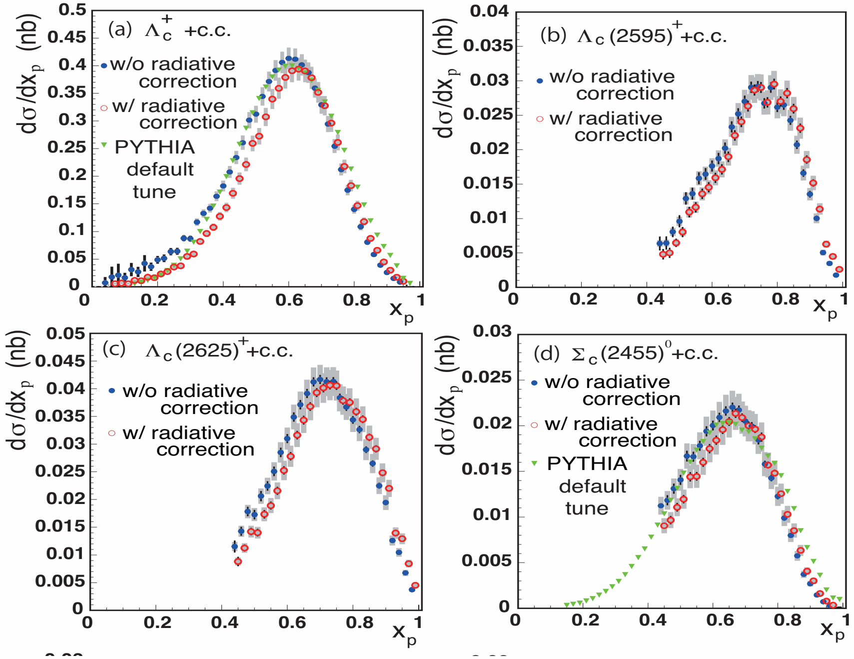




BARYON FORMATION

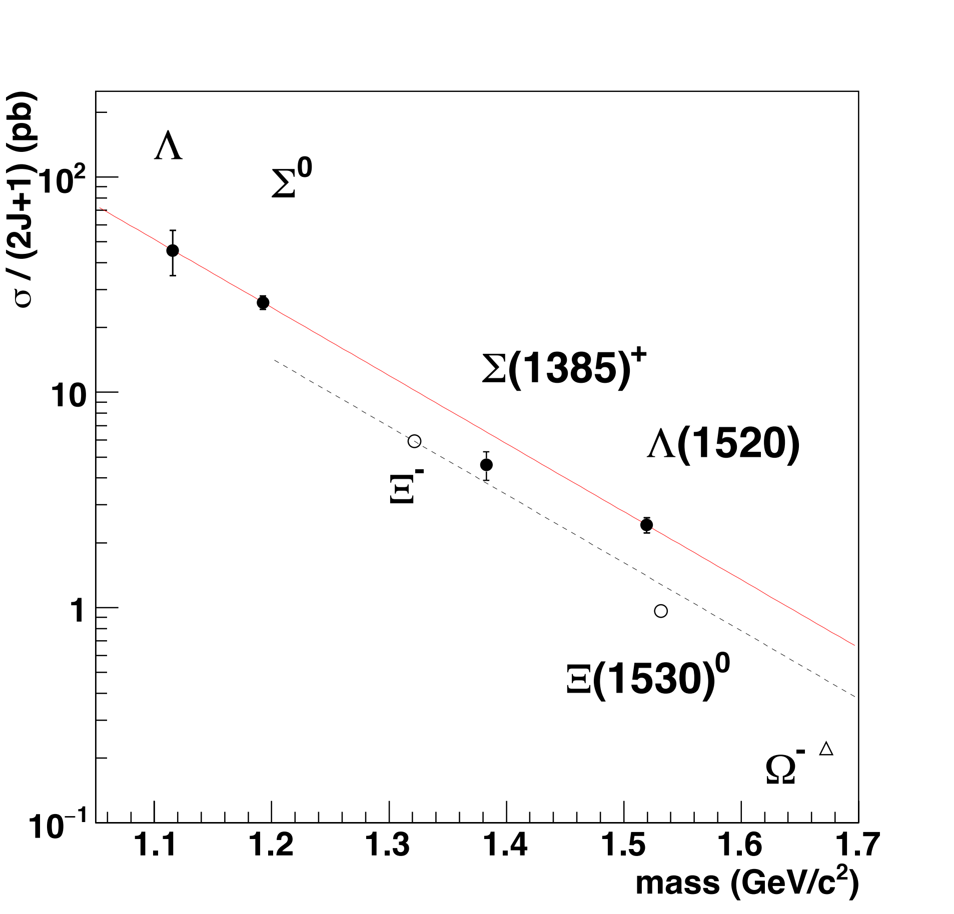
PRODUCTION OF CHARMED AND NON CHARMED BARYONS

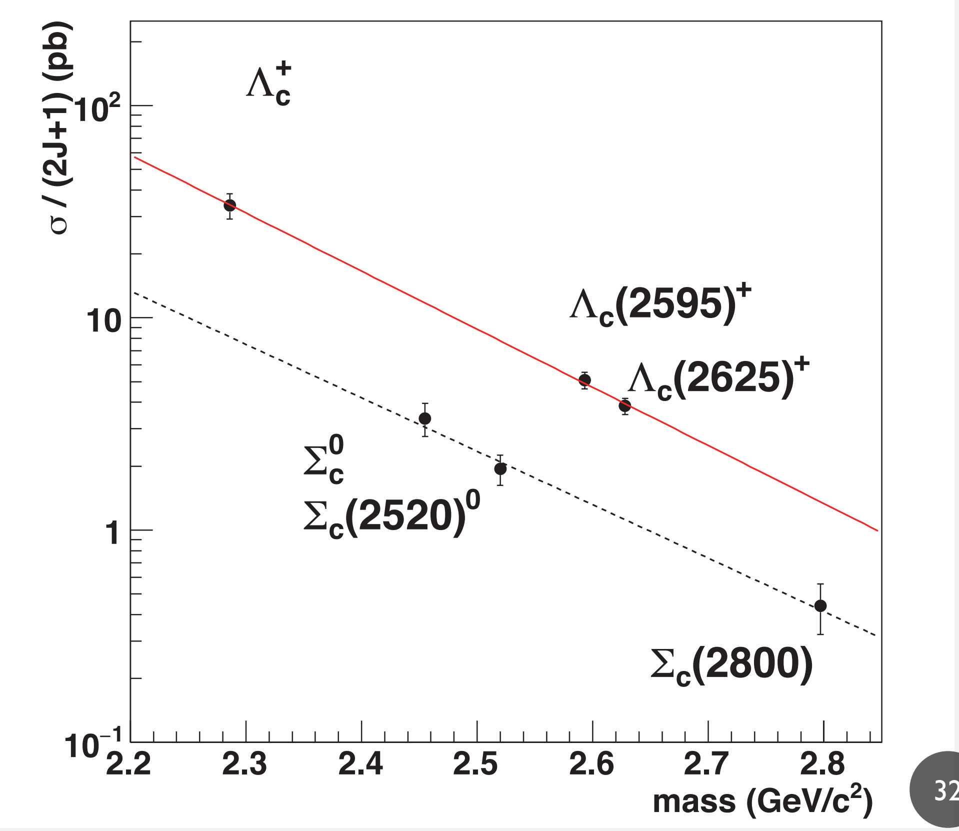




- Ξ^-, $\Xi(1530)$, Ω^- Σ_c, Ω_c, Ξ_c not shown

MASS DEPENDENCE CONFIRMS DIQUARK MODEL





OUTLINE

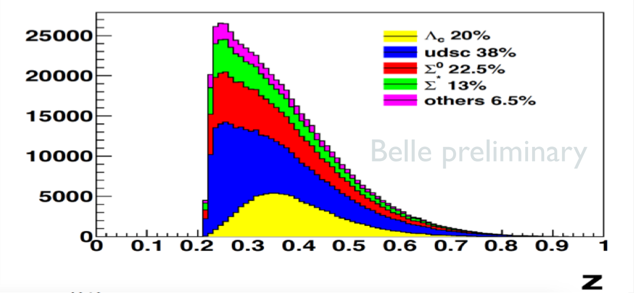
- Belle (I) Legacy
  - Quarkonium (like)
  - Hadronization (Fragmentation function measurements)
- SuperKEKB and Belle II
  - Upgrade
  - Status
  - Early Physics program
  - Outlook

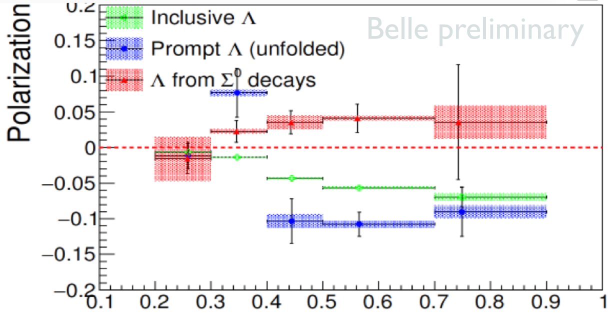
BACKGROUND UNFOLDING

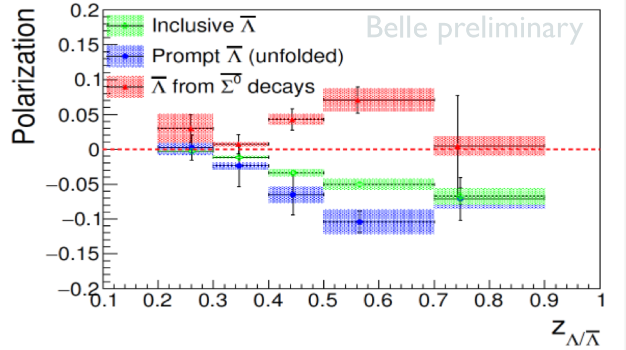
- Σ^* decays to Λ strongly, is included in the signal.
- Feed-down from Σ^0(22.5%), Λ_c(20%) decays need to be understood.
- The Σ^0-enhanced ($\Sigma^0 \rightarrow \Lambda + \gamma$) (Br~100%). and Λ_c-enhanced($\Lambda_c \rightarrow \Lambda + \pi^+$)(Br~1.07%) data sets are selected and studied.
- The measured polarization can be expressed as:

$$P^{mea.} = (1 - \sum_i F_i) P^{true} + \sum_i F_i P_i,$$

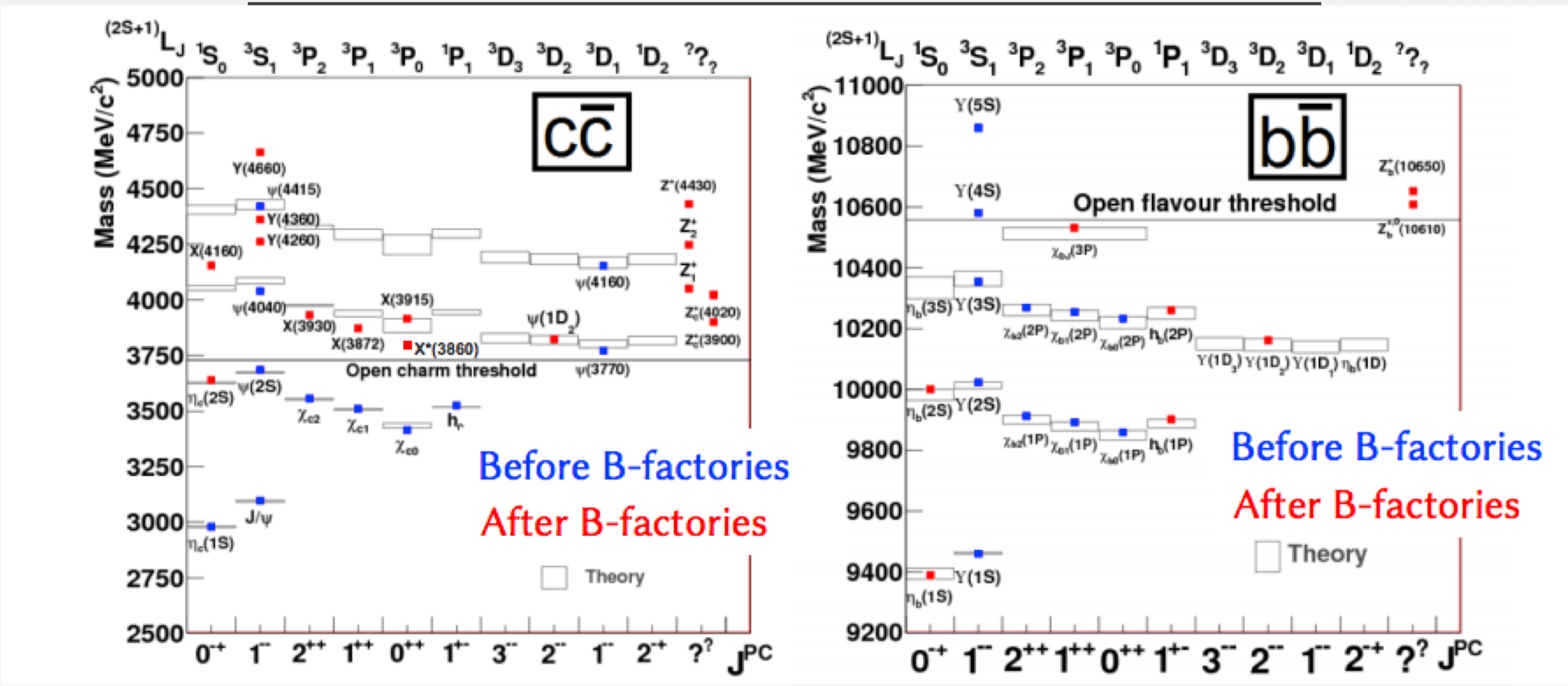
- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.







R. Gatto, Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)



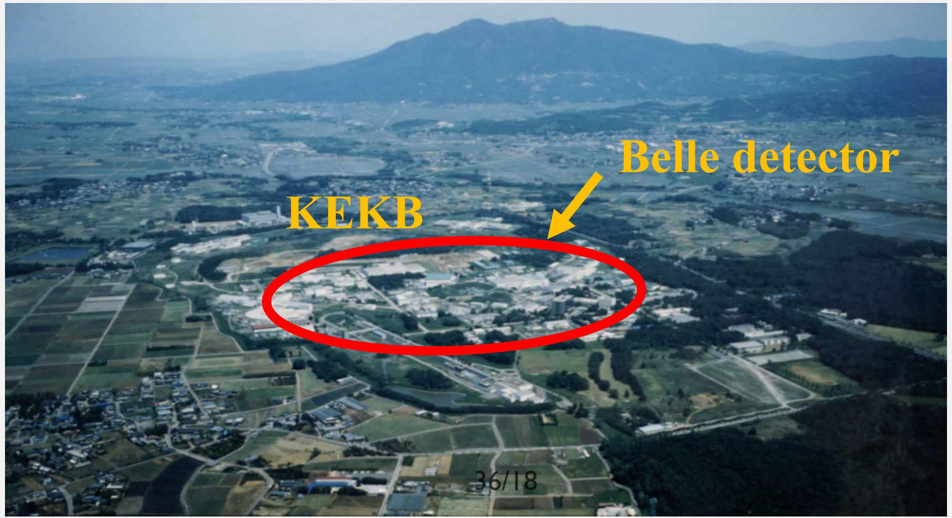
cc̄
Mass (MeV/c²)
(2S+1)LJ
Open charm threshold
Y(4660)
ψ(4415)
Y(4360)
Y(4260)
X(4160)
ψ(4040)
X(3930)
X(3872)
X(3915)
X*(3860)
ψ(1D2)
ψ(4160)
ψ(3770)
Z⁺(4430)
Zc⁺(4020)
Zc⁺(3900)
ηc(2S)
ψ(2S)
χc2
χc1
χc0
J/ψ
ηc(1S)
Before B-factories
After B-factories
Theory
0⁻⁺ 1⁻⁻ 2⁺⁺ 1⁺⁺ 0⁺⁺ 1⁺⁻ 3⁻⁻ 2⁻⁻ 1⁻⁻ 2⁻⁺ ?? JPC
bb̄
Open flavour threshold
Υ(5S)
Υ(4S)
Zb⁺(10650)
Zb⁺(10610)
χbJ(3P)
ηb(3S)
Υ(3S)
χb2(2P)
χb1(2P)
χb0(2P)
hb(2P)
Υ(1D3)
Υ(1D2)
Υ(1D1)
ηb(1D)
ηb(2S)
Υ(2S)
χb2(1P)
χb1(1P)
χb0(1P)
hb(1P)
Υ(1S)
ηb(1S)
Before B-factories
After B-factories
Theory

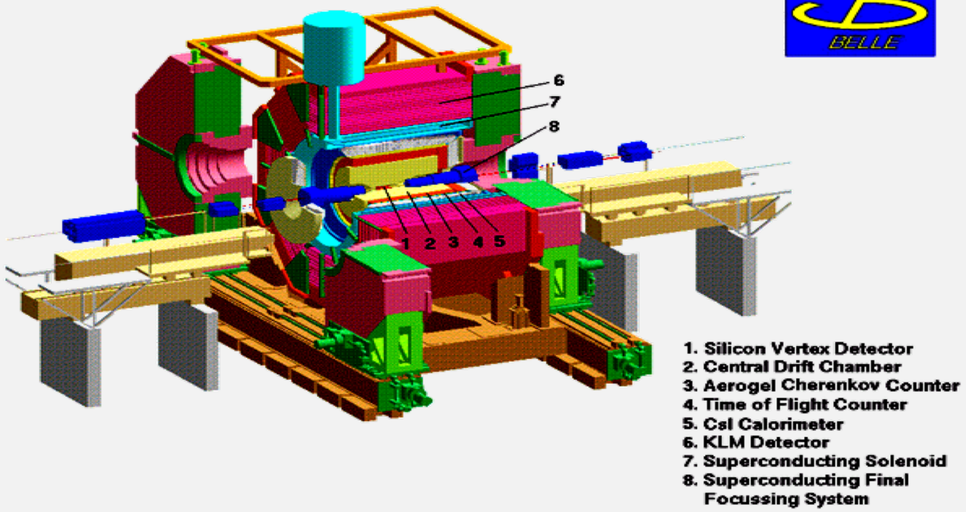
Before Belle II there was BELLE

- KEKB: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ = **10.58 GeV,** $e^+e^- \to \Upsilon(nS) \to B/\bar{B}$ + continuum
  - $\sqrt{s}$ = 10.52 GeV, e+e- → qqbar (u,d,s,c) 'continuum'
- Ideal (at the time) detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1 ab^{-1} total
  - ~1.8 $*10^9$ events at 10.58 GeV,
~220 $*10^6$ events at 10.52 GeV

Experiment	Scans/ Off. Res.	$\Upsilon(5S)$ 10876 MeV		$\Upsilon(4S)$ 10580 MeV		$\Upsilon(3S)$ 10355 MeV		$\Upsilon(2S)$ 10023 MeV		$\Upsilon(1S)$ 9460 MeV	
	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102

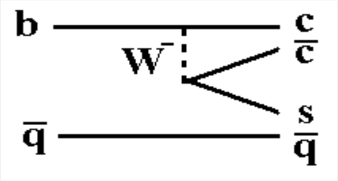
BELLE Detector (took data till 2010)



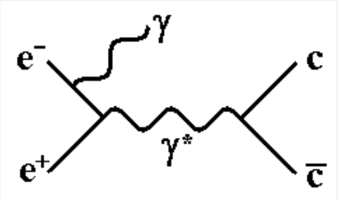


BELLE LEGACY IN HADRONIC PHYSICS – QUARKONIUM (-LIKE) PRODUCTION

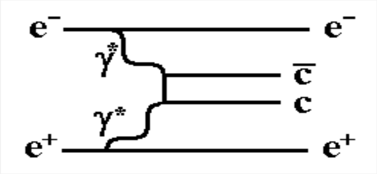
- B decays
  - Charmonium only
  - All quantum numbers available



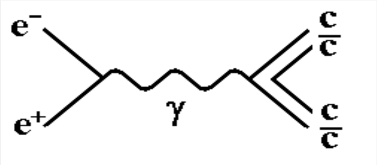
- Direct production / Initial State Radiation (ISR)
  - E_{CM} or below
  - $J^{PC}=1^{--}$



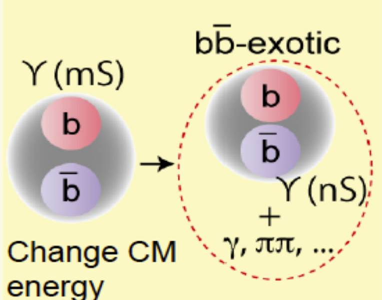
- Two-photon interaction
  - J^{PC} = 0-+, 0++, 2++



- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ (J/ψ, ψ(2S)) plus J=0 states (C=1?)

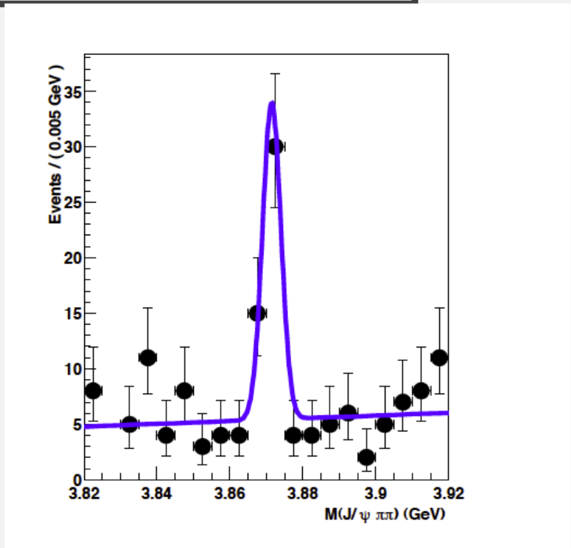


- Quarkonium transitions
  - Hadronic/radiative decays between states



QUARKONIUM STUDIES AT BELLE II BUILD ON THE SUCCESSFUL BELLE PROGRAM

- XYZ revolution kicked off by discovery of X(3872) at Belle 2003
- Precision study of Charmonium: States above the DDbar threshold are a strongsuit of B factories → can access energy spectrum continuously)
- Precision studies of Bottomium states and transitions



(Choi et al, PRL91 (26) 262001)