FCCee energy calibration using reference low energy storage ring

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BINP

FCC-ee Polarization Workshop

18-27 Oct. 2017

Goal

PDG booklet:

"The Z pole, W mass and neutral-current data
can be used to search for and set limits on deviations
from the Standard Model."

By now: m_z = 91.1876±0.0021 GeV, $\Delta m_Z / m_Z = 2.3 \cdot 10^{-5}$

One of the new high energy e+e- colliders (FCCee*,CEPC)
tasks is obtaining of $\Delta m_Z / m_Z \sim 10^{-6}$

To achieve this, the beam energy should be measured with the same accuracy.

*) For numerical estimations below we use the FCCee parameters (D.Shatilov, K.Oide. 59th FCC-ee Optics Design Meeting, 25 Aug. 2017)

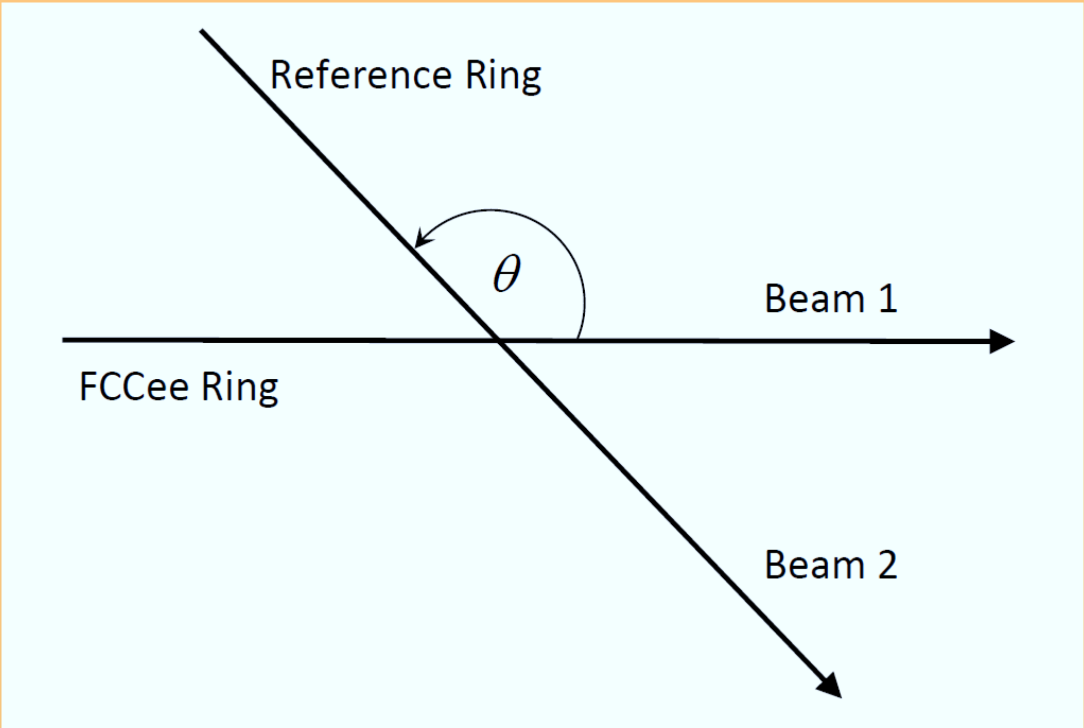
FCCee energy measurement techniques

- Resonant depolarization (Blondel, Wenninger, …)
- Laser Compton method with registration of electrons/positrons which lose energy (Muchnoi)
- Waveguide Compton monitor of beam energy. The accuracy of 10^{-4} is relevant rather in experiment on the top-quark mass measurement at 175 GeV (Nikitin/Levichev)
- Kinematic reconstruction of events under elastic scattering of beam particles on quasi-rest electrons of internal target (Koop)

The methods are either not so good (do not give a full guarantee for the required accuracy of $\sim10^{-6}$) or as one of them is suitable not for the Z mass measurement, but for the t-quark one. By this reason

we dare to study another one

Lorentz invariant of collision



$$M^2 = 2E_1E_2(1+\cos\theta)$$

= squared energy in center-of-momentum frame=
=squared mass of two colliding particle system

Concept briefly

- We propose to build two additional low energy storage rings around FCCee IP (ring length is ~200-300 m)
- They cross the main FCCee rings at large angle θ to produce in collision narrow resonances (either J/Psi or Y) used as reference points (like isotope lines in Compton Backscattering method)
- Energy E_2 of reference ring is changed and measured using RD with accuracy of~10^{-6} in several points of resonance curve
- Fitting experimental data we find position of resonance peak on RR energy scale (related E_2)
- FCCee beam energy E_1 is determined using PDG value of resonance mass $M=M_r$, precise knowledge of crossing angle θ and related value of E_2.

Precision estimate

Total error

$$\frac{\Delta E_1}{E_1} = 2\frac{\Delta M_r}{M_r} - \frac{\Delta E_2}{E_2} + \frac{\sin\theta}{1+\cos\theta}\cdot\Delta\theta$$

is minimal at $\theta = 0$. Obviously, such case is excluded.

Case $\theta \to \pi$ is unacceptable ($E_2, \Delta E_1 / E_1 \to \infty$).

Case $\pi / 2 \le \theta < \pi$ would be compromise option.

Case $0 < \theta \le \pi / 2$: too low RR energy required.

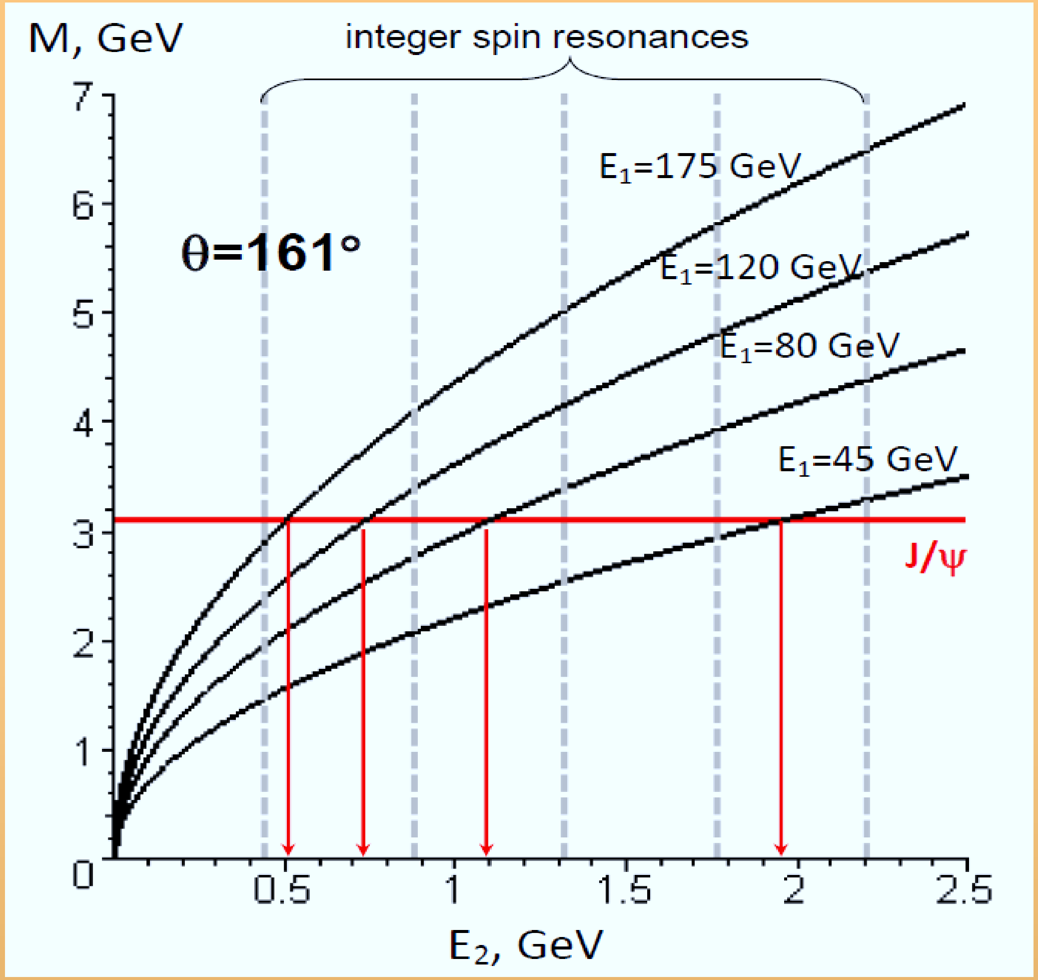
Different kinematic schemes were considered depending on crossing angle and kind of narrow resonance chosen as benchmark with option of beam reversal. For instance:

FCCee energy E_1, GeV	Crossing angle θ	Reference Ring energy E_2, GeV	Benchmark	Beam rotation direction
45	90^0	1	Υ_1 and Υ_1	clockwise/anti-clockwise
	135^0	3.4	Υ_1	-
	144^0	0.55	J/ψ and Υ_1	clockwise/anti-clockwise

Beam reversal, combined with use of precision BPM, makes it possible to dispense with accurate measurement of θ.

Below, we consider another option that seems more universal, accurate and effective

J/ψ meson as benchmark



To produce J/ψ we need:
At **θ=161°**
FCCee energy **E1=45 GeV**,
RR energy **E2=1.95 GeV**;
…
FCCee energy **E1=175 GeV**,
RR energy **E2=0.6 GeV**.
All spin integer resonances in RR are avoided.

For comparison,
at **θ=144° , E2=0.550 GeV**.
No possibility to apply for 80, 120 and 175 GeV because of too low values of E_2

We need to know crossing angle with accuracy~10^{-6} rad

Luminosity on non-collinear beams

Equation for luminosity is derived from its general definition (Möller, 1947):

$$L = \frac{1}{c}\int d^3\vec{x}\, dt\; \rho_+(\vec{x},t)\rho_-(\vec{x},t)\cdot\sqrt{c^2(\vec{v}_+ - \vec{v}_-)^2 - (\vec{v}_+ \times \vec{v}_-)^2}$$

Single collision luminosity at an arbitrary crossing angle θ

$$L_{sc} = \frac{1}{2\pi\sqrt{(\sigma_{v1}^2 + \sigma_{v2}^2)\cdot(\sigma_{h1}^2 + \sigma_{h2}^2)\cdot\left(1 + \underbrace{\frac{\sigma_{l1}^2 + \sigma_{l2}^2}{\sigma_{h1}^2 + \sigma_{h2}^2}\tan^2\frac{\theta}{2}}_{\text{Generalized Pivinski's parameter}}\right)}}$$

$\sigma_{...}$ - beam sizes; *v*- vert., *h* –hor., *l* –long. denote own coordinate axes of each ring ; $\sigma_l << \beta_v$ (no change of sizes over interaction range).

Orthogonal single collision θ=90°:

$$L_{sc} = \frac{1}{2\pi\sqrt{(\sigma_{v1}^2 + \sigma_{v2}^2)\cdot(\sigma_{h1}^2 + \sigma_{h2}^2 + \sigma_{l1}^2 + \sigma_{l2}^2)}}$$

Total luminosity

$$L = f_0 \cdot N_{B2} \cdot N_{p1} \cdot N_{p2} \cdot L_{sc}$$

f_0 = FCCee revolution freq.; N_{B2} = number of bunches in RR;

N_p =particle number per bunch; same duty ratio in FCCee and RR.

COM energy spread and shift

Mean COM energy at accounting the angular ($\delta_{v,h}$) and energy (σ_E) spreads

$$\overline{M} \approx \sqrt{2E_1E_2(1+\cos\theta)}\left\{1-\frac{1}{4(1+\cos\theta)}\cdot\left[\frac{E_1}{E_2}\left(\delta_{h1}^2+\delta_{v1}^2\right)+\frac{E_2}{E_1}\left(\delta_{h2}^2+\delta_{v2}^2\right)\right]-\frac{1}{8}\left(\sigma_{E1}^2+\sigma_{E2}^2\right)-\frac{1}{8}\frac{\sin^2\theta}{(1+\cos\theta)^2}\left(\delta_{h1}^2+\delta_{h2}^2\right)\right\}$$

COM energy shift

$$\Delta M = \overline{M} - \sqrt{2E_1E_2(1+\cos\theta)}$$

COM energy dispersion

$$\sigma_M^2 = \overline{M^2} - \overline{M}^2 = \frac{1}{2}E_1E_2(1+\cos\theta)\cdot\left[\sigma_{E1}^2+\sigma_{E2}^2+\frac{\sin^2\theta}{(1+\cos\theta)^2}\left(\delta_{h1}^2+\delta_{h2}^2\right)\right]$$

Energy resolution in determination of the resonance

$$\frac{\sigma_M}{\sqrt{N_e}} \sim \frac{\sigma_M^{3/2}}{\sqrt{\tilde{L}\sigma\Gamma}},$$ N_e - number of events, σ - the resonance cross section in the peak,

Γ - the resonance width, $\tilde{L}$ - the luminosity integral collected

Main factors for option choice

- RR energy: not so high and not so low . $E_2 \sim 0.5$ -2 GeV from the view point of polarization and luminosity issues

- Focus on using J/Psi benchmark which has the largest cross section and best accuracy (effective cross sections below are given for VEPP-4M and VEPP-4 colliders with $\sigma_M = 0.67$ MeV at J/ψ and $\sigma_M = 4.5$ MeV at Υ_1)

J/ψ	ψ'	Υ_1
3800 nb	**700 nb**	**18nb**
2 ppm	**2.7 ppm**	**~10 ppm**

Example of J/ψ reference collider

Parameters	FCCee	Reference Ring
beam energy E, GeV	45	1.95
circumference, km	97	0.2
hor. emit. ε_h, nm	0.27	10
v. emit. /h.emit. ε_v pm	1	100
vert. IP optics β_v^*, cm	5	0.2
hor. IP optics β_h^*, cm	20	10
beam length σ_l, cm	0.35	0.5
hor. ang. spread δ^*_h, rad	$3.7 \cdot 10^{-5}$	$3.2 \cdot 10^{-4}$
energy spread σ_E	$3.8 \cdot 10^{-4}$	$3 \cdot 10^{-4}$
bunch population N_p	$1.7 \cdot 10^{11}$	$3 \cdot 10^{10}$
bunch number N_B	$1.7 \cdot 10^4$	200
crossing angle θ, °	161	
resonance mass M, MeV	3097	
inv.mass spread σ_M, MeV	3.04	
max luminosity L, $cm^{-2}.s^{-1}$	1.3×10^{33}	
max event rate $\dot{N}_e$, kHz	3.4	
amount of E_2 points n	5	
max $\int L dt$ pb^{-1}	4	
effective resolution ε_M, keV	2.8	
min time to position J/ψ, min	50	

BB tune shifts at non-collinear collision

Horizontal and vertical tune shifts of probe particle

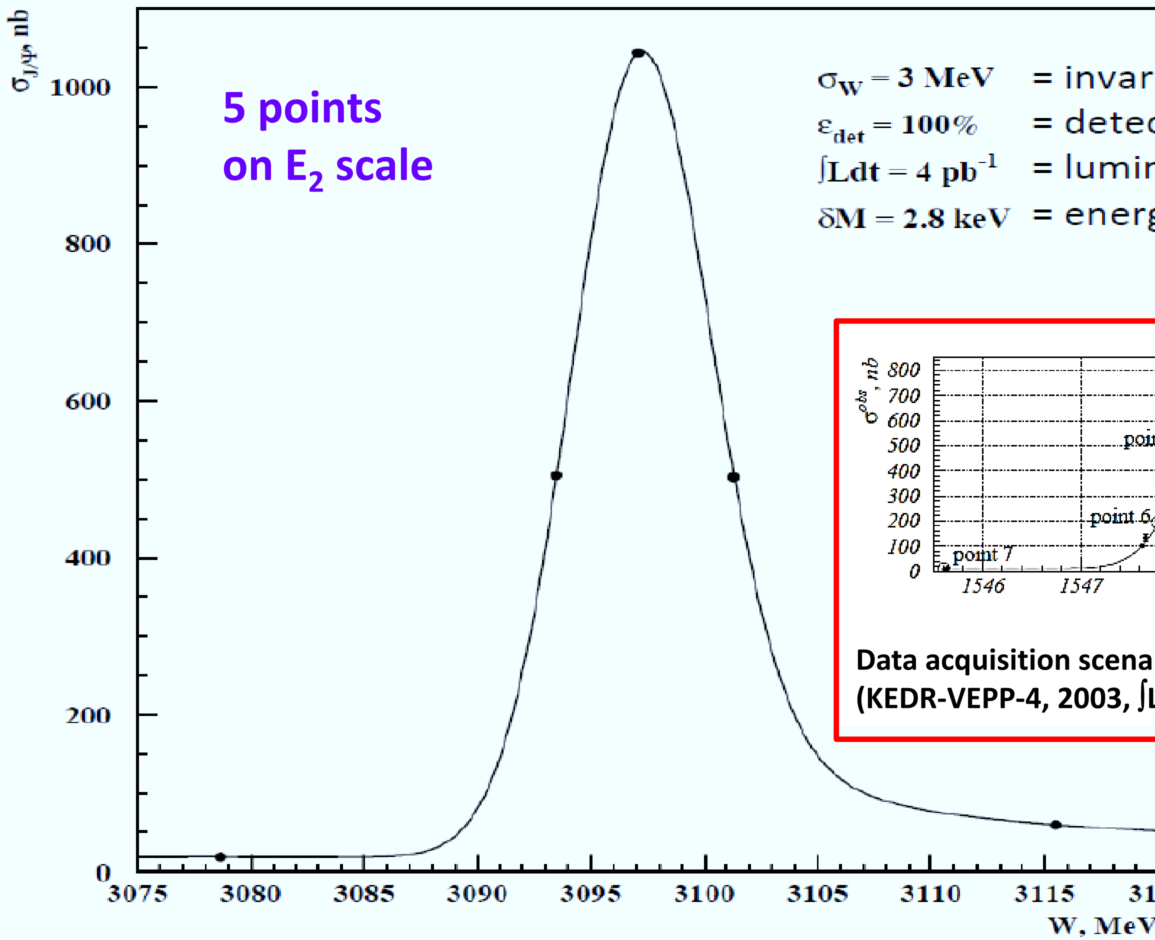
(M.Zobov, D.Shatilov. DAΦNE Technical Note G - 59, 2003)

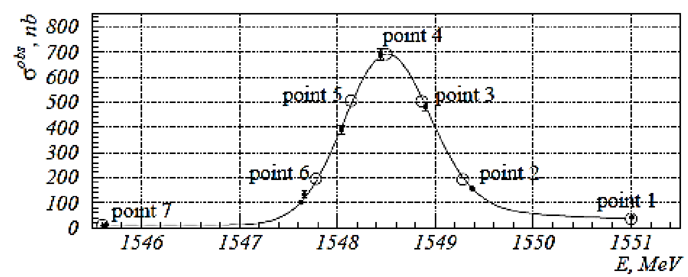
$$\xi_h = \frac{r_e N}{2\pi\gamma} \frac{\beta_h^*}{\sqrt{\sigma_l^2 \tan^2(\theta/2) + \sigma_h^2}\left[\sqrt{\sigma_l^2 \tan^2(\theta/2) + \sigma_h^2} + \sigma_v\right]}$$

$$\xi_v = \frac{r_e N}{2\pi\gamma} \frac{\beta_v^*}{\sigma_v\left[\sqrt{\sigma_l^2 \tan^2(\theta/2) + \sigma_h^2} + \sigma_v\right]}$$

For Reference Collider parameters at previous slide the tune shifts are very small. In particular, ξ_v=0.008, $\xi_h=4\cdot10^{-6}$ for probe particle from RR beam. This allows us to hope for a realistic estimate of the luminosity

Model fit of experimental data to position J/ψ on RR energy scale with 10^{-6} resolution



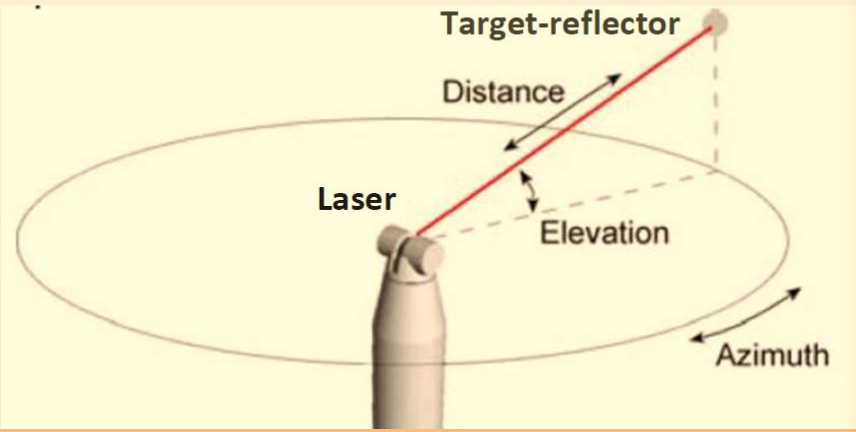


Data acquisition scenario for J/ψ and actual points (KEDR-VEPP-4, 2003, $\int Ldt=50\ nb^{-1}$, $\sigma_W=0.67$ MeV)

Andrei Shamov (KEDR Team, BINP)

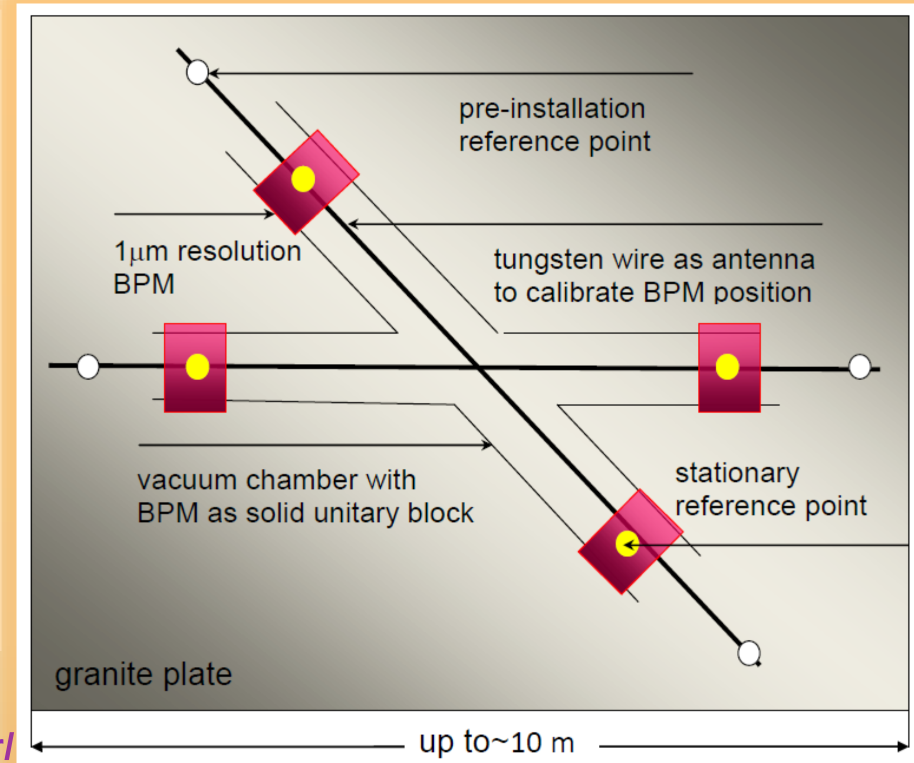
At 1.3×10^{33} max luminosity of ‘benchmark collider’ with crossing angle $\theta=161^{\circ}$, it is required to spend at least 50 min, i.e. to take 4 pb^{-1}, for positioning J/ψ resonance on RR energy scale with statistical error of 2.8 keV.
For comparison, PDG accuracy of J/Psi mass is determined by systematic error of 6 keV (2 ppm).
Error of fitting increases total error by 10%.

Determination of crossing angle using Laser Tracer



Laser Tracer –NG	
Measuring uncertainty for spatial displacement (95%)	0.2 µm + 0.3 µm/m
Resolution	0.001 µm
Measuring range	0.2 –20 m

http://www.etalon-ag.com/en/products/lasertracer/



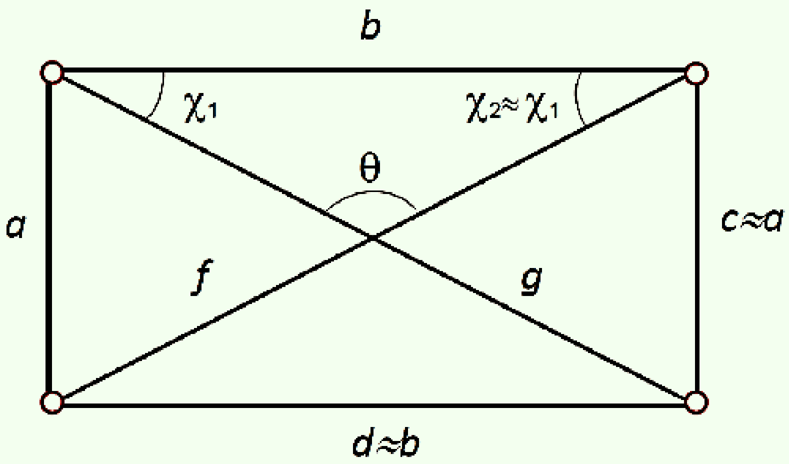
- **LT** measures the 3D location of a mobile target with an accuracy of a **few microns**, over a range of **tens of meters.** To find the angle one needs to **measure 6 distances** among **4 reference points**
- **BPM electrical center location** is found using a tungsten wire as antenna, stretched inside the vacuum chamber between two reference points

Pre-installation and regular geodesic tests

- Pre-installation reference points are intended to determine the crossing angle before installing the X-form vacuum chamber section with four BPMs into the ring structure. Simultaneously, the electrical BPM null positions should be calibrated using the tungsten wire as antenna. The wire is rigidly attached to pre-installation geodesic marks.
- Stationary reference points are needed to occasionally check the intersection angle based on the current BPM data during the experiment.
- It allows consideration of the extended deformations of the vacuum chamber. Mutual arrangement of the BPM electrodes are assumed to remain unchanged.

Length measurement error contribution

Quasi rectangle case:



$$\cos\chi_1 = \frac{g^2 + b^2 - c^2}{2gb}$$

$$\cos\chi_2 = \frac{f^2 + b^2 - a^2}{2fb}$$

$$\theta = \pi - \chi_1 - \chi_2$$

r.m.s. error $\quad \delta\theta \le 2\frac{\delta L}{L}\cot\frac{\theta}{2}, \qquad \frac{\delta L}{L} = \max\left\{\frac{\delta a}{a}, \frac{\delta b}{b}, \frac{\delta c}{c}, \frac{\delta f}{f}, \frac{\delta g}{g}\right\}$

$$90^\circ < \theta < 180^\circ \;\rightarrow\; \delta\theta < 2\frac{\delta L}{L}$$

Contribution to $\frac{\delta E_1}{E_1} = \ldots + \frac{\sin\theta}{1+\cos\theta}\delta\theta = \ldots + 2\frac{\delta L}{L}\cdot\frac{\sin\theta}{1+\cos\theta}\cdot\cot\frac{\theta}{2} = \ldots + 2\frac{\delta L}{L}$

No dependence on θ!

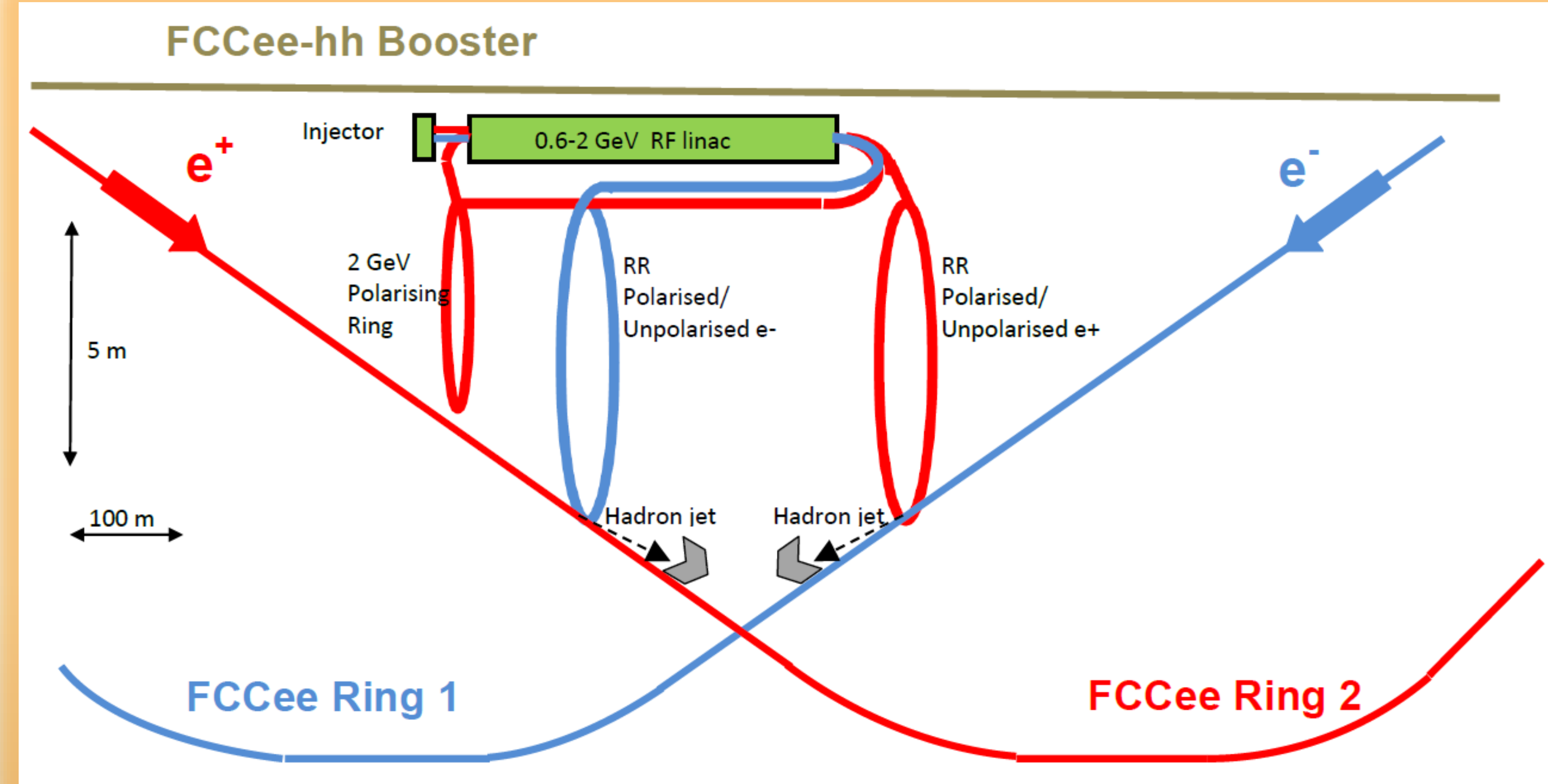
Estimate of total error at J/ψ benchmark

$$\underbrace{\left(\frac{\delta E_1}{E_1}\right)^2}_{\substack{\text{FCCee} \\ \text{energy} \\ \text{uncertainty}}} = 4\left[\underbrace{\left(\frac{\delta M_{J/\psi}}{M_{J/\psi}}\right)^2}_{\substack{\text{PDG} \\ 2^2\ \text{ppm}^2}} + \underbrace{\left(\frac{\delta L}{L}\right)^2}_{\substack{\text{Laser Tracer,} \\ \text{BPM} \\ \sim 1^2\ \text{ppm}^2}}\right] + \underbrace{\left(\frac{\delta E_2}{E_2}\right)^2}_{\substack{\text{Res.Dep.} \\ \sim 1^2\ \text{ppm}^2}} + \underbrace{\left(\frac{\delta E_2}{E_2}\right)^2}_{\substack{\text{Syst. error} \\ \sim 2^2\ \text{ppm}^2 \\ \text{like at} \\ \text{VEPP-4M}}} \approx 5^2\ \text{ppm}^2$$

At VEPP-4M luminosity was several orders of magnitude lower, and long-term stability was worse than we expect in case of reference collider. But σ_M in VEPP-4M is several times smaller (0.7 MeV versus 3 MeV). Systematic error like in VEPP-4M, given above, allows for some reserve upward.

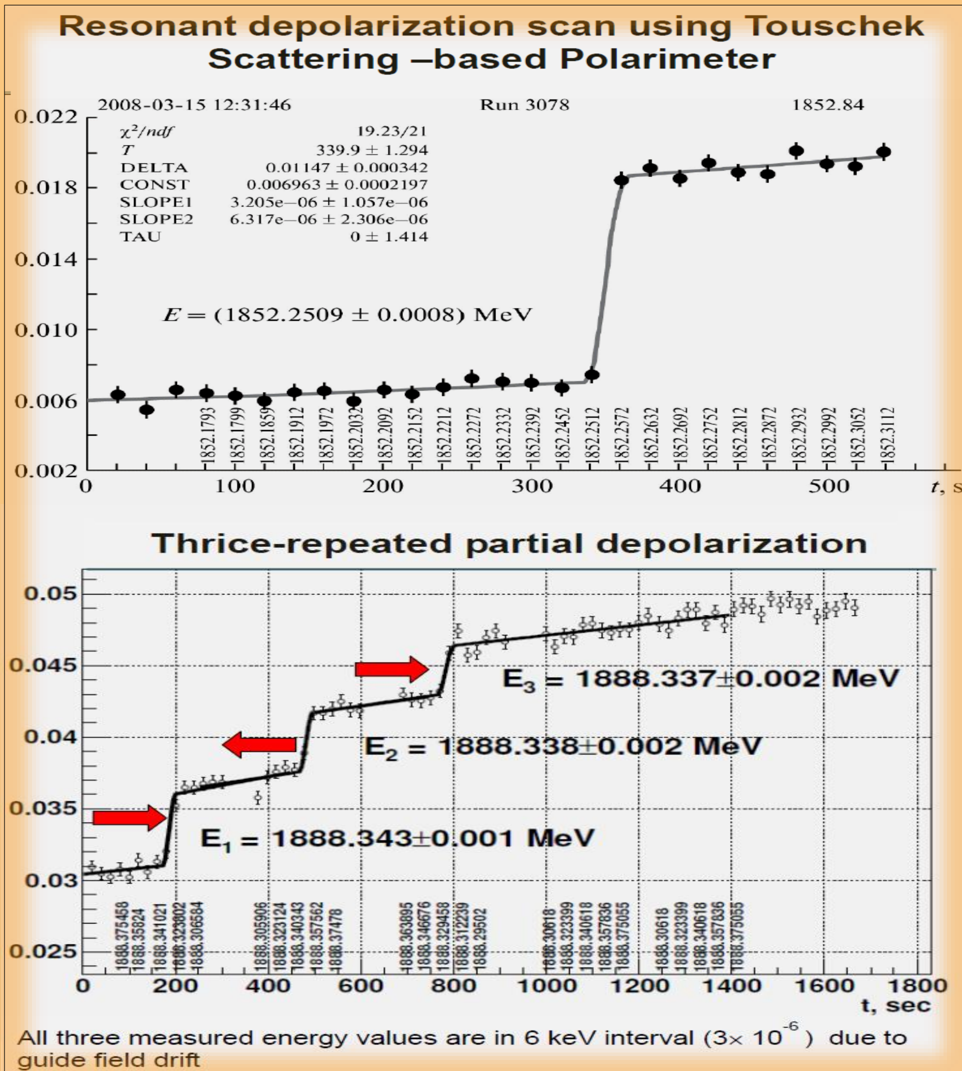
It is worth thinking about clarifying the J/ψ mass in new series of experiments (KEDR-VEPP-4M again?)

Supposed layout of RRs and related setups



Attention! The vertical and horizontal scales strongly differ!

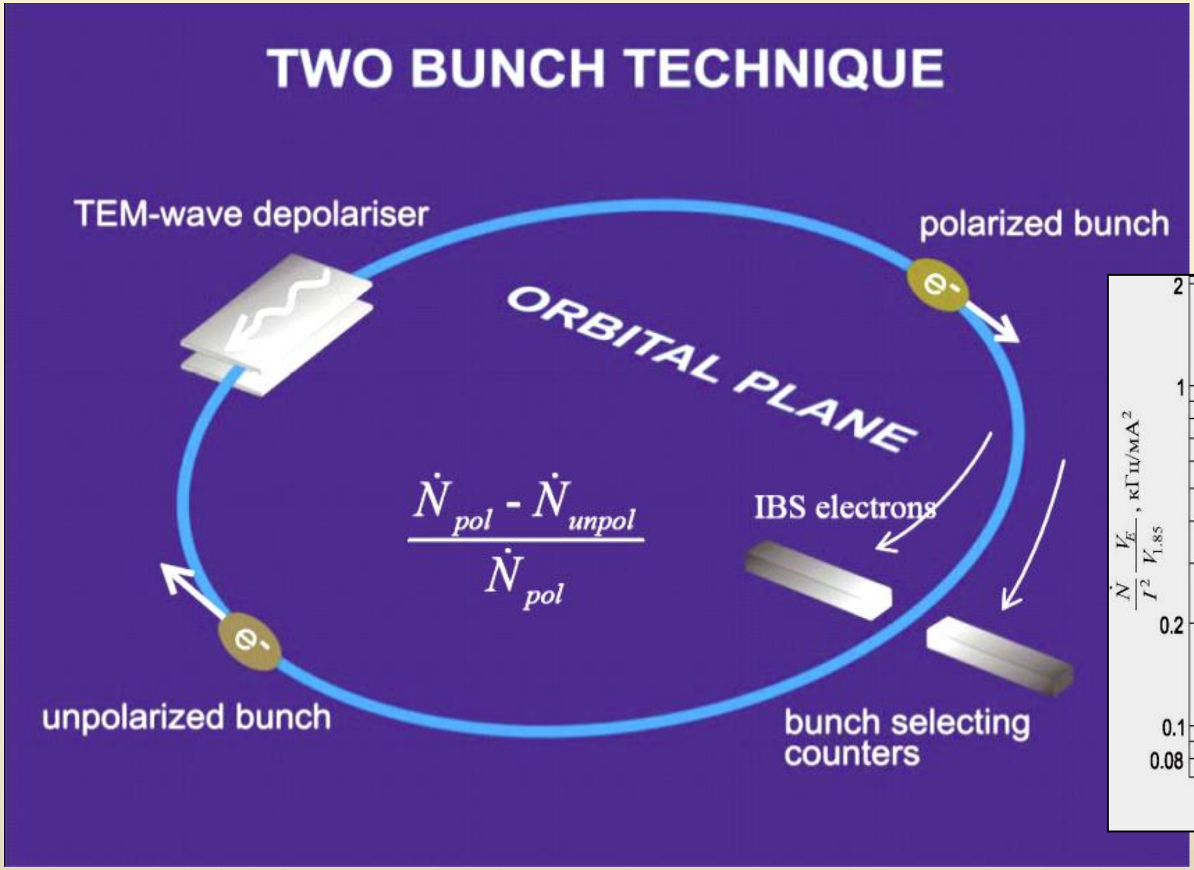
10^{-6} accuracy Resonant Depolarization technique to measure energy at VEPP-4M



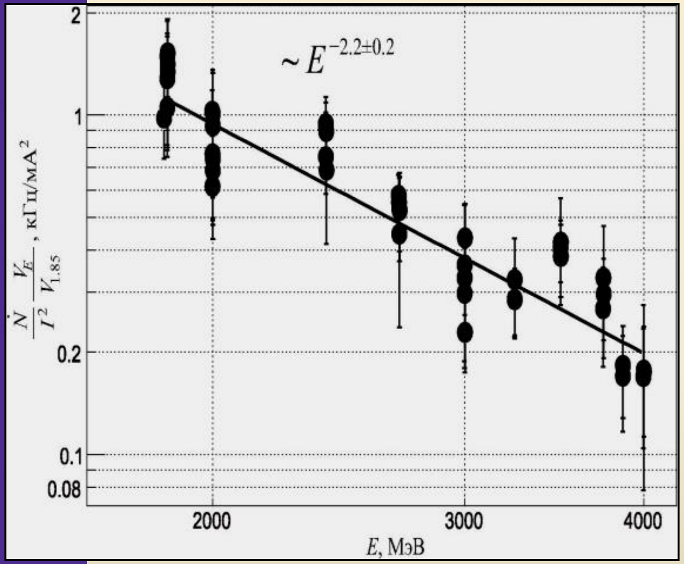
Particle	$\Delta m/m$, *ppm*
n	0.04
p	0.04
e	0.04
μ	0.09
J/ψ	2.0
$\pi^{\pm}$	2.5
ψ'	2.7
π^{0}	4.5

PDG data (red) based on KEDR-VEPP-4M experiment

Touschek polarimeter



Counting rate normalized on beam volume and squared current vs beam energy (VEPP-4M measurement)



In supposed RR energy range 0.6÷2 GeV, expected efficiency of Touschek polarimeter is high!

‘Free bonus’ of reference collision

- **Experiments using longitudinal polarization in the electron RR** **(Siberian Snake added)**
  - It is enough to have the longitudinal polarization with a changeable sign of helicity in one of the colliding beams (no polarization in the e+ main ring needed)
  - Measurement of the parameters of weak interaction by means of the production of J/ψ and Υ_1 mesons in e+e- annihilation
  - LP increases a sensibility of experiments on search of CP violence in tau -lepton decays in several times
- **Production of ditaonium (bound state of $\tau^+ \tau^-$) which is a heaviest leptonic atom sensitive to a New Physics**

These interesting opportunities are worth exploring

Discussion

- FCCee beam energy can be determined at a relevant level if the crossing angle θ can be defined and monitored with good accuracy

- We choose the J/Psi peak like an isotope calibration line because of its high cross section and best accuracy data on mass

- Necessary accuracy in pre-installation determination of θ can be made using present Laser Tracers in combination with electrical calibration of BPM positions

- Because of a large boost the space over IP section of a few meters scale is free to arrange geodesic means of crossing angle monitoring

- Beam energy is determined just in the straight section with the main IP (no systematics related to the radiative energy loss)

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- Reference method with J/ψ as benchmark at θ=161° works across the entire working spectrum of FCCee energy from 45 GeV to 175 GeV. All spin integer resonances in RR are avoided.

- Hadron jet detector should be similar to those applied in fixed target experiments. It is remote from IP of reference collider to distance of several meters or more (large boost!).

- As compared with assumed complicated use of RD technique directly at supercollider rings, the Reference Collider method allows application of that at small rings in the convenient range from 0.5 to 2 GeV, where a great deal of corresponding experience has been accumulated at VEPP-2M and VEPP-4/VEPP-4M.

- No need to obtain polarization in the FCCee ring at 175 GeV, where depolarizing effect of resonant spin diffusion (the instant spin tune spread due to the energy spread ~ 1) dominates.

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- With longitudinal polarization in the reference electron ring, the reference high luminosity collider makes it possible to carry out the experiments on measuring vector weak coupling constant of b-quark with Z-boson in the region of intermediate energies (at J/ψ and Υ_1 resonances). They should supplement the similar experiments performed at Z-pole and atomic transitions.

- Another attractive bonus of Reference Collider may be hypothetical opportunity to study ditaonium production

- In spite the method needs additional storage rings, their length and cost are negligible compare to the whole FCCee project!

Acknowledgment

We thank E.Bekhtenev, A. Blinov, D.Burenkov, A.Milstein, A.Polyansky, A.Shamov, D.Shatilov, K.Todyshev for participation in discussions on problems concerned

Thank you for attention!